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TW: 6G and Artificial Intelligence & Machine Learning

Curtis Watson, PhD
Kelvin Woods, PhD
DJ Shyy, PhD

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Abstract

As the fifth generation (5G) technology deployment rate increases and standards continue toward steady state, researchers have turned their attention toward 6G. New use cases and the potential of performance shortfalls have started the research buzz. Early efforts center on key fundamental research that will support target goals such as 1 Tbps peak data rate, 1 ms End-to-End latency, and up to 20yr battery life for this next generation of communication networks. To support this research, international conferences have sprung up; for instance, 6G wireless summits and 6G symposiums where several key research topics have started to rise to the top. Topics include THz communications, quantum communications, big data analytics, cell-free networks, and pervasive artificial intelligence (AI).

In this paper we focus on pervasive AI, which has the potential to drastically shape the new 6G network. To achieve the faster rates and lower latency performance gains, an efficient network will be required. The network must dynamically allocate resources, change traffic flow, and process signals in an interference-rich environment. Pervasive AI is a leading candidate to accomplish these tasks. AI and machine learning (ML) will play an important role as an enabler of 6G technology by optimizing the networks and designing new waveforms. Discussions and research have already focused on applying AI to various parts of the proposed network, which can be best summarized by mapping AI applications to the standard Open Systems Interconnection network layers model. All layers including physical, data link, network, and applications appear to be early research targets. Novel approaches to dynamic security and network slice management are also being considered. All of these thrusts are leading toward an intelligent ecosystem. Also, 6G technology itself will enable further advances in AI/ML, such as exploiting the data that is local to the 6G sensor by efficiently transporting the (AI/ML) algorithms. Despite being in the early phase of development, 6G shows potential evolutionary changes poised to enrich users’ experiences and enable new use cases.

Executive Summary

6G technology will represent an evolution for communication networks that plan to offer fully immersive connectivity with persistent information sharing. The number of users, types of data, and use cases all are projected to drive the need to develop 6G technologies. Several global conferences are entering into their second year as key research areas start to emerge. Areas such as THz communication, quantum communication, and pervasive artificial intelligence, and expansive use cases like augmented reality, holographic telepresence and e-health, and industry 4.0 and robotics, are being discussed to help drive 6G target key performance indicators.

AI and machine learning (ML) are poised to play a significant role in 6G network development as the 6G network will need to rapidly optimize between competing interests of user quality of service, cybersecurity, and the laws of physics. As a result, data as a commodity will become more important, with value being generated through data creation, data consumption, and, most important, data information content. The quality of the data will produce the value of the commodity for this intelligent communication ecosystem.

6G technology will drastically impact all our government stakeholders as modes of operations change and data sources and access methods evolve. There is a need for investigations into both fundamental research issues and system-level implementation challenges. At a high level, we envision four keys areas to begin addressing:

- Improved Understanding of **Data** regarding information content in a finite data set and an improved radio frequency (RF) data catalog for algorithm benchmarking.
- Cross-Layer Wireless **Optimization** to enable massive machine-to-machine communication through coordination of multi-function devices, sharing data, and AI tasks.
- **Test and Evaluation** for rapid algorithm development and deployment along with RF-centric AI/ML algorithm diagnosis/monitoring approaches
- Submit contributions to global standards bodies to **Influence 6G Direction** reflecting US government requirements and 6G use cases.

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Table of Contents

List of Figures

List of Tables

1 Introduction

As the fifth generation (5G) technology starts to take hold, in the form of increased deployments and standards stabilization, use cases are being discussed that will exceed the capabilities of the current network evolution. This has caused researchers to turn their attention toward the next sixth generation (6G), network. Early indications point toward 6G being a collection of technologies leveraging previous generations, but with new enablers set to drive innovations. To better understand and frame 6G, we briefly give a summary of 5G.

5G is being promoted as the unifying fabric to interconnect virtually everything, including mobile handsets, autonomous vehicles, robots used in smart factories, Internet of Things (IoT) sensors for home appliances, smart warehouses, and smart cities [1]. There are three main use cases for 5G: (1) enhanced mobile broadband (EMBB), (2) low latency and high reliability mission critical communications, as well as (3) massive IoT. Currently, mainly EMBB services are being offered by 5G service providers; deployment of the other usage scenarios is expected to occur over the next few years. The key performance indicators (KPIs) of 5G are defined by International Telecommunication Union's (ITU's) International Mobile Telecommunications-2020 (IMT-2020) [2] and shown below.

