EXECUTIVE SUMMARY

1. THE ROAD FROM 2023 TO 2033

The 2023 Edition of the IEEE Future Networks International Network Generations Roadmap (INGR) points to trends, challenges, and solutions in the current and near-term mobile network landscape, and the future vision as being cultivated through the activities of Standards Development Organizations and the industry around the globe. This Executive Summary offers brief glimpses into current and forward-looking focal and interworking areas from each of INGR's working groups. Noteworthy areas to watch for rapid development and integration into other technology and network functions include satellite communications, artificial intelligence and machine learning, and energy efficiency. As the industry continues to advance, the evolution and deployment of network generations is influenced and impacted by emerging, evolving, and potential convergence of technologies, but also by local and world socio-economic conditions, health conditions, and politics. The inaugural INGR was released in 2020 and its focus was primarily on the evolution of 5G networks. The intention of the 2021 INGR Edition was to take a more end-to-end perspective that included integrating future network technologies and establishing a transdisciplinary framework and a predictive model for mobile networks. This 2022 INGR Edition broadened applications of the transdisciplinary framework, progressed each technology and system challenge while interworking with other. This 2023 Edition focuses on the beyond 5G horizon, the standardization and technologies that might enable it and 6G. All working groups in the INGR have examined the technologies and systems over three-, five-, and ten-year time periods. It is expected that this approach will better reveal the challenges, possible solutions and opportunities that are likely to exist in network deployments over varying timelines.

2. WHAT'S NEW IN THE 2023 EDITION

In this publication of the INGR document, you will see increased focus on beyond 5G, efforts toward standardization to enable rapid development, and how to meet consumer demand globally and ethically. The INGR is expanding and establishing frameworks for network functions and systems, broadening and even redefining roles of technologies, pursuing converging points of working group as well as governments and agencies areas where results will be greater than the sum of the parts, smoothing pathways for an aggressive period of deployment, and continuing to push out its horizon. Below are descriptions of the mandates and focal points of each INGR chapter, as reported by the working groups.

2.1. System Optimization

Fifth generation (5G) networks are now in the early deployment stages in networks around the world. Use cases driving this transition for 5G networks focus on the need to support heterogeneous traffic such as enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC). On the software and control side, 5G and beyond networks are enabled through Software-Defined Networking (SDN) and Network Function Virtualization (NFV) technologies and leverage the merging of communication and computing.

Although not yet in the standardization stage, early thinking on 6G networks focuses on the convergence of physical, human, and digital worlds, including support for:

- digital twinning (tight synchronization between the physical world and the twin),

- immersive communication (support of pervasive haptics),
- cognition (awareness of human intentions, desires, and mood), and
- connected intelligence (trusted AI everywhere with interaction between virtual representations).

All this also needs to be realized in sustainable fashion [1].

With the deployment of novel applications and the expected increase in their usage and demand, the scope of innovation within future networks will be governed by: (a) limitations and boundaries of available resources; (b) limitations of the adaptability of legacy solutions (scalability and flexibility); (c) limitations of available decision making entities (network slice orchestrators and SDN controllers will not be enough); and (d) lack of intelligent management and control solutions for multi-variate optimization. Technologies are available for efficient use and self-adaptive optimization of resources using enablers such as AI-powered autonomic control loops. With ever-increasing complexity expected for beyond-5G networks, there is a necessity for novel design, planning and operations paradigms. There is a need for assessment of legacy tools versus new Artificial Intelligence solutions for applicability to systems optimization, and a need for introduction of novel methods to model and study the behavior of highly complex systems developed for the realization of 5G and beyond networks. The goal of this working group (WG) is to assess complexity challenges for the 5G era and beyond, explore novel design, planning and operations techniques for networks and services, and to create the Systems Optimization roadmap of the IEEE Future Networks Initiative (FNI) Systems Optimization WG.

2.2. Edge Services & Platform

This third edition (2023) continues to reflect the Edge service roadmap and journey with evolving key drivers and developments. It replaces the two earlier versions.

5G deployments have reached critical markets and are fast evolving towards 6G promising higher performance and near sub-millisecond latency. Higher automation in use cases fueled by AI (e.g. like ChatGPT) is expected to be the core of future applications and services.

The service providers have started re-focusing on use cases that can leverage the new and improved capabilities for better average revenue per unit (ARPU) for both consumers and enterprises.

Some of the edge relevant Service oriented use cases are based on key constraints (low latency, high throughput, low jitter)

- Industrial Internet of Things (IIoT) Industry 4.0
- Vehicle to anything - V2X (autonomous vehicle / intelligent transportation / traveling edge)
- Telehealth / telemedicine / remote diagnostics
- Content delivery (with caching, real time, rich media internet applications)
- Ad hoc, temporary or on as needed mission specific edge services (emergency, ad hoc major events, DoD combat mission, and more)
- Enabling sustainable development edge applications.

