6G Global Roadmap

A TAXONOMY

PURDUE UNIVERSITY

CISCO · DELL Technologies · ERICSSON · intel · NOKIA · Qualcomm

Authors*

Purdue University

Christopher Brinton | Elmore Chaired Assistant Professor, Elmore Family School of Electrical and Computer Engineering
Mung Chiang | President
Kwang Taik Kim | Research Assistant Professor, Elmore Family School of Electrical and Computer Engineering
David Love | Nick Trbovich Professor, Elmore Family School of Electrical and Computer Engineering

Cisco Systems

Michael Beesley | Vice President/Chief Technology Officer

Dell Technologies

Morris Repeta | Director of Advanced Wireless Technology
John Roese | President and Global Chief Technology Officer

Ericsson

Per Beming | Head of Standard and Industry Initiatives
Erik Ekudden | Senior Vice President and Chief Technology Officer

Intel

Clara Li | Senior Principal Engineer
Geng Wu | Intel Fellow

Nokia

Nishant Batra | Chief Strategy and Technology Officer
Volker Ziegler | Senior Advisor and Chief Architect

Qualcomm

Tingfang Ji | Vice President
Rajat Prakash | Senior Director
John Smee | Senior Vice President

**Authors from each institution are listed in alphabetical order.*

Table of Contents

Sections:

Executive Summary

6G wireless networks promise not only faster speed, lower latency, and better coverage, but also connecting more devices than people and offering a foundational service to all sectors, across different types of networks and public/private deployment scenarios.

This is the intermediate report produced in 2022-23 by a group of six companies alphabetically listed on the cover and hosted by Purdue University. It is a taxonomy "dictionary" over the modularized layers and over time horizon, describing a dozen enabling network architectures, protocols, and tools in the evolution of this decade from 5G to 6G, without prescribing one over the rest:

- Enabling ultra-low latency applications
- Supporting intermittent connectivity
- Creating wireless service platforms
- Densifying cells
- Scaling up edge/fog computing
- Sharing spectrum
- Using sub-THz spectrum bands
- Sharing infrastructure
- Using open interfaces
- Utilizing Artificial Intelligence (AI) and Machine Learning (ML)
- Internetworking with WiFi
- Internetworking with satellite networks

In other words, this technology report is meant to be a foundation of policies, not a policy itself. It is written with policymakers as the primary audience, although colleagues in the industry and in pre-standardization groups might also find the taxonomy interesting. The core of the report is Section 3.2, where the 12 technologies are summarized and potential societal impact outlined.

In the meantime, we do strongly recommend the speeding up and scaling up of 5G deployments in the United States right now. More 5G infrastructure and resulting applications are essential to any roadmap to 6G.

This industry-academia group continues to collaborate toward its next report, which will address further recommendations built on the taxonomy in the following pages.

1. Introduction

Over the last decade, the availability of high-rate wireless communication has become a necessity, arguably approaching the level of electricity, food, and clean water. This has elevated the issue of future wireless standards to one of international technical and public policy importance. Further, both the number of wireless devices and the demand for wireless data are continuing to scale at an exponential rate [1]. To fulfill these ever-growing requirements, both technical and public policy innovations are needed.

Wireless networks are predominantly governed by international standards created by companies and research groups from around the world. Since the late 2000s, the dominant standards that have fueled wireless growth are 4G Long Term Evolution (LTE) and its descendants. Over the last few years, deployments have shifted to 5G New Radio (NR), which improves upon LTE with various radio and network layer enhancements. Both standards were produced by the 3rd Generation Partnership Project (3GPP), which is expected to be the critical standards body for mobile cellular access in the coming years. Efforts for 6G discussions are well under way. Currently, these discussions have been distributed across different parts of the world—for example, the Next G Alliance in the United States, Hexa-X in the European Union, the China Academy of Information and Communications Technology (CAICT)'s IMT-2030 6G promotion group in China, and the Telecommunications Technology Association (TTA) in Korea. While interest is high, there are still many questions on what 6G research and development should accomplish as both viable in this decade and sufficiently distinct from what 5G can provide today. In this taxonomy report, we take a general view of the technological and policy needs that 6G must address.

From our discussions, we find that distinct features of target societal impact of 6G have coalesced into four areas of societal focus: sustainability, trustworthiness, digital inclusion, and scalability.

- **Scalability:** Each year, the amount of data consumed per device increases exponentially. At the same time, the number of devices, and the heterogeneous nature of these devices—in terms of the diverse sets of applications that they serve—also is growing. 6G will serve many more devices than humans and serve as the foundation of all other digital sectors. Scalable solutions are necessary to accommodate an unknown future of wireless demand.
- **Sustainability:** Energy needs have affected almost all areas of engineering and policy. Unfortunately, technology solutions that rely solely on innovations in hardware will likely be unable to keep up with future wireless demands and may be further hampered by potential shortages in important battery-making materials. Advances in energy efficiency and low-power operation are needed to facilitate future application areas.
- **Trustworthiness:** The widespread availability and ever-decreasing cost of communications and computing devices have revolutionized the world. This availability and the diversity in their production, however, have given rise to security concerns that previously have not been felt in commercial wireless networks. 6G networks must focus on a "built-in" approach to security.
- **Digital Inclusion:** The internet has generated major economic and social improvements in many parts of the world. Despite this, there are still large regions of the world, even in developed countries, that lack access to broadband wireless. There is an urgent need to improve rural and third-world access through innovative wireless networks.

This report surveys the technical areas that we believe will drive 6G development and solve the important problems faced in these focus areas. These technical innovations range from radio enhancements, such as the use of new frequency bands and signal improvements to support higher data rates, to network deployment changes, including the ways operators install and utilize base stations and allocate functions to edge networks, as well as new computation and software solutions, which could disrupt the wireless ecosystem and supply chain.

This taxonomy report is organized as follows. In Section 2, we provide a background on wireless spectrum, allocation, and regulation that is important to many of the technical innovations. Then, in Section 3, we present the specific technical focus areas that we believe are of great importance to 6G systems. Each subsection also outlines how each of these focus areas will address the cross-cutting societal impacts mentioned above. Subsequently, in Section 4, we discuss what we believe is necessary from a standardization and like-minded nations' partnership perspective to support the technological innovations for 6G.

Some use cases are described in this document to illustrate how some technological challenges could be addressed in 6G. However, this report does not aim to provide an exhaustive list of use cases.

2. Background: Wireless Spectrum and Allocation

In wireless systems, spectrum is perhaps the most valuable resource. Wireless systems rely on signals transmitted from antennas that propagate through space. When the signal is transmitted, its power is concentrated at certain frequencies. The frequencies that a transmitter can use for signaling are usually heavily regulated, meaning that a transmitter must limit its signal to a predefined set of frequencies that the receiver can use to identify and receive it. It also is important for receivers to be able to reject interference from adjacent frequencies where other regulated and authorized transmitters operate.

Spectrum is a critical driver of network capacity—for example, the amount of data that can be carried across all users in a specific geographic area. Each new generation of wireless communications has led to increased network capacity. One way of increasing capacity and coverage without introducing new spectrum allocations is by increasing the deployment density; that is, how many base stations are deployed within an area. An increase in deployment density, however, translates to an increase in mobile network operator expenses, due to the cost associated with the acquisition and maintenance of new sites. In some instances, increasing network density may simply be impractical due to local regulations or supporting infrastructure.

Without densification, network capacity enhancements come from roughly two different sources, both related to spectrum. The first source relates to improving the network spectral efficiency—for example, the efficiency with which the available spectrum is used. This improvement comes about from new algorithms, hardware, and/or network design. The second source is new spectrum. This allows data to be transmitted over frequencies that were not previously available to the network.

Technological enhancements and standardization typically focus on network spectral efficiency. This leads to complex engineering challenges and often a need for new modeling breakthroughs and hardware enhancements. The challenges, however, are generally technical. On the other hand, new spectrum allocations come with many challenges associated with public policy, regulations, and economic impact.

6G spectrum roughly can be grouped into the following categories: sub-1GHz (Gigahertz), mid-band, upper mid-band, mmW (millimeter Wave), and sub-THz (Terahertz). Sub-1GHz spectrum has a long history of use, going back to the early days of wireless access when it was first regulated. In particular, cellular providers have extensively built out technology for bands in 600-900MHz (Megahertz) over the last 20+ years. The distinguishing property of the Sub-1GHz spectrum is good coverage, but limited capacity, which was a suitable characteristic for early cellular networks that supported voice and limited data services. This spectrum also is relevant for 6G, as it is suitable for many Internet of Things (IoT) use cases with light traffic characteristics but stringent requirements on reliable connectivity.

Mid-band spectrum, roughly defined as 1-7 GHz, emerged as a driving force in 4G and 5G deployments as the need for more capacity grew and governments began allocating these bands. The digital cellular 4G LTE revolution was facilitated by spectrum availability in the 2 GHz range, with the Broadband Personal Communications Services (PCS) and later the Advanced Wireless Services (AWS) bands. As the need for more data exponentially grew, 5G deployments were allocated 3-4 GHz bands. Making use of this spectrum required a combination of technology improvements, such as the use of massive multi-antenna systems and network densification to ensure adequate capacity and coverage.

In the case of 5G, the need for extreme capacity is addressed by utilizing the mmW spectrum that includes frequencies in 24-71 GHz range. While these bands address the high-capacity needs, the propagation characteristics at these frequencies require very dense base station deployments. These requirements may be met for hot spot scenarios but can be prohibitively expensive for wide area coverage.

6G deployments are expected to utilize all the spectrum ranges mentioned above, and to introduce new bands for exclusive 6G use. As the need for even higher capacity grows, it is very important that the new spectrum is suitable to meet those requirements. As in previous generations, coverage requirements will also play a significant role in selecting suitable spectrum:

- For applications that require very high capacity, but do not require wide area coverage, sub-THz spectrum that includes frequencies in the 100-300 GHz range may be suitable.
- For use cases that require high capacity and wide area coverage, upper mid-band spectrum, roughly defined as 7-16 GHz band, may be suitable. New technologies (discussed in Section 3.2.10) can utilize upper mid-band in 6G to address expected higher capacity demands and ensure coverage comparable to 5G deployments without requiring expensive network densification. The suitability of these bands to be handled over existing infrastructure for wide area coverage as well as the use of existing and new low and mid-band spectrum ensures the economical deployment of 6G and its success in delivering economic benefits to society.

Wireless standards also consider the possibility of sharing the same spectrum across different groups of users. An example of the concept of spectrum sharing between commercial users and lightly used government bands is the use of Citizens Broadband Radio Service (CBRS) around 3.5 GHz (as described in Section 3.2.7). To maximize socio-economic benefit, a major effort is needed to identify bands that could be shared between federal and commercial users. Reasonable rules that account for practical impacts should be defined for spectrum sharing between different commercial technologies. For example, some spectrum currently utilized by commercial satellite service could be utilized for 6G if there is no significant performance or business impact on satellite service providers. These regulations should consider that technologies like spectrum sensing and coordinated spectrum use can be combined to alleviate almost all interference concerns.

At the same time, legacy non-wireless broadband systems often are using equipment that is decades old. This concern was brought to the media's attention during the radar altimeter debate between 5G operators, wanting to use additional mid-band spectrum that is closer to where radar altimeters operate. Even though these bands are still more than 200 MHz apart, it causes issues for older receivers utilized by radar altimeters that are susceptible to interference from adjacent bands. The government must find ways to encourage spectrum users to update their equipment and avoid using devices that are overly susceptible to out-of-band interference. Similarly, wireless broadband operators now have access to powerful signal processing and hardware that can limit interference if provided with proper side information.

3. 6G Technology Innovations

We now provide a taxonomy of specific technology innovations for 6G that currently are being focused on throughout the industry, government, and academic sectors. These are the technologies that need to be of central focus in like-minded partnerships given their anticipated impacts on societal goals.

3.1. *Placing 12 Technology Innovations Toward 6G on a Taxonomy Table*

Twelve key technical focus areas for 6G were identified by the task force. Each of these areas is at a different level of readiness/maturity, from highest (for example, one to two years out) to lowest (for example, more than five years out). They also can be divided into different layers of the networking/communications protocol stack, from lowest to highest: radio frequency (RF)/physical (PHY) layer; medium access control (MAC) layer; network (NET)/transport (TRANS) layers; and application (APP) layer. Figure 1 (below) summarizes a rough partitioning of the technologies according to these dimensions.