- EMBB's primary focus is higher data rates. The improvement of peak data rates from 4G to 5G is from 1 gigabit per second (Gbit/s) to 20 Gbit/s. The typical applications include 4K/8K ultra-high-definition video, fiber replacement, augmented reality (AR), and virtual reality (VR).
- Mission critical communications require enhanced capabilities for high reliability (up to 99.999% for packet success rate), low latency (down to 1 millisecond [ms]), and high mobility (up to 500 kilometers [km] per hour). Some of the applications include vehicle-to-everything communications, remote surgery, industrial automation, and disaster recovery using drones.
- Massive IoT requires the design of low-complexity and low-power consumption devices, which translates to longer battery life. In addition, it requires the ability for the network to serve up to one million devices per square kilometer.

Even as network roll outs are maturing, and standards are being extended, such as "Beyond 5G" (B5G), researchers around the world are beginning the definition phase of 6G targeting the 2030-timeframe as seen in Figure 1. Several international initiatives are already under way and will form the bases for 6G technology research [3]. For example, the 6G Flagship Program[1] has begun in Europe and expects startups in South Korea, China, and Japan. Additionally, the program has partnered with Nokia Bell Labs, Keysight, and Interdigital (and is looking for more partnerships) to define this 6G vision [4]. This collaboration is a pioneer in publishing a 6G vision as well as hosting the first 6G summit in 2019.

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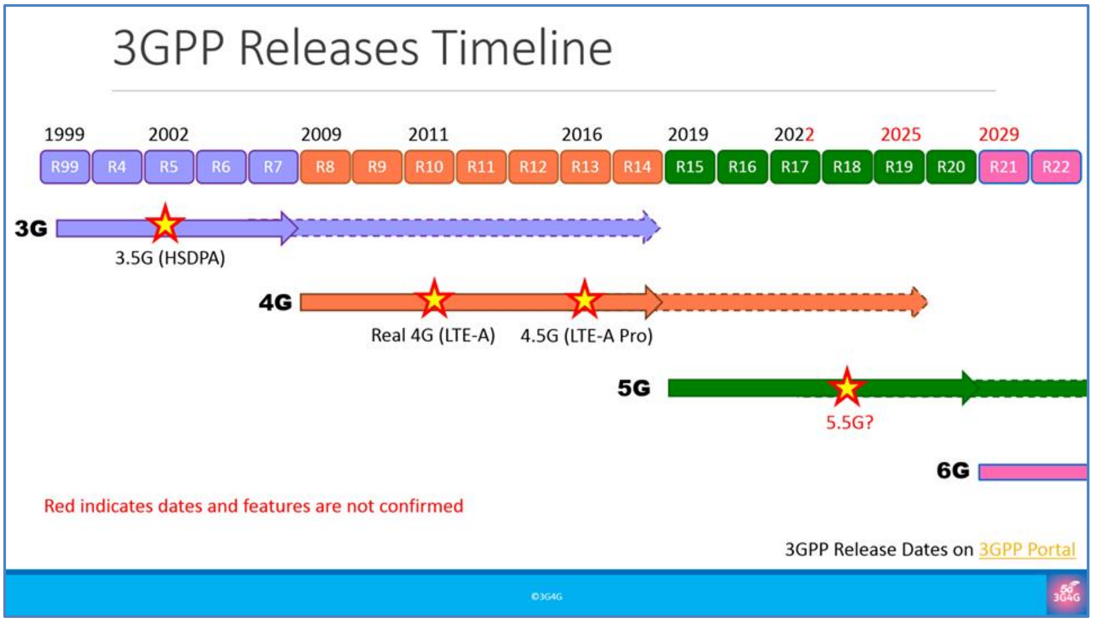
[1] https://www.oulu.fi/6gflagship


3GPP Releases Timeline

Red indicates dates and features are not confirmed

3GPP Release Dates on 3GPP Portal

Figure 1: Timeline mapping 3GPP releases to network generation [5]

Other early initiatives are the Alliance for Telecommunications Industry Solutions (ATIS) which launched a Next G Alliance initiative[2] in October 2020. Its objectives are to counter the Chinese influence in ITU-T Focus Group Technologies for Network 2030 (FG NET-2030) and to develop a 6G initiative purely from a US/North American viewpoint. One objective is to influence US policy for 6G. Please note: MITRE is a founding member of the Next G Alliance.