Key elements of the edge-inspired infrastructure to support such services may be noted as follows:

- Enabling edge with AIML, e.g., OpenAI / *ChatGPT
- Radio-based Multi-Access Edge (MEC) to provide different services

- Real-time / near real time enabled radio control, management, and xApps based on O-RAN
- Constraint-based edge infrastructure to optimize power, form factor, and updates to NFV-SDN with the IoT middleware standards OneM2M from ETSI to cover IoT applications
- The focus on data privacy, security, data "localization and analytics"
- Intelligent edge microservices and applications deployed using newer infrastructure components from Semiconductor innovations e.g. DPU, IPU, etc.
- MEC and 5G integration to support location-based edge platform API adaption
- Small cells and private B5G networks

We classify platform aspects with Edge Platform Framework (EPF) and Services with Edge Service Framework (ESF) updates and overall aspects as Edge Service and Platform Framework (ES&PF) for an integrated view.

2.3. Massive MIMO

The use of a large number of antenna elements, known as Massive MIMO, is seen as a key enabling technology in the 5G and Beyond wireless ecosystem. The intelligent use of a multitude of antenna elements unleashes unprecedented flexibility and control on the physical channel of the wireless medium. Through Massive MIMO and other techniques, it is envisioned that the 5G and beyond wireless system will be able to support high throughput, high reliability (low bit-error-rate (BER)), 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 mmWave bands to support large channel bandwidths. It is envisioned that 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 networks (HetNet) configurations. Accurate and useful channel estimation remains 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. Carrier frequency offset (CFO), which arises due to the relative motion between the transmitter and receiver, is another important topic. Recently, maximum likelihood (ML) methods of CFO estimation have been proposed, that achieve very low root mean square (RMS) estimation errors, with a large scope for parallel processing and well suited for application with turbo codes.

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, the latest advances in artificial intelligence (AI) and machine learning (ML) techniques will be leveraged to monitor and optimize the Massive MIMO sub-system. As such, a cross-layer open interface can facilitate exposing the programmability of Massive MIMO through techniques such as network slicing (NS) and network function virtualization (NFV). Finally, security needs to be integrated into the design of the system so the new functionality and performance of Massive MIMO can be utilized in a reliable manner.

2.4. Standardization Building Blocks

This chapter, produced by the Standardization Building Blocks (SBB) Roadmap Working Group, describes a wide range of global standards, consortia, and alliance activities enabling and defining future networks use cases, architectures, technical interface specifications, compliance, and test requirements, and regulatory environment over a ten-year time horizon.

The primary objective of the SBB Roadmap is to illustrate the “master timeline” for the standardization of wireless communications technologies. 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. Accordingly, the scope of the SBB includes:

- depicting the value chain of the global system integrator Standards Developing Organizations (SDOs), and
- illustrating the effort of relevant alliances and consortia that drive standardization, and open-source activities.

The target audience for this roadmap are end-users, content producers using networks for content distribution, network service providers, equipment manufacturers, infrastructure vendors, component suppliers, and test and measurement service and equipment providers.

This roadmap recommends that the core technology stakeholders take a proactive approach to harmonize standardization with their vision for long-term technology evolution.

2.5. Deployment

Wireless technologies have become a fundamental part of our daily life in the 21st century. They connect us to each other and to rich sources of information. They give us the ability to make efficient use of our time, allow us to have remote control over other technologies in our life, and make our lives better in innumerable ways. To function, our wireless devices need to connect to cellular sites that provide good coverage both outdoors and indoors. Thus, the success of any wireless network is predicated on successful deployment of equipment and systems. As the number of users grows and the amount of data transferred increases, the laws of physics and information theory require placement of wireless sites closer to populated areas – creating new challenges for carriers, site developers, and local governments. Wireless communications facilities cannot be deployed in a vacuum; communication across the product development chain and between private and public entities is critical to enabling practical solutions.

This chapter reviews public and private stakeholder perspectives to examine ways to ensure that all stakeholder perspectives are communicated and understood.

2.6. Satellite Report

The fifth generation (5G) wireless communication systems development has brought about a paradigm shift using advanced technologies; including softwarization, virtualization, massive MIMO, and ultra-densification, in addition to introducing new frequency bands. However, as societal needs for any form of information grow, it is necessary to satisfy the UN’s Sustainable Development Goals (SDGs). Migrations to 6G and beyond systems are envisioned to provide augmented capacity, so massive IoT, with better performance relying on optimization made possible by artificial intelligence, it is absolutely necessary. Non-Terrestrial Networks (NTNs), including satellite systems, High-Altitude Platforms (HAPs), and Unmanned Aerial Vehicles (UAVs), provide the best solutions to connect the unconnected, unserved, and underserved in remote and rural areas.

