IEEE

International Network Generations Roadmap

-2021 Edition-

Executive Summary

IEEE Future NETWORKS™

An IEEE 5G and Beyond Technology Roadmap

futurenetworks.ieee.org/roadmap

This edition of the INGR is dedicated to the memory of Earl McCune Jr., who left us tragically and too soon on 27 May 2020. Earl was a microwave/RF guru, brilliant technologist, major industry/IEEE contributor, global visionary, keen skeptic, and all around fantastic human being. He was a major contributor to the INGR's early work on energy efficiency, millimeter-wave, and hardware. He worked for a technologically advanced yet more energy efficient world, and the contents of the INGR are a tribute to that vision. Rest in peace, Earl!

EXECUTIVE SUMMARY

1. A DAY IN THE LIFE AT THE INTRODUCTION OF 6G

The year is 2031. The fifth generation of communications networking technology is finishing its run as the mobile network of the last decade. You're beginning to read about early deployments of 6G and you're expecting even more exciting things coming from 6G than you've enjoyed with 5G.

At Home

The 5G networks allowed you to move into a previously "unconnected" area that still has not been reached by fiber and cable networks. This meant you could move to this bucolic setting and still have high-speed Internet access through a heterogeneous network that combines 5G with non-terrestrial networks, including satellite systems.

As you get ready to make the trip into the city, you get an alert to remind you that the grocery store will be delivering the perishable groceries your refrigerator had ordered for you. The groceries arrive exactly on time and you quickly get them into your refrigerator without delaying your departure.

As you wait for your delivery, you realize that your diet has improved over the years. The precision farming techniques that were developed with the help of 5G make it possible to buy much of your produce locally and at attractive prices.

This improved diet has definitely improved your health. It also helps that any health issues that arise are addressed quickly and with little wait by accessing telemedicine technologies that approximate a visit to the doctor's office without the long waits.

In Manufacturing

As lovely as your country home is, today you are traveling into the city to look into an issue that developed with some equipment at your manufacturing facility. You were alerted across all your devices that a sensor element seemed to be providing faulty data and may need a recalibration, or replacement.

Of course, the ordering of a new sensor could have been initiated automatically, and an appointment made with a technician to replace the part. Plus, you had already looked over the plant with an augmented reality (AR) app and leveraged tactile capabilities to troubleshoot the issue. Indications were that robot assistance couldn't adequately address the problem.

But you decided to go into the city and look for yourself—it gives you an opportunity to meet up in-person with old friends. As you think about your upcoming social engagement, you wonder if you will still feel this same way when 6G networks offer holographic video conferencing.

Transportation

Small delays to your trip are not too much of a concern because you're confident that there won't be any traffic issues driving into the city. With 5G networks there's been a sharp decrease in the number of traffic accidents since the advent of Intelligent Transportation Systems (ITS) and Vehicle-to-Anything (V2X) communications.

You've also noticed over the last 10 years that not only is there less traffic, but also the air seems clearer as a result. Of course, you're able to ponder all these changes because most of the driving is being automated for you and the cars around you.

You get to the plant without delay or incident at which point you realize it makes more sense to just automate the delivery of the part and let the ordering system arrange an appointment with the technician to replace it. This gives you even more time to visit with your friends and get back home in time for dinner.

2. The Road to 2031

Creating a predictive model for mobile networks

Both this vision of 2031 described above and the applications that will likely be enabled by the late stages of 5G are essentially based on broad improvements to providing data over mobile networks, namely: Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communication (URLLC) and Massive Machine-type Communications (mMTC).

However, our glimpse into the future of 2031 is based on current thinking of the applications and capabilities we expect to see develop out of 5G networks as they evolve into a next-generation network. We can reasonably expect that circumstances may lead to other applications coming to the fore that we had not fully considered.

For instance, if we go back to the introduction of 2G, much of the excitement was the ability to offer digital voice rather than analog. This prediction didn't fully recognize that text messaging would become so important to users. It was also expected that 3G would address an anticipated demand for video conferencing. While video conferencing has become an important application, it didn't fully emerge with 3G networks. Finally, 4G was thought to be primarily for multimedia and voice services, namely video. While that certainly has happened in a significant way (YouTube and WhatsApp), one could argue that 4G found its lifeblood in the massive app economy and non-video/voice apps, like Uber, Twitter and notification pushes.