This report provides an overview of the current state of 6G. It also discusses how AI and ML will evolve the state-of-the-art toward an Intelligent Communication Ecosystem. Lastly, there is a discussion of potential impacts within the Federal Government.

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[2] https://nextgalliance.org/

2 6G Overview

6G promises to offer persistent and immersive connectivity to humans, machines, and other devices [3] As with 5G, the focus of information transfer will continue to shift from humans to devices as the number of devices on the network explodes (Table 1). As a data point, the current number of IoT devices is on the order of the human population worldwide [6]. Yet, by 2030 it is expected that the number of connected devices will be roughly 15 times the number of humans on the planet [7]. Increasingly, machines will need to be connected by means of wireless communications. Examples of connected machines include vehicles, robots, drones, home appliances, displays, smart sensors installed in various infrastructures, construction machinery, and factory equipment [8]. This is a significant new growth driver for 6G.

Table 1: Global trends of wireless connectivity [9]

Issue	2010	2020 (predicted)	2030 (predicted)	Unit
Mobile Subscriptions	5.32	10.7	17.1	Billion
Smartphone Subscriptions	0.645	1.3	5.0	Billion
M2M Subscriptions	0.213	7.0	97	Billion
Traffic Volume	7.462	62	5016	EB/month
M2M Traffic Volume	0.256	5	622	EB/month
Traffic per Subscriber	1.35	10.3	257.1	GB/month

The 6G network will touch all aspects of society, which will require several key attributions [10], such as:

- Open and Flexible – Consider that the first 30 years of cellular focused on voice, text, and mobile broadband whereas in the past five years the needs have exponentially grown with the IoT, network-to-network, and unmanned autonomous vehicles (UAV).
- Sustainable – Energy consumption, battery lifetime, and environmental impacts are a few considerations for the sustainment of an immersive communication network.
- Algorithm Intelligence – Edge AI and network sensing will drive new value paradigms.
- Trusted – The network must ensure security and privacy demands.

Reliable data connectivity is vital for an increasingly intelligent, automated, and ubiquitous digital world. Mobile networks will create a fully connected, intelligent digital world from people to vehicles, sensors, data, cloud resources, and robotic agents [11].

2.1 Requirements and Enablers

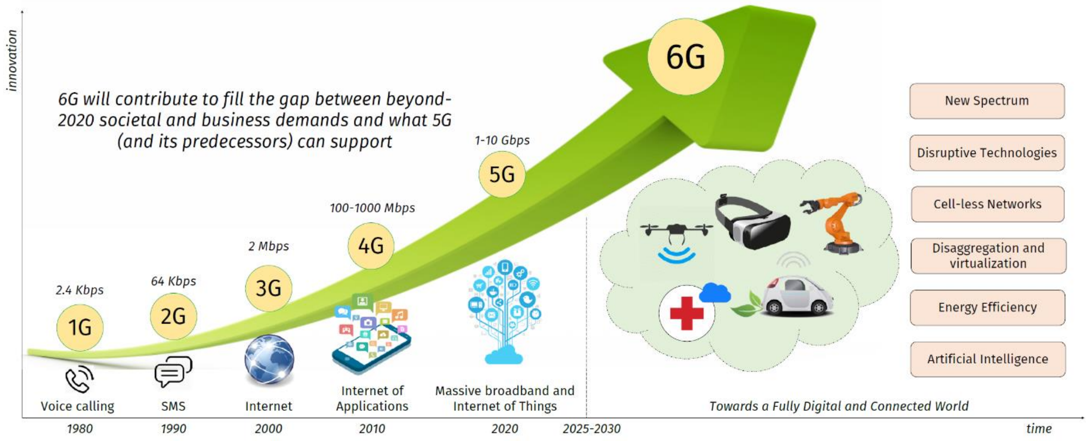
The realization of this vision requires disruptive communication technology within innovative and novel network architectures. To help enable these 6G ideas, some fundamental issues need to be addressed such as higher system capacity, higher data rate, lower latency, and improved QoS compared to the 5G system [7]. Table 2 outlines the expected KPIs and enabler technologies for 6G compared to the legacy 4G and 5G technologies.