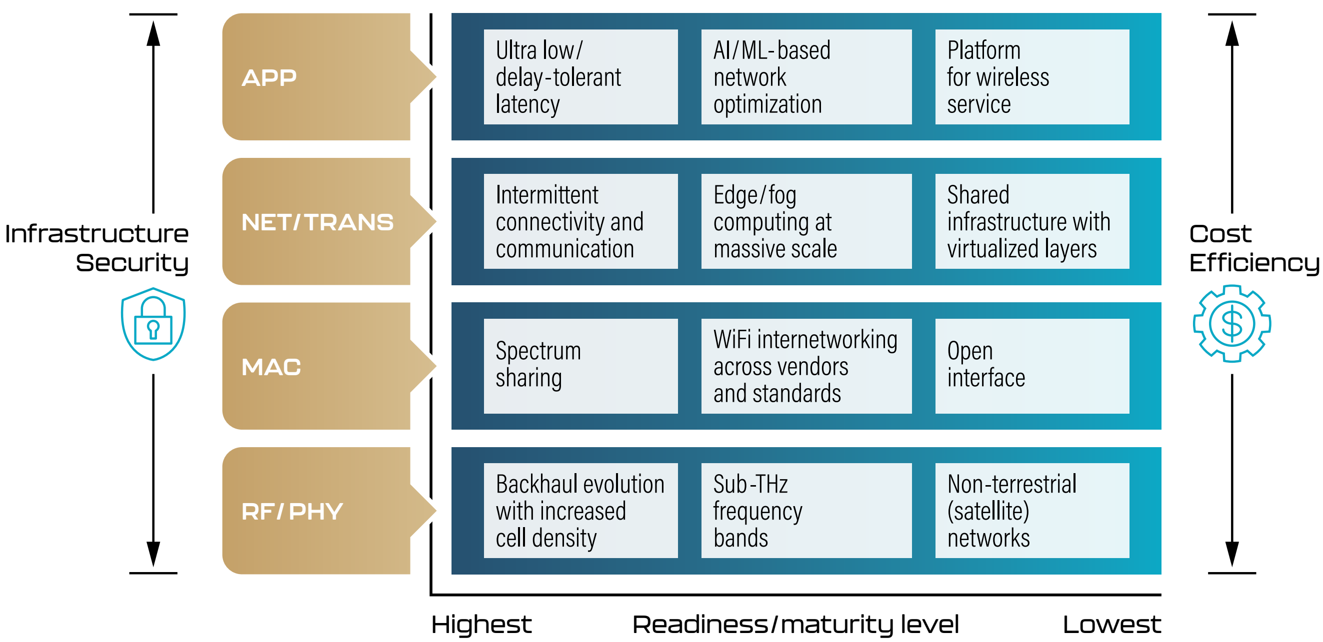

Figure 1: 6G technical focus areas by protocol layer and technical readiness.

For all technologies, in all protocol layers, infrastructure security and cost efficiency are key design considerations. These tie in with the societal goals outlined in Section 1.

These focus areas also are envisioned to impact different deployment environments, from indoor/local wireless environments to urban/suburban settings, to rural/regional environments. We break down the technologies according to their primary target settings in Figure 2 (next page).

In the rest of this section, we provide a technical synopsis of each of these 12 focus areas, including their readiness levels and the innovations under way.

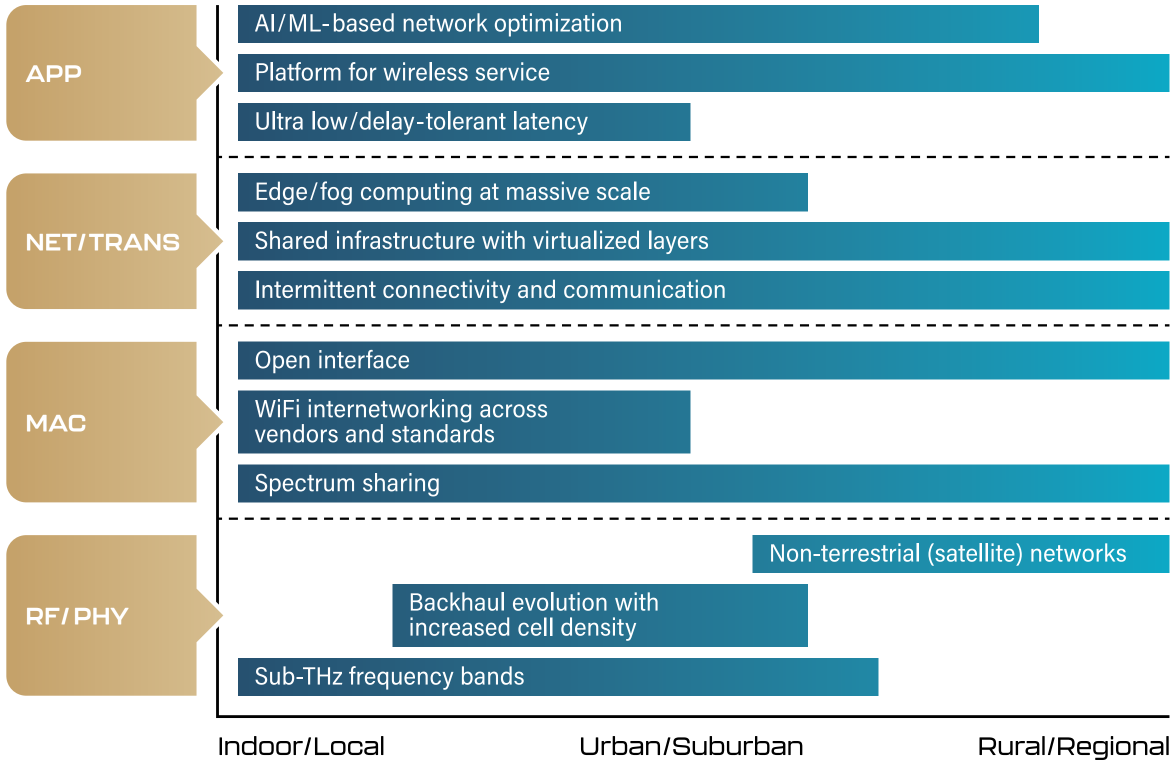

Figure 2: 6G technical focus areas organized by primary target deployment environment.

3.2. Technology Descriptions

3.2.1. Ultra Low/Delay-Tolerant Latency

The aim of addressing vertical markets with 5G widened the operating ranges required to be supported for many key networking parameters, including latency. On one extreme, some applications were thought to require the support of low latency with a high degree of reliability. This class of applications was categorized as Ultra-Reliable Low Latency Communications (URLLC). It is now understood that higher latencies may be tolerable for many of these applications if the latency is bound with a very high degree of reliability. At the other extreme, 5G also was designed to support devices and applications that can tolerate very long latencies. This is a characteristic of many IoT applications where a large number of such devices need to be supported simultaneously by the network. Any communications over non-terrestrial networks also need to be inherently more delay-tolerant than communications over terrestrial networks.

6G will further expand the vertical markets addressed and will need to support an even wider range of latency requirements. Support for ultra-low latency on the radio interface is enabled in current 5G technology using multiple approaches. One approach is operation at higher frequencies, where Orthogonal Frequency Division Multiplexing (OFDM) is used with higher Sub-Carrier Spacings (SCS). The higher SCS results in shorter OFDM symbol intervals, and consequently shorter transmission time intervals over which transport blocks containing information are sent. The other (and often preferred) approach is enabling the transmission of transport blocks over shorter time intervals composed of fewer OFDM symbols. This approach allows for ultra-low latencies even at lower frequencies where the OFDM symbol durations are longer.

Support for applications that require ultra-low latency puts stringent processing demands on the devices and the network. In contrast, support for delay-tolerant applications does not put such demands on devices directly. The demands on devices in these applications come from the need to support device operation with very low energy consumption, while the demands on the network come from the need to support a large number of devices and maintain their connectivity context over long periods of time. It may be noted that the typical end-to-end latency in a mobile network is much greater than the latency purely on the radio interface (for example, 10 milliseconds vs. 1 millisecond). Therefore, low end-to-end latencies require latency improvements throughout the network. 5G made significant improvements here in comparison to 4G, and 6G is expected to improve this metric further. However, for some applications where ultra-low latency is required in very localized environments, such as among industrial Internet of Things (IoT) devices working on a factory floor, minimizing the network components required for the application can help reduce the latency significantly. Furthermore, splitting a carrier into uplink and downlink time slots—as is typically done for Time Division Duplex (TDD) systems—will have significant impact on the latency since a time slot "in the right direction" might not be available when latency-critical data needs to be transmitted.

The technologies necessary to achieve ultra-low latency are mature from a standards point-of-view, and partly from a product development perspective, since these have been cornerstones of 5G and will continue to be improved upon in 6G. Technologies that support delay-tolerant IoT applications also are quite mature since support for these has been present since 4G standards, and there are deployed devices in this category already. Technologies that support maintaining connections while tolerating delays inherent in satellite communications also are reasonably mature as the 5G specifications already support non-terrestrial networks.

To facilitate future demands, research will be needed on understanding the fundamental limits of latency and how to achieve these limits. The research community's understanding of finite blocklength communication is limited to only the simplest cases. Theory is far from providing significant insight into more complicated network operation. This is especially true when looking at multi-hop, point-to-multipoint, or multipoint-to-point communication settings.

The support of ultra-low latencies can be important for applications such as Augmented Reality (AR)/Virtual Reality (VR), autonomous vehicles, real-time human machine collaboration, haptic feedback, robotics and control of machines and processes. AR/VR is needed for the Metaverse and haptic feedback is central to the evolution toward a tactile internet. For many of these use cases, the processing demands require significant processing to be offloaded from the user device to the edge of the network. Ultra-low latencies can help to enable such offloading while maintaining a truly immersive experience.

Delay-tolerant technologies that can support a large number of such devices are useful for many machine-to-machine applications. Delay-tolerance is also necessary for providing ubiquitous service continuity especially in remote regions where non-terrestrial communication is needed to maintain coverage. While the processing demands for these technologies and the greater number of devices in an expanding suite of applications can cause an overall increase in energy consumed, these technologies can also be made energy-efficient to manage energy consumption. The ability to manage energy usage by turning network elements on or off with greater agility can be enhanced by the support of ultra-low latencies and delay-tolerant technologies in many cases.

3.2.2. AI/ML-Based Network Optimization

The need for Artificial Intelligence (AI)/Machine Learning (ML)-powered automated network optimization is driven by the increasing complexity of networks. New technologies and design approaches, such as network densification, network slicing, and evolvable network topologies—coupled with other advanced radio link features, such as beamforming, enhanced massive Multiple Input Multiple Output (MIMO), spectrum sharing, and joint communication and sensing—pose increasing challenges to traditional optimization approaches that have been embedded in earlier standards. The success that deep learning architectures have demonstrated in modeling complex processes in various domains, from computer vision to natural language processing, motivate their consideration for complex network systems as well.

AI/ML for network optimization is an active research and technology development area for both 5G systems and next-generation 6G systems. It is anticipated that AI/ML approaches will lead to a number of benefits, including device and network energy savings, improved communication quality, and intelligent solutions to network resiliency and information security. However, according to the Next G Alliance, achieving these benefits will first require concerted efforts along three important dimensions [2]:

- The 6G wireless standards need to be developed in an AI-native way, with an open architecture to allow applications of a rich set of AI/ML algorithms.
- Open datasets need to be made available to the research and development community to expedite the customization of AI/ML algorithms in the wireless domain.
- Operators need to embrace AI/ML as their new tool for increasing efficiency and quality of service over their networks.

The definition of the network architecture and interfaces that will support AI/ML for network optimization is well under way. Significant efforts have been made in 5G standards development to enhance the functions in the control and management planes of networks to include data collection for AI/ML model training and model inference. 6G will continue this effort with its AI-native design running on a cloud-native system infrastructure. These efforts should lead to a diverse set of measurement types being made available to AI/ML algorithms running on devices and at other nodes throughout the network, from radio-layer data like wireless channel state, received signal strength, and bit error rates to higher layer data like round trip times, jitter, and route failures that can be processed to optimize network control protocols.