Over the past few decades, Geo Synchronous Orbits (GSO) satellite systems have been deployed to support broadband services, backhauling, Disaster Recovery and Continuity of Operations (DR-COOP), and emergency services. Recently, novel non-GSO satellite systems are attracting significant interest. Within the next few years, several thousands of Low Earth Orbit (LEO) satellites and mega-LEO constellations will provide global internet services, offering user throughput comparable to terrestrial mobile or fixed access networks.

This report represents the 2023 Edition of the INGR Satellite Working Group Report, following the previous three editions [1], [2], [3]. This edition of the INGR Satellite Working Group Report addresses NTN and 6G more in detail, adding further contributions on optical wireless communications, artificial intelligence techniques, seamless handover, security, and recent standardization efforts given the prospected unification of terrestrial and NTN components of 6G.

2.7. Artificial Intelligence & Machine Learning

In the evolution of artificial Intelligence (AI) and machine learning (ML); reasoning, knowledge representation, planning, learning, natural language processing, perception, and the ability to move and manipulate objects have been widely used. These features enable the creation of intelligent mechanisms for decision support to overcome the limits of human knowledge processing. In addition, ML algorithms enable applications to draw conclusions and make predictions based on existing data without human supervision, leading to quick near-optimal solutions even in problems with high dimensionality. Hence, autonomy is a key aspect of current and future AI/ML algorithms.

This chapter focuses on the development and implementation of AI/ML technologies for 5G and future networks. The objective is to illustrate how these technologies can be migrated into 5G systems to increase their performance and to decrease their cost. To that end, this chapter presents the drivers, needs, challenges, enablers, and potential solutions identified for the AI/ML field as applicable to future networks over three-, five-, and ten-year horizons.

AI/ML applications for 5G are wide and diverse. Some key areas described include networking, securing, cloud computing, and others. Over time, this paper will evolve to encompass even more areas where AI/ML technologies can improve future network performance objectives.

2.8. Energy Efficiency

This 2023 Edition of the IEEE International Network Generations Roadmap (INGR) updates the already very comprehensive chapter dedicated to Energy Efficiency, which builds upon the initial white paper released in April 2020[1] with subsequent annual updates to the roadmap (available from IEEE). For this purpose, the Energy Efficiency Working Group developed an analysis of the energy efficiency constraints across the whole ecosystem of the Fifth Generation "5G" and following network infrastructure, which can be leveraged by all stakeholders to prioritize resource allocation and technology development to ensure that both technical and economic forecasts can be met. The complexity of the ecosystem and the traditionally siloed approach within the industry has often prevented the adoption of a holistic approach to addressing the fundamental problem of energy, which is the ultimate constraint to any complex deployment. The proposed framework facilitates an assessment of bottlenecks and their implication on the network. It may be used by both academic and industry stakeholders to develop solutions that address the real issues and enable a healthy ecosystem.

After a comprehensive survey of the ecosystem and its challenges, the following key areas were selected for a more in-depth analysis:

- Network Efficiency
- Small Cell Migration
- Base Station Power
- Economic Factors
- Grid / Utility

This chapter also identifies the need for a comprehensive "Systems-of-Systems" (SoS) analysis to address the complex inter-relationships among the multiple layers, which the infrastructure leverages. An initial proposal describes how a model can be built to enable a comprehensive assessment of energy requirements across such a diverse ecosystem. A future step in the process will consolidate a proposal for standardization of this model, which can be utilized by all stakeholders for both analysis and forecasting of capabilities and return on investment. **Being green is also green ($$$)!**

2.9. Applications & Services

The Institute of Electrical and Electronic Engineers (IEEE) Future Networks International Network Generations Roadmap (INGR) Applications and Services Working Group developed a Transdisciplinary Framework that extends across end-to-end ecosystems, and caters to different stages of priorities, resources, and technologies. The Transdisciplinary Framework is sustainable, structured, flexible, adaptable, and scalable. It may be used by academic stakeholders for new research topics of interest, industry stakeholders to develop solutions for roadmap identified opportunities while minimizing negative risks, and government stakeholders for governance and policy development.