Predicting the applications that will result from a new generation of mobile networks is challenging, and perhaps even more so with 5G and Beyond networks. Unlike previous mobile generations, 5G was not built to address a single perceived need. Instead, 5G is somewhat different in that it will be addressing an overall trend of creating higher data efficiency and greater bandwidth rather than meeting a specific application demand.

This combination of only identifying a broad improvement of delivering data with the inherent challenges in predicting what applications will come out of a new mobile network indicates two things. First, with only a generic aim of improved data, we should be cautious about expecting that 5G will automatically usher in the kind low-latency applications we are expecting, or, for that matter, any other specific application. Second, and perhaps more importantly, it's become clear that we need to improve our predictive models for building roadmaps for future mobile networks.

The challenges of predicting the directions for a new mobile generation extend beyond merely knowing how applications will develop. More importantly, this lack of a robust predictive model makes it difficult to detect future inflection points that may come our way. If we can see these inflection points coming, industry can preemptively find solutions to prevent those inflection points from becoming disruptions.

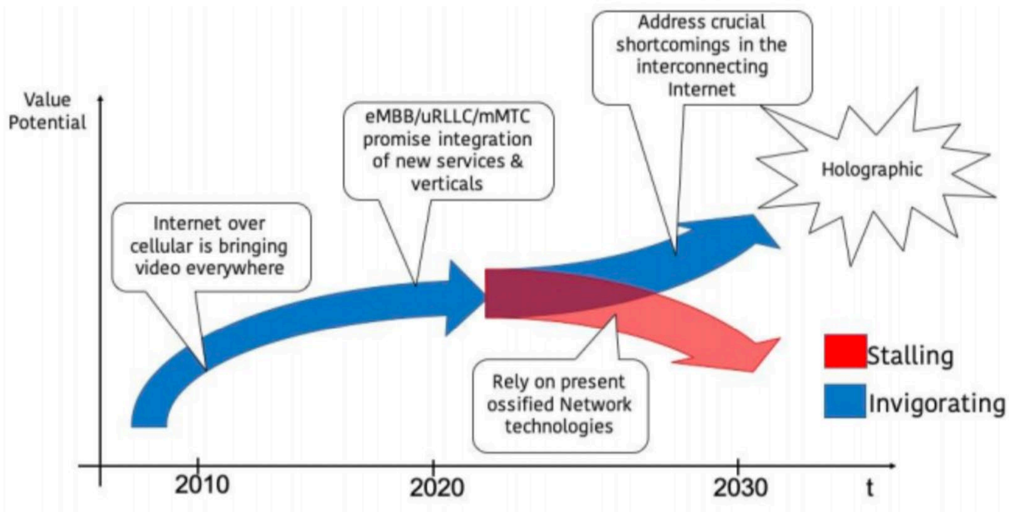

Figure 1. Source: Paolo Gargini, INGR

During the last three decades of evolving generations of mobile communications, we have managed to overcome any pitfalls that have sprouted up. As a result, we have overlooked how critical a roadmapping tool can be. However, now it seems we have reached an inflection point that is far more fundamental than new signaling protocols or new modulations, and our habit of handling these issues when they suddenly appear may no longer be a viable approach.

We need to have landmarks on the evolutionary path from 5G to 6G that go beyond after-the-fact recognitions of little more than coincidences, such as the observation that all the even numbered mobile generations (i.e., 2G and 4G) are likely the ones with the more significant impacts.

It would certainly be helpful for mobile networks to have a predictive model like Moore's Law, which has guided the way for the chip industry for more than five decades. But developing a similar predictive tool with its extremely regular biannual waypoints has proven elusive for the mobile industry.

3. INGR's Purpose

The challenge associated with developing more robust predictive models is precisely why the IEEE International Network Generations Roadmap (INGR) was created under the IEEE Future Networks Initiative. The aim of the INGR is to provide a roadmap to identify challenges or inflection points, so that industry and the research community can generate solutions to these issues before they become disruptions.