Research on AI/ML for wireless based on available datasets has begun to shed light on which techniques will be effective for optimization in 6G. Recurrent Neural Network (RNN) architectures for time series processing of wireless measurements have demonstrated promising capabilities in signal detection/classification, transmission coding design, traffic anomaly detection, and other intelligence tasks. Deep reinforcement learning techniques have shown the ability to serve as intelligent controllers for various network processes as well, including programming of reconfigurable surfaces, proactive file caching, and traffic route selection. However, the development of such AI/ML-powered network optimization applications still is at a relatively early stage. Implications of such techniques to robustness, effectiveness, and security still need to be fully studied and understood. In particular, the trend in many domains of improving inference accuracy by making AI/ML models "deeper" does not necessarily translate to higher efficacy in 6G systems, as taming the complexity of network protocols to minimize execution time is a critical objective. Several important research programs are working extensively on these hard problems through industry-academia collaborations, including the National Science Foundation (NSF)/Intel Partnership on Machine Learning for Wireless Networking Systems (MLWiNS) and the NSF Resilient and Intelligent NextG Systems (RINGS) project.

One of the main benefits of AI/ML-powered network optimization is its ability to deal with complex network planning, configuration, operation management, near-real time or non-real time network optimization, and self-healing at reduced complexity and cost. With the implementation of AI/ML technologies, networks are expected to be able to configure themselves according to the performance requirements of different use cases, to adapt to different network topologies and device mobility, and to defend themselves against cybersecurity attacks with network anomaly detection for resilient network operation.

To be more specific, AI/ML can directly optimize the network toward higher energy efficiency. In fact, "Network Energy Saving" is a key use case that 3rd Generation Partnership Program (3GPP) is actively working on in Release-18. Support of extreme data rate, low latency and reliable radio transmission for immersive user experience or real-time robotic control can be more cost-effectively achieved through AI/ML-powered dynamic network configuration and optimization. With the network's ability to manage user connectivity across multiple carrier frequencies and across different systems, the availability and reliability of the network connection is significantly improved both for human users and services and for Machine to Machine (M2M) communications. Finally, as the whole network becomes intelligent and easily and securely reconfigurable, the support for user-oriented network security becomes possible.

3.2.3. Platform for Wireless Services

Technological advancements in compute infrastructure have enabled solutions previously developed on purpose-built hardware to move to software running on general-purpose computing platforms. This trend has accelerated with the adoption of cloud technologies for application workloads and has resulted in the ability to develop and deploy services with greater agility. It also has influenced the handling of workloads in mobile network systems where the move to software-based solutions and services has increased from 4G to 5G and is expected to further accelerate for 6G.

Together with advances in transport technologies, the proliferation of cloud platforms has provided an additional impetus for creating open interfaces in the network architecture. However, the deployment of Radio Access Networks (RAN) on cloud platforms also has highlighted the need for custom hardware accelerators for some critical functions in the RAN due to the strict latency constraints and high reliability requirements that must be met by these networks. Examples of such functions include channel decoders, equalizers, and processing for multiple antenna MIMO systems.

These technological developments have resulted in increased programmability and configurability of the mobile network that allows service providers to cater to a wider range of requirements from an ever-growing range of new applications and use cases. This has enabled 5G mobile networks to serve a wide range of heterogeneous use cases for vertical industries, enterprises, and governments in addition to traditional voice and mobile broadband. The applications and use cases that need to be addressed will further expand with 6G systems, accentuating the importance of innovations in network programmability and configurability that will allow them to adapt to different traffic and deployment scenarios.

As discussed in Section 3.2.2, AI/ML technology is making an impact on numerous aspects of wireless communications, and the wider Information and Communication Technologies (ICT) sector more generally. The evolution to more programmable networks yields opportunities for AI/ML to enable a more intelligent and adaptable global network platform. The network platform, thus enhanced with AI/ML, can in turn provide distributed intelligence as a service to applications using AI/ML running on the platform.

Foundational elements needed for this type of network platform are Application Programming Interfaces (APIs), which, when exposed to developers, enable them to create applications and services that depend on wireless connectivity. Examples include APIs for Quality of Service (QoS), security, location, identity, billing, and mobile payments, as well as services such as messaging. The set of APIs is expected to expand as mobile networks support more sectors of business and society including enterprise, public safety, and education, among others. A cognitive global network platform accessible through APIs hides the underlying complexity while enabling the provision of advanced 6G applications and services that require connectivity, and may in addition integrate computing, sensing, and control capabilities.

6G will be developed as a flexible global network platform, providing a wider range of wireless services. This general platform approach will offer significant benefits for many use cases and achieve multiple long-standing societal goals. For instance, a more adaptable network can reduce energy consumption when idle thus improving energy efficiency. Furthermore, it can enhance a variety of use cases such as immersive communications by providing services that can facilitate the distribution of intensive processing functions to the network edge. Similarly, applications relying on M2M communications and sensing capabilities can be better supported. A programmable and cognitive network with greater room for optimization of functions in software can support a wide range of use cases while improving service availability, trust, and security.

3.2.4. Intermittent Connectivity and Communication

Intermittent connectivity and communications have been fundamental design elements of network systems since their inception. Even before the proliferation of wireless communications, wireline networks needed to support bursty traffic patterns in which connected devices are active for short periods of time, demanding network resources yet remaining idle for relatively long periods in-between. This was one of the driving principles behind the migration from circuit-switched to packet-switched networks for internet traffic back in the 1970s—for example, so that devices did not occupy network resources unnecessarily when they were idle.

Wireless introduces a whole new set of challenges related to intermittent connectivity. Many of these stem from device mobility, which has been a focal point of wireless standards since 2G. Cellular mobility management technologies typically use two major connection states—the idle and connected states [3]. The mobile device is kept in "idle state" when there is no data exchange and intermittent connectivity is used to update the user's location. In the "connected state," an intermittent connectivity technique commonly known as Connected Mode Discontinuous Reception (C-DRX), allows the mobile to turn off radio and save power when there is bursty and intermittent data.

Intermittent connectivity and communication is an important consideration at higher layers of the protocol stack, too. The User Datagram Protocol (UDP) uses a simple connectionless communication model with a minimum of protocol mechanisms, which makes it the transport of choice for intermittent protocols such as transaction-oriented protocols (for example, Domain Name System and the Net Time Protocols), tunneling protocols, streaming, and bootstrapping of other protocols. Message Queuing Telemetry Transport (MQTT) is another protocol to address intermittent connectivity and communication, running instead on the connection-oriented Transport Control Protocol/Internet Protocol (TCP/IP). It is a lightweight transport publish/subscribe messaging protocol, minimizing network and device resource requirements and today is in widespread consideration as a standard for IoT communications [4].

Many of the network and transport technologies that support intermittent connectivity and communication have reached a high level of maturity in their current context. For example, cellular Discontinuous Reception (DRX) technology for both idle and connected states has been around since the era of 2G and has been optimized to improve network resource and energy efficiency in 5G networks. These optimizations include a transitionary state between idle and connected, the Wake-Up Signal (WUS), and additional configurations to support more traffic and device types. TCP/IP has been built upon over time to adapt to rapid changes in available throughput in general. However, it has not been specifically optimized for mobile communications and intermittent connectivity, which will be important for 6G network standards.

6G networks are envisioned to provide a unified platform for next-generation broadband wireless services and interactive, collaborative, and autonomous communication between machines, as well as address some of the environmental sustainability challenges facing our world today. To achieve these lofty goals, it is imperative that scenarios with intermittent connectivity and communication be supported in a manner that ensures the performance requirements of these emerging use cases are adequately met.

In the following paragraphs, we highlight some of the intermittent communications requirements for 6G M2M communications and energy efficiency.

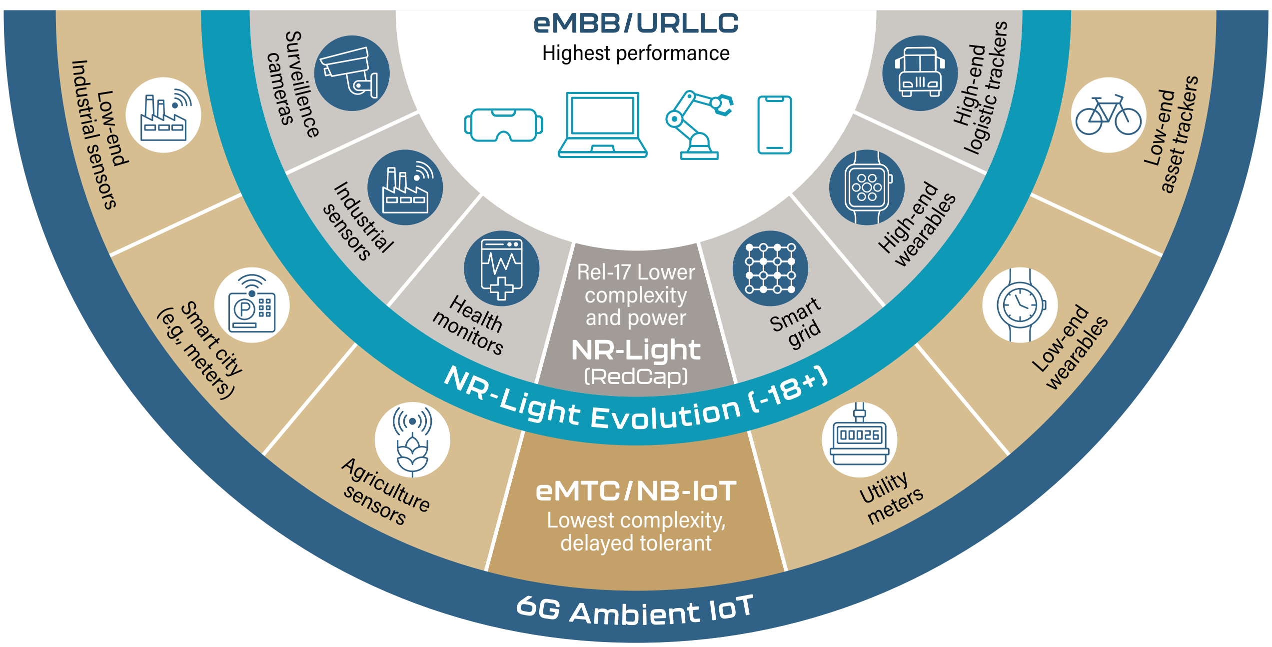

Figure 3: Intermittent machine-to-machine communications in 5G New Radio (NR) and expansion to 6G.

- **Scaling to Support Machine-to-Machine (M2M) Communications:** In addition to supporting existing 5G and 5G advanced M2M use cases, 6G networks will support machines (such as sensors, actuators, vehicles, and robots) communicating in a more interactive, collaborative, and autonomous fashion. Additionally, the number of IoT devices is expected to increase to tens of billions by 2030 [5]. This will likely increase heterogeneity in traffic types, device types, and device densities—potentially driving new performance requirements. For example, higher node densities imply that the simultaneous connection density would increase. While existing network and transport layer technologies (for example, TCP/IP, UDP, MQTT, etc.) can be leveraged in supporting the intermittent communication typically associated with M2M communication, enhancements driving efficient use of computing, radio and energy resources (such as reduced packet overhead, fewer handshake, etc.), reduced latency, and increased reliability would be required. In addition, enhancements for supporting traffic types with separate Mobile Originated (MO) and Mobile Terminated (MT) traffic requirements or even traffic with low-duty cycle yet low latency would be required.

- **Sustainability and Improving Energy Efficiency:** As mentioned above, environmental sustainability is an important usage scenario envisioned to be addressed by 6G networks. On the network side, there could be significant energy saving by designing a protocol that enables tradeoffs of where to spend the energy to minimize the overall energy consumption. In one example, it is envisioned that improvement in energy efficiency and carbon footprint reduction would be achieved by using ambient IoT/zero-energy devices for tracking and monitoring purposes in verticals such as food, logistics, transportation industries, smart cities, etc. These devices are powered using electrical energy converted from ambient energy sources such as solar, thermal, wind, light, or even Radio Frequency (RF) [6], which may be intermittently available, introducing additional dimensions of intermittence typically not addressed in existing IoT devices. Therefore, even though existing network and transport layer technologies can be leveraged to support these ambient IoT devices, further extensions would be required to support the unintentional intermittence due to unpredictable power availability.
- **Latency Reduction:** The support of ultra-low latencies can be important for applications such as AR/VR, autonomous vehicles, real-time human machine collaboration, haptic feedback, robotics, and control of machines and processes. AR/VR is needed for the Metaverse, and haptic feedback is central to the evolution toward a tactile internet. For many of these use cases, the processing demands require significant processing to be offloaded from the user device to the edge of the network. Ultra-low latencies can help to enable such offloading while maintaining a truly immersive experience.