The 2023 edition provides additional details on the Applications and Services Transdisciplinary Framework from Smart Cities, developed in the 1st edition, and was extended towards Smart Communities that include both urban and non-urban areas in the 2021 and 2022 editions. This edition of the IEEE INGR Application and Services roadmap chapter includes:

- **Transdisciplinary Framework**: a dynamic sustainable framework for applications and services that extends across end-to-end ecosystems, and caters to the priorities, resources, and technologies for local urban and non-urban areas.
    - **Ecosystem of Ecosystems:** intra-ecosystem and inter-ecosystem alignments for agriculture, education, electrical power, health care, media and entertainment, public safety, transportation, and water distribution and wastewater treatment ecosystems.
    - **Network of Networks**: Future networks components (access, service delivery, operations and service management, and network extensions), use case categories and network operations enhancements.
    - **Governance Function of Functions:** strategic and governance related functions to support local area objectives that include economic development, quality of life, stakeholder attraction and retention, and policy development.
- **Transdisciplinary Framework Scenarios and Use Cases**: climate change, smart cities, smart communities, pandemic response planning, and media and entertainment scenarios and use cases.

The Applications and Services Working Group will extend the reach and depth of this framework to add new ecosystems and enhance existing ecosystems already addressed for future INGR editions.

2.10. Optics

Optical networks have long played a central role in telecommunication networks, forming the fiber backbone of the internet. Over time, fiber optic systems have evolved and found deployment increasingly closer to the network edge. Today, optical systems extend to the server network interface cards and home access networks. New application areas have emerged, such as the use of free space communications using LiFi technologies, space communication networks between satellites, and ground stations. Looking ahead, optical systems in many areas will continue to be driven by the need for higher speeds and capacity to keep up with traffic demands. In addition to faster interface speeds, parallel fibers or spatial division multiplexing will be used for future capacity growth. In several application areas, new functionality is expected, such as low latency in XHaul networks and optical switching and co-packaged optics in data centers. LiFi will become critical for mitigating RF interference for in-building networks. Intense research is underway to develop quantum networks to connect quantum computers. This general trend toward new functionalities for optical systems, moving beyond capacity growth in fiber networks, is driven in large part by the increasing performance and demands of today's user equipment and applications. From the network edge to the data centers, components are reliant on optics. However, many of these developments are occurring quite independently and this situation carries the risk of creating problems down the road when eventually all of these components need to be seamlessly connected to maximaze efficiency. Therefore, integration of optics into these new applications and the higher levels of functionality demanded of optics motivate the use of roadmaps to guide research and development to overcome future roadblocks.

2.11. Connecting the Unconnected

Connecting the Unconnected or under-connected (CTU) is the holy grail of transforming the lives of over 3 billion people around the globe with wireless internet who are yet to experience its value in multiple ways. If this could be accomplished, its impact on the society would be enormous as everyone would have access to information and an opportunity to improve their quality of life and income.

This chapter from the IEEE Future Networks CTU Working Group endeavors to highlight the need to consider the CTU requirements in 5G and B5G networks in the standardization process and in the development of the use cases and affordable solutions. In its Vision 2030 SDG (Sustainability Development Goals) the United Nations has proclaimed access to internet as basic human right and has said these goals cannot be achieved without affordable access to internet by everyone on this planet[65].

While there are numerous projects and initiatives ongoing around the world, these are fragmented and lack the critical mass and coordination to be able to impact the future standards, product development, and cost of deployment otherwise achievable by economy of scale. Although difficult to pin down, to define a threshold for basic connectivity for all is important. But it would need to be flexible to adapt to changing times. It is the goal of the CTU group to create an open platform where the experts can bring their ideas, solutions, and potentially collaborate to create large global projects and influence the network service providers, manufacturers and their governments. This paper defines the CTU working group's charter, scope, and provides a brief overview of the relevant stakeholders and linkages between them. Then the paper goes into the current status of the CTU landscape and where we want to reach to accomplish the vision of connecting everybody, especially those living in rural and remote areas. We present the various standards and industry fora and how they are interlinked. While technologies are available today, they need to be customized and optimized at the systems level to bring down the cost of the network to be affordable. In addition, the content needs to be relevant and in local languages to be useful, not to mention the need to offer innovative human computer interaction (HCI) solutions (that are not text based) so that people who are not literate or are digitally disadvantaged can easily use the devices and consume services. Another important area is that of flexible spectrum allocation regime at the lower range of the spectrum to increase reach and coverage. Use of renewable energy sources will enable deployment in remote areas where there is lack of power grid, or it is intermittent. Thus, this paper identifies a number of technology gaps to be filled in by 5G and B5G networks, such that access is affordable and content and services are actually consumed by the targeted set of users. Although hitherto unexplored, artificial intelligence (AI) an machine learning (ML) have tremendous role to play for serving the rural and remote communities both to deliver the most needed services and to customize them to the digital capacity of the end users. Technology aside, the need to develop innovative business models is a must to be commercially sustainable in the long-term. A number of such models, especially designed for the rural population, are proposed, such as Village Level Entrepreneur (VLE) Freemium (Free + Premium), revenue sharing among the chain of service providers, subsidized billing by USOF (Universal Service Obligation Funds). Finally, the paper presents a 10-year roadmap starting from the current state to three years, five years, and ten years.