Table 2: Requirements and enablers comparison of 6G with 4G and 5G [9]

Issue	4G	5G	6G
Per Device Peak Data Rate	1 Gbps	10 Gbps	1 Tbps
End-to-End Latency (E2E)	100 ms	10 ms	1 ms
Maximum Spectral Efficiency	15 bps/Hz	30 bps/Hz	100 bps/Hz
Mobility Support	Up to 350 km/hr	Up to 500 km/hr	Up to 1000 km/hr
Satellite Integration	No	No	Fully
AI	No	Partial	Fully
Autonomous Vehicle	No	Partial	Fully
XR	No	Partial	Fully
Haptic Communication	No	Partial	Fully
THz Communication	No	Very limited	Widely
Service Level	Video	VR, AR	Tactile
Architecture	MIMO	Massive MIMO	Intelligent Surface
Maximum Frequency	6 GHz	90 GHz	10 THz

2.2 Use Cases

There are two lines of reasoning for 6G use cases and capabilities. The first thought considers the extension of 5G capabilities. 6G can make significant improvements on 5G KPIs. For example, 6G can further increase the data rate and lower latency, etc. The second viewpoint is that 6G promises new capabilities that have not been previously proposed in 5G. One such 6G use case is to unify experience across physical, digital, and biological worlds enabled by new technologies that cannot be supported by 5G. Potential use cases being discussed include AR and VR, holographic telepresence and e-health, continuous and pervasive connectivity, and industry 4.0 and robotics. Figure 2 shows this exponential growth in use cases and requirements.



6G will contribute to fill the gap between beyond-2020 societal and business demands and what 5G (and its predecessors) can support

Figure 2: Evolution of 1G to 6G cellular networks and representative application by generation [11]

2.3 Network Architecture

While we are in the early phases of 6G standards development, the consensus belief is that the architecture of such a standard will go beyond the mobile internet architecture of the 4G and 5G standards. Figure 3 shows a potential future 6G network architecture and how it could span across all of the communication layers (physical, data, network, etc.) as well as incorporate a heterogeneous mixture of enabling hardware architectures.

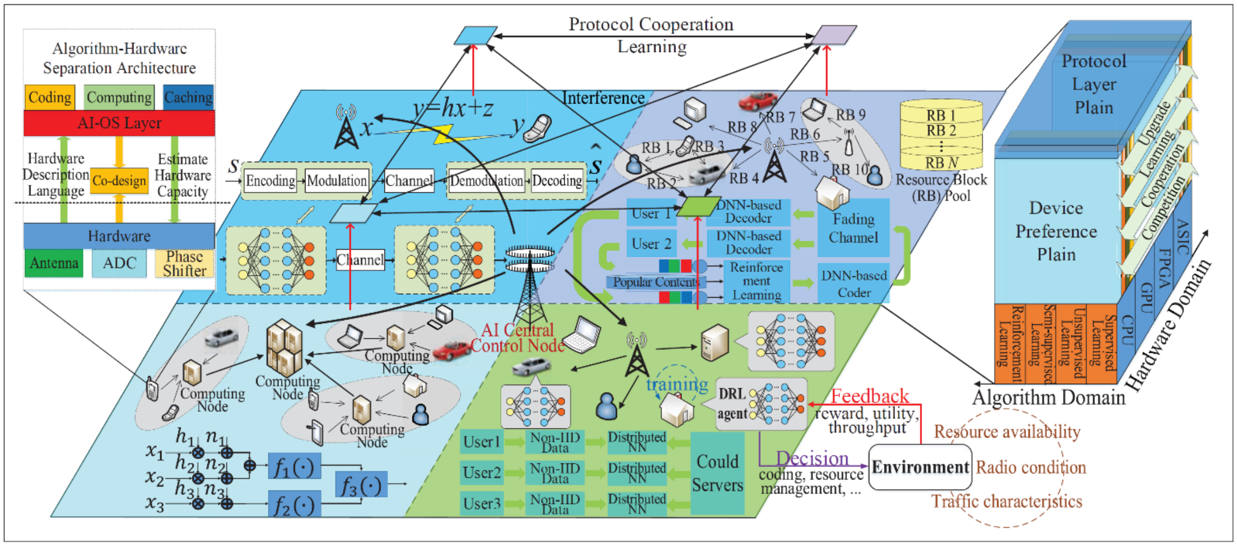


Figure 3: Potential vision of the system architecture for 6G [12]

As such a network is realized, it becomes clear that AI will be one of the most important enablers. The network complexities associated with providing services that efficiently meet these KPIs is beyond what can be done algorithmically with humans in the loop. Only with AI can the network adapt quickly enough to maximize traffic routing and spectral efficiency to meet these new requirements. Support from ubiquitous AI services will play a critical role in designing and optimizing 6G architectures, protocols, and operations [12] [13]. In fact, 6G technology represents an enabler for a new **Intelligent Communication Ecosystem**.

