Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research

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ABSTRACT Emerging applications such as Internet of Everything, Holographic Telepresence, collaborative robots, and space and deep-sea tourism are already highlighting the limitations of existing fifth-generation (5G) mobile networks. These limitations are in terms of data-rate, latency, reliability, availability, processing, connection density and global coverage, spanning over ground, underwater and space. The sixth-generation (6G) of mobile networks are expected to burgeon in the coming decade to address these limitations. The development of 6G vision, applications, technologies and standards has already become a popular research theme in academia and the industry. In this paper, we provide a comprehensive survey of the current developments towards 6G. We highlight the societal and technological trends that initiate the drive towards 6G. Emerging applications to realize the demands raised by 6G driving trends are discussed subsequently. We also elaborate the requirements that are necessary to realize the 6G applications. Then we present the key enabling technologies in detail. We also outline current research projects and activities including standardization efforts towards the development of 6G. Finally, we summarize lessons learned from state-of-the-art research and discuss technical challenges that would shed a new light on future research directions towards 6G.

INDEX TERMS Beyond 5G, 6G, mobile communication, emerging technologies, survey.

I. INTRODUCTION

WHILE the fifth-generation (5G) mobile communication networks are deployed worldwide, multitude of new applications and use-cases driven by current trends are already being conceived, which challenges the capabilities of 5G. This has motivated researchers to rethink and work towards the next generation mobile communication networks "hereafter 6G" [1], [2]. 6G mobile communication networks are expected to mark a disruptive transformation to the mobile networking paradigm by reaching extreme network

capabilities to cater to the demands of the future data-driven society.

So far, mobile networks have evolved through five generations during the last four decades. A new generation of mobile networks emerges every ten years, packing more technologies and capabilities to empower humans to enhance their work and lifestyle. The pre-cellphone era before the 1980s is marked as the zeroth-generation (0G) of mobile communication networks that provided simple radio communication functionality with devices such as walkie-talkies [3]. The first-generation (1G) introduced publicly and commercially available cellular networks in the 1980s. These networks provided voice communication using analog mobile technology [4]. The Second Generation (2G) of mobile communication networks marked the transition of mobile networks from analog to digital. It supported basic data services such as short message services in addition to voice communication [5]. The third-generation (3G) introduced improved mobile broadband services and enabled new applications such as multimedia message services, video calls, and mobile TV [6]. Further improved mobile broadband services, all-IP communication, Voice Over IP (VoIP), ultra high definition video streaming, and online gaming were introduced in the fourth-generation (4G) [7] (A list of important acronyms is given in Table 1).

5G mobile communication networks are already being deployed worldwide. 5G supports enhanced Mobile Broadband (eMBB) to deliver peak data rates up to 10 Gbps. Furthermore, ultra Reliable Low Latency Communication (uRLLC) minimizes the delays up to 1 ms while massive Machine Type Communication (mMTC) supports over 100x more devices per unit area compared to 4G. The expected network reliability and availability is over 99.999% [8]. Network softwarization is a prominent 5G technology that enables dynamicity, programmability, and abstraction of networks [9]. Capabilities of 5G have enabled novel applications such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), autonomous vehicles, Internet of Things (IoT), and Industry 4.0 [10], [11].

Recent developments in communications have introduced many new concepts such as Edge Intelligence (EI), beyond sub 6GHz to THz communication, Non-Orthogonal Multiple Access (NOMA), Large Intelligent Surfaces (LIS), swarm networks, and Self-Sustaining Networks (SSN) [12], [13]. These concepts are evolving to become fully-fledged technologies that can power future generations of communication networks. On the other hand, applications such as Holographic Telepresence (HT), Unmanned Aerial Vehicles (UAV), Extended Reality (XR), smart grid 2.0, Industry 5.0, space and deep-sea tourism are expected to emerge as mainstream applications of future communication networks. However, requirements of these applications such as ultra-high data rates, real-time access to powerful computing resources, extremely low latency, precision localization and sensing, and extremely high reliability and availability surpass the network capabilities promised by 5G [14], [15]. IoT,

TABLE 1. List of important acronyms.

Acronym	Definition
3GPP	3rd Generation Partnership Project
AEC	AI-assistive Extreme Communications
AI	Artificial Intelligence
AR	Augmented Reality
BAN	Body Area Network
BCI	Brain Computer Interface
CAV	Connected Autonomous Vehicles
CS	Compressive Sensing
D2D	Device-to-Device
DLT	Distributed Ledger Technologies
DRL	Deep Reinforcement Learning
ELPC	Extremely Low-Power Communication
ETSI	European Telecommunications Standards Institute
eMBB	enhanced Mobile Broadband
eRLLC	extremely Reliable Low-Latency Communication
FeMBB	Further enhanced Mobile Broadband
FL	Federated Learning
HT	Holographic Telepresence
IoBNT	Internet of Bio-NanoThings
IIoMT	Intelligent Internet of Medical Things
IIoT	Industrial Internet of Things
IoE	Internet of Everything
IoT	Internet of Things
ITU	International Telecommunication Union
IRS	Intelligent Reflecting Surface
KPI	Key Performance Indicator
LDHMC	Long Distance and High Mobility Communications
LED	Light Emitting Diodes
LIS	Large Intelligent Surfaces
LTE	Long Term Evolution
MBBLL	Mobile BroadBand and Low-Latency
MEC	Multi-access Edge Computing
MIMO	Multiple-Input and Multiple-Output
ML	Machine Learning
mLLMT	massive Low-Latency Machine Type
mMTC	massive Machine Type Communication
MR	Mixed Reality
MTC	Machine Type Communication
NOMA	Non-Orthogonal Multiple Access
NTN	Non-Terrestrial Networks
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
SDN	Software Defined Networking
SDO	Standards Developing Organizations
SSN	Self-Sustaining Networks
umMTC	ultra-massive Machine-Type Communication
uRLLC	ultra Reliable Low Latency Communication
VLC	Visible Light Communincaiton
ZSM	Zero touch network and Service Management

which is enabled by 5G, is even growing to become Internet of Everything (IoE) that intends to connect massive numbers of sensors, devices, and Cyber-Physical Systems (CPS) beyond the capabilities of 5G. This has inspired the research community to envision 6G mobile communication networks. 6G is expected to harness the developments of new communication technologies, fully support emerging applications, connect a massive number of devices and provide real-time access to powerful computational and storage resources.

A. 6G MOBILE COMMUNICATION NETWORKS

6G networks are expected to be more capable, intelligent, reliable, scalable, and power-efficient to satisfy all the expectations that cannot be realized with 5G. 6G is also required to meet any new requirements, such as support for new technologies, applications, and regulations, raised in the coming
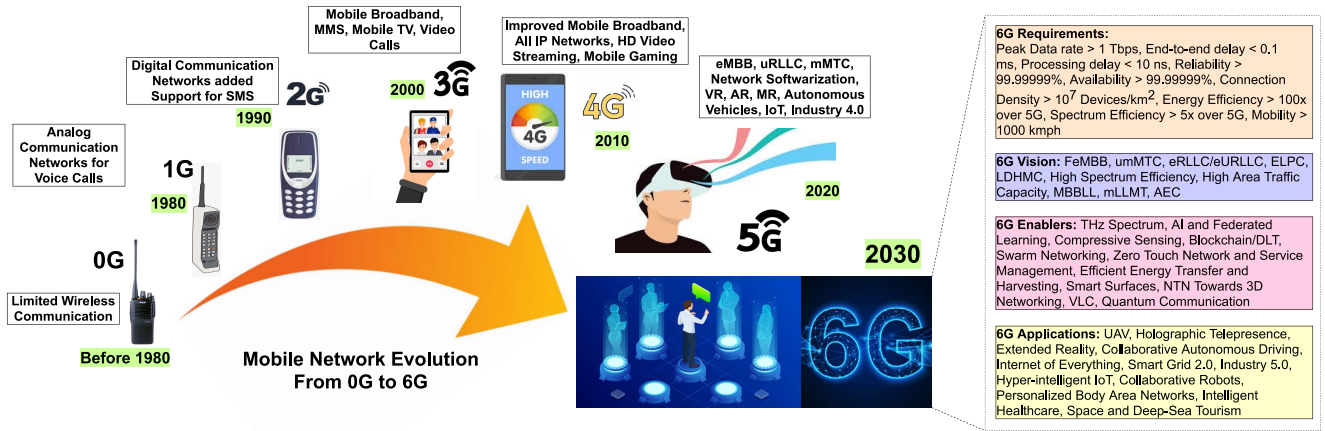
FIGURE 1. Evolution of Mobile Networks from 0G to 6G.

decade. Fig. 1 illustrates the evolution of mobile networks, elaborating key features of each mobile network generation. Envisaged 6G requirements, vision, enablers, and applications are also highlighted to formulate an overview of the present understanding of 6G.

1) 6G AS ENVISIONED TODAY

6G mobile communication networks, as envisioned today, are expected to provide extreme peak data rates over 1 Tbps. The end-to-end delays will be imperceptible and lie even beneath 0.1 ms. 6G networks will provide access to powerful edge intelligence that has processing delays falling below 10 ns. Network availability and reliability are expected to go beyond 99.99999%. An extremely high connection density of over 10^7 devices/km^2 is expected to be supported to facilitate IoE. The spectrum efficiency of 6G will be over 5x than 5G, while support for extreme mobility up to 1000 kmph is expected [12].

It is envisioned that the evolution of 6G will focus around a myriad of new requirements such as Further enhanced Mobile Broadband (FeMBB), ultra-massive Machine-Type Communication (umMTC), Mobile BroadBand and Low-Latency (MBBLL), and massive Low-Latency Machine Type communication (mLLMT). These requirements will be enabled through emerging technologies such as THz spectrum, Federated Learning (FL), edge AI, Compressive Sensing (CS), blockchain/Distributed Ledger Technologies (DLT) and 3D networking. Moreover, 6G will facilitate emerging applications such as UAVs, HT, IoE, Industry 5.0, and collaborative autonomous driving. In light of this vision, many new research work and projects are themed towards developing 6G vision, technologies, use-cases, applications, and standards [1], [2].

2) 6G DEVELOPMENT TIMELINE

6G developments are expected to progress along with the deployment and commercialization of 5G networks, and the final developments of 4G Long Term Evolution (LTE), being LTE-C, which followed LTE-Advanced and LTE-B [16].

FIGURE 2. Expected Timeline of 6G Development, Standardization and Launch [14], [16]–[18].

The vision for 6G is envisaged to be framed by 2022 - 2023 to set forth the 6G requirements and evaluate the 6G development, technologies, standards, etc. Standardization bodies such as the International Telecommunication Union (ITU) and 3rd Generation Partnership Project (3GPP) are expected to develop the specifications to develop 6G by 2026 - 2027 [16]. Network operators will start 6G research and development (R&D) work by this time to do 6G network trials by 2028 - 2029, to launch 6G communication networks by 2030 [14], [16]–[18]. The expected timeline for 6G development, standardization and launch is presented in Fig. 2.

B. PAPER MOTIVATION

6G has already become a key topic in the area of mobile communication research. Many research work are published on 6G vision, enabling technologies, possible applications, and use cases. A vision for 6G is proposed in [12], [18], [20], [26], [28], [30], highlighting the key requirements that range from extremely high data rates through FeMBB to mLLMT communication. This vision is based on emerging technologies and applications that are expected to boom in the coming decade. Many research

TABLE 2. Summary of important surveys on 6G.