  Delay-tolerant technologies that can support a large number of devices are useful for many M2M applications. Delay tolerance is also necessary for providing ubiquitous service continuity, especially in remote regions where non-terrestrial communication is needed to maintain coverage. While the processing demands for these technologies and the greater number of devices in an expanding suite of applications can cause an overall increase in energy consumed, these technologies can also be made energy-efficient to manage energy consumption. The ability to manage energy usage by turning network elements on or off with greater agility can be enhanced by the support of ultra-low latencies and delay-tolerant technologies in many cases.
- **Digital Inclusion:** Technologies enabled by intermittent connectivity go beyond basic broadband services. They allow services such as health monitoring, environmental sensing, electronic payments, and personal security to reach underserved communities.

Further details about intermittent connectivity applications can be found in [7, 8, 9].

3.2.5. Edge/Fog Computing at Massive Scale

In the early 2000s, cloud computing began exploding in popularity as a cost-effective means for offering remote computing and storage services to network users at scale. However, as the number of data-hungry wireless devices continues growing exponentially, it is no longer feasible to centralize all this computation in datacenters while providing the results back to devices rapidly enough to satisfy latency requirements. In particular, AI/ML-based services, such as those discussed in Section 3.2.2, have contributed to a significant upswing in the volumes of data to be processed over networks. Centralization also comes with privacy and security concerns, as it requires transferring large volumes of user-generated data over network infrastructure that is constantly being tested by new adversarial threats.

To address these challenges, edge computing emerged in the early 2010s as a paradigm for leveraging the increasingly powerful processing capabilities of connected machines at the network edge—such as smartphones, tablets, and intelligent IoT sensors—to handle computation services closer to the point where the requests originate. Different from the cloud, these edge devices often are heterogeneous in their communication and computation capabilities, which becomes a key consideration for optimizing task services in edge computing. While the cloud provides an ideal configuration for processing tasks with large datasets and wide geographic proximities that can nonetheless tolerate some delay (for example, weather forecasting based on volumes of sensor inputs across a large region), the edge allows for servicing more localized tasks that have more stringent delay and/or privacy requirements (for example, medical diagnostics based on real-time data from wearable health monitors).

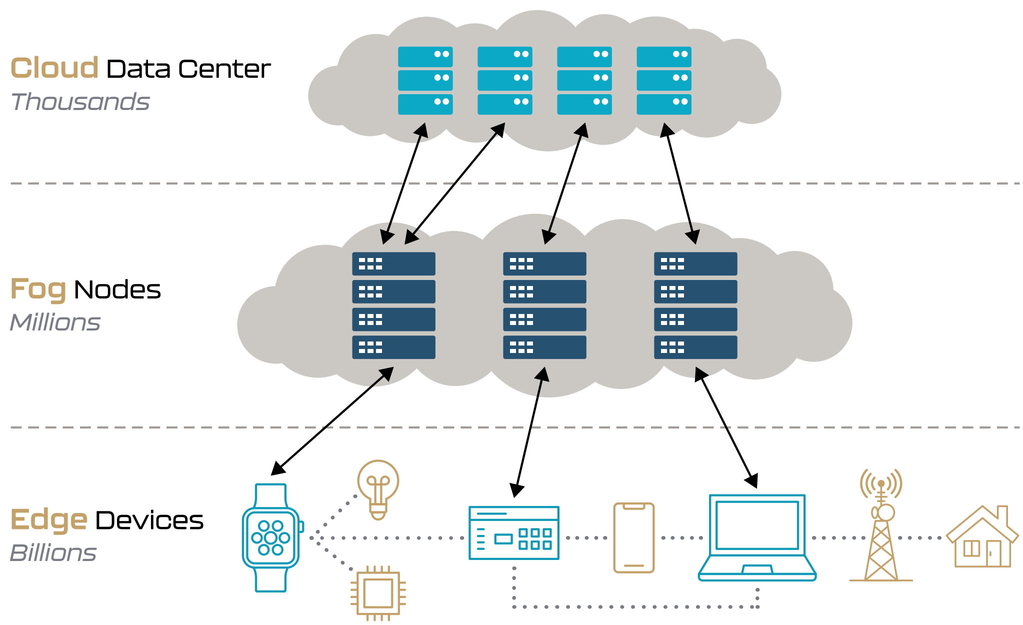

Figure 4: Fog computing aims to orchestrate computing resources to serve data processing tasks along the cloud-to-things continuum.

As discussed in Section 3.2.1, there is a wide variety of task latency requirements—from ultra-low to delay-tolerant tasks—that must be satisfied simultaneously. Edge and cloud computing can be viewed as the two "extremes" of a processing and storage service model. Since the late 2010s, a key technology direction has been how to architect a hybrid between them, while also leveraging the intermediate network nodes connecting the edge and cloud (for example, routers, base stations, intermediate servers) to optimize how tasks are serviced. This has given rise to the term "fog computing," which aims to intelligently orchestrate compute, storage, and networking services between end devices and cloud computing data centers, as summarized in Figure 4 (above). An important thread of investigation in fog computing is how to determine an appropriate set of nodes across the "cloud-to-things continuum" to manage a particular task, in the presence of a multitude of other tasks that have their own diverse service requirements.

6G wireless is a critical component of fog computing, as it will dictate the mechanisms by which tasks are routed from the edge devices —where they originate — to the rest of the computing infrastructure. The continued proliferation of direct Device-to-Device (D2D) and Machine-to-Machine (M2M) communications will provide more opportunities for edge devices and fog nodes to service tasks by pooling their local resources together, rather than placing added burdens on the long-range upstream/downstream communication infrastructure separating edge and cloud. Preliminary research in the emerging area of "fog learning," which specifically aims to orchestrate AI/ML tasks over fog networks, has shown how this type of local coordination among wireless edge and fog nodes can lead to substantial improvements in service quality, latency, and energy consumption metrics [10].

The movement toward Metaverse and immersive experiences for end users requires handling increasingly complex computing tasks in terms of their size and latency requirements. One of the key objectives of fog computing in 6G will be to facilitate this at scale, through intelligent orchestration of networking resources across the cloud-to-things continuum. Many IoT services will be supported through this paradigm, with D2D and M2M communications complementing upstream/downstream wireless transmissions in 6G.

Energy efficiency also is one of the key metrics considered in fog computing orchestration. In general, there is a fundamental tradeoff between resource efficiency and service quality, which must be carefully controlled depending on end user requirements and fog network constraints. User-oriented network security will be a high-priority service class executed in fog computing, with cloud-to-things orchestration providing a means for collaborative detection and mitigation of adversarial threats that emerge with 6G wireless.

3.2.6. Shared Infrastructure with Virtualized Layers

End-to-end virtualization is a pivotal feature needed to support multi-tenant, multi-operator shared environments. The telecommunications industry has begun to evolve toward a fully software-defined, cloud-native architecture paradigm due to the contributions of organizations like the 3rd Generation Partnership Program (3GPP) and the Open-Radio Access Network (O-RAN) Alliance discussed further in Section 4. These organizations have introduced network virtualization functions and have defined the disaggregated RAN as key architectures in 5G. This includes (i) a vertical split of protocol stack functions across the Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU) of a RAN, which can then be located in different parts of the deployment region, as well as (ii) a horizontal separation of control and user planes. Thus, 5G promotes a Service-Based Architecture (SBA)—a collection of software running on commercial off-the-shelf hardware powered by general purpose Central Processing Units (CPUs)—as an alternative to traditional fixed function, proprietary hardware.

Cloud-based orchestration and management principles can be applied to a fully virtualized SBA-based RAN. With the help of versatile cloud platforms that enable developers to build, deploy, and execute server-side applications swiftly, operators using shared network infrastructure can run network functions as highly disaggregated and distributed microservices, as illustrated in Figure 5 (next page). These services can run both within a single server and across multiple servers within a rack. As a result, incorporating virtualization into communications systems significantly improves the flexibility, scalability, and cost-effectiveness of operators by enabling them to deploy many network functions on a single platform.

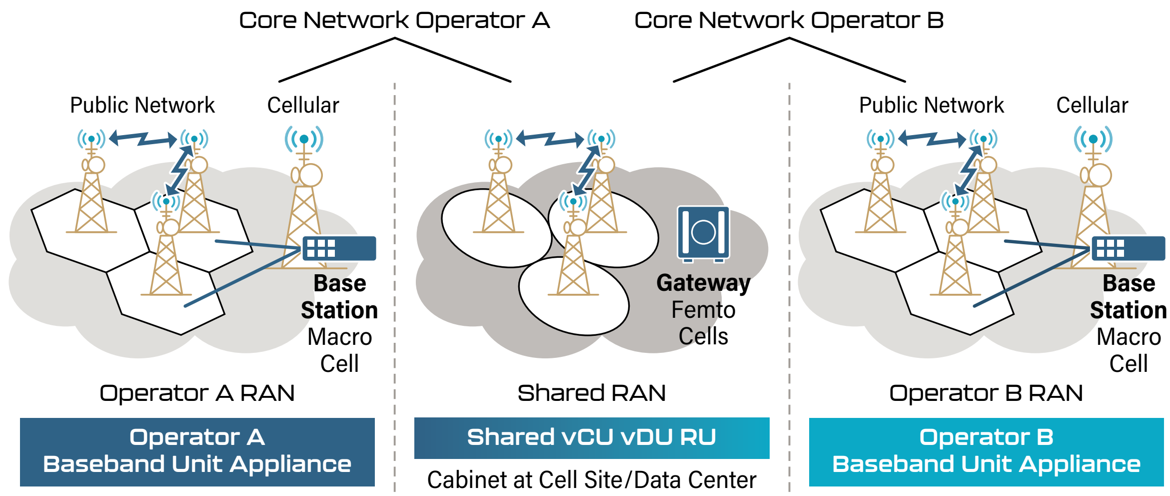

Figure 5: Operators who utilize shared network infrastructure can execute network functions as highly disaggregated and distributed microservices.

Sharing examples also can include sharing part of the RAN. For example, the DU and CU can be virtualized and remain separate, but the RU may be shared. This approach enables a static partition of the spectrum among operators, but also allows for dynamic reuse or spectrum sharing (see Section 3.2.7).

As indicated by lab experiments and field pilot deployments, the telecommunication industry's transition to virtualized RAN is well under way. Yet, the interdependence of network functions, for example, remains a barrier to achieving fully cloud-native implementations in current and previous system architectures. Such efforts will be critical to supporting the 6G wireless vision.

Today's networks are extremely siloed. Operators primarily operate on equipment they directly own or lease. Algorithmically, hardware-specific and vendor proprietary implementation limit network adaptability. 6G will alter this, with new open RAN implementations and operator sharing models. Network level benefits include:

- **Sustainability with Improved Hardware Energy Efficiency:** Telemetry data for tracking CPU, memory, and input/output consumption can be gathered by operators on a shared infrastructure with virtualized layers. The data gathered can be utilized to adjust the clock rate and power consumption of relevant CPU cores in the network function, as well as to reduce the number of servers required for the task at hand and turn off any idle machines. Open interfaces allow different logical functions to be flexibly hosted on the compute resources that can best deliver the required performance-energy tradeoff.
- **Scalability to Address Demand from the Metaverse/Immersivity/Tactile Internet:** Non-real time and near-real time RAN Intelligent Controllers (RIC) enable the combination of network platform and application telemetry. Shared infrastructure with virtualized layers can use RIC to increase spectral efficiency and usage of deployed radio resources with active antenna management and orchestration and boost real-time responsiveness by dynamically allocating network function resources as network conditions change.
- **Trustworthiness and User-Oriented Device-Level Security:** Security functions can be "softwarized" and virtualized with embedded intelligence thanks to fully virtualized platforms. State-of-the-art intelligent security functions in containerized virtual network functions monitor traffic—for example at gateways, to enforce policies and detect, contain, mitigate, and prevent threats or attacks. These functions work in tandem with real-time, detailed platform telemetry information.

- **Digital Inclusion:** Open interfaces allow the implementation of networks customized to serve different use cases and geographic scale, including rural areas and underserved urban areas. This presents a significant opportunity to improve digital inclusion.

3.2.7. Spectrum Sharing

Radio spectrum is a limited natural resource allocated and used through government regulations, as discussed in Section 2. It should optimally be used at high spectral efficiency, achieved through meticulous engineering and maximizing utilization for specific applications and services in a market.