These solutions do not necessarily have to come from within the INGR. The INGR may propose potential solutions, but we do not profess to have a crystal ball. Instead, INGR will serve as both an investigator and aggregator of these challenges and solutions, so there is a resource that serves as a unified understanding of where future communication networks are headed. The aim is to create a feedback loop among all the stakeholders in the evolution of 5G networks, including academia, industry, standards development organizations (SDOs) and the INGR itself.

It is the belief of both individual INGR members and collectively that wide participation of all the stakeholders will mitigate some of the technical and engineering risks associated with future networks.

The INGR started in 2017 as a white paper with 37 contributors. Since then, we have grown into 15 distinct working groups made up of more than 100 experts spanning industry, academia and research labs. The first full edition of the INGR was published in December 2019. New editions or updates will be published annually.

4. Challenges of 5G and Beyond

All of the chapters of the 2021 Edition of the INGR will highlight some of the main challenges that are faced in each of the areas that are addressed. However, there are some clear challenges that represent overarching issues for 5G and future networks.

- *Edge Standardization and Ultra Low Latency:* The scalability (horizontal and vertical) of edge service delivery is still constrained in such a way that ultra-low latency communication cannot be assured. Additionally, edge platforms and their associated services are seriously lacking in standardization.
- *Satellite Integration*: New network architectures with network virtualization and softwarization are needed to support satellite integration with terrestrial 5G and beyond.
- *Network Management Issues*: AI/ML approaches are needed to address various network management issues such as resource allocation, routing, cross-layer optimization, mobility, and handover decisions in 5G and beyond non-terrestrial networks.
- *Network Security and Privacy:* There are additional security risks introduced by the new enablers of the future generations of networks. The importance of risk management frameworks and development of mitigation techniques by various use cases cannot be understated.
- *Growing Resident Resistance:* While many of the technical challenges associated with this SBS architecture have been addressed, we continue to see a growing number of news reports describing how communities around the world are resisting the installation of these antennas in their neighborhoods.
- *Energy Conservation:* A lurking threat behind the promise of 5G delivering up to 1,000 times as much data as today's networks is that 5G could also consume up to 1,000 times more energy. A Systems-of-Systems framework that uses a universal currency of energy could lead to solutions for economically viable and widespread deployment.
- *Regulatory Issues*: We may see limits established for the power of RF transmissions based on safety or noise level.

- *The Battle for the Final Mile*: The lessons of history and current trends indicate that this old battle may not be a zero-sum game, but instead evolve into a symbiotic relationship between Ethernet, Wi-Fi and Cellular.

5. WHAT'S IN THE 2021 EDITION

In the inaugural INGR, the focus was primarily on the evolution of 5G networks. In this 2021 Edition the aim is to start turning our attention to 6G technologies, as well as to take a more end-to-end perspective that includes integrating future network technologies.

To do this, all chapters in this INGR have examined the technologies, their challenges and possible solutions over 3-, 5- and 10-year time periods. It is expected that this approach will better reveal the technical gaps that are likely to exist in network deployments over varying timelines.

Below is a description of what to expect in each of the INGR Chapters.

5.1. Applications and Services Working Group

Figure 2. Smart Cities Framework—Key Enablers and Ecosystems

In this chapter, we see the evolution of the Applications and Services framework extending beyond "Smart Cities" to include "Smart Regions" that reach both urban and non-urban areas.

These Applications and Services will be offered to these "Smart Regions" through a heterogeneous network that includes a variety of access technologies, including: 5G new radio (NR), long-term evolution (LTE), IEEE 802.11, and satellite.

As the boundaries of the framework expand outward, new and derivative applications may emerge that make 5G more than just a bandwidth pipe, but also help to create a whole new suite of applications, such as:

- Energy efficient buildings
- Connected vehicles
- Remote surgery
- Urban air mobility
- Enhanced city services
- Precision agriculture

5.2. Artificial Intelligence & Machine Learning (AI/ML) Working Group

The development of AI/ML technologies for 5G and Future Networks is actively being undertaken by a number of organizations. This initial AI/ML roadmap is intended to describe some of the areas in which AI/ML are being applied in 5G and Future Networks.