Ref.	6G Driving Trends	Applications/Use Cases	Requirements/Vision	Technical Challenges	Enabling Technologies	Ongoing Activities	Research Directions	Remarks
[14]	L	M	L	M	H	L	L	Developments, core technologies, scenarios and challenges of 6G.
[19]	L	M	L	M	H	L	M	6G taxonomy, key enabling technologies, use cases, emerging technologies, research challenges, and future directions.
[20]	L	H	M	M	H	L	M	6G vision, network architecture, emerging technologies, applications, communication requirements and possible technologies.
[12]	M	M	M	L	M	L	H	6G vision, drivers, applications, technological trends, service classes, performance requirements, enabling technologies and research directions.
[21]	L	M	M	L	H	L	L	Wireless evolution towards green 6G, 6G architectural changes, pervasive AI, enhanced network protocol stack and potential technologies.
[22]	L	M	M	M	H	M	M	5G NR, next-generation wireless communication architecture for 5G/6G networks, technologies and applications of 6G networks, ongoing projects on 6G.
[16]	L	H	M	H	M	L	L	6G architecture, AI technologies, AI Applications and hardware-aware communication.
[17]	L	H	L	L	H	L	L	Different 6G use cases and enabling technologies.
[23]	L	M	L	M	H	L	L	6G applications, enablers, AI and technologies.
[24]	M	L	H	L	M	L	L	Drivers, 6G requirements, system architecture and technologies.
[25]	L	H	L	M	H	L	H	6G use cases, communication technologies, and future research directions.
[26]	M	L	H	M	H	L	L	6G vision, requirements, technologies and challenges.
[27]	L	L	L	H	H	L	L	6G technologies and challenges.
[28]	L	L	M	L	H	L	L	6G vision, use cases, requirements, AI and technologies.
[29]	M	M	M	L	H	L	L	6G use cases, requirements, KPIs, design, key technologies and solutions.
[30]	L	M	M	M	M	L	L	6G vision, use cases, challenges and technologies
[18]	L	H	M	M	H	L	L	6G vision, features, applications, requirements, enabling technologies and envisaged issues.
[31]	L	M	M	M	H	L	L	6G communication technologies, security and privacy, AI, and applications.
[32]	L	M	L	H	H	L	L	Technologies, opportunities, challenges and application in 6G convergent communication, sensing and localization.
This paper	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**A comprehensive survey of 6G driving trends, applications, use cases, requirements/vision, technical challenges, enabling technologies, projects, research work, standardization approaches and future research directions.**

L	Low Coverage	M	Medium Coverage	H	High Coverage

work including [14], [19]–[23], [32] are focussed on elaborating technologies including THz communication, edge intelligence, blockchain, swarm networks, and 3D networks that are envisaged to become enablers of 6G mobile communication networks. Furthermore, the development of applications such as IoE, UAVs, HT, XR, and Connected Autonomous Vehicles (CAV) that will utilize future 6G networks are discussed in [16]–[18], [20], [25], [31]. The challenges in bringing those futuristic applications into reality through advanced communication technologies are explained in [16], [19], [26], [27], [30]. Societal and technological trends that trigger the drive towards 6G are discussed in [12], [24], [26], [29]. However, few papers, including [22] have discussed the ongoing 6G projects, research activities, and standardization approaches.

Research directions towards realizing 6G are elaborated in [12], [22], [25]. Table 2 summarizes existing research work that surveys the developments in different areas of 6G. This highlights that the available papers have only discussed several focused areas, but no paper has surveyed the overall development of 6G to date. In response, this survey paper presents a holistic view of 6G developments, focusing on a wide range of aspects, including driving trends, applications, requirements/vision, enabling technologies, projects and research activities, standardization efforts, lessons learnt, related limitations, and future challenges.

C. PAPER CONTRIBUTION
To the best of the authors' knowledge, this is the first attempt to survey the path towards 6G comprehensively by

considering a broad range of aspects, as clearly indicated in Table 2. Accordingly, the main contributions of this survey are presented below.

- **Explore 6G driving trends:** This paper identifies the societal and technological driving trends that would urge a new generation of mobile communication networks by 2030.
- **Discuss emerging applications:** The development of a wide range of new applications that are expected to bloom is discussed elaborating how these applications are enabled by the capabilities of future 6G networks.
- **Present 6G requirements/vision:** The paper shapes a vision for 6G elaborating the envisaged requirements.
- **Explain enabling technologies:** Enabling technologies of 6G that will cater to the requirements raised by emerging applications are discussed exhaustively.
- **Summarize projects, research work, and standardization approaches:** Existing 6G projects that focus towards developing the 6G vision and technologies are summarized. The research activities and approaches for standardization are also discussed in this paper.
- **Propose a roadmap for future research directions:** A roadmap for future 6G research directions is presented considering the lessons learnt throughout the development of 5G, and the challenges of developing 6G.

D. PAPER OUTLINE

The rest of the paper is organized as follows. Section II presents the existing and anticipated, societal and technological trends that drive towards 6G. Applications that are emerging to harness the capabilities of 6G are elaborated in Section III. Section IV presents the requirements/vision of 6G as envisaged today. 6G enabling technologies are presented in Section V. Projects and relevant activities focused around the development of 6G are presented in Section VI, whereas Section VII discusses 6G standardization efforts. Research directions, lessons learnt, related limitations and future research directions towards realizing a 6G network are portrayed in Section VIII. Finally, Section IX concludes the paper. The structure and the flow of the paper are presented in Fig. 3.

II. KEY DRIVING TRENDS TOWARDS 6G

This section discusses the key 6G driving trends elaborating why and how each trend is demanding a new generation of communication networks. Fig. 4 illustrates the 6G driving trends that are discussed in this section.

A. EXPANSION OF IOT TOWARDS IOE

IoT envisions to weave a global network of machines and devices that are capable of interacting with each other [35]. The number of IoT devices are on the rise and is expected to grow up to 24 billion by 2030 due to the growth of applications such as Industrial Internet of Things (IIoT).

The total IoT market is also expected to rise up to USD 1.5 trillion in 2030 [36]. IoE is expected to expand the scope of IoT to form a hyper-connected world connecting people, data and things to streamline the processes of businesses and industries while enriching human lives [37]. IoE will connect many ecosystems involving heterogeneous sensors, actuators, user equipment, data types, services, and applications [38].

Importance of the Driving Trend: Importance of this driving trend is discussed considering the challenges in overcoming the limitations of existing networks to facilitate IoT development towards IoE. One of the key challenges in this development is the integration of Artificial Intelligence (AI) and Machine Learning (ML) technologies to mobile communication networks [39]. These technologies are essential to process massive amounts of data collected from heterogeneous IoE devices to obtain meaningful information and enable new applications, and use-cases envisioned with 6G [40]. Processing massive amounts of data using AI and ML requires future communication networks to provide real-time access to powerful computational facilities. The communication between IoE devices and mobile networks should also be power efficient to minimize the carbon footprint. For instance, intelligent traffic control and transportation systems in future smart cities are expected to utilize future 6G communication networks to massively exploit data-driven methods for real-time optimization [41]. Such systems will require AI and ML to efficiently process large amounts of data collected from heterogeneous sensors in real-time to provide insights that will be useful to minimize traffic.

Preserving data security and privacy in existing IoT networks is yet another important requirement. Since everything in IoE is connected to the Internet, distributed AI technologies will be required for training data-sets spread unevenly across multiple edge devices. This exposes IoE networks to security vulnerabilities associated with distributed AI such as poisoning attacks and authentication issues [42]. Solving these issues require AI and DLT based adaptive security solutions that should be integrated with future communication networks [43]. DLTs, blockchain in particular, is a key enabler of IoE. The decentralized operation, immutability and enhanced security of blockchain are instrumental in overcoming the challenges concerned with the exponential expansion of IoT [44]. Moreover, traditional Orthogonal Multiple Access (OMA) based schemes cannot provide access to a massive number of IoE devices due to limitations in the radio spectrum. This requires new technologies such as NOMA to be applied to cellular IoT to provide access to a massive number of IoT devices [13], [39]. In addition, providing seamless connectivity to IoE devices that lie beyond the coverage of terrestrial cellular networks requires UAV and satellites to work in coordination to form a cognitive satellite-UAV network [45]. Such technologies are expected to be integrated with the next-generation of mobile communication networks to facilitate the smooth progression from IoT towards IoE.
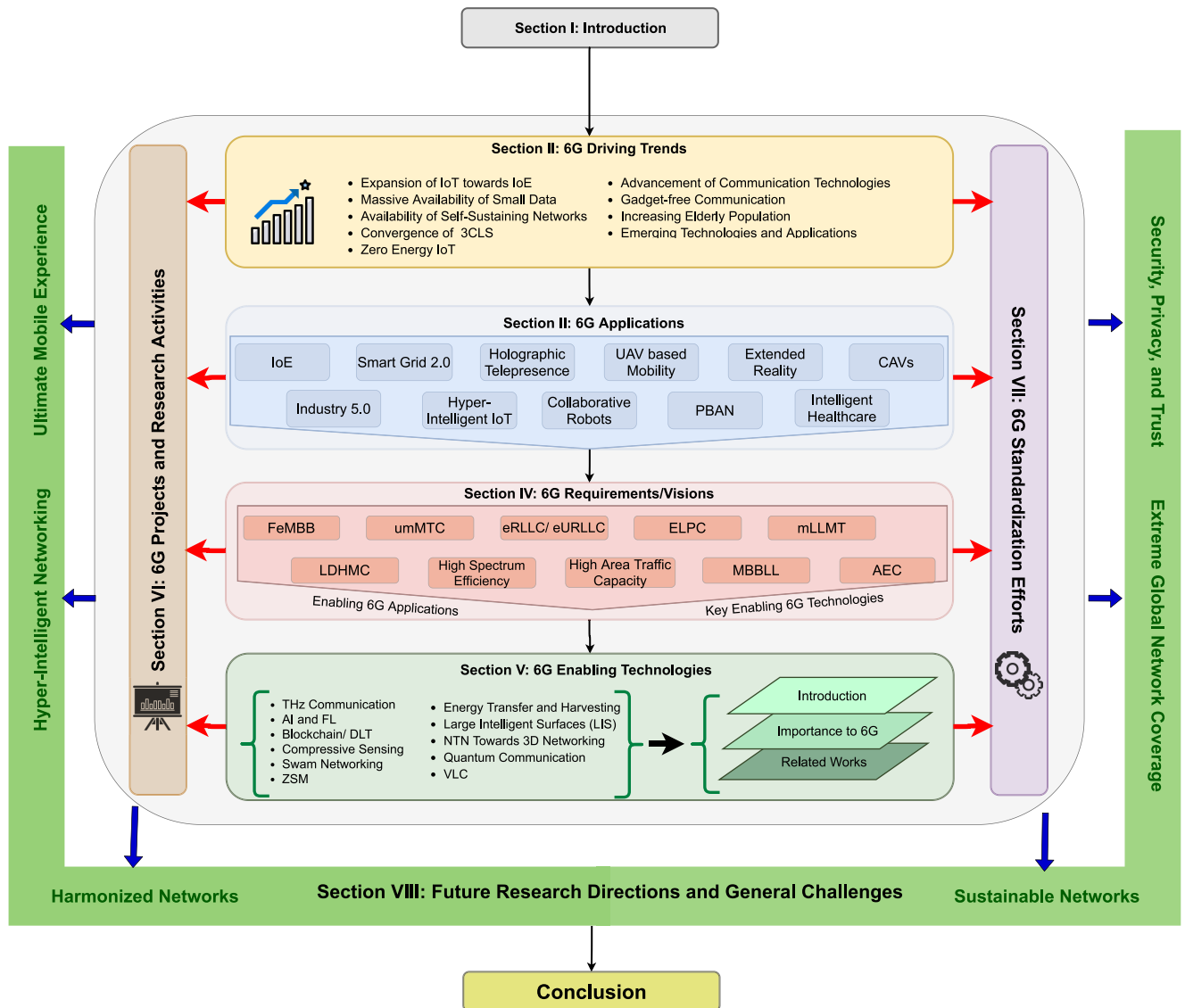
FIGURE 3. Structure and the outline of this paper.

B. MASSIVE AVAILABILITY OF SMALL DATA

The term "Small Data" refers to small data sets representing a limited pool of data in a niche area of interest [46]. Such data sets can provide meaningful insights to manage massive amounts of IoT devices. Unlike Big Data that concerns with large sets of historical data, Small Data is concerned about either real-time data or statistical data of a limited time. Small Data will be instrumental in many applications, including the real-time equipment operation and the maintenance of massive numbers of machines connected in IIoT. IIoT is expected to grow connecting billions of CPS, devices, and sensors in the coming decade as discussed in Section II-A. Another example is the growing demand for Small Data based analytics in the retail industry that collects data from various sensors, personal wearables, and IoT devices [47]. Such analytics are useful to provide real-time personalized services for customers. These applications give rise to the generation of massive amounts of small data sets that should be efficiently collected and processed using AI and ML [12].