Historically, spectrum sharing has mostly taken place using static, semi-dynamic, or autonomous best-effort mechanisms. An example of static sharing is when an operator is migrating its radio carrier from 4G to 5G and reutilizing the same spectrum by splitting it into two parts. Semi-dynamic sharing is exemplified by U.S. Citizen's Broadband Radio Service (CBRS) (3.55-3.7 GHz), which is shared between federal incumbent users, Priority Access Licensees (PAL), and General Authorized Access (GAA) users via a Spectrum Access System (SAS). The Listen-Before-Talk (LBT) scheme of WiFi represents an autonomous best-effort approach to spectrum sharing.

In a recent development, 3GPP introduced a Dynamic Spectrum Sharing (DSS) feature for 5G NR [11]. This enables 4G LTE and 5G NR to operate in the same frequency band on the same carrier simultaneously. This is an important instantiation of DSS. DSS, as defined by 3GPP, could be further developed for next-generation systems to incorporate more, or all, possible dimensions, including across locations, frequencies, time, users, and applications. Next-generation DSS designs could consider new technologies, such as advanced spectrum sensing, interference analysis and avoidance, AI/ML-based sharing control, inter-system/inter-user direct signaling for spectrum sharing, and hierarchical spectrum management system for DSS, among others.

Nevertheless, there are several design challenges and practical considerations in the development of next-generation DSS technology. For instance, the coordination between two systems may not be possible or may be overly complex in certain radio environments. Furthermore, there are legacy devices and networks incapable of supporting DSS upgrades, which are particularly prevalent in many IoT markets. Therefore, a holistic and systematic effort involving regulators, infrastructure operators, device users, and the academic community is desirable to advance the implementation of DSS in next-generation wireless standards.

The evolution to 5G has caused changes in the way operators use spectrum. The success of mid-band and the deployment in shared bands gives hope that the long-held promises of spectrum sharing may become reality. Dynamic spectrum sharing, as defined by 3GPP, adds another important engineering dimension to the system. Efforts can be made to improve systems' overall energy efficiency by exploring different radio access options enabled by DSS. Additionally, DSS may offer critical relief to areas and frequency bands where traffic loading is high and bursty, which are often associated with next-generation Metaverse and tactile internet use cases. With DSS, multiple systems may share the same frequency band and free up spectrum for other systems. In general, this helps with the goal of achieving ubiquitous connectivity for all users and application using 3GPP technologies. For M2M communication, where dedicated spectrum may not be available in a market, DSS can be a key technology that enables certain vertical markets.

The development and the implementation of DSS by network operators involve many aspects, including regulatory framework, business models, and technical feasibilities. For example, although direct coordination among two or more systems could dramatically improve DSS efficiency, such coordination may not be viable due to business reasons. Finally, it is worth mentioning that DSS operation may impact systems' achievable QoS. So, for applications that impose stringent latency and reliability requirements, DSS needs to be carefully designed and engineered.

3.2.8. WiFi Internetworking Across Vendors and Standards

The era of 6G cellular communications will usher in use cases requiring enhanced security, higher bandwidths, more economical and sustainable infrastructure, lower latencies, higher reliability, and importantly, better, more seamless coverage across different environments. These environments include different indoor and outdoor settings serviced by cellular and WiFi vendors and systems. To this end, ensuring that standards bodies and industry consortia work collaboratively to provide standards specifications, technical architectures and operational frameworks that facilitate a high degree of interworking and user experience compatibility across 6G and WiFi systems is an area of significant importance.

The key features that must be established for interworking and standards alignment include:

- **Common Identity:** A method to establish common identity for a user and/or a device, allowing consistent bandwidth and latency policies, security enforcement and analytics, networking roaming privileges, and other attributes applied to that user and/or device.
- **Security Policy:** The ability to have a consistent and uniform security policy pertaining to a user, a device, or an IoT "thing." Regardless of the access method (WiFi or 6G), the resultant communications must adhere to the required security functions, and the resultant security analytics and alerts should have commonality of processing.
- **Open Roaming:** Seamless, zero touch roaming between 6G and WiFi networks should be facilitated, ensuring a user or a device can have "always on" connectivity without requiring any user intervention or a user-driven configuration change.
- **Power and Experience Optimization:** In environments where connectivity is simultaneously available via both a WiFi network and a 6G network, an end device should be able to make a network choice based on the real-time power (and resultant cost) profiles of the available options, taking into account factors such as bandwidth, latency, and reliability characteristics of the set of available networks.
- **Multi-Path Connectivity:** Considering a future set of use cases that may demand extremely high bandwidths and potentially very low latency, devices should be able to use all available spectrum and radio assets simultaneously such that WiFi and 6G networks can be bonded together with resultant communications flowing over all available paths in parallel.

To ensure elevated levels of interworking between WiFi and 6G, the features mentioned above need to be developed collaboratively across the respective standards bodies in both domains. This requires active participation of various stakeholders discussed in Section 4 such as the user community, device manufacturers, silicon component suppliers, network technology vendors, regulatory agencies, and communications service providers.

WiFi and 6G Internetworking is a pivotal foundation for achieving the positive societal impacts outlined in Section 1 of this document. By effectively combining licensed spectrum with unlicensed WiFi spectrum, the required scalability and bandwidth requirements of next-generation use cases can be achieved. Given the lower power footprint of WiFi, such interworking can be instrumental in lowering the total energy footprint required for connectivity. Use cases that require highly reliable, always on wireless connectivity are more easily served through such a heterogeneous approach, especially ones that require that connectivity to span both indoor and outdoor. And finally, being able to use all radio resources within user devices ensures service can be delivered economically facilitating full digital inclusion.

3.2.9. Open Interface

The mobile communications ecosystem has a rich tradition of open interfaces, starting with the interface between mobile devices and operator networks. Open interfaces have enabled a diverse group of suppliers for devices and networks.

Open interfaces also play a role within the mobile network by providing a standardized mechanism for different components to interoperate. This creates the possibility of specialized and optimized design for individual network components and potential sourcing from different vendors. For instance, the RAN and Core Network (CN) have been connected through an open interface since 3G. This has allowed companies without traditional radio expertise to enter the CN market and increase innovation and market competition. The trend toward open interfaces has continued with the separation of the RAN into specialized component functions in 5G (as was discussed in Section 3.2.6) and is expected to play an even more important role in 6G technology.

In particular, different parts of the 6G network will rely on different types of building blocks—for example, general purpose computing, specialized signal processing with accelerator functions, and power amplifier and antenna functions at the cell site. In 5G systems, we see this happening with RAN disaggregation: the CU utilizes general-purpose computing, and the DU relies on signal processing and accelerators, while the RU hosts power amplifiers and radio antennas. Within the CU, there is a further separation of packet processing functions, Central Unit–User Plane (CU-UP) and control plane functions, Central Unit–Control Plane (CU-CP). With open interfaces between these functions, providers specializing in specific areas of technology, such as power amplifiers for the RU or signal processing for the DU, can work to develop best-in-class solutions. A well designed open interface then allows the functions to be brought together to build a high performing network solution.

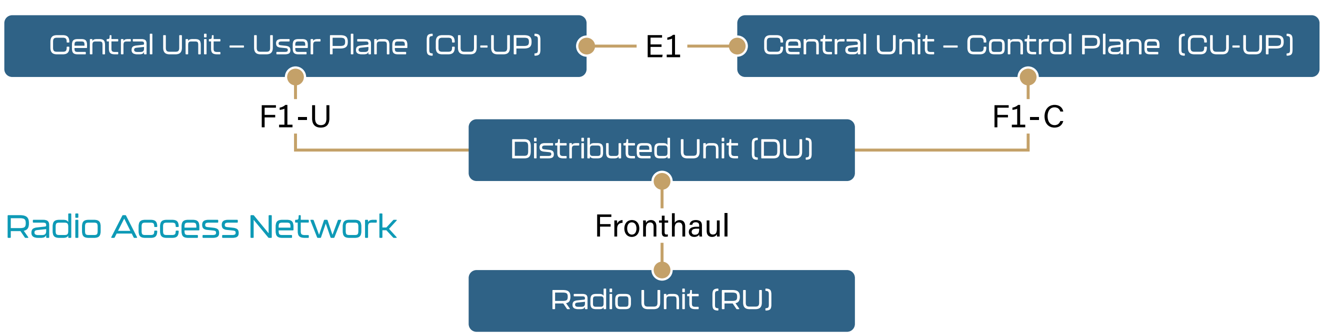

Figure 6: Open Interfaces in 5G RAN.

Standards for open interfaces in the RAN context are being developed by 3GPP, the O-RAN Alliance and the Small Cell Forum. The technology is currently in the early stages of deployment across commercial 5G networks. Figure 6 (above) gives an illustration of 5G RAN with recently introduced open interfaces: 3GPP has introduced the F1 interface in 5G as an open standard between the DU and CU, and the O-RAN Alliance has introduced the Open Fronthaul between the DU and RU.

Both 3GPP and the O-RAN Alliance are working toward open interfaces to improve ML applications in 5G. Already, 3GPP has started the standardization work to support AI/ML network optimization for 5G systems (see Section 3.2.2), including the Network Data Analytic Function (NWDAF) and the Management Data Analytics (MDA) features. At the O-RAN Alliance, work on the RAN Intelligent Controller (RIC) has been ongoing to enable AI/ML capabilities for both near-real-time and non-real-time control loops.

The open interfaces in 6G RAN may be different from the 5G RAN in keeping with evolving technology capabilities and deployment scenarios. One key component of this development will be the availability of testbeds to prove out solutions based on open interfaces. Examples of organizations providing such testbeds include the Telecom Infrastructure Project, the SONIC Lab in the UK, and NSF-funded projects such as Colosseum in the United States.

In addition to interworking of logical functions, interworking of software and hardware is an important area of technology. The software driven approach using more general-purpose hardware has played a significant role in cloud computing and data center technology and can offer numerous advantages to next-generation wireless platforms:

- **Improved Network Energy Efficiency:** Not only can software-driven techniques more efficiently utilize the hardware, but they can also change the way devices within the network adapt to operating conditions. Open interfaces allow vendors for each node to focus on improving energy efficiency within their domain. Further, a well-designed open interface allows the energy optimization functions in each node to exchange information and work together for overall energy efficiency.
- **Metaverse/Immersivity/Tactile Internet:** To deliver an immersive experience, the next-generation network has to be customized to different scenarios. A one-size-fits-all approach does not scale across stadiums, enterprises, downtowns, and rural areas. Open interfaces allow components to be stitched together more flexibly across diverse deployments.
- **Ubiquitous User Service Connectivity:** Economic obstacles often prevent connectivity from reaching remote, rural, or low-income areas, including critical education and healthcare sectors. With open interfaces, the cost of building networks can potentially be reduced, for example, due to more competition among equipment vendors, thereby removing some of the economic barriers to connectivity for all.
- **Supporting Machine-to-Machine (M2M):** M2M communication ranges from high bandwidth and low latency applications such as precision robotics to low bandwidth delay-tolerant communication such as solar-powered sensors. Open interfaces add flexibility to network design, making it possible to customize the network depending on the use case.
- **User-Oriented Network Security:** Open interfaces allow scrutiny from researchers and white-hat hackers to quickly identify gaps. Open interfaces also use state-of-the-art security technologies for encryption and authentication and rely on more reuse from the wider networking and communications ecosystems. This makes systems based on open interfaces secure.

Further details about open interfaces can be found in [12] and [13].

3.2.10. sub-THz Bands

In the 6G era of the 2030s, the utilization of sub-THz bands from 100GHz to 300GHz is expected to primarily cater to localized peak access capacity, backhaul (cf. also 3.2.11) as well as high-precision sensing needs in cellular radio networks [2] [14]. Use cases and sectoral relevance discussed here are depicted in Figure 7 (next page).