Some of the areas that AI/ML is being increasingly applied to 5G networks, include:

- Network Automation
- Network Slicing
- Network Digital Twins
- Security
- Dynamic Spectrum Access
- Cloud Computing
- Multi-access Edge Computing

This initial AI/ML roadmap is intended to lay the groundwork for future developments by focusing on these core applications so that in subsequent editions greater focus will be applied to refine these initial roadmaps and the introduction of new roadmaps for other technology areas.

5.3. Edge Automation Platform (EAP) Working Group

After last year's EAP Framework roadmap saw the consideration of several Open-Source cloud stacks, the emergence of "Kubernetes" has evolved (an open-source system for automating the deployment and management of containerized applications) as the de facto standard for cloud and edge infrastructure.

The scope of the disruption over the last year has been so far beyond the considerations of the inaugural edition that this 2021 edition can be seen as a complete replacement.

Beyond how the Covid-19 disruption has expedited the Digital Transformation, and the emergence of an Edge Platform & Services, this edition examines the emergence of the same.

Based on this examination, an idea has formed that there should be a revision the IEEE 1934 beyond Fog/IoT to various edges under proposed a IEEE INGR.EAPF & IEEE INGR.ESPF.

5.4. Massive MIMO Working Group

In part, this chapter on Massive MIMO is a recognition of two main points: Massive MIMO is the backbone enabler of 5G networks and Massive MIMO will need to continually evolve and develop to meet the demands of future networks.

As Massive MIMO progresses through its future 5G NR Releases, it will need to develop in the following areas to reach its full potential:

- Deployment of Massive MIMO systems in heterogeneous network will require different deployment scenarios:
    - mmWave
    - Time-Division Duplex (TDD)
    - Frequency-Division Duplex (FDD)
    - Indoor/Outdoor
    - Small Cells
    - Macrocells
- Support different Massive MIMO hardware implementation architectures: e.g., digital, analog, hybrid
- Apply AI/ML and Big Data techniques to the monitoring, operation, and optimization of Massive MIMO systems
- The Massive MIMO radio access network (RAN) is transitioned from being a passive network layer to an intelligent decision-making network component

5.5. Standardization Building Blocks (SBB) Working Group

The SBB chapter describes the wide range of global standards, consortia and alliance activities that represent the regulatory environment of future networks, use cases, architectures, technical interface specifications, compliance, and test requirements over a ten-year time horizon.

The challenges that these standardization efforts are facing in future networks include:

- Growing trend to Open Source projects
- Exponentially growing number of relevant core technologies, SDOs, and alliances

- Increasing stakeholders' impatience that demands a fast time-to-market track for emerging technologies
- The risks, and at times disruption, that emerging technologies present to the Industry

The overall recommendation is that there needs to be a greater level of harmonization between all the standardization stakeholders, especially for emerging technologies.

5.6. Connecting the Unconnected (CTU) Working Group

With a grand vision to connect the population of the world to affordable broadband Internet access, the CTU Working Group has identified system concepts, architectures, standards and public policies needed to achieve this goal: connecting the unconnected.

The CTU group has positioned itself in this 2021 Edition of the INGR as an open platform where experts can bring their ideas and solutions into a collaborative environment to influence network service providers, manufacturers and governments on how to achieve the United Nations goal stated in its Vision 2030 SDG (Sustainability Development Goals) of providing affordable access to the Internet by everyone on the planet.

5.7. Satellite Working Group

The Satellite Working Group recognizes that 5G has brought on a paradigm shift in wireless communications driven by advanced technologies such as Massive MIMO and the exploitation of new frequency bands.

However, future networks will need to include a mix of non-terrestrial Networks including satellite systems, Unmanned Aerial Vehicles (UAVs) and High Altitude Platforms (HAPs) to connect the unconnected, un-served and underserved in remote and rural areas in particular.