Importance of the Driving Trend: The importance of this driving trend is discussed considering the processing and communication limitations of existing mobile communication networks. Processing massive amounts of Small Data sets is not efficient in existing cloud computing and edge computing infrastructure, that is designed to process large data sets [48]. This requires new means of efficiently processing massive amounts of Small Data sets in the Edge AI infrastructure in future communication networks. This will also require new ML techniques beyond classical big data analytics to enhance network functions and provide new services envisaged in future communication networks [12]. Furthermore, future networks should maximize the energy-efficiency of offloading massive amounts of Small Data to edge computing facilities. This requires the optimization

IoT Expansion

Massive Availability of Small Data

Self-Sustaining Networks

Communications, Computing, Control, Localization, and Sensing

Zero Energy IoT

Advancement of Communication Technologies

Gadget-free Communication

Increasing Elderly Population

Emerging Technologies and Applications

FIGURE 4. 6G Driving Trends [33], [34].

of joint radio and computation resources while satisfying the maximum tolerable delay constraints [49]. On the other hand, communication networks will need to support massive amounts of Small Data transmission from heterogeneous IoT devices. Overheads of this type of communication can be significant compared to the size of data that is being transmitted, making this type of data communication less efficient [50], [51]. This requires new methods to reduce transmission and contention overheads in future communication networks.

C. AVAILABILITY OF SELF-SUSTAINING NETWORKS

SSNs can perform tasks such as self-managing, self-planning, self-organizing, self-optimizing, self-healing, and self-protecting network resources to continuously maintain its Key Performance Indicators (KPIs) [12]. This is performed by adapting network operation and functionalities considering various facts, including environmental status, network usage, and energy constraints [52]. These types of intelligent and real-time network operations in SSNs are facilitated using machine learning/deep learning/quantum machine learning techniques that enable fast learning of rapid network changes and dynamic user requirements [19]. Using SSNs, future networks are expected to enable seamless access to emerging application domains under highly dynamic and complex environments [12].

Importance of the Driving Trend: The importance of this driving trend is discussed considering the incapability of existing mobile networks to function as SSNs. SSNs require the ability to obtain network statistics in real-time to automatically manage resources and adapt functionalities to maintain high KPIs [12]. Therefore, SSNs require a novel self-sustaining network architecture that can adapt to rapid changes in the environment and user requirements. These operations should be facilitated through real-time analysis of massive amounts of Small Data obtained by network nodes.

Small Data analysis can be performed using edge intelligence capabilities envisaged in future networks, as explained in Section II-B. Furthermore, self-optimization of radio resources needs to bank on software-defined cognitive radios through operations such as radio scene analysis [19], [53]. In addition, SSNs should facilitate energy self-sustainability at the infrastructure side as well as the device side to provide uninterrupted and seamless connectivity. Therefore, energy harvesting in network infrastructure should play a pivotal role to extend the range and stand-by times [20], [54]. This also requires future communication networks to be designed in an energy-aware fashion to enable devices to harvest energy, be self-powered, share power and last long [17], [55]. Furthermore, handling massive numbers of IoT devices in an energy-efficient manner under various channel conditions and diverse applications requires self-learning through context-aware operation to minimize the energy per bit for a given communication requirement [56].

D. CONVERGENCE OF COMMUNICATIONS, COMPUTING, CONTROL, LOCALIZATION, AND SENSING (3CLS)

Future communication networks are expected to converge computing resources, controlling architecture and other infrastructure used for precise localization and sensing [12]. This convergence is essential to facilitate highly personalized and time-critical future applications. For instance, Human-Centric Services (HCS) are expected to bank on 3CLS services to facilitate efficient communication and real-time processing of a large number of data streams gathered through sensors that are centered around humans [57], [58].

Importance of the Driving Trend: The development of 3CLS services is an important driving trend towards the next generation of mobile communication networks as existing 5G technologies has not fully explored the interdependence between computing, communication, control, localization, and sensing in an end-to-end manner [59].

Realizing 3CLS services will require future mobile communication networks to possess collective network intelligence at the edge of the network to run AI and ML algorithms in real-time [12], [60]. Moreover, the network architecture should also be open, scalable, and elastic to facilitate an AI orchestrated end-to-end 3CLS design services [12], [61]. Precise localization and sensing should also coexist with communication networks by sharing network resources in time, frequency, and space to facilitate emerging applications such as extended reality, connected robotics, CAVs, sensing, and 3D mapping [12], [62].

E. ZERO ENERGY IOT

Zero energy IoT devices can harvest energy from the environment to obtain infinite power [63]. For instance, Radio Frequency (RF) energy harvesting can harvest energy from RF waves to extend the network lifetime. Nodes that harvest more energy can share their energy with other nodes using energy cooperation. Presently, only about 0.6% of the 1.5 trillion objects in the real world are connected to the Internet [64]. The remaining devices are also expected to be connected in an energy efficient fashion together with the growth of future communication technologies and applications.

Importance of the Driving Trend: Zero energy IoT is an important driving trend towards future communication networks to enable maintenance-free and battery-less operation of a massive number of IoT devices. This requires mobile networks to be able to support ultra-low-power communication and efficient energy harvesting [64]. However, existing 5G network infrastructures do not support energy harvesting, especially as the electronic circuitry cannot efficiently convert the harvested energy into electric current [17]. Therefore, the electronic circuitry in future communication networks should be designed and developed to support efficient energy harvesting. Furthermore, circuits that harvest energy should allow devices to be self-powered to enable off-grid operations, long-lasting IoT devices, and longer stand-by times [17]. Wireless power transfer is also expected to play a key role in the next generation of mobile communication networks considering the feasibility of doing so due to much shorter communication distances in denser communication networks [30]. Furthermore, data communication stacks can also be optimized in an energy-aware fashion to minimize energy usage.

F. ADVANCEMENT OF COMMUNICATION TECHNOLOGIES

Mobile communication has seen significant technological advances recently. For instance, electromagnetically active Large Intelligent Surfaces (LIS) made using meta-materials placed in walls, roads, buildings and other smart environments with integrated electronics will provide massive surfaces for wireless communication [65]. Furthermore, novel channel access schemes such as NOMA have found to
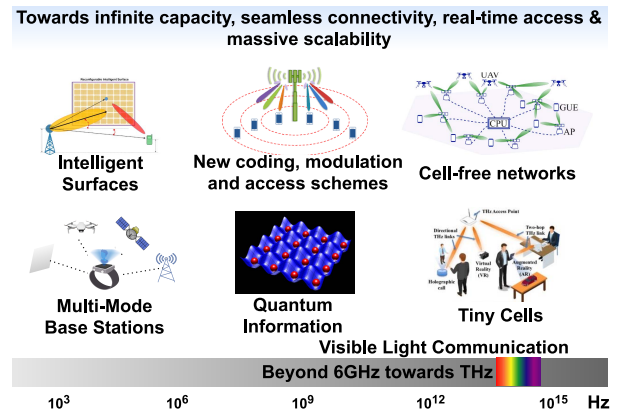

FIGURE 5. Advancement of communication technologies towards 6G [12], [65]–[67].

provide many advantages such as being more spectral efficient compared to prevailing schemes. Beyond millimeter Wave (mmWave) communication at THz frequency bands are also being exploited to provide uninterrupted connectivity in local and wide area networks [66]. Key advancements of communication technologies are illustrated in Fig. 5.

Importance of the Driving Trend: The emergence of new communication technologies that cannot be integrated with existing 5G networks is discussed to highlight the importance of this driving trend. For instance, future communication networks will need to shift from existing small cells towards tiny cells to support high-frequency bands in the THz spectrum. This requires a new architectural design supporting denser network deployments and mobility management at higher frequencies [66]. Furthermore, multi-mode base stations will be necessary to facilitate networks to operate in a wide range of spectra ranging from microwave to THz to provide uninterrupted connectivity. Furthermore, utilizing LISs as transceivers require low-complexity channel demodulation banking on techniques such as joint CS and deep learning, which is not feasible with 5G [68]. Also, none of the recent advancements in communication technologies such as providing AI powered network functionalities using collective network intelligence, Visible Light Communication (VLC), NOMA, cell-free networks, and quantum computing and communications are realized in 5G [12], [67], [69]. Therefore, integration of these advanced communication technologies demands a new paradigm of mobile communication networks.

G. GADGET-FREE COMMUNICATION

Gadget free communication eliminates the requirement for a user to hold physical communication devices. It is envisaged that the digital services centered around smart and connected gadgets will move towards a user-centric gadget-free communication model as more and more digital interfaces, intelligent devices and sensors get integrated to the environment [70], [71]. Since most of our data and services are already based on cloud platforms, the move towards a ubiquitous gadget-free environment seems to be the natural

progression. The hyper-connected smart digital surroundings will provide an *omnipotential* environment around the user to provide the all the digital services needed in their every-day life. Hence, in the future, any user can live *naked*, i.e., users can access Internet based services without any personal devices, gadgets or wearables [72].

Importance of the Driving Trend: The limitations of present 5G network technologies to facilitate gadget-free communication also highlights it as an important driving trend towards the next-generation of networks. Gadget-free communication requires users to stay connected seamlessly with high availability, high network performance, increased energy efficiency and lower costs. This requires future communication networks to be highly automated, context-aware, adaptable, flexible, secure and self-configurable to provide users with a satisfactory service [72]. Facilitating such requirements demands future communication networks to be equipped with powerful distributed computing with edge intelligence, which is lacking in present 5G implementation [60]. Future networks are also required to facilitate extreme data-rates, negligible latencies, and extreme reliability to facilitate holographic communication that will enable users to fully utilize the potential of gadget-free communication [23]. Furthermore, existing measures for network security and privacy also needs to be improved. For instance, efficient, secure and privacy, ensuring authentication mechanisms using lightweight operations are required to be integrated with future communication networks to facilitate gadget-free communication [73].

H. INCREASING ELDERLY POPULATION

The world's older population continues to grow exponentially due to advance healthcare facilities, life prospects, and access to new medicine and healthcare facilities. Presently, there are more 60-year olds than children under the age of five, and this trend is expected to grow [33]. The World Health Organization (WHO) in 2015 has also predicted that the elderly populations will double from 12% to 22% by 2050 [34]. The elderly population is prone to old-age diseases. Thus, they need continuous health monitoring to ensure well-being. However, frequent hospital visits might not be a feasible solution due to costs, transportation difficulties, and body movement restrictions. This requires technologies to aid physicians to manage their patients in real-time while measuring parameters such as heart rate, body and skin temperature, blood pressure, respiration rate and physical activity using multiple wearable devices and environmental sensors [74]. Concepts such as Human Bond Communication (HBC) are developing to detect and transmit information using all five human senses (sight, smell, sound, touch, and taste) [33]. Ambient Assisted Living (AAL) is another developing concept that will allow remote monitoring of health as well as other hazards such as smoke or fire [75].

Importance of the Driving Trend: The importance of increasing elderly population as an emerging trend is identified considering the limitations of existing network infrastructure to provide smart healthcare and other related facilities to the increasing elderly population. It is observed that the requirements of future healthcare applications can extend up to very high data rates, extremely high reliability (99.99999%), and extremely low end-to-end delays (≤ 1 ms) [17], [76]. Furthermore, emerging applications such as Intelligent Internet of Medical Things (IIoMT) requires powerful edge intelligence to process massive amounts of data in real-time for early detection of adverse medical conditions such as cancers. Similarly, Hospital-to-Home (H2H) services that can provide urgent treatments for patients will also require seamless connectivity with extreme reliability [76]. In addition, VLC is expected to be integrated with mobile networks to facilitate in-body sensors to provide vital information for patient monitoring [33]. Moreover, the massive amounts of health information that will be gathered should be protected by future networks with powerful and intelligent measures to ensure data security and user privacy [76], [77]. These requirements are beyond 5G capabilities and demand a new generation of mobile communication networks.