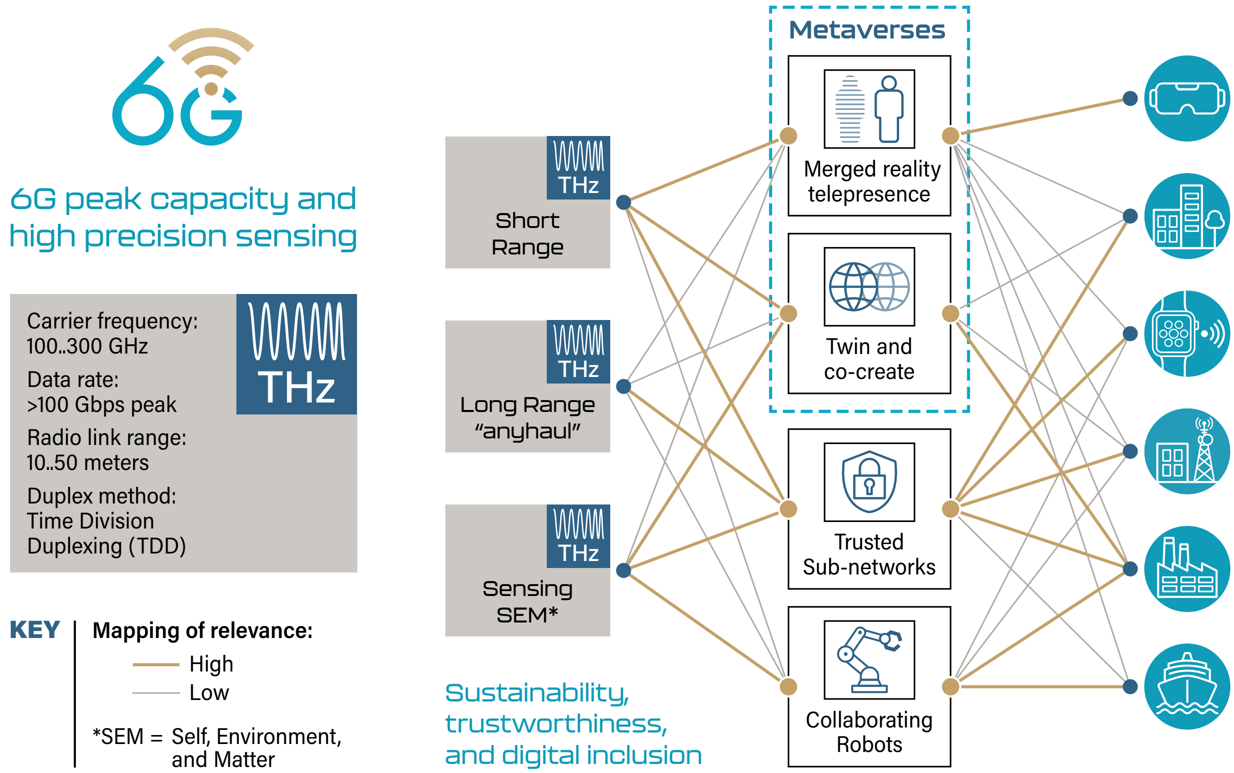

Figure 7: Sub-THz technology can be broadly clustered into functional enablers of access, backhaul, and sensing. Indicative mapping of these enablers is shown to key use cases of the 6G era including merged reality telepresence, twinning and co-creation, specialized and trusted sub-networks, and collaborating robots [2] [20]. The sectoral relevance of these use cases is visualized on the right by weighted lines to key sectors (from top to bottom) such as media and entertainment, smart city, health, work sites, factories, and logistics and transport.

Typically, sub-THz will be used in specialized, often localized, use case scenarios, as well as for high-precision sensing. Sub-THz carrier frequencies will enable data rates of more than 100 Gbps peak and radio link ranges from 10 to 50 meters. There is an ongoing debate surrounding methods between Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) for enabling simultaneous transmission and reception. TDD's edge lies in its full-channel reciprocity—meaning the channel in one direction can be estimated from information about the other direction—whereas FDD requires additional hardware efforts for channel estimation. As part of this ongoing debate, the World Radio Conference (WRC) is expected to determine the allocation of paired bands in their 2027 meeting.

Currently, the development of sub-THz solutions for RAN and Joint Communication and Sensing (JCAS) is still in the research stage, with the technology readiness level remaining relatively low. Nevertheless, there are already existing use cases for sub-THz spectrum with moderate technology readiness in the field of backhaul solutions. These solutions will enable integrated access and backhaul networks of the future. The sub-THz bands, by leveraging pencil beam point-to-point links, can free up the lower mmWave bands of spectrum for access purposes. The use of sub-THz bands for environmental, material, and human sensing may emerge as significant application scenarios. Future applications may also incorporate short-range sub-THz connectivity options, such as for server interconnects in data centers and connections between display and compute devices.

The objective of ongoing 6G sub-THz research involves the design of air-interface and radio modules for the sub-THz bands, to be used for both access and backhaul. Power-efficient transmission strategies are needed to mitigate typical impairments found in frequencies above 100 GHz, such as path loss, phase noise, and Peak to Average Power Ratio (PAPR). Consequently, ongoing research is focused on developing novel architecture and system concepts and defining key parameters of the radio layer design. This includes exploring advanced options of beamforming and MIMO phase arrays, waveform, numerology, and optimization of analog-to-digital converters. The most effective solutions will deliver optimized performance in terms of both energy efficiency and spectral efficiency.

At sub-THZ frequencies, the design and mitigation strategies for hardware limitations will be of key importance. Along with spectral efficiency, channel characterization and coverage analysis will serve as design criteria. The end goal is the production of well-designed hardware transceiver and phased array devices, known as Radio Frequency Integrated Circuits (RFICs). Cutting-edge RFICs equipped with on-chip or on-board antenna arrays and integrated phase shifters to provide narrow beams are anticipated. To optimize costs, the adoption of new component technologies, such as antenna-on-glass, could be beneficial. Hybrid beamforming will be the preferred choice to meet massive capacity targets from single-user or multiple-user MIMO, while maintaining energy efficiency. Innovative receiver architectures could include pre-combining before the low-noise amplifier. Research into AI/ML techniques for waveform design can also lead to reduced power consumption.

Due to its performance attributes of ultra-high throughput and sensing capabilities, sub-THz technology will contribute to the 6G societal impact of enablement of digital transformation and digital inclusion in conjunction with use cases such as immersive telepresence, digital twinning, and, more generally speaking, enhanced local coverage and reliability. Ubiquitous user service connectivity in the sense of capacity expansion for dense and ultra-dense context will become viable by leveraging sub-THz spectral bands to complement fiber access and backhaul. In industrial environments, THz technology will primarily be used for sensing and localization purposes. If used for connectivity, it could find application in the industrial metaverse use cases rather than for inter-robots and sensors.

i. Metaverse enablement with use cases such as immersive telepresence and digital twinning will be supported by the local availability of sub-THz bands and associated bandwidth availability. The choice of sub-THz bands will affect and drive technologies such as new devices and form factors, new air interface, network and device as a sensor as well as options of enhanced side-link.

ii. Ubiquitous user service connectivity for dense and ultra-dense context in the sense of capacity expansion is correlated with the trend of wireless network densification on the path to 6G. Sub-THz enabled densification will be a key enabler to meet local coverage and reliability targets at the higher frequency bands. Design priority will be low-cost rather than maximum spectral efficiency. This will favor decentralized access point topology and solutions (whereas in Frequency Range 2 [FR2] bands higher spectral efficiency may have the priority leading to more centralized approaches). Integrating access and backhaul as well as integrating optical fiber and the sub-THz wireless approach will allow efficient backhaul and fronthaul solutions for the 2030s.

iii. Advanced M2M communications and collaborating robots can be considered interesting 6G use case families. However, the main use of sub-THz in the industrial environment is likely to be sensing and localization. Connectivity, if it is used, will focus on enabling industrial metaverse use cases (cf. (i)) rather than for inter-robot communication and sensor connectivity.

3.2.11. Backhaul Evolution with Increased Cell Density

The mobile backhaul, which connects the RAN to the core network, is a crucial component of mobile wireless networks. Increasing backhaul capacity and flexibility is necessary to realize the benefits of increased performance with each network generation, enabled by innovations in the radio interface and other parts of the network. For this context, we also include fronthaul, which connects parts of the RAN to the radio units and antennas that support communication with the user equipment over the air, as it is sometimes supported by similar transport technologies.

The backhaul can be realized with multiple technology options. Wireline backhaul, typically fiber-based, is capable of supporting data rates at terabits-per-second with very high reliability. Wireless (microwave point-to-point) backhaul traditionally uses frequencies in the 6-42 GHz and 70-80 GHz ranges. Future backhaul could utilize frequencies in the W band (75-110 GHz) and the D band (110-170 GHz) more extensively—for example, in or approaching sub-THz ranges (see Section 3.2.10). Roughly 50% of city-based sites are estimated to connect via wireless backhaul. There are significant geographical variations in the percentage of wireless backhaul connections, and this figure is expected to remain fairly stable over the next 5-10 years. This is because, while fiber deployment increases, network densification also leads to an expansion of in-site numbers.

Each new mobile network generation has sought to increase data rates, thus requiring more bandwidth and higher frequency spectrum. As discussed in Section 2, 5G already supports frequencies up to 71 GHz, and 6G is expected to extend to sub-THz frequencies. Notably, these higher frequency ranges (>6 GHz) overlap with those traditionally used for wireless backhaul, making co-existence solutions between access and backhaul critical, particularly within the lower frequency ranges of 6-21 GHz. The sub-THz frequency ranges are likely to be primarily used for backhaul, although 6G is expected to enable ultra-high performance access to user devices within these frequencies, albeit with limited coverage.

The use of higher frequencies for radio access, coupled with devices having limited antenna sizes and transmission power, significantly curtails coverage. This necessitates denser base stations placement. This increased density can spike costs when using fiber backhaul. Fiber deployment can be sluggish and even infeasible in certain circumstances. One approach to mitigate this is self-backhauling, where part of the spectrum used for access services also is used for backhaul purposes. This technology, known as Integrated Access and Backhaul (IAB), is expected to play a greater role in 6G.

Layer 1 relaying is another technology that can augment backhaul. While performance gains from L1 relays can be limited when used for the general case of extending access coverage, they can be beneficial for providing coverage extension when used for specific backhaul cases, especially when used alongside beamforming technology and stationary nodes. Other contributing technologies to backhaul evolution include multi-beam systems and MIMO, both already cornerstones of 5G and anticipated to be inherent to 6G. These technologies reduce cross-link interference between backhaul and access links, thereby allowing higher densification of deployments using self-backhauling.

Wireline and traditional wireless backhaul technologies, having been used in mobile networks for decades, are highly mature. While being based on common 5G radio technology, it already has been shown that self-backhauling can be regarded as a reasonably mature technology from a specification [15] and development [16] perspective, and it also has been operator tested [17]. However, self-backhauling has not been widely deployed yet, possibly due to its higher complexity, which is an important consideration for 6G.

The high rates experienced by uses in wireless networks is facilitated through a backhaul network that connects cells to the core network and external networks. Newer 4G and 5G deployments primarily have utilized wired fiber backhaul. Fixed service wireless backhaul, however, is a cost-effective alternative to fiber and is responsible for the 50% penetration of wireless backhaul. Evolution of these wireless backhaul solutions will continue with smarter microwave networks, higher spectral efficiency, wider bandwidths, and expansion to higher frequencies, all of which will help with 6G deployments. Self-backhauling can result in lower development and network implementation costs since the same technology can be used for access and backhaul, although its complexity and cost of development can be further reduced in the future. Re-use of spectrum between access and backhaul can result in more efficient spectrum utilization, which is desirable even though spectrum at higher frequencies is more available. Wireless self-backhauling can contribute to nomadic deployments in, for example, public safety and emergency scenarios. In some cases, wireless self-backhauling also can enable the provision of services in areas that otherwise may not be possible to cover economically, for example, see the left side of Figure 8 (below), which is critical to the goal of ubiquitous service connectivity. Wireless backhaul also is critical to increased network capacities in deployments where local smaller cells that connect to a macro cell are used for boosting capacity—for example, see the right side of Figure 8.

The benefits of wireless backhaul solutions can translate to the greater capacity needed for immersive experiences enabled by the Metaverse and a tactile internet. While energy efficiency is a challenge with denser deployments when overall energy consumption and environmental impact is considered, smart use of backhaul technologies [18], traffic-aware power save and carrier deep sleep can increase the ability to manage energy consumption while enabling key use cases and experiences that 6G is expected to deliver. In some cases, a densified network also could help to improve coverage for machine types of communications with low-power, low-range devices.