In previous network generations, the cellular industry was the driving force, but 6G brings newcomers to this ecosystem will include industries such as automotive, automation, government, and satellite [6]. The collective efforts of signal processing, cybersecurity, and AI communities will be needed to develop this ecosystem to support the integration of wireless information and energy transfer, integration of sensing and communication, and integration of access-backhaul networks [9].

6G technology will require many developments and improvements on the current state-of-the-art communication techniques. Real-time intelligent optimization will cross the boundaries between the traditional layers of communication in order to achieve the desired KPIs. AI algorithms will likely be investigated as class of algorithms to implement this optimization.

3 6G Intelligent Communication Ecosystem

Many 6G academic papers discuss use cases, technical capabilities, and enablers and how AI and ML will impact overall design and improve performance of 6G networks [14] [15] [16]. These papers provide a good discussion of the current state of the 6G community. The vision of future 6G wireless communication and its network architecture is an Intelligent Communication Ecosystem that combines several emerging technologies to fulfill the growing demands of connectivity and data resources [9]. Thus, this intelligent ecosystem will require self-awareness via AI and ML sensing and algorithms. AI and ML will be integrated in the whole 6G architecture and is fused inside every protocol layer as well as computation architecture including virtual functions, network slices, edge/cloud, and network orchestration and management. Inspecting the traditional Open Systems Interconnection (OSI) model helps to identify the uses of AI/ML algorithms in 6G technology. As with the push to offer fully immersive connectivity with persistent information sharing, optimizing across layers will be necessary to leverage all resources (communication, compute, memory, data, etc.) within the network.

Table 3 lists a few use cases for the most prominent OSI layers where AI/ML algorithms will have applicability.

Table 3: AI/ML use cases within the OSI layer model [17] [18]

OSI Layer	AI/ML Use Case	Algorithm Class
Application	• Dynamic spectrum allocation • Network performance management automation • ML-aided UAV control • Opportunistic data transfer (vehicular examples)	• Supervised learning • Unsupervised learning • Reinforcement learning
Network	• Energy optimization • Fault recovery • Scheduling	• Supervised learning • Unsupervised learning • Reinforcement learning
Data Link	• End-to-end learning • Dynamic spectrum • Predictive resource allocation • Predictive power management	• Supervised learning • Reinforcement learning • Federated learning
Physical	• Channel estimation • Symbol detection • Channel coding • Beamforming	• Supervised learning • Deep learning • Federated learning

3.1 AI and ML Use Cases

AI and ML will play an important role as an enabler of 6G technology by optimizing the networks and designing new waveforms. Also, 6G technology *itself* will enable further advances in AI/ML, such as exploiting the data that is local to the 6G sensor by efficiently transporting the (AI/ML) algorithms. This statement reveals two important distinctions on the AI/ML use cases with 6G technology. Specifically, AI/ML will enable 6G technology, and AI/ML will leverage 6G technology as seen from the examples and discussion below.

AI Enables 6G Technology:

The physical layer and networking access layer will remain important. However, information will flow across these boundaries to optimize the KPI objectives. As a consequence, the boundaries between these layers will become less rigid. AI and ML algorithms are expected to have a significant role in this technology development, which might increase throughput or network capability through novel techniques.

The configuration and optimization of current networks are done by model-based and algorithm-based approaches that may fail to capture the complex relations between physical systems and actions, thereby resulting in suboptimal solutions that cannot fully satisfy end-to-end network requirements. The modeling of dynamic and complex 6G networks using the same methodology would be highly impractical due to their scale, density, and heterogeneity. AI will play a critical role in optimizing future 6G networks by addressing the challenges that cannot be presented easily using closed-form models [19]. Specifically, AI will address problems related to the efficient resource utilization and support of diversified QoS/QoE requirements through continuous learning and model adaptation. This will justify a call for the development of new network architectures and system models, as well as standardized interfaces, protocols, and data formats to facilitate large deployment of 6G networks [20].