I. EMERGING TECHNOLOGIES AND APPLICATIONS

The advancement of technologies will enable many novel and resource-intensive applications by connecting over 125 billion devices worldwide by the year 2030 [17]. For instance, XR technologies are expected to play a significant role in many applications, including Brain Computer Interfaces (BCI), smart healthcare and education [12]. HT is another key area that is envisaged to grow and teleport users to create a sense of presence in virtual spaces [78]. Similarly, synergistic use of machines and people labor together with AI is envisioned to enhance human capabilities and personalize autonomous manufacturing in Industry 5.0 [79], [80]. On the other hand, the evolution of smart grids will give rise to *Internet of Energy* that will monitor and control heterogeneous energy sources and energy storage systems [81]. CAVs will be another popular application that will utilize data gathered from heterogenous sensors to provide vital information related to navigation, passenger safety, road safety, and passenger infotainment [82]. UAVs is another area that is expected to grow from being a 19.3 billion USD industry in 2019 up to 45.8 billion USD by 2025 [83].

1) IMPORTANCE AS A DRIVING TREND

Emerging technologies and applications is another important driving trend towards the next-generation of networks. According to [17], present 5G network technologies are not capable of delivering the extreme data-rates, extreme reliability, extreme-availability, extreme low-delays and massive scalability demanded by emerging technologies and applications. For instance, utilizing XR technologies in BCI applications will require over 1 Tbps data rates [12]. Furthermore, a raw hologram used in HT applications requires over 4 Tbps data rates with sub-millisecond latency [84]. These
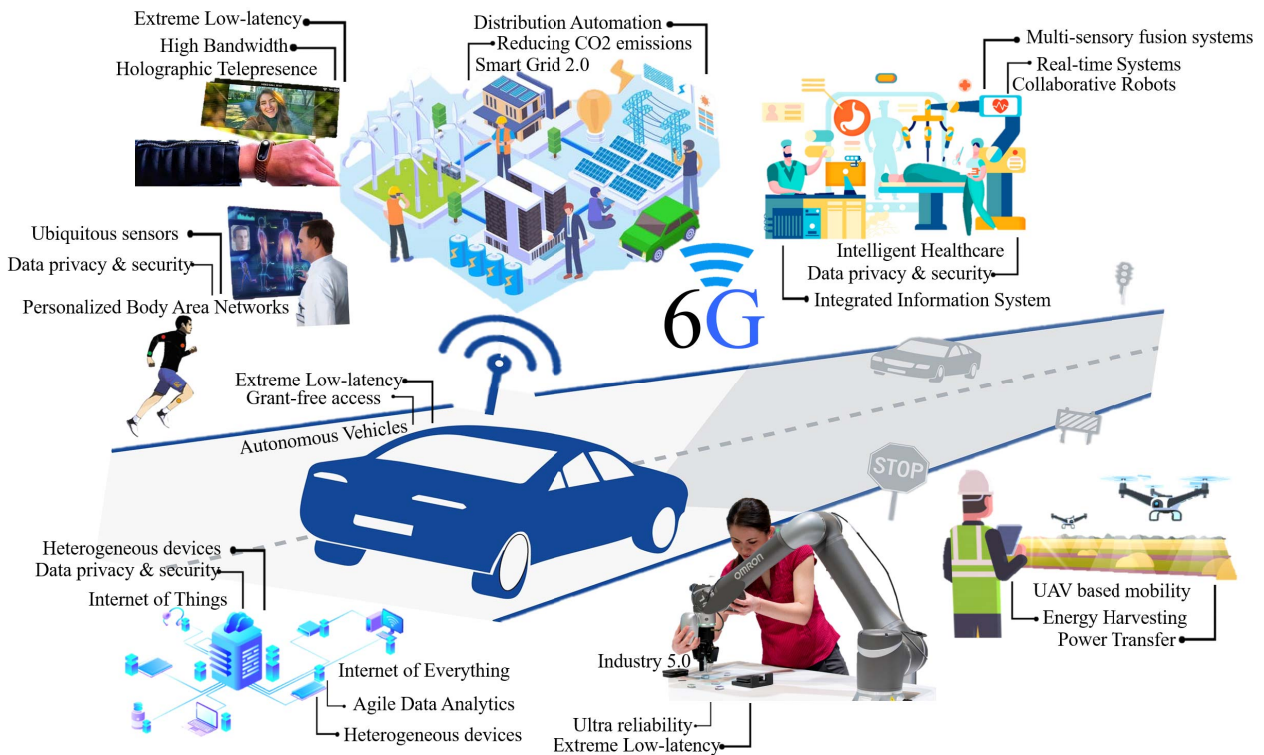
FIGURE 6. Emerging 6G Applications.

applications demand extreme reliability and extreme availability (> 99.99999%). Also, applications such as CAVs demand up to 1000 km/h mobility [17]. Seamless communication between billions of Internet connected devices is essential for emerging IoE applications. Furthermore, future networks are also expected to have significantly better energy efficiencies than 5G to facilitate lower-costs, massive scalability and lower carbon footprint. Additionally, existing 5G networks are also not designed to handle unique security vulnerabilities such as paging occasion and stingrays in UAV applications [83]. Therefore, a new generation of networks is required to address all these limitations of 5G networks to facilitate emerging technologies and applications towards the 2030 world.

III. 6G APPLICATIONS

The above discussed trends will motivate the development of a wide range of new applications to shape the human society of 2030s. This section discusses some of the key emerging applications that will bank on future 6G network capabilities, as illustrated in Fig. 6. Requirements of each application discussed in this section are presented in Table 3.

A. INTERNET OF EVERYTHING (IOE)

IoE is an extended version of IoT that includes, things, data, people, and processes [87], [88]. The main concept of IoE is to integrate various sensing devices that can be related to "everything" for identifying, monitoring the status, and taking decisions in an intelligent manner to create

new prospects. Sensors in IoE are capable of acquiring many parameters such as velocity, position, light, bio-signals, pressure, and temperature readings. These sensors are used in applications ranging from healthcare systems, smart cities, traffic to industrial domain to facilitate decision support systems.

6G is expected to become a key enabler for the IoE that will help in accommodating massive machine type communication and sensor devices [76], [89]. The integration of 6G and IoE will be helpful in improving the services related Internet of Things, Internet of Medical Things, robots, smart grids, smart city, body sensor networks, and many more avenues.

It can also be predicted that many new applications will emerge from the fusion of IoE and 6G communication [90]. However, IoE is expected to be dependent on 6G as it requires the capacity to connect N-intelligent devices where N term is scalable and can reach to billions. Moreover, IoE also needs the high data rates to support and facilitate the N number of devices with low latency [76]. Therefore, IoE and 6G together can facilitate the business processes to not only create magnitudes of data but also to re-invent the digitalization with improved and agile data analytics.

1) RELATED WORK

A number of researchers have explored the potential of 6G in a rhetorical way. Saad *et al.* [12] presented the associated applications and trends that can be potentially enhanced with

TABLE 3. Expected 6G applications requirements [85], [86].

Use Cases / Primary Applications	Requirements				Enabling Technologies										
	Data Rate	End-to-End Latency	Network Size/ Availability	Security Level	THz Communication	AI and FL	Compressive Sensing	Blockchain/DLT	Swarm UAVs	Zero Touch Networks	Energy Transfer / Harvesting	Large Intelligent Surfaces	NTN/3D Networking	Visible Light Communication	Quantum Communication
Internet of Everything	100-1000 Mbps	ms to s	$> 20 \times 10^6$ devices	MEDIUM	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Smart Grid 2.0	10-2000 Mbps	1-10 ms	>2 over 10-100 km	MEDIUM		✓	✓	✓		✓	✓				
Holographic Telepresence	> 2-4 Tbps	0.1 ms	> 1	MEDIUM	✓	✓	✓				✓		✓	✓	✓
UAV based Mobility	10-100 Mbps	1-10 ms	> 10	MEDIUM		✓		✓	✓	✓	✓	✓	✓		
Extended Reality	> 2-4 Tbps	0.1 ms	> 1	MEDIUM	✓	✓	✓				✓		✓	✓	✓
Connected and Autonomous Vehicles	1-10 Gbps	> 10	> 1	MEDIUM	✓		✓		✓			✓			
Industry 5.0	100-1000 Mbps	1-10 ms	10^6 devices per km^2	MEDIUM	✓	✓		✓	✓			✓		✓	✓
Hyper-intelligent IoT	> 24 Gbps	10-100 μs	$> 125 \times 10^6$ devices	MEDIUM	✓	✓	✓		✓	✓	✓	✓	✓		✓
Cobots	> 24 Gbps	2.8 ms	> 1	MEDIUM	✓	✓			✓				✓		
Personalized BANs	1-50 Mbps	ms to s	$> 10^3$ nodes per cm^3	VERY HIGH	✓		✓	✓				✓		✓	
Intelligent Healthcare	> 24 Gbps	< 1 ms	> 99.999 %	HIGH	✓	✓	✓	✓	✓				✓	✓	✓

■ Pre-5G Capabilities   ■ 5G Capabilities   ■ Expected 6G Capabilities

the use of 6G communication. The study also discusses the key enabling technologies and research problems, which 6G systems might face in its realization phase. A similar study was carried out by Chowdhury *et al.* [20], which discussed the challenges associated with 6G systems along with potential applications. Both of these studies present IoE as the key enabler for 6G communication systems. Yang *et al.* [27] also conducted a similar study but with the focus on potential techniques that could be used to bring the 6G systems closer to commercialization. This study also emphasizes on super flexible integrated networks which can help 6G systems to be applicable in variety of applications including IoE.

Al-Turjman [91] focused on the potential sensors that can be employed for the integration of IoE and 6G communication systems from physical and electronic communication point of views. Janbi *et al.* [38] proposed a distributed AI as a service (DAIaaS) framework by integrating IoE and 6G characteristics. The evaluation showed that the DAIaaS can help in reducing the inference time while allowing the developers to systemize the automation process. Mardini *et al.* [92] proposed a IPv6 routing protocol for lossy networks and low-power systems based on the IoE and 6G networks. The study suggests that similar nodes representing a common objective can be considered as an instance and such instances can be used with Low-Power and Lossy Networks

(RPL) for enhancing the performance of healthcare systems, accordingly.

Summary: The IoE requires uninterruptible and massive low-latency communication in order to facilitate things, services, and people in a single integrated framework.

B. SMART GRID 2.0

Smart Grid 2.0 integrates intelligent decision systems with the smart meters in a way that the consumption could be monitored accurately. Moreover, smart grid 2.0 also includes the goal of detecting outages, sensing of power quality, demand response, and network connectivity to cater to the ever increasing energy demand [19], [93].

Since the inception of smart grid development, communication has been one of the challenges as large number of devices are ought to be connected in order to monitor and control the electrical equipment from remote locations [18]. For realization of such control strategy, the system needs high quality transmission, security, and administration of communication resources. All the physical objects such as towers, transformers and other components need to be detected and monitored for the provision of effective services and reliable supply [76]. 5G communication meets with the requirement of low-latency and high bandwidth so far with limited number of devices in order to commercialize the

smart grid project. However, if we are concerned about the diversification and the ramifications of climate change, 6G communication systems are required to fulfil the need [19]. For instance, monitoring CO2 emissions require sensors to be connected and integrated with decision systems such as machine learning, so that the appropriate load balancing and distribution measures can be taken [18].