To meet this overarching aim some key issues need to be addressed:

- Addressing standards for multi-layer systems, such as UAVs and HAPs
- Achieving system interoperability between terrestrial 5G and aerial components
- Addressing the weather limitations of using mmWave spectrum with satellites
- Leveraging AI/ML to solve routing, resource allocation, cross-layer optimization and hand-over decisions

5.8. Energy Efficiency (EE) Working Group

The EE working group has examined energy efficiency through the lens of the universal currency of energy. This perspective has helped to form a Systems-of-Systems (SoS) framework that will integrate technical and business drivers in such a way as to position EE optimization at the forefront of considerations for future networks. The group's methodologies employ new, proposed metrics/terminology and overall modeling/simulation approaches to solving global EE optimization challenges.

Equipped with this approach from the SoS framework, the critical issues that need to be addressed in future networks when taking into account EE, include:

- Network Efficiency: Leveraging spectral efficiency, low-power operating modes, improved Massive MIMO, and energy harvesting to stabilize the grid infrastructure.
- Migration to Small Cells: Ensure that future cell-free architectures develop control and automated coordination.
- Reducing Base Station Energy Consumption: Develop higher fidelity transmitters and Massive MIMO, leveraging the integration of RF, signal processing, power management, and cooling techniques to achieve implementations that can be deployed in a dense environment.

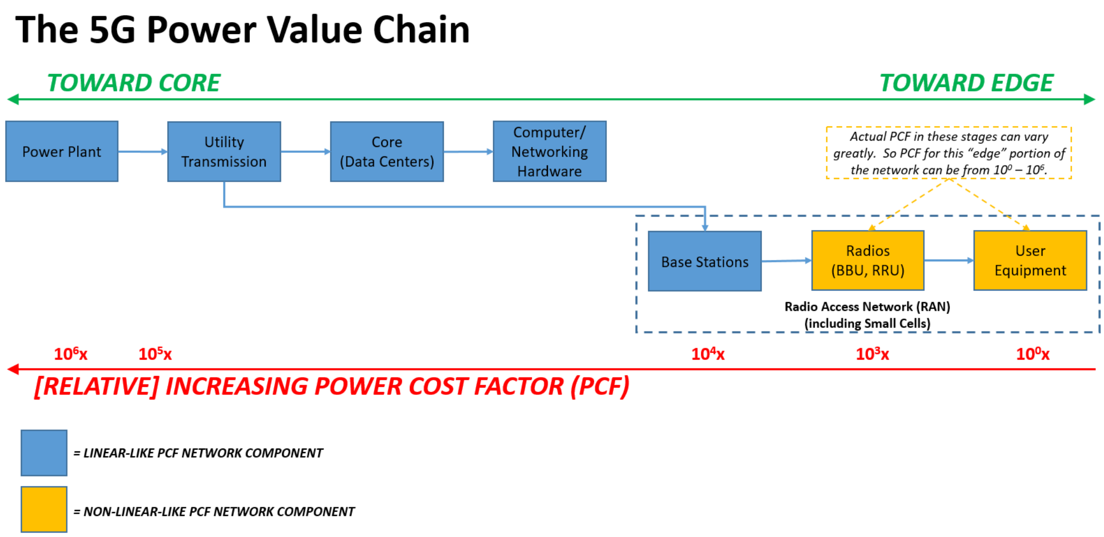

Figure 3. The Power Value Chain (PVC) from Network Edge to Power Plant, courtesy of PowerRox

5.9. Deployment Working

The Deployment Working Group identifies the keys to the deployment of 5G and future networks as education and communication. This communication and education must be undertaken with the following stakeholders:

- Local governments, agencies, and jurisdictions
- Residents, citizens, and businesses
- Wireless carriers and site owners/operators
- The wireless equipment and semiconductor industries

The motivations of the for-profit companies of the wireless and semiconductor industries may not naturally align with the motivations and missions of local governments, businesses, and the public. However, it will be incumbent on industry to better understand these missions and motivations in order to develop attainable strategies for the deployment of 5G networks in terms of scale and timelines, and for local governments to prioritize deployment of communication networks as a benefit for citizens, residents, and businesses.