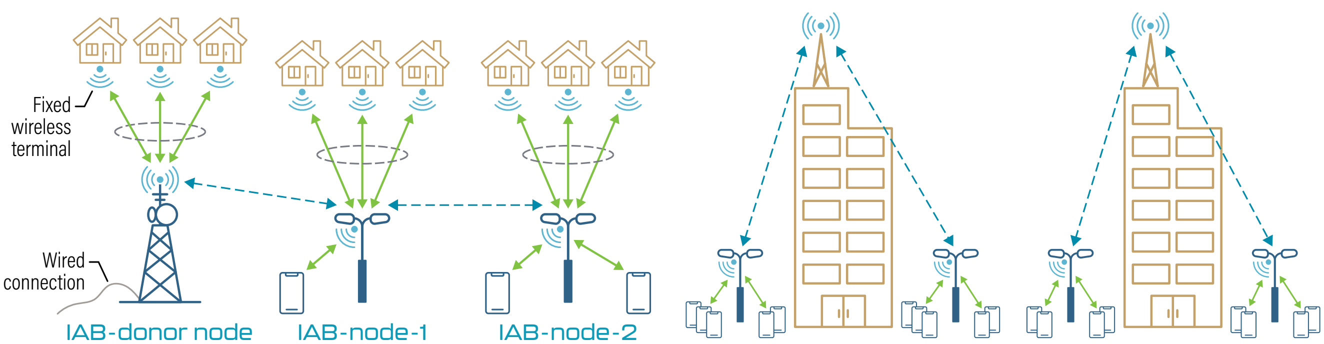

Figure 8: (Multi-hop) Wireless backhaul as a coverage enhancer and service enabler (left) and as a bandwidth-efficient local capacity and bit rate booster in a macro-cell deployment with connected smaller cells.

3.2.12. Non-Terrestrial (Satellite) Networks

Satellite communications address various coverage gaps in existing ground-based terrestrial infrastructure, such as rural areas and maritime applications. Non-Terrestrial Networks (NTN) have been an important enabler of applications that require global coverage, high availability, and/or high resilience, but that are nonetheless relatively delay-tolerant (see Section 3.2.1). An NTN uses high-altitude platform stations, such as solar powered drones and airships, and/or satellites, to provide wireless connectivity access.

It is anticipated that the integration of space and terrestrial networks will enable a future where global communications and connectivity are seamless and ubiquitous. This integration will help reduce the digital divide, expand service offerings in existing verticals and create entirely new, global market segments. As a result, billions of dollars are once again being invested into satellite technology—this time focusing on proliferated Low Earth Orbit (LEO) constellations to complement the traditional fleets in Medium Earth Orbit (MEO) and Geostationary Orbit (GEO). While much of the recent effort around NTN services has been directed at military and defense deployments, it is critical to consider how 6G wireless will be optimized through satellite-terrestrial integration.

There are two potential commercial NTN deployment scenarios employing LEO satellite constellations. The first scenario is to integrate the LEO satellite network with 5G ground-based base stations, as illustrated in Figure 8 (on previous page). In this scenario, the LEO constellation acts as a backbone for existing 5G telecommunication networks and it is referred to as backhauling. Instead of connecting base stations to network with optical fiber or microwave links, the base stations communicate with LEO satellites. This scenario has been adopted by the 3GPP standards body in 2021 (TS 38.821, Release 16).

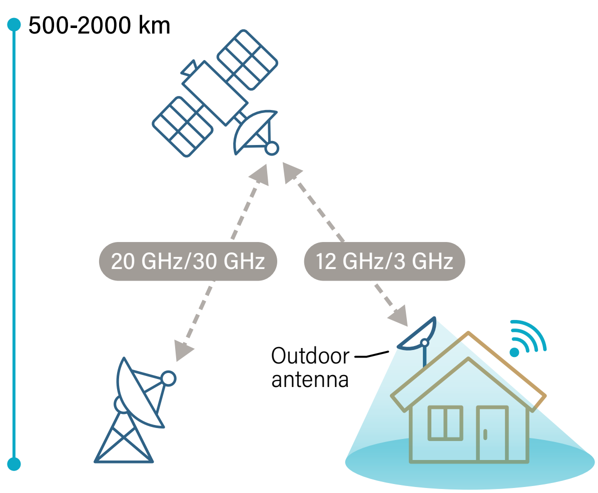

Figure 9: Satellite integration with ground base stations.

The second scenario is based on the direct use of LEO constellations, such as Starlink, to deliver broadband internet without using ground base stations. This is depicted in Figure 9 (left). The user equipment communicates directly with the satellites. The first intent of this was to provide broadband internet to remote areas that could not be reached by fiber broadband or 5G internet (which was a study item in 3GPP TS 38.811 (Release 15). Recently, 3GPP Release 17 included support for 5G direct-to-device satellite connectivity. It is anticipated that NTN-enabled 5G chipsets will be available for commercial cellphones within two years. The two dominant chipset providers, Qualcomm and MediaTek, both have announced silicon testbeds supporting NTN functionality.

As mentioned earlier, there are three types of satellite constellations: GEO, at an altitude of ~36,800 km, MEO, at an altitude of 2,000-20,000 km, and LEO, at an altitude 500-2,000 km. The focus in NTN integration for 5G-and-beyond is on the LEO constellation for a few reasons. These include the low cost of satellite deployment, low latency, and low signal propagation loss because of lower altitude. But LEO also comes with complex challenges, such as number of satellites required for global coverage, a high system complexity, and high handover requirement, since any given satellite is only in a field of view for a few minutes (it travels around the earth in 1.5-2 hours). The handover is required to ensure that the communication link between the user equipment or the ground base station is not broken.

The cost of satellite launches has significantly decreased in recent years. Compared to space shuttle launches in the 1980s, the cost has decreased by 100x, and a further 10x decrease is expected in the next few years. This is crucial to making NTN commercially viable. On the other hand, there are many technical challenges to making such a system functional. These include the handover requirements discussed above, and additionally, the migration from "2D" to "3D" wireless networking. Specifically, in a typical communication system, transmission and reception are the fundamental problems. In a terrestrial "2D" network, signal transmission has gone from omni-directional to using narrow signal beams aimed at the receiver to improve reception. In non-terrestrial 3D-based networks, the problem becomes significantly more complex; beamforming transmission, interference cancellation reception, spectrum sharing with coexistence between satellites and ground base stations, and spectrum sensing are just some of the challenges that lie ahead.

The needs for rural, third world, and maritime communication, which were never a critical use case of 4G and 5G networks, have substantially grown over the last decade. Satellite communication has been used for decades in many commercial and government deployments for these scenarios, but 6G systems may move far beyond satellite-only solutions by utilizing NTNs operating at various altitudes including Unmanned Aerial Vehicle (UAV), high-altitude platform, LEO satellite, and GEO satellite operation. NTN operation could even play a supporting role in congested urban and suburban deployments.

NTN offers the possibility of 3D-spatial networking, compared with today's terrestrial cellular 2D approach. This new approach to network design holds the potential to revolutionize connectivity in locations where fiber connectivity is impractical due to user density, capital cost, or regulatory issues that obviate terrestrial-only deployment. For example, NTN-based backhaul using satellite could dramatically reduce network capital costs in rural and third world scenarios because there is no need for fiber deployment to provide core and external connectivity. NTN's 3D networking could potentially reduce the carbon footprint of 6G relative to 5G. To fulfill NTN's potential, major research and development advances are needed.

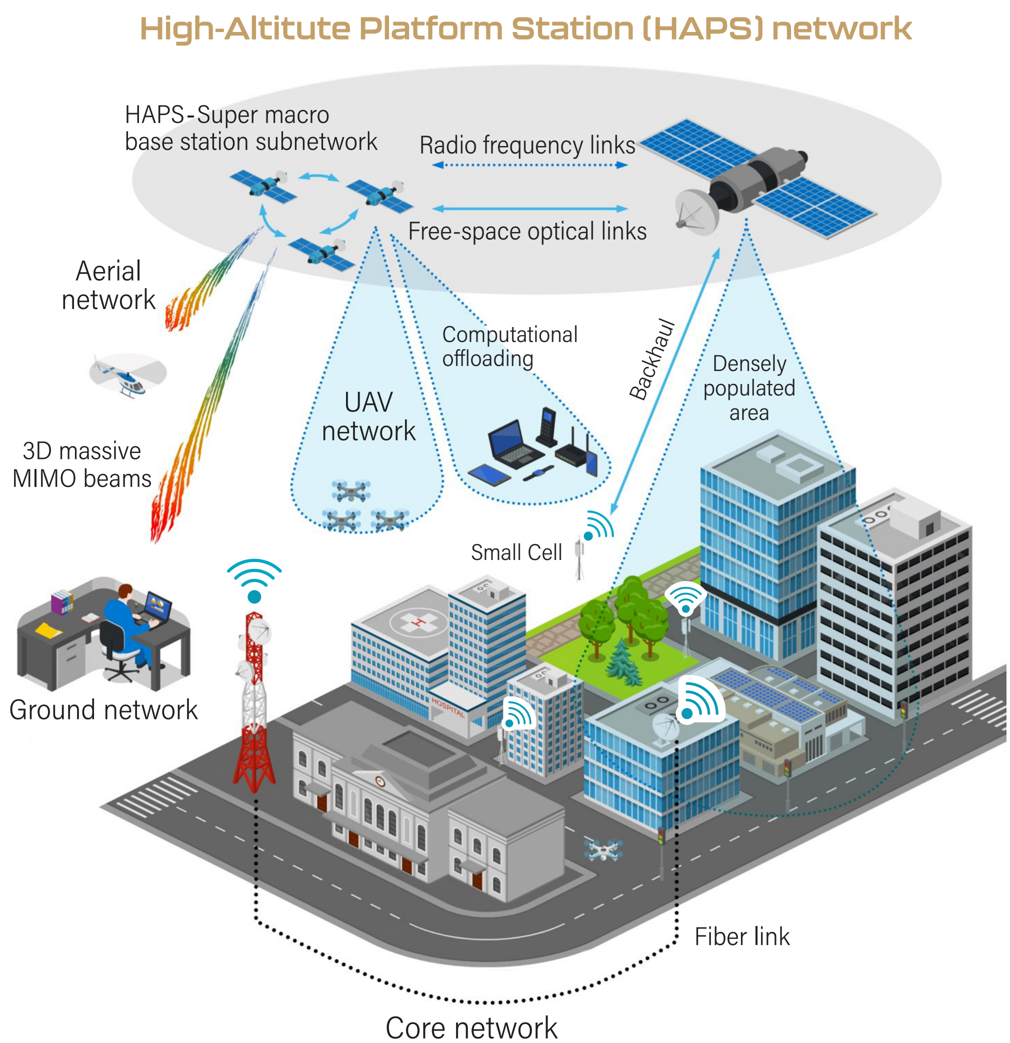

Figure 10: Direct satellite connectivity to end user devices.

4. Partnerships Among Like-Minded Nations

In today's 5G era, technological advancement is the result of collaborative efforts by different stakeholders, including Standard Development Organizations (SDOs), industry alliances or organizations, global research initiatives, and regulators. For 6G systems, there are several important challenges that industries, research communities, and governments in like-minded nations need to work together to advance the speed of innovation and scale of deployment and operation.

4.1. Standards Groups and Regulations

There are an increasing number of stakeholders in the communications community responsible for device manufacturing, network operation, computing platforms, and other aspects. More collaboration between these stakeholders is required to ensure that 6G technologies support existing and emerging requirements. Specifically, increasing cooperation is necessary between SDOs like the Organization for the Advancement of Structured Information Standards (OASIS), Internet Engineering Task Force (IETF), and the Alliance for Telecommunications Industry Solutions (ATIS), each of which may be focused on different aspects of the wireless technology that ultimately need to interoperate. Global consortiums like the 3rd Generation Partnership Project (3GPP) already have united a handful of SDOs around developing and maintaining existing wireless standards. Established in 1998, 3GPP is responsible for many of the standards from 2G to 5G, including the Global System for Mobile Communications (GSM), IMT-2000, Long Term Evolution (LTE), and 5G New Radio (NR). Such efforts must continue through 6G and beyond with a growing body of organizational partners.

For instance, global standards will be key to assuring global economy of scale and interoperability for 6G opportunities associated with new spectrum bands including sub-THz bands. Framework conditions are needed that provide incentives for technology contributions to standardization and promote widespread adoption of the resulting standards. A balanced and transparent licensing system for intellectual property associated with standards needs to be maintained, and fair access to standards for all market players must be preserved. Specifically, a Fair, Reasonable and Non-Discriminatory (FRAND) standards patent framework is essential to assure value capture and research and development investment capability of leading sub-THz technology companies.

The European Telecommunications Standards Institute (ETSI) recently announced the formation of an Industry Specification Group (ISG) around sub-THz technology. This ISG strives to provide the opportunity to prepare for future standardization of sub-THz technology by inviting ETSI members worldwide to share their pre-standardization efforts and insights.