1) RELATED WORK

The works combining 6G and smart grids are quite limited due to the lack of available data and hypothetical situations. Khan *et al.* [19] explored potential applications and advancements related to 6G communication systems including computing, networking, communication, and key-enabling technologies. One of the explored applications was zero-energy-enabled 6G which suggests the integration of radio-frequency and renewable sources for harvesting energy. The idea is to monitor the excessive energy being utilized by radio frequency so that the same amount of energy could be harvested and sent back to the grid, hence, zero-energy. Ho *et al.* [94] carried out a survey for discussing the implications and solutions for smart grids in conjunction with 5G communication systems. However, the study provides a brief vision for leveraging 6G system characteristics to improve the smart grid performance. Katz *et al.* [93] considered the ideas from 6Genesis flagship program (6GFP) proposed by Finnish industrial and academic consortium for hypothetically bridging the ecosystem and smart society with 6G communication systems. The study focuses on ultra-reliable low latency communication and mobile edge computing aspects of 6G communication to be the key enablers for smart grid applications. Dang *et al.* [18] proposed a systematic framework for the 6G applications and subdivided them based on their key features. The study suggests that the smart grids might leverage 6G characteristics in a way that the users will be able to generate energy more than the required capacity and can sell the residual electricity to the companies, accordingly. Similar studies hypothetically suggest the concept of using distributive techniques such as blockchain along with 6G communication systems to improve the smart grid performance [95]–[97].

Summary: There are various implications of smart grid such as heterogeneous renewable sources, load balancing, efficient distribution, and more, that expect to progress to its realization with the integration of 6G communication systems.

C. HOLOGRAPHIC TELEPRESENCE

HT can project realistic, full-motion, real-time three-dimensional (3D) images of distant people and objects with a high level of realism rivaling of the physical presence [98]. It can be used for full-motion, 3D video conferencing and news broadcasting or TED talk like applications [17], [99]. HT captures footage of people and surrounding objects, which are compressed and transmitted over a broadband network, in

the initial stage. Later, the transmitted information is decompressed at the receiver's end and projected with the aid of laser beams [98]. HT helps to minimize business travel costs, and allows people to appear in many locations simultaneously, while tactile and interactive content are key factors to engage the audience. On the other hand, there are some road blocking factors in the path of adopting the HT technology. Ultra low latency (1 ms) and high data rate of 10 Gbps are some of the core challenges partially covered by the 5G. For complete immersive uninterruptible experience, 6G with latency of 0.1 ms and data rates of multi Gbps is required [17].

1) RELATED WORK

Holographic communication is based on multi-view camera image communication that demands significantly higher data rates [19]. This is possible with 5G with several restrictions including dedicated network resources and limited or no mobility [30]. The human propensity to communicate remotely with high fidelity will raise significant connectivity challenges for the next-generation network, i.e., 6G. The authors in [98] discussed the details of a 3D holographic display's data rate requirements: a raw hologram will require 4.32 Tbps, without any compression, with colors, high parallax, and 30 fps. As compared to the few needed for VR/AR, the latency requirement will reach 0.1 ms. In addition, all the 5 human senses (sight, hearing, touch, smell, and taste) are intended to be digitized and transmitted through future networks to completely realize an immersive remote experience [100], raising the total target data rate. Using 5G, such communications are infeasible, because they require data rates in the order of Tbps [23], [84], [101].

Summary: A successful HT application is evaluated by the seamless and quality of connection between users, which requires massive low-latency and extremely high data rate. The foundation of 6G communication is based on the provision of aforementioned connection characteristics which makes 6G a key-enabler for the said service.

D. UAV BASED MOBILITY

UAVs have been used extensively for defense applications such as remotely controlled aircraft, autonomous drones, and so forth [102]. Over the years, the application of UAVs have been expanded in military as well as civil field. For instance, UAVs have been proposed for disaster relief, agricultural plant protection, traffic monitoring, and environmental detection [103]. UAVs are also expected to be an essential module for future wireless technologies such as 6G, which supports high data rate transmission for communities living remotely, facing disaster situations such as earthquake, terrorist attacks, and with no typical cellular infrastructure presence. Key features associated with UAV's as compared to the fixed infrastructure are: easy deployability, line-of-sight (LoS) connectivity [104], [105] and most importantly, controlled mobility. The rapid development of UAV technologies will penetrate new domain such as passenger taxi, automated

logistics and military operations [106]. With the emergence of 6G and IoE, researchers have explored the use of UAV-to-Everything (U2X) network that expands the paradigm of sensing applications by adjusting the communication modes to their full potential [107]. One of the key challenges for the integration of 6G, IoE, and UAVs as U2X networks is the design of radio resource management, and joint transmission and sensing protocol for its realization. In terms of application, the biggest challenge of the U2X networks is the trajectory design, which will be domain specific. For instance, trajectory design for passenger taxis and provision of cellular infrastructure would have different dynamics and need to be designed as per the application requirements.

1) RELATED WORK

In the telecommunications sector, increasing UAV applications such as relay BSs, live data streaming and communication gateways are expected to model the growth in the UAV market [108]. The possible role of UAVs in a hot zone, congested areas and as a relay-BSs makes it an inherent part of [104], [109] the next-generation networking infrastructure. Liu *et al.* [110], for the first time made a breakthrough using UAV for quantum communication. They revealed a quantum network of UAV-based distribution of entanglements. Many resources have lately been committed to the design of ultra flexible interconnected networks. In particular, the Flying Base Station (FBS) aided dynamic networks may be designed to boost the traditional static structure, as discussed in [111], the growing number and types of aerial vehicles, such as balloons, airships, and UAV. For example, several various FBS initiatives have appeared in recent years, with Google's Loon project using airborne UAVs (balloons) to deliver consistent Internet services to remote and rural areas. In the near future, Amazon's prime air initiative will shortly launch a UAV-based frequent parcel delivery system [112]. Some work initiated by Nokia and Qualcomm, i.e., 5G drone project, currently performing numerous tests using UAVs [113], [114] for next-generation communication.

Summary: With the integration of 6G with AI, some major problems associated with UAV based mobility such as efficient route planning and power transfer expected to be resolved.

E. EXTENDED REALITY

XR is an emerging immersive technology with the fusion of physical and virtual worlds where wearables and computers generate human-machine interactions [30], [115]. The fab four (AR, VR, MR, XR) technologies use different sensors to collect data regarding the location, orientation and acceleration. This requires strong connectivity, extreme data rates, high resolution and extreme low latency, that is envisioned to be facilitated 6G.

1) RELATED WORK

Latency plays a key role in all of the VR, AR, MR and XR technologies. This empowers the real time user interaction in the immersive environment to meet the demand of massive low latency, data rate needs to touch Tbps rather than Gbps in 5G. Authors in [12] discussed that a truly XR experience is not only possible with the engineering (wireless, computing, storage) functionalities but it also need perceptual requirements stemming from human senses, cognition, and physiology. Liao *et al.* [116] highlighted the issues of resource requirements, faster data rates, and scalability of devices for services related to virtual and augmented reality. The study proposed an information-centric massive IoT based method that could guarantee the required quality of service in 6G networks. The paradigm concerning AR/VR services has been shifted to edge computing and caching for faster responses and managing the communication resources. Authors in [117] discuss challenges, opportunities and applications for the aforementioned paradigm shift. However, authors in [118] proposed a novel architecture that uses UAV based clustering for multi-task multi-modal offloading and managing the communication, caching, and computing resources in an efficient manner.

Summary: Similar to the HT, extended reality also requires massive low-latency and extremely high data rate for the efficient service provision. With the integration of AI and compressed sensing approaches, 6G is expected to provide uninterruptible and seamless communication services for better XR experience.

F. CONNECTED AND AUTONOMOUS VEHICLE

Both academia and industry sectors have drawn substantial interest in next generation transportation systems such as autonomous driving, cooperative vehicle networks, Internet of Vehicles (IoV) [119], [120], Vehicular Ad-hoc NETworks (VANETs), *air-to-ground networks*, and *space-air-ground interconnected networks* [121]. Particularly, AI-enabled future vehicle networks that has benefited from these vehicle-related operations paves the way for future 6G Intelligent Transport System (ITS) and intelligent V2X communications. A rare potential for a radical shift in urban transportation is the advent of CAVs. Such innovation could lead to the development of cities that are productive, more sustainable and greener. It is expected that more companies will be investing in CAVs with the advent of 6G that surely will bring truly autonomous, reliable, safe and commercially viable driverless cars in near future. When this happens, new ecosystem will emerge such as driver-less taxi and driver-less public transport, which will make everyday life more comfortable [60], [82]. 6G expected to satisfy the more rigorous KPIs which 5G partially fulfilled for vehicle communication to unleash the full capacity of CAVs, such as extremely high reliability, exceptionally low latency (0.1 ms),and extremely high throughput [122].

1) RELATED WORK

It is envisioned that various key technologies such as 6G, AI, DLT will be integral part of CAV [122]. CAV applications such as smart cooperative platooning, smart intersections,

and cooperative vision that can greatly boost road safety and efficiency, fuel usage and congestion, [122]. To realize above mentioned applications, researchers worked on several key areas such as location prediction based scheduling and routing was studied in [123], [124], [125] using different methodologies; hidden markov models, variable-order markov models, and recursive least squares respectively. Other factors such as network congestion control [126], [127], load balancing [128], network security [129], virtual resource allocation [130], resource management [131], [132], and distributed resource management [133], were explored using various machine learning approaches such as reinforcement learning, k-means clustering, long short term memory networks (LSTM), and feed forward neural networks.

Summary: Autonomous vehicles heavily rely on the connection based on extreme low-latency along with AI based techniques to provide efficient route planning and decision making. However, the problems with connection-less services is the grant-free communication that has been extensively explored in 5G communication systems. It is to be believed that with the emergence of 6G services, the communication protocols for grant-free access will be more efficient and seamless, accordingly.

G. INDUSTRY 5.0

Industry 5.0 refers to people working alongside robots and smart machines to add a personal human touch to Industry 4.0 pillars of automation and efficiency [79]. Similar to Industry 4.0, cloud/edge computing, big data, AI, 6G, and IoE are expected to be the key-enabling technologies of Industry 5.0 [134]. In particular, a massive number of things in Industry 5.0 are connected either using wired or wireless technologies to provide various applications and services that are enabled by a complete integration of cloud/edge computing, big data, and AI.

1) RELATED WORK

Although there are no precise definition and standard of 6G, much effort has been dedicated to investigate the role of 6G systems and technologies in solving the issues and challenges in Industry 5.0. Recognized by many studies, Industry 5.0 is considered as an important use case in 6G, where not only communication, but also computation, caching, control, and intelligence are jointly optimized [12]. With a huge amount data generated by massive things, robots is likely to become more intelligent due to the advent of AI and 6G wireless systems. For example, the impedance of robots is optimized via a joint use of control theory and imitation learning [135], and the proposed approach is shown to have superior performance of tracking error and the interaction forces over two benchmarks schemes. As emerging applications requires a very high reliability and very low latency, e.g., tele-surgery, massive production, and autonomous decision-making manufacturing, 6G is a potential solution as massive uRLLC solutions will be available in 5G [12], [19]. Since a huge volume of data is

generated by industrial robots and sensors, only processing the data at the central cloud is not an effective solution, and this demands a need for coordination with computing nodes at the network edge [136], [137]. Moreover, 6G with many promising technologies such as wireless power transfer, energy harvesting, and backscatter communications will provide sustainable solutions for energy-limited sensors and robots in Industry 5.0.

Summary: As both Industry 5.0 and 6G networks are still under development, we can expect that there will be more research works their integration and applications in practice.

H. HYPER-INTELLIGENT IOT

Next generation of hyper-intelligent IoT applications will utilize AI methods to optimize the processing of data and also integrate novel robotic devices, UAVs and digital assistants to deliver more smart and intelligent services [138]. It is imperative because massive IoT devices will be connected to the Internet and with each other, and therefore a huge amount of mobile data is generated that should be intelligently processed at the network edge. In 4G/5G systems, the typical workflow for IoT data processing invloves sending data to an access point at the edge, which then processes the received data and/or forwards the data to the central cloud for further processing. However, the current network generation is not able to support IoT data processing in various circumstances when the network becomes ultra-dense and when wireless connections are not available, of which examples are mountains areas, hard-to-reach locations, IoT applications in marine and aerial environments. Providing intelligent and always-available solutions for hyper-dense IoT expedite the research and development of beyond 5G and future 6G networks.