AI-based predictive resource allocation methods, which focus on problems associated with random network access and latency, can address network resource demands caused by massive IoT deployments. For example, [21] investigates the predictive resource allocation approach where base stations actively allocate network access to devices, thereby minimizing collisions and latency. Reinforcement learning methods are often used to solve adaptive network access scheduling problems, where decisions are made considering a wide state-action space that includes various channel conditions and traffic characteristics. Deep reinforcement learning is leveraging neural networks as a function approximator to learn rewards in the feedback loop between the decision-maker and a physical system so that the decision-maker can iteratively refine its action based on systems feedback. Deep reinforcement learning methods have been applied to various domains, including adaptive modulation, coding scheme selection, power selection, and beamforming [17].

AI Leverages 6G Technology:

In the past few years, the exponential rise of mobile devices caused the shift from cloud computing toward the network edge in the form of mobile edge computing [22]. IoT technology, which develops rapidly and is expected to dominate the 6G networks, will follow a similar trend and accelerate AI’s adoption on the network edge. As device compute and storage abilities increase, running of AI and ML algorithms on them becomes more feasible, which will cause a shift from traditional cloud-based computing toward novel, collaborative, distributed AI platforms, where each node (device) has a fraction of data and passes results around instead of raw data. Other examples have edge devices exchanging their locally trained models, so the inference process is done collectively across the network. While working on the shared data model, the devices will play a role in data preparation by performing data abstractions, data cleaning, and dimensionality reduction.

Enabling distributed ML at the network edge introduces novel fundamental research problems related to joint optimization of the model training process, communication under strict latency requirements, and privacy and data security issues. One popular technique that addresses the problem of distributed model training is federated learning [22].

This ML method enables users to collaboratively build a shared learning model while keeping all training data on the network nodes, thereby protecting data privacy. In particular, each node computes updates to the current global model based on its local training data, which are then aggregated on a central server. All nodes have access to the same global model, which they periodically retrieve to update the local model. This process repeats until an accuracy level of the global learning model is reached.

3.2 Open RAN AI and ML

Open radio access network (RAN) is an emerging architecture that transforms the network through infrastructure virtualization, flexibility, and embedded intelligence to deliver more agile services and advanced capabilities to end users [23]. The Open RAN approach will enable a heterogenous system of commercial off-the-shelf hardware and software to optimize and self-organize to achieve the overall ecosystem objectives and KPIs. One of the important innovations is the introduction of the RAN Intelligence Controller (RIC), which does not exist in the traditional RAN design (see Figure 4). In the traditional RAN design, the intelligence is typically the RAN vendor's "secret sauce" (e.g., Ericsson, Nokia, Samsung, and Huawei). The service providers are limited to choosing RAN features from the offerings of those RAN vendors. Service providers need to sign multi-year contracts with RAN vendors and are not able to switch vendors easily.

Open RAN intends to break this vendor lock paradigm via support for an ecosystem of vendors leveraging the RIC. With the RIC, service providers can add their own features to control the RAN functionalities to support advanced use cases. RIC supports two main categories of use cases: near real-time (near-RT) and non-real-time (non-RT).[3] RIC is a software platform that can host advanced applications called xApps, which interact with different elements of an Open RAN base station. The current focus of the industry is non-RT RIC.

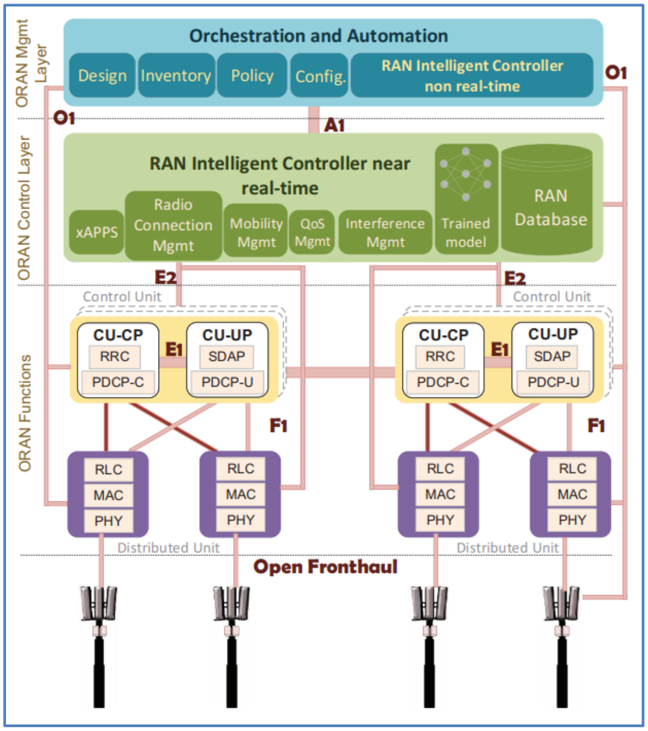


Figure 4: Representation of Open RAN architecture with RAN intelligent controllers (near real-time and non-real time), control and distributed units [23]