Many 6G innovations are expected to arise from the proliferation of open interfaces between hardware and software (see Section 3.2.9). This may enable a global network platform that provides services on a large scale around the world, which could have many societal and economic benefits. The success of such a platform inherently depends on partnership between ecosystem stakeholders to develop standards. In this respect, over the last few years, the Open Radio Access Network (O-RAN) Alliance has been bringing together a large community around standardization, open software development, and implementation testing/integration of RAN technologies, with an eye toward virtualization and interoperability (see Section 3.2.6). 3GPP will continue to develop and enhance connectivity solutions along with standards from the IETF. The Cloud Network Computing Forum (CNCF) is an important provider of tools for cloud deployments that would be part of this global platform. The TeleManagement (TM) Forum, which is developing tools for automation, and CAMARA, an open-source project within the Linux Foundation that is working on a set of

Application Programmable Interfaces (APIs), also will be crucial for such a network platform. Collaboration within and among these organizations, as well as alignment with government strategies, is essential.

4.2. Industry Alliances and Organizations

Similarly, several alliances have been formed among the industries impacted by wireless technologies. The 5G Alliance for Connected Industries and Automation (5G-ACIA) is a global forum focused specifically on shaping 5G for the industrial domain, with participants from the operational, information, and communication technology sectors. The collaborative effort intends to create a platform upon which an ecosystem of industries using 5G for different purposes can be supported, from applications in manufacturing to transportation. The 5G-ACIA also is lately considering the growing body of 5G applications that are delay-tolerant compared with others that have stringent latency requirements (see Section 3.2.1).

The GSM Association (GSMA) also has been a forum for collaboration on cellular IoT solutions like Narrowband IoT (NB-IoT) and LTE Machine Type Communication (LTE-M) that are delay-tolerant, producing reports and recommendations for use of these technologies. The continuation of these efforts for 6G will be desirable. For instance, mobile backhaul—the part of a mobile network that connects the core to the wireless radio access (see Sec. 3.2.11)—is a crucial component that will affect 6G deployment worldwide across a wide range of use cases that have different latency requirements. Global collaborations through organizations such as the GSMA that bring together operators worldwide can help to foster an ecosystem of backhaul solutions that increases market adoption and lowers cost. Collaboration forums in key use case sectors such as public safety also can serve to drive the technology forward.

Global alignment also is critical to 6G solutions for spectrum sharing. Successful implementation and deployment of these solutions will require regulatory frameworks to coordinate and share best practices around the associated technical innovations. International collaboration in providing spectrum specific to industrial applications will provide a significant boost to market uptake. Delay-tolerant technologies also will be shaped by global coordination on spectrum sharing: In the case of satellite connectivity (see Sec. 3.2.12), both the satellite and terrestrial industries are well established and have numerous avenues for collaboration. More collaboration, especially on spectrum-related aspects, would be beneficial.

Another important consideration for 6G partnerships is to align on the technologies that connect the wireless access points through the inner network infrastructure. The Industry IoT Consortium (IIC) was created in 2019 through merging the OpenFog Consortium, which focused on standardizing fog/edge computing with the Industrial Internet Consortium, which brought together stakeholders to promote reference architectures and testbed demonstrations of industrial internet technologies. The amalgamated IIC has established several working groups of industry, government, and academic partners focused on topics including communications, edge/fog computing (see Section 3.2.5), and even vocabulary for establishing common IoT terminologies [19]. 6G alliance groups need to form global partnerships with consortiums like IIC to synergize standardization of next generation wireless access and core network technologies.

The heavy desire to leverage AI and ML technologies in 6G also calls for more like-minded industry and government partnerships. In North America, the Next G Alliance has identified AI-native Wireless Networks as one of its six audacious goals [2]. More datasets on wireless systems need to be made available and agreed upon as global standards for benchmarking competing AI/ML solutions to be included in 6G standards. Next-generation network infrastructure will need to be data-centric and cloud-native to support AI-native workloads. Greater openness in wireless infrastructure platforms, architectures, interfaces, and implementation employed across industries is essential for global interoperability and economy of scale.

4.3. Research Activities

Finally, partnerships are needed around the research activities shaping 6G globally. This includes connections between industry and academic research labs, as well as between the research priorities of like-minded nations. Technologies for improved access to, and use of, spectrum at all frequency ranges including sub-THz technology, as one of the revolutionary building blocks for 6G communications, are being investigated by leading 6G flagship research programs worldwide. In the United States, this includes activities by the NextG Alliance, through National Science Foundation (NSF) programs such as Resilient and Intelligent NextG Systems (RINGS), and in programs funded by the Department of Defense, which fund both industry and academic research labs. The European Union funded its 6G Flagship project Hexa-X, which has identified AI-driven communication and computation designs as well as intelligent orchestration and service management for future networks among its main deliverables. Other flagship research efforts in Europe exist on a more national scale, including the Finnish 6G Flagship and German 6G-Access, Network of Networks, Automation, and Simplification (ANNA) projects.

5. Concluding Remarks

Wireless technology has made great strides in the last few decades, culminating in the 4G and 5G communications that many parts of the world enjoy today. 6G represents the next giant leap on the horizon by the end of this decade. This report provides a neutral taxonomy for the various innovations that will coalesce into 6G standards, ranging from advancements in computing to radio access design to deployment. Focused research in the identified technologies is poised to make significant advancements in four areas of societal impact: scalability, sustainability, trustworthiness, and digital inclusion. It will be critical that these research efforts are coordinated across like-minded partnerships, alliances, and standardization groups to preserve and advance the speed and scale of this industry.

6. References for Further Reading

[1] Cisco, "Cisco Annual Internet Report (2018-2023)," 2023. [Online]. Available: https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html.

[2] NextG Alliance, "Roadmap to 6G," 2022. [Online]. Available: https://www.nextgalliance.org/white_papers/roadmap-to-6g/.

[3] 3rd Generation Partnership Project, "Medium Access Control (MAC) Protocol Specification (Release 17)," 2022. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/38_series/38.321/38321-h30.zip.

[4] "MQTT: The Standard for IoT Messaging," [Online]. Available: https://mqtt.org/.

[5] Statistica, "Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2023, with forecasts from 2022 to 2030," 2023. [Online]. Available: https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/.

[6] 3rd Generation Partnership Project, Technical Specification Group Services and System Aspects; Study on Ambient power-enabled Internet of Things (Release 19), 2022. [Online]. Available: https://www.3gpp.org/ftp/tsg_sa/WG1_Serv/TSGS1_100_Toulouse/Docs/S1-223508.zip.

[7] "5G—The Future of IoT," 5G Americas, 2019. [Online]. Available: https://www.5gamericas.org/5g-the-future-of-iot/.

[8] "With 5G here, what's next for the Internet of Things?," Qualcomm, 2020. [Online]. Available: https://www.qualcomm.com/news/onq/2020/05/5g-here-whats-next-internet-things.

[9] "5G NR-Light (RedCap): Revolutionizing IoT | Qualcomm," Qualcomm, 2022. [Online]. Available: https://www.qualcomm.com/news/onq/2022/07/what-is-5g-nr-light--a-k-a--redcap--and-how-will-it-accelerate-t.

[10] S. Wang, S. Hosseinalipour, V. Aggarwal, C. Brinton, D. Love, W. Su and M. Chiang, "Towards Cooperative Federated Learning over Heterogeneous Edge/Fog Networks," IEEE Communications Magazine, 2023.

[11] 3rd Generation Partnership Project, "Release 17 Description; Summary of Rel-17 Work Items (Version 17.0.1)," 2023. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/21_series/21.917/21917-h01.zip.

[12] "The Evolution of Open RAN," 5G Americas, 2023. [Online]. Available: https://www.5gamericas.org/the-evolution-of-open-ran/.

[13] "Toward enabling secure 5G networks with O-RAN," Qualcomm, 2022. [Online]. Available: https://www.qualcomm.com/news/onq/2022/04/toward-enabling-secure-5g-networks-o-ran.

[14] Nokia Bell Labs, "Communications in the 6G era," 2020. [Online]. Available: https://www.bell-labs.com/institute/white-papers/communications-6g-era-white-paper/.

[15] 5G Americas, "White Paper: Innovations in 5G Backhaul Technologies: IAB, HFC & Fiber," 2020. [Online]. Available: https://www.5gamericas.org/wp-content/uploads/2020/06/Innovations-in-5G-Backhaul-Technologies-WP-PDF.pdf.

[16] Ericsson Technology Review, "Introducing Integrated Access and Backhaul," 2020. [Online]. Available: https://www.ericsson.com/4ac691/assets/local/reports-papers/ericsson-technology-review/docs/2020/introducing-integrated-access-and-backhaul.pdf.

[17] Fierce Wireless, "Verizon, Ericsson fete IAB proof-of-concept trial for 5G," 2020. [Online]. Available: https://www.fiercewireless.com/wireless/verizon-ericsson-fete-iab-proof-concept-trial-for-5g.

[18] Ericsson, "Ericsson Microwave Outlook: How to reduce power consumption in microwave networks," 2022. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/microwave-outlook/articles/reducing-power-consumption-in-microwave-networks.

[19] "Industry IoT Consortium," [Online]. Available: https://www.iiconsortium.org/.

[20] M. A. Uusitalo, P. Rugeland, M. R. Boldi, E. C. Strinati, P. Demestichas, M. Ericson, G. P. Fettweis, M. Filippou, A. Gati and M.-H. Hamon, "6G Vision, Value, Use Cases and Technologies From European 6G Flagship Project Hexa-X," IEEE Access, vol. 9, pp. 160004-160020, 2021.

7. Frequently Used Acronyms

3GPP .... 3rd Generation Partnership Project
5G-ACIA .... 5G Alliance for Connected Industries and Automation
AI .... Artificial Intelligence
API .... Application Programming Interfaces
APP .... Application
AR .... Augmented Reality

CAICT .... China Academy of Information and Communications Technology
CBRS .... Citizens Broadband Radio Service
C-DRX .... Connected Mode Discontinuous Reception
CN .... Core Network
CPU .... Central Processing Unit
CU .... Central Unit
CU-CP .... Central Unit – Control Plane
CU-UP .... Central Unit – User Plane

D2D .... Device-to-Device
DSS .... Dynamic Spectrum Sharing
DU .... Distributed Unit

ETSI .... European Telecommunications Standards Institute

FDD .... Frequency Division Duplexing

GAA .... General Authorized Access
Gbps .... Gigabits per second
GEO .... Geostationary Orbit
GHz .... Gigahertz
GSM .... Global System for Mobile Communications

IAB .... Integrated Access and Backhaul
ICT .... Information and Communication Technologies
IETF .... Internet Engineering Task Force
IIC .... Industry IoT Consortium
IoT .... Internet of Things
ISG .... Industry Specification Group

JCAS .... Joint Communication and Sensing

LBT .... Listen-Before-Talk
LEO .... Low Earth Orbit
LTE .... Long Term Evolution

M2M .... Machine to Machine
MAC .... Medium Access Control
MDA .... Management Data Analytics
MEO .... Medium Earth Orbit
MHz .... Megahertz
MIMO .... Multiple Input Multiple Output
ML .... Machine Learning
MLWiNS .... Machine Learning for Wireless Networking Systems
mmW .... millimeter Wave
MQTT .... Message Queuing Telemetry Transport

NR .... New Radio
NSF .... National Science Foundation
NTN .... Non-Terrestrial Network
NWDAF ..... Network Data Analytic Function

OFDM .... Orthogonal Frequency Division Multiplexing
ORAN .... Open-Radio Access Network

PAL .... Priority Access Licensees
PAPR .... Peak to Average Power Ratio
PHY .... Physical

QoS .... Quality of Service

RAN .... Radio Access Network
RF .... Radio Frequency
RFIC .... Radio Frequency Integrated Circuits
RIC .... RAN Intelligent Controllers
RINGS .... Resilient and Intelligent NextG Systems
RNN .... Recurrent Neural Network
RU .... Radio Unit

SAS .... Spectrum Access System
SBA .... Service-Based Architecture
SCS .... Sub-Carrier Spacings
SDO .... Standard Development Organization

TCP/IP .... Transport Control Protocol/Internet Protocol
TDD .... Time Division Duplex
THz .... Terahertz
TTA .... Telecommunications Technology Association

UAV .... Unmanned Aerial Vehicle
UDP .... User Datagram Protocol
URLLC .... Ultra-Reliable Low Latency Communications

vCU .... Virtualized Central Unit
vDU .... Virtualized Distributed Unit
VR .... Virtual Reality

WRC .... World Radio Conference
WUS .... Wake-Up Signal