1) RELATED WORK

According to [139], the total data traffic generated by applications, machines, and things at the edge is 850 ZB, whereas the total data center traffic is only 20.6 ZB. As a result, enabling intelligence at the network edge (also known as edge AI or edge intelligence) has the potential to provide diverse feasible solutions and applications for hyper-dense IoT. For example, a communication-efficient approach based FL is proposed in [140] to efficiently process IoT data at the edge, but with data privacy preservation. Another example can be found in [141], where deep neural networks are employed in a three-layer manner, IoT device-edge-and cloud, in order to process IoT data. However, the concept of edge intelligence is still in its infancy stage and many (non-)technical challenges should be solved such as resource-friendly AI design and novel incentive models [139]. To complement the terrestrial network, aerial and satellite communications are considered as important components in 6G systems [142]. The ground-aerial-satellite network architecture is very promising as it can provide a seamless coverage over the globe and enable various emerging applications with different quality-of-service (QoS) requirements [142], [143].

As illustrated in [144], deploying data centers and clouds in the satellites is a promising solution for intelligently processing IoT data of geo-distributed applications such as precision agriculture and remote surveillance services.

Summary: A number of research works have been developed for hyper-intelligent IoT solutions. However, most existing works focus on the 5G network scenarios such as deep learning for hierarchical edge computing systems in [141]. More studies are necessary to explore the potential of 6G and better exploit massive amounts of data.

I. COLLABORATIVE ROBOTS

Collaborative robots (cobots in short) are directly collaborate with people by work side-by-side with humans. These cobots take over tedious, repetitive and risky tasks to maintain human worker's health and safety and automate the production lines [145]. Although cobots can offer various benefits, enabling cobots in Industry 5.0 demands revolutionary solutions of reliability, safety, and trust. Moreover, cobots should process huge data and make decision in real-time to support emerging applications, which is however not practical in many case due to the limitation in storage capacity, and computing and communication connections. This work is motivated by the fact that processing data of individual source such as radars, wearable devices, and vision equipment is not very efficient, whereas a multi-sensory fusion technique can achieve superior performance in terms of accuracy-delay tradeoff and human-cobot minimal distance.

1) RELATED WORK

A number of promising research works have been investigated to improve the performance of cobot systems. For example, Kianoush *et al.* [146] proposed an edge-cloud framework to protect workers in human-robot interaction environments, via a joint processing approach of multi-sensory data collected from various sensing and IoT devices. In [147], the concept of cobot and wireless charging is integrated into a holistic system. In particular, a single robot is deployed to wirelessly power nearby electric devices and the computation workload of the robot is offloaded to the cloud for remote processing. However, this system is required to be pre-trained in an offline manner before real deployment. With the advent of AI and mobile broadband connections in 6G, it is expected that the robot can learn online and then the accuracy/efficiency of the system can be significantly improved.

Summary: Despite a key enabler, there are a limited number of studies on cobots in the context of beyond 5G and 6G networks. Enabled the capabilities of 3CLS services, the performance and applications of cobots can be improved significantly.

J. PERSONALIZED BODY AREA NETWORKS

Body Area Networks (BANs) with integrated mobile Health (mHealth) systems are advancing towards the personalized health monitoring and management. Such personalized BANs can collect health information from multiple sensors, dynamically exchange the such information with the environment and interact with networking services including social networks [148]. Personalized BANs has a wide range of applications, covering both medical to non-medical domains. For example, personalized BANs can be used to avoid the need of cable wiring in polysomnography tests (also known as sleep disorder diagnosis). Personalized BANs has also found in non-medical applications such as emotion detection, entertainment, and secure authentication applications [149]. More recently, the Internet of Nano-Things (IoNT) and the Internet of Bio-Nano-Things (IoBNT) have been developed as the next generation of IoT for healthcare services. The concept of IoBNT engineers information communication within the biochemical domain, while connecting to the Internet via the electrical domain [150].

1) RELATED WORK

Despite various applications, IoBNT is still in the infant stage of research and development. In order to realize IoBNT, some efforts have been denoted to the design of nano-sensors. Graphene membranes are utilized to develop highly-sensitive capacitive nanomechanical sensors, which are shown to have a superior responsivity over the commercial nanosensors [151]. From the wireless communication perspective, Akyildiz *et al.* [25] pointed out several significant challenges in IoNT and IoBNT such as energy consumption, interference control, network and routing protocols, coding scheme and modulation technique, experimental validation, and data management. The features of 6G such as high data rate, reliability, new spectrum (visible light and THz) communications, and ultra-low latency will help to address these challenges, along with other efforts from existing studies for IoNT and IoBNT.

In [152], the human insulin-glucose system is analyzed in terms of the data rate, channel capacity, and propagation delay, and from the communication perspective. Several characteristics of the correlation between insulin rate/resistance and the derived models are illustrated via the experimental results. Due to the diffusion and attenuation properties of molecular communications in IoBNT, extending the coverage range is of importance. To address this issue, Wang *et al.* [153] proposed to deploy an intermediate nanomachine to relay, amplify, and then forward the received signals between the transmitter and receiver. Various performance metrics such as mean square error, minimum error probability, and maximum probability detection are derived, and more interestingly the performance gain can reach 35 dB when the number of released molecules is 500. For the architecture designs of transmitters and receivers in IoBNT molecular communications, the interested readers are invited to read the review article [154].

Summary: The potential of integrating wireless and IoT technologies into BANs and IoBNT systems have been well demonstrated via various existing works. Since this topic has not been fully explored and more promising technologies will

be developed, more studies should be conducted to further improve the performance of personalized BANs and leverage the advantages of new technologies.

K. INTELLIGENT HEALTHCARE
1) INTRODUCTION TO THE APPLICATION

Similar to the industrial evolution from Industry 1.0 to Industry 5.0, there have been various evolutions in the healthcare development, which is now Healthcare 5.0 with the emergence of digital wellness. AI-driven intelligent healthcare will be developed based on various new methodologies including Quality of Life (QoL), Intelligent Wearable Devices (IWD), IIoMT, H2H services, and new business model [33], [76]. Thanks to recent advances in wearable sensors and computing devices, it is possible to monitor and measure the health data in real-time. The sensing data collected from wearable devices can be pre-proceeded by the nearby edge node and then sent to the doctors for remote diagnosis. Also, with the realization of holographic communications, tactile Internet, and intelligent robots in 6G, the doctor can remotely do the surgery. Such a tele-surgery would remove the need of on-site operations and avoid the risks caused by virus spreading, especially when we are living with coronavirus-19 as well as with many other transmissible diseases.

2) RELATED WORK

Many studies have considered 6G as a key enabler of intelligent healthcare (i.e., Healthcare 5.0). In particular, promising technologies such as edge intelligence (i.e., cloud/edge computing + AI), holographic communications, tactile Internet, and IoBNT are expected to play a key role. For example, since mission-critical healthcare applications would have different QoS requirements (e.g., latency and computing resources), Ge *et al.* [155] investigated an approach, namely ACTION, by jointly employed tactile Internet and network function virtualization techniques. Considering that passive optical network has the potential to support bandwidth-hungry healthcare applications, the work in [156] developed a joint dynamic wavelength and bandwidth allocation framework. The experimental results show that the proposed framework can provide better performance than the benchmarks in terms of packet loss and delay.

As the healthcare data is huge in volume an increase significantly, exploiting AI (e.g., deep learning) to develop data-driven healthcare solutions has become one important trend in healthcare research and development [157]. Meanwhile, since most patients do not want to share their personal health data, if not mandatorily requested by the governments and medical staffs, effectively overcoming the security and privacy challenges of healthcare data usage is of importance. Among many solutions, FL and blockchain are promising. In particular, in FL-based healthcare solutions, the users need not share their raw data, instead they just need to share information of the local model [158]. With its

decentralization and security nature, blockchain is a promising technique to provide security and privacy for transferring and acquiring of healthcare data [159].

Summary: Traditional healthcare systems have various challenges such as healthcare data are not exploited effectively and ambulance services are unsatisfactory in many scenarios. 6G has great potential to provide intelligent healthcare services, such as telesurgery services, precision medicine, and IIoMT.

IV. 6G REQUIREMENTS/VISION

This section embraces the several requirements, which are adopted from various studies [40], [160]–[163]. This section also discusses how the 6G requirements can be improved as compared to the existing networks. Each requirement is then followed by several enabling applications and their key enabling technologies.

A. FURTHER ENHANCED MOBILE BROADBAND (FEMBB)

eMBB represents a continuing evolution from traditional LTE, which enables mobile broadband in limited applications. The speed of eMBB is the gigabits in 4G. In 5G, eMBB is being enhanced greatly [160]. In addition, it has been predicted that a series of exciting immersive applications including 3D extended reality features, 3D multimedia, IoE will be enabled by high quality of services that would need the peak of tens of Gbps [40]. Therefore, 6G mobile broadband speed has to be further improved beyond the limits of 5G, and to provide the peak of mobile broadband data rate at Tbps level. Moreover, as the end users will be using more high-definition contents, their mobile data rates should also be improved up to Gbps level.

1) ENABLING 6G APPLICATIONS

It will enable many use-cases, for instance: (i) Super-Fast Hot spot – FeMBB can dramatically enhance broadband in highly dense or populated regions including public transportation (e.g., high-speed trains and smart cities); (ii) Enhanced multimedia: FeMBB would enable many of exciting ultra-high definition media applications (e.g., 4D video gaming and mobile TV [164]). Other areas of eMBB growth in the technical work include autonomous manufacturing and growth of connected wearables and sensors. As a result, 6G will enable broadband everywhere on the planet.

2) ENABLING 6G TECHNOLOGIES

6G will be deployed across large number of areas through the fixed wireless access, which will leverage 6G technologies to deliver wireless broadband to everywhere on the planet [165]. Another popular technology is THz band, which is one of the main frontiers in beyond 5G communications as of today. The THz band would offer virtually unbounded capacity for supporting wide-channels and extremely high data rates [66]. In addition, the work in [166] deliberately supported that the THz communications can attain high data rates through VLC.

Recently, AI/ML has been proposed to use at the physical and MAC layers [167]. ML can optimize synchronization, manage power allocation, and modulation and coding schemes. Furthermore, ML would assist with efficient spectrum sharing, channel estimation and enable adaptive and real-time massive Multiple-Input and Multiple-Output (MIMO) beamforming. However, such AI/ML based solutions are still under research. Therefore, it becomes viable that we would need more intelligent algorithms that can determine in which domains two systems can share the spectrum with high coexistence efficiency [167].

Internet of Healthcare (IoH) or future hospitals

x000 miles away

Patient in hospital operated by a multi-armed robot

Medical surgeon with smart surface/console

FIGURE 7. An application example (IoT Healthcare [172]) for eURLLC.

B. ULTRA-MASSIVE MACHINE-TYPE COMMUNICATION

In the IoE revolution, 5G communications are expected to support massive machine type communication for billions of devices. The ability to connect and transfer data up to 1 million sensors per km^2. In addition, the work in [161] suggested that the scale of machine type communications will turn upside down by IoT devices and their connectivity in IoE world. In the IoE architecture surprisingly, a trillion of sensors and actuators will be automated to send their data back and forth. In such massive scale networks, the current machine type communication architecture would not be able to cater the effective and efficient connectivity. However, beyond 5G and/or 6G network potentially require umMTC architecture that can support reliable connectivity to massive scale of networks, e.g., trillion of devices [168]. Thus, connection density will be further improved in 6G due the popularity of novel concept of IoE.

1) ENABLING 6G APPLICATIONS

In 6G, umMTC will enable several key applications include Internet of Industrial smart Things (IIosT), smart buildings, Internet enabled supply-chain, logistics and fleet management, as well as air and water quality monitoring [161], [169]. In addition, other applications will be ultra-dense cellular IoT networks, container tracking, nature/wildlife sensing, mines/road and/or forest works monitoring [170].