5.10. Security and Privacy Working Group

The Security and Privacy Working Group champions the importance of embedding security capabilities of 5G networks from the moment the architecture is defined and standardized. The security requirements need to overlay and permeate through the different layers of the 5G systems (physical, network, and application).

With this approach in mind, the WG suggests that work on the security of future networks should include:

- In-depth coverage of data sharing and privacy in all layers of communication including access, core, and services. For example, it could include various types of access networks such as satellite communication, New Radio (NR), optics, and other enablers, namely edge cloud, SDN/NFV, network slicing, physical layer security, identity and access management, and application security.
- Relevant use-cases and applications for various verticals with a description of end-to-end security requirements, risk scenarios, and risk mitigation techniques.
- A few security standards through existing IEEE standardization vehicles in collaboration with other working groups.
- High-level generic security reference architecture as a generalization of existing detailed models.
- An end-to-end threat analysis and develop threat taxonomy for future networks.

5.11. Systems Optimization Working Group

With ever increasing complexity expected for 5G networks and beyond, there is a necessity for novel design, planning and operations paradigms. While technologies such as AI/ML are available for self-adaptive optimization of resources, there remains a need at this point to assess legacy tools versus new AI solutions for systems optimization. To make this comparison there needs to be an assessment of complex challenges for 5G and beyond.

5.12. Testbed Working Group

With the major aim of Testbed Working Group to define future network attributes and challenges universally with a global context, it has proposed to create a global testbed inventory, each with specialist attributes defined by the testbed coordinator.

The testbed will always remain voluntary and a member can opt out of data sharing at any time. However, for those participants who are interested in sharing their learning proactively, the INGR Testbed WG intends to broker these facilities to other interested parties to accelerate the scoping of the INGR initiative.

5.1. mmWave Working Group

The mmWave Working Group continues to believe that exploiting the narrow beam widths achievable at mmWave frequencies will do a great deal to leverage mmWave communication bands to improve overall data rates and energy efficiency. However, they acknowledge that the full promise of mmWave communications will not be achieved without two key improvements in the underlying mmWave hardware technology.

The first key issue that will make a big difference going forward is improving the underlying efficiency/linearity tradeoff at mmWave frequencies. The second issue revolves around the development of improved electronic packaging. While this is not a focus of the chapter, the mmWave Working Group argues that developing cost-effective approaches to packaging mmWave hardware, particularly where mixed silicon/III-V systems are employed, will be a key issue in the next 3-, 5-, and 10-year frames.

6. A Final Note

We hope that this summary has encouraged you to dig deeper and read the full chapters from each of our working groups. And if you are inspired to join the cause, we welcome new experts to join our ranks and help with new updates and editions of INGR.

Below is a listing of each working group and an email address to reach them:

- Applications and Services - 5GRM-appssvcs@ieee.org
- Artificial Intelligence/Machine Learning - 5GRM-AIML@ieee.org
- Connecting the Unconnected - 5GRM-connecting@ieee.org
- Deployment - 5GRM-deployment@ieee.org
- Edge Automation Platform - 5GRM-eap@ieee.org
- Energy Efficiency - 5GRM-energy@ieee.org
- Massive MIMO - 5GRM-massiveMIMO@ieee.org
- Millimeter Wave and Signal Processing - 5GRM-mmWave@ieee.org
- Optics - 5GRM-optics@ieee.org
- Satellite - 5GRM-satellite@ieee.org
- Security - 5GRM-security@ieee.org
- Standardization Building Blocks - 5GRM-standards@ieee.org
- Systems Optimization - 5GRM-sysopt@ieee.org
- Testbed - 5GRM-testbed@ieee.org

List of Figures

ANTI-TRUST STATEMENT

Generally speaking, most of the world prohibits agreements and certain other activities that unreasonably restrain trade. The IEEE Future Networks Initiative follows the Anti-trust and Competition policy set forth by the IEEE Standards Association (IEEE-SA). That policy can be found at https://standards.ieee.org/develop/policies/antitrust.pdf.