The role of AI/ML in Open RAN is discussed in the document "O-RAN Working Group 2 AI/ML Workflow Description and Requirements." The document provides an overview of types of ML algorithms: (1) supervised learning, (2) unsupervised learning, and (3) reinforcement learning. It further details how ML can be applied to enhance the performance of

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[3] https://www.thefastmode.com/expert-opinion/18213-the-ultimate-guide-to-open-ran-open-ran-intelligent-controller-ric-part-1

Open RAN depending on the time scale of Open RAN operation for non-RT RIC, which also dictates in which Open RAN elements the ML should reside. The time scales include < 10 ms (e.g., resource scheduling and spectrum management), 10–500 ms (e.g., QoS and load balancing), and > 500 ms (e.g., system operation and management).

As technology moves to algorithm-driven design, we must research our ability to evaluate and understand the decisions made by the algorithms. Several information theoretic questions are open for research [24], including but not limited to the following:

- Are "post-Shannon" transmission technologies possible where two AI networks communicate efficiently and reliably by recalling past messages to infer the new messages?
- What is the capacity of a deep learning network?
- Is it necessary to recover errors in channel if the networks can learn prior context?
- Can classic communication KPIs factor ML computation time and resources bottlenecks?

3.3 Network Slicing and Security

Network slicing and network security are becoming more important. Rather than treating them as an afterthought as with previous generations, 6G technology plans to leverage AI and ML to help strengthen these aspects within the ecosystem. One use case leveraging ML for improving QoS is to perform autonomous slice configurations as well as slice scheduling for different devices/users based on dynamic applications' requirements [25]:

- Forecasting overall network load and traffic patterns
- Dynamic slice admission control, dynamic slice resource allocation, and dynamic slice traffic scheduling

Another use case is to use ML on network data analytics to perform autonomous cybersecurity attack detection with security mitigations in networks:

- Monitoring events and data packets as well as detecting anomalies/abnormal behaviors in the user equipment, virtual function, network slice, RAN, and core network.
- Threat mitigation by configuring network parameters.
- Dynamically deriving a route for end-to-end network slicing (from user equipment to RAN and to core) to ensure untrusted nodes (e.g., due to supply chain threat concerns) are bypassed.
- Adjusting the security protection levels (communication security and transmission security) dynamically per network slice session to meet dynamic government mission requirements.

As the community collects lessons learned from 5G security, it is expected that 6G will close many 5G security vulnerabilities but also introduce new vulnerabilities. Even though AI and ML can provide performance improvements in a 6G system, there are also security and privacy concerns since 6G attack vectors are not yet well understood and many of the proposed 6G use cases will make use of more human data (e.g., haptic, olfactory sensing data in addition to auditory and visual).

4 Potential Sponsor Impact

The mobile cellular industry is in the early stages of 6G technology speculation with some preliminary research efforts being pursued. The impact on our sponsors and government stakeholders is guaranteed. Key enablers such as THz and VLC, edge computing, quantum computing, security models, and ubiquitous AI and ML stand to change network interaction and generate new use cases not yet conceived. However, the use of AI and ML technology will be a critical component, which requires a greater understanding of the decision-making processes that these data-driven approaches discover. For example, understanding AI-driven decision making will likely be necessary to justify changes to US Federal Communications Commission policy about spectrum usage and communication standards in general.

AI and ML is likely to impact end-to-end communications via signaling, routing, quality of service, and security as information crosses the network in new evolutionary ways. The concept of securing a communication channel becomes dynamic as the network changes to handle loading, network conditions, and users' specific use cases. All these changes will foster in new operation paradigms and upgraded system components for our sponsors.