2) ENABLING 6G TECHNOLOGIES

Technologies, such as SigFoX and LoRa [161], will be the potential candidates for network connectivity and coverage towards the 6G network. In another vein, MTC architecture and its features can also be realized in 6G using a licensed spectrum that would overlay on existing communication infrastructure (e.g., RAN). In addition, such architecture can provide guaranteed more reliability to the devices in the 6G communications. In order to achieve this mainly two technologies can be utilized as enabling technologies: (i) enhanced MTC and, (ii) Narrow Band IoT (NB-IoT), among others [168]. The eMTC can provide high bandwidth data rate (e.g., up to 1 Mbps) and can support high mobility to many of 6G enabled applications such as Internet of Vehicles (IoV) [169]. Whereas the NB-IoT can enable
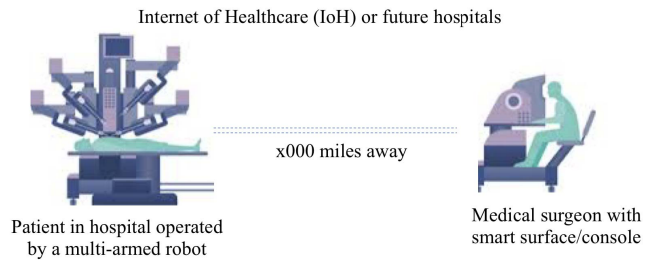
and/or support many applications which required low data bandwidth (e.g., in the order of Kbps) [168].

In another vein, Massive MIMO is one of the substantial candidates that can enhance efficiency of spectrum in multi-user environment [171]. As a result, it can enhance the channel capacity in 5G and beyond networks. In order to simulate massive MIMO, the authors in [171], applied MIMO to solve the issues of perfect channel allocation (PCA) issue. The authors used bit-error rate for PCA. Moreover, they utilized a narrowband (shared) communication to collect network data traffic from MTC devices (i.e., connected devices in the network). To enhance the broadband efficiency, they used clustering technique where heterogeneous devices share own cluster's resources [171].

C. EXTREMELY RELIABLE LOW-LATENCY COMMUNICATION

The 5G is backed by uRLLC and its reliability is 99.999% [162]. However, by 2030, innovations would need extremely super high ultra-reliability not only in MTC but in several other communications as well, such as device-to-device communication, WiFi, device-to-cloud, and so on. In a practical scenarios, consider a medical surgeon is sitting in front of a telecommunications-based smart surface or console in Chicago city, while the patient lies on an operation bed 4000 miles away in Dublin, Ireland, as shown in Fig. 7. Using the smart surface and other communication technologies, the medical surgeon can remotely control the movement of a multi-armed surgical robot to remove the 70-year old patient's diseased gallbladder. However, such time-critical robotic surgery application will demand ultra high reliability and low-latency communication. Therefore, in 6G, the researchers must explore and develop new or enhance techniques that can enable eRLLC to provide the high reliability rate (99.99999%) than the 5G.

1) ENABLING 6G APPLICATIONS

eRLLC and (enhanced Ultra Reliable Low-Latency Communication (eURLLC) will enable several applications such as telemedicine, XR, Internet of Healthcare (IoH) revolution includes HT, and AI-Healthcare. All of these applications demands superior-ultra-reliable communication [12].

2) KEY ENABLING 6G TECHNOLOGIES

Designing of eRLLC systems (i.e., high reliability and low latency), demand various parameters, such as end-to-end fast turnaround time, intelligent framing and coding, efficient resource management, intelligent up-link and down-link communication and so on. For more details please refer to [162]. Alsenwi *et al.* [164] discussed another enabling technology that would be useful in uplink grant-free structures and in reducing the transmission latency. In [164], the authors proposed to not use of a middle-man cognitive operation that would typically require a committed scheduling grant technique.

D. EXTREMELY LOW-POWER COMMUNICATION

Internet-enabled resource-constrained objects are increasing rapidly and these objects required highly efficient hardware that can be self-powered. However, research revealed that the traditional devices are integrated with large-scale antenna arrays (e.g., MIMO) that will inevitably bring high power consumption [13]. In 5G network, several technologies are available to facilitate low power communication with 5G communication networks. For instance, back-scatter communication, hybrid analog/digital hybrid precoding, lens-based beam domain transmission technology, sparse array and sparse RF link designing. Nevertheless, such approaches may not be fully being able to control the environmental issues such as the nature of the wireless communication and that may consume more power [13]. Therefore, 6G communication must focus on maintaining high-speed transmission while reducing energy consumption.

1) ENABLING 6G APPLICATIONS

Several applications will require extremely low power communications, however, currently the promising applications are smart homes, smart cars, UAV, etc.

2) ENABLING 6G TECHNOLOGIES

In order to achieve Extremely Low-Power Communication (ELPC), the researchers propose to deploy the Intelligent Reflecting Surface (IRS), which is known as Reconfigurable Intelligent Surface (RIS) [13]. With the use of few antennas, the IRS may help to reduce the dependencies of hardware complexities in transmitter and receiver. In addition, utilizing passive artificial arrays to greatly reduce energy consumption. In another vein, the IRS technology is being quite attractive from an energy consumption point of view. In IRS, no power amplifier is being used to amplify and forward the incoming signal. As a result, since no amplifier is used, an IRS will consume much less energy than a regular amplify-and-forward relay transceiver [173].

E. LONG DISTANCE AND HIGH MOBILITY COMMUNICATION

In large dimension networks, Long Distance and High Mobility Communications (LDHMC) are indispensable
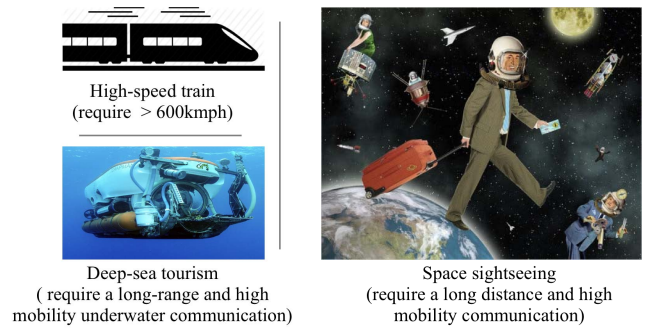

High-speed train
(require > 600kmph)

Deep-sea tourism
(require a long-range and high mobility underwater communication)

Space sightseeing
(require a long distance and high mobility communication)

FIGURE 8. Application examples (such as space tourism [176], deep-sea tourism [177], high-speed trains [178]) for LDHMC.

requirements in 6G [174]. In 5G, LDHMC services are undeniable as they can support up to 500 km/h. Consider a science-fiction example, a high-speed rail will operate over 500 km/h in the next few decade and that will require long distance and high mobility to support communications and services for on-board crew and passengers. Therefore, 5G-based LDHMC may not be enough for the future applications, as they may require long distance communication for many thousands of km and may require seamless mobility. In addition, the research reveals that the node mobility is highly challenging in different environments (such as deep water) [175]. Therefore, 6G must require long distance and high mobility communication (e.g., >1,000 km/h) based seamless services for future applications.

1) ENABLING 6G APPLICATIONS

Following the [175], 6G will enable many exciting applications, few of the examples are as space sightseeing, deep-sea tourism, high-speed transportation, as shown in Fig. 8.

2) ENABLING 6G TECHNOLOGIES

There are several enabling technologies such as accurate channel estimation. Due to severe time and frequency spreading in high mobility wireless communications, channel estimation is very challenging. Filter based alternative waveforms [179] (alternatives to orthogonal frequency division multiplexing), such as filter-bank multicarrier and universal filtered multicarrier are good candidates for 6G high mobility communications.

F. HIGH SPECTRUM EFFICIENCY

As projected in [180], [181], a high magnitude of devices or smart objects is anticipated to grow many times in 6G network. Specifically in the region of thousand(s) of smart devices including machines, equipment's, sensors, and many more, in a given cubic meter [182]. Nevertheless, ultra high definition video streams such as holographic contents need will required high bandwidth spectrum that may not be supported by the spectrum of the millimeter-wave. This will pose an unmanageable disturbance related to the area efficiency where high number of devices may not be able

to connect appropriately to the current network. This will lead to deploy the new technology in the 6G domain such as sub-THz and THz bands, that can bridge the meet the requirements of for the high spectrum efficiency network based applications [182].

1) ENABLING 6G APPLICATIONS

6G network will enable data-hungry applications, such as augmented reality/mixed reality. This is going to enable new smart services in smart cities, smart agriculture, retail, supply chain and much more to function seamlessly.

2) KEY ENABLING 6G TECHNOLOGIES

In [183], two open loop beamforming methods with the help of location information (i.e., the location based MIMO precoding and the location assisted MIMO precoder cycling) are being proposed. These techniques can be attributed the early enabling technologies for high spectrum efficiency.

G. HIGH AREA TRAFFIC CAPACITY

Area traffic capacity corresponds to the total traffic throughput served per geographic area (bit/s/m^2) [184]. In this regard, it is widly anticipated that 5G may enable a traffic capacity of 10 Mbps per square metre in dedicated hotspot areas. However, the applications such as 3/4-D multimedia would require high traffic capacity and that may be not supported by current 5G communications. Therefore, 6G must provide ten times the area traffic capacity of 5G, as suggested in [174]. More importantly, this will reach up to 1 Gb/s/m^2 for the real-world applications [174].

1) ENABLING 6G APPLICATIONS

Enabling applications are followings: urban networks, weather forecasts, automated vehicles, high-density rail networks.

2) ENABLING 6G TECHNOLOGIES

To attain high traffic capacity in automated vehicles, the work in [185] proposed a novel technique. The authors assumed that each smart vehicle comprises of two distinct modules, a leader and a follower. However, the proposed technique ensures a high traffic capacity and vehicle density in a dense geographical location. In addition, the authors claimed that their proposal can avoid the traffic congestion significantly. For more details the interested readers may refer to [185].

H. MOBILE BROADBAND AND LOW-LATENCY (MBBLL)

MBBLL will be the enabling necessity in 6G communications. In order to understand the concept of MBBLL, consider an example of a VR application [186]. In VR environments, requiring high latency is the utmost demand for a pleasant experience of an immersive VR headset to its users [187]. The human eye typically requires free and perfect smooth movement, i.e., low Motion-To-Photon (MTP) response time without any interruption. Here, the MTP is the

time within a moment and the pixels of a picture frame that represents to the new field of view (FoV) which has shown to the human eye [187]. However, a high MTP response time may directs contradictory signal values to the vestibulo-ocular reflex (VoR), i.e., between the head movement and eye. In addition, a high MTP response time might lead to an apparent motion illness. More precisely, practically, in the simple setting, the value for MTP's upper bound is $< 15 - 20$ ms. At the same time, the loop back response time of 4/5G is 25 ms in the given ideal functioning conditions. However, such VR-based applications require high data bandwidth rates (e.g., downlink peak data rate > 1 Tbps, and user experienced data rate > 10 Gbps) including ultra high definition pictures, videos and other immersive instructions such as human gestures. Moreover, it demands low response time for real-time voice-based commands (< 0.1 ms) and prompt control receptions (< 1 ms). In addition, these requirements must also be assured in high-mobility use-cases (> 1000 km/h), for example space tourism, deep-sea tourism, high-speed transportation, and so on.

1) ENABLING 6G APPLICATIONS

Typical MBBLL applications include mobile AR, VR, and HT [186].

2) ENABLING 6G TECHNOLOGIES

The work in [188] introduced a proposal where multi-edge computing is being used to attain an end-to-end guaranteed low latency for VR video streaming using the immersive technologies. The authors designed a low-complexity mechanism that can offload the high computations tasks to MEC, and can achieve energy efficiency. Such proposal can be attributed as the enabling techniques for 6G communications.

I. MASSIVE LOW-LATENCY MACHINE TYPE COMMUNICATIONS (MLLMT)

The purpose of MTC in the 6G automation is associated with the many services, such as data availability, ultra scalability, and more importantly low latency in the 6G enabled applications. Such low latency services are highly paramount for time critical applications where decision making will happen on a scale of fraction of milliseconds. However, such requirements (e.g., low latency, high availability, etc.) may not be met by the existing wireless network including 4/5G network due to several challenges, such as confined resources of communication technologies, lack of automation of operations, human-centric devices, and so on. Hence, 6G has to increase its mission-critical mLLMT communication to support future applications.