2.12. Security & Privacy

The digital transformation brought on by 5G is redefining current models of end-to-end (E2E) connectivity and service reliability to include security-by-design principles necessary to enable 5G to fulfill its promise. 5G trustworthiness highlights the importance of embedding security capabilities from the very beginning while the 5G architecture is being defined and standardized. Security requirements need to overlay and permeate through the different layers of 5G systems (physical, network, and application) as well as different parts of an E2E 5G architecture within a risk-management framework that takes into account the evolving security-threats landscape. 5G presents a typical use-case of wireless communication and computer networking convergence, where 5G fundamental building blocks include components such as Software Defined Networks (SDN), Network Functions Virtualization (NFV), and the edge cloud. This convergence extends many of the security challenges and opportunities applicable to SDN / NFV and cloud to 5G networks. Thus, 5G security needs to consider additional security requirements (compared to previous generations) such as SDN controller security, hypervisor security, orchestrator security, cloud security, edge security, etc. At the same time, 5G networks offer security improvement opportunities that should be considered. Here, 5G architectural flexibility, programmability and complexity can be harnessed to improve resilience and reliability.

The working group scope fundamentally addresses the following:

- 5G security considerations need to overlay and permeate through the different layers of 5G systems (physical, network, and application) as well as different parts of the E2E 5G architecture including a risk management framework that considers the evolving security threats landscape.
- 5G exemplifies a use-case of heterogeneous access and computer networking convergence, which extends a unique set of security challenges and opportunities (e.g., related to SDN / NFV and edge cloud, etc.) to 5G networks. Similarly, 5G networks by design offer potential security benefits and opportunities through harnessing the architecture flexibility, programmability, and complexity to improve its resilience and reliability.

- The IEEE FNI security WG's roadmap framework follows a taxonomic structure, differentiating the 5G functional pillars and corresponding cybersecurity risks. As part of a cross-collaboration effort within IEEE FNI, the security working group also looks into the security issues associated with other roadmap working groups.

2.13. TestBed

The Testbed Working Group (WG) is one component of the INGR project and will help collaborate with the existing 5G testbeds to make those available to the IEEE communities (industry & academia) to ease the deployment of 5G & accelerate the development of next generation network (e.g., 6G). This Testbed WG will collaborate with the vendor community and research community and thus will expand upon the existing testbeds towards federated development of testbeds for next generation networks. The working group has established stronger relationships with IEEE & ITU's standardization study group.

Some of the key deliverables from the Testbed WG will be the specification and/or standards for functional testing, rapid prototyping, proof of-concept and other forms of technology evaluation. The goal is to cover various 5G, 6G, and other future networking system characteristics at different layers and also supporting various specific applications such as the Internet of Things (IoT), tactile internet, and augmented reality. To deliver the vision of INGR, 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/s that will provide access to the IEEE community to get access and run experiments. In order to fuel the testbed evolution, the Testbed WG will continue to hold workshops and go over various 5G and beyond use case scenarios as well as define the avenue for 6G and beyond networks.

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 for 5G and beyond.

2.14. mmWave & Signal Processing

The "Millimeter-Waves and Signal-Processing" Working Group (MMW-SP WG) will examine improvements in current millimeter-wave architectures, hardware capabilities, and signal processing techniques to enable 5G systems to achieve the 3GPP Release 16 requirements for enhanced massive mobile broadband (eMBB), 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 three-, five-, and ten-year timeframes.

3. A FINAL NOTE

This Executive Summary merely touches upon the high points of work underway in the IEEE INGR overall and each Working Group. Delve into complete chapters to see the full substance and scope of work. Although this Executive Summary is free, access to individual chapters requires the simple and affordable step of IEEE Future Networks membership, which ranges from free to a maximum of $15 USD per person. You can join IEEE Future Networks at https://bit.ly/fni-join. We also encourage and welcome new working group members to bring their enthusiasm, expertise and insights to the INGR. Select a Working Group where you can help envision the future of networks and plan a path that helps avert and overcome challenges, while helping to realize the full potential of the current and future telecommunications network generations. Email contacts for each INGR Working Group:

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ANTI-TRUST STATEMENT

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