6G technology will likely be an arena for the emerging "Great Power Competition" between the US, China, and Russia. The war-of-words has begun by some in China to suggest that the US is already behind China in both (future) military and civilian uses:

> The reason why US media organizations are hyping the leapfrogging to 6G technology is because the US is lagging behind in 5G technology research and development and construction. Whether the US can surpass Huawei on 6G in the future is not yet known, but we know that the US has such plans. But if the US needs 6G to push its military communication technology, it only means that US military lags behind in communication technologies, which we used to think were advanced. [26]

Certainly, our sponsors and government stakeholders will need to follow these developments. Further, US government funding of 6G research must be aware that Chinese foreign nationals that perform research at US universities **may** have ties back to China. As stated in [27], "The 'National defense technology research requires the participation of universities,' according to the Chinese government agency overseeing efforts to safeguard classified information at universities. The agency describes universities as one of three parts of the national defense science and technology innovation system." Understanding China's (and Russia's) technology priorities might provide potential overlaps and concerns with respect to 6G research.

5 Summary

6G technology will represent an evolution for communication networks that plan to offer fully immersive connectivity with persistent information sharing. The number of users, types of data, and use cases all are projected to drive the need to develop 6G technologies. Several global conferences are entering into their second year as key research areas start to emerge. These research areas are summarized in Table 4.

Table 4: 6G enabling technology research areas.

Pervasive AI	Immersive Data Sharing
Advance Communication Technologies (THz, VLC, etc.)	Radar-Enable Contextual Communications
Cell-Free Networks	Quantum Communications and Networks
Innovative Network Architectures	Integrating Intelligence in the Network
Big Data Analytics	Blockchain

Expansive use cases, such as augmented reality, holographic telepresence, e-health, industry 4.0 and robotics, are being discussed to help drive 6G target key performance indicators. Per device peak data rate of 1 Tbps, end-to-end latency of 1ms and maximum frequency range 10 THz are a few of the 6G KPIs that have received the most attention.

AI and ML are poised to play a significant role in 6G network development as the 6G network will need to rapidly optimize between competing interests of user QoS/QoE, cybersecurity, and the laws of physics. Preliminary industry discussions have AI and ML enabling 6G and being enabled by 6G. Several OSI layers such as Physical, Data Link, Network and Application have seen interests as researchers explore supervised, unsupervised, federated, and reinforcement learning approaches to solving resource allocation and optimization problems [12].

As a result, data as a commodity will become more important, with value being generated through data creation, data consumption, and, most important, data information content. The quality of the data will produce the value of the commodity for this intelligent communication ecosystem. Research is required to quantify this value so that, in the future, the 6G network can learn about the characteristics of supported services and update its architecture and functionality autonomously.

The Open RAN concept, which will be supported by AI and ML, has also received attention. Supporting heterogenous system of commercial off-the-shelf hardware and software to optimize and self-organize is a key step forward. Another important innovation is the introduction of RIC which will help break the vendor lock seen in current RAN architectures.

6G technology will drastically impact all our government stakeholders as modes of operations change and data sources and access methods evolve. There is a need for investigations into both fundamental research issues and system-level implementation challenges. At a high level, we envision four keys areas to begin addressing:

- Improved Understanding of **Data** about information content in a finite data set and an improved RF data catalog for algorithm benchmarking.
- Cross-Layer Wireless **Optimization** to enable massive machine-to-machine communication through coordination of multi-function devices, sharing data, and AI tasks.

- **Test and Evaluation** for rapid algorithm development and deployment along with RF-centric AI/ML algorithm diagnosis/monitoring approaches.
- Submit contributions to global standard bodies to **Influence 6G Direction** reflecting US government requirements and 6G use cases.

Abbreviations and Acronyms

Term	Definition
1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3G Public-Private Partnership
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
AR	Augmented Reality
ATIS	Alliance for Telecommunications Industry Solutions
EMBB	Enhanced mobile broadband
cMTC	Critical Machine Type Communication
ETSI	European Telecommunications Standards Institute
IMT	International Mobile Telecommunications
IoT	Internet of Things
ITU	International Telecommunication Union
KPI	Key Performance Indicator
M2M	Machine to Machine
MAC	Medium Access Layer
MIMO	Multiple Input Multiple Output
ML	Machine Learning
mMTC	Massive Machine Type Communication
MTC	Machine Type Communication
NFV	Network function virtualization
O-RAN	Open Radio Access Network
OSI	Open Systems Interconnection
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency

RIC	RAN Intelligence Controller
RT	Real Time
SIM	Subscriber Identity Module
SWAP-C	Size, Weight, Power and Cost
THz	Terahertz
UAV	Unmanned Autonomous Vehicles
UE	User Equipment
VLC	Visible Light Communication
VLEO	Very Low Earth Orbit
VR	Virtual Reality
XR	Mixed Reality

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