1) ENABLING 6G APPLICATIONS

Multiple application domains include such as home and building automation, integration of distributed energy resources with the energy plants, unmanned vehicle systems, IoT-enabled healthcare infrastructures, and controlling and

monitoring industrial 4.0 use-cases. To boost such innovative and immersive IoE applications and many others (e.g., space tourism), there is a pressing demand for new wireless technologies that can enable and support a massive number of connections among IoE devices and ground to space and vice-versa.

2) ENABLING 6G TECHNOLOGIES

There are several existing technologies that can directly be adopted to enable the mLLMT services in 6G ecosystem. For instance, Park and Saad [189], proposed a mechanism that may enable low latency machine type communication where the resources of IoE devices can be shared within a fraction of response time (in milliseconds). The authors designed a novel finite memory multi-state sequential learning framework that will suitably fulfill the requirements in several scenarios, such as delay-tolerant applications, periodic messages delivery, and urgent and critical messages exchanges. Park *et al.*'s claimed that their suggested learning framework will enhance the latency of IoE devices or MTC to learn the several number of critical messages, and to redistribute the network and communication resources for the delivery of periodic messages that to be used for the critical messages in many of 6G applications.

J. AI-ASSISTIVE EXTREME COMMUNICATIONS

In next the two-three decades, AI will immerse in every aspect of communication and will be heavily used for communication purposes. Here, we propose a term *AI-assistive extreme communications (AEC)*. However, as of today, 4/5G network would not be able to deal with such massive scale of devices, applications, heterogeneous standard and non-standard practices, different stakeholders, etc. Therefore, 6G must require such AEC.

1) ENABLING 6G APPLICATIONS

The AEC network may control and monitor trillions of devices in various verticals (e.g., IoT manufacturing and supply chain) across the globe. These devices keep track of several intelligent parameters – bandwidth allocation, decision making in data routing and aggregation, knowledge sharing, are few examples. Other application opportunities are AI-empowered data-driven network planning, operation, intelligent mobility, handover management, and smart spectrum management to achieve many of real-world traditional environments to dynamic communication environments in 6G.

2) ENABLING 6G TECHNOLOGIES

There are various machine learning techniques that can be enable dynamic communication, networking, and security and trust elements in vehicular-to-infrastructure networks, and envisions the ways of supporting AI-centric futuristics 6G smart or driverless vehicular networks. In [190], the authors surveyed several ML techniques including supervised multilayer perceptron to equalize channels by intelligently
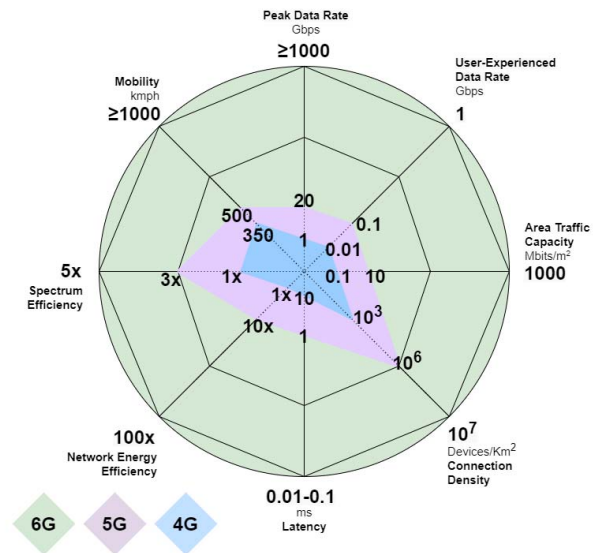
FIGURE 9. 6G Requirements [28], [76], [191].

and creatively redefining the communication symbols. A support vector machine based nonlinear equalization mechanism can be used in the wireless network and communication of 6G, where the temporal correlation exists in the collected inter symbol interference data. For the more details, interested readers may refer to [190].

In summary, to realize new applications, 6G networks have to provide extended network capabilities beyond 5G networks. Fig. 9 illustrates such requirements which need to be satisfy by 6G networks to enable future applications. Finally, Table 4 summarises various requirements in 6G applications.

V. 6G ENABLING TECHNOLOGIES

This section expounds numerous technologies which are deemed to be the key enablers for future 6G communication systems. The way this section is organized is as follows. For every technology, we start with a brief discussion on the basic concepts of the technology following with its importance in the 6G realm, and finally summarize the latest related works.

A. BEYOND SUB 6 GHZ TOWARDS THZ COMMUNICATION

The rapid increase in wireless data traffic is estimated to have seven fold increase in mobile data traffic from 2016 to 2021 [192]. Wide radio bands such as the millimeter-waves (up to 300 GHz) are expected to fulfill the demand for data in 5G networks. However, applications such as HT, BCI and XR are expected to require data rates in the range of Tbps which would be difficult with mmWave systems [193]. This requires exploring the Terahertz (THz) frequency band (0.1-10 THz). This type of communication will especially be useful for ultra high data rate communication with zero error rates within short distances.

TABLE 4. Requirements of different 6G applications.

6G Applications	6G Requirements									
	FeMBB	umMTC	eRLLC	ELPC	LDHMC	High Spectrum Efficiency	High Area Traffic Capacity	MBBLL	mLLMT	AEC
UAV based Mobility	H	L	H	L	H	L	H	M	M	L
Holographic Telepresence	H	H	L	H	H	L	H	L	H	H
Super-Fast Hot spot	H	H	M	H	L	L	L	H	M	L
IoT manufacturing	L	M	M	H	H	L	M	M	H	L
IoT supply chain	L	H	L	H	M	M	L	L	M	L
IoT Healthcare	H	H	H	M	M	L	L	H	H	H
Drone-based systems	M	H	H	H	M	L	L	H	M	L
IoE	L	L	L	M	L	M	M	L	L	M
Industrial Internet of smart things	H	M	M	H	L	M	M	L	H	L
Ultra-dense cellular IoT networks	H	M	L	H	L	M	H	L	L	M

H	High	M	Medium	L	Low

1) IMPORTANCE TO 6G

6G is expected to deliver over 1000x increase in the data rates compared to 5G in order to meet the target requirement of 1 Tbps. More spectrum resources beyond sub 6 GHz are explored by researchers to cater to this significant increase in data rates. Early 6G systems are expected to bank on sub 6 GHz mmWave wireless networks. However, 6G is expected to progress by exploiting frequencies beyond mmWave, at the THz band [66]. The size of 6G cells are expected to shrink further from small cells in 5G towards tiny cells that will have a radius of only few tens meters. Thus, 6G networks will require to have a new architectural design and mobility management techniques that can meet denser network deployments than 5G [12]. 6G transceivers will also be required to support integrated frequency bands ranging from microwave to THz spectra.

2) RELATED WORK

THz waves are located between mmW and optical frequency bands. This allows the usage of electronics-based and photonics-based technologies in future communication networks. As for electronic devices, nano-fabrication technologies can facilitate the progress of semiconductor devices that operates in the THz frequency band. The electronics in these devices are made from Gallium Arsenide, Indium Phosphide and various Silicon-based technologies [194], [195]. Authors in [196] present a scalable Silicon architecture that allows synthesis and shaping of THz wave signals in a single microchip. The feeding mechanism of optical fibers to THz circuits is prominent to achieve

higher data rates in terms of photonics-devices. Conventional materials used at lower frequencies in the microwave and mmWave ranges are not enough efficient for high frequency wireless communication. Devices made from such materials exhibit large losses at the THz frequency range. THz waves require electromagnetically reconfigurable materials. In this context, Graphene is identified as a suitable candidate to reform THz electromagnetic waves by using thin graphene layers [197], [198]. Graphene based THz wireless communication components have exhibited promising results in terms of generating, modulating and detecting THz waves [199]. THz wireless communication allows small antenna sizes to achieve both diversity gain and antenna directivity gain using MIMO. Authors in [200] introduced 1024x1024 ultra-Massive MIMO as an approach to increase the communication distance in THz wireless communication systems.

THz band channel is considered highly frequency selective [201]. These channels suffer from high atmospheric absorption, atmospheric attenuation, and free-space path loss. This requires the development of new channel models to mimic the behavior of THz communication channels [192]. Reference [202] proposed the first statistical model for THz channels. This model depends on performing extensive ray-tracing simulations to obtain statistical parameters of the channel. Recent studies in [203]–[206] provides more accurate channel models. Various research works have also focused on applications of THz communication. A hybrid radio frequency and free space optical system is presented in [207], where a THz/optical link is envisaged

as a suitable method for future wireless communication. In addition, [208] presents using THz links in data centers to improve performance while achieving a massive savings in minimizing the cable usage.

Summary: THz communications are expected to pave the way for Tbps data rate to meet the demands of future applications and has potential to strengthen backhaul networks. Nevertheless, it suffers from high propagation losses and demands LoS for communications. More efforts are required to understand the behavior of THz signals and better channel models are required.

B. ARTIFICIAL INTELLIGENCE AND FEDERATED LEARNING

Thanks to distinctive features and remarkable abilities, AI has found various applications in wireless and mobile networking. Massive data generated by massive IoT devices can be exploited by AI approaches to extract valuable information, and thus improving the network operation and performance. Recently, FL has emerged as a new AI concept that leverages on-device processing power and improves the user data privacy [209]–[211]. The rationale is to collaboratively train a shared model such that participating devices train the local models and only share the updates (instead of data) with the centralized parameter server [15], [212]. According to [213], FL can be classified into horizontal FL, vertical FL, and federated transfer learning.

1) IMPORTANCE TO 6G

With 6G being envisioned to have AI/ML at its core, the role of AI/FL becomes important to 6G. The use of conventional centralized ML approaches is suitable for network scenarios, where centralized data collection and processing are available. As the amount of mobile data and advancements in computing hardware and learning advancements, numerous problems in future 6G networks can be effectively by AI approaches such as modulation classification, waveform detection, signal processing, and physical layer design [141], [164], [214]. To overcome limitations of centralized AI such as privacy concern and huge communication overhead [15], FL is gaining popularity and is emerging as viable distributed AI solution that enables 'ubiquitous AI' vision of 6G communications [215]. FL offers multitude of benefits to 6G, as summarized by authors in [216], are communication-efficient distributed AI, support for heterogeneous data originating from different devices pertaining to different services that can lead to non-identically distributed (non-IID) dataset, privacy-protection since data remains locally and is not uploaded anywhere, and enabling large-scale deployment.

2) RELATED WORK

The last few years has witnessed the use of different AI techniques for numerous problems in wireless networks. For example, Luong *et al.* [217] reviewed applications of Deep Reinforcement Learning (DRL) for three important topics, including network access and rate control, data caching and computation offloading, security and connectivity preservation, and for a number of miscellaneous issues such as resource allocation, traffic routing, signal detection, and load balancing. The applications of ML for wireless networks was reviewed in [218], where AI-enabled resource management, networking, mobility, localization solutions are discussed. The use of transfer learning, deep learning, and swarm intelligence for future wireless networks can be in [219]–[221]. Some of related work pertaining to use of FL in wireless networks. Khan *et al.* [222] propose a Stackelberg game-based approach to incentivize the interaction between global server and devices participating in training model. Xiao *et al.* [215] proposed a FL framework for IoT networks with the aim to simultaneously maximize the utilization efficiency of edge resources and minimize the cost for IoT networks. Kang *et al.* [223] proposed an incentive FL mechanism using contract theory to allows highly-reputed devices to engage in the training task. Some challenges of FL are highlighted in [15], [209], including cost of communications, significant hardware heterogeneity, high device churn, privacy leakage through model update, and security issues.

Summary: AI and FL techniques enable the design of intelligent mechanisms for future 6G networks via exploiting massive mobile data and increasingly computing resources available at the network edge. Nevertheless, in order to effectively realize AI, the very first challenge is the existence of high-quality training datasets. Another challenge is the inclusion of AI in beyond 5G and future 6G networks [16]. Moreover, the bottlenecks of AI caused by 6G wireless networks with many new advanced technologies, device heterogeneity, and emerging intelligent applications, should be further studied. Regarding FL, the devices need to be incentivized to participate in training process and also, the rouge devices need to be detected as early as possible. Moreover, the challenges like privacy leakage via model updates and hardware heterogeneity also need to be met [224].

C. COMPRESSIVE SENSING

Sampling is an integral part of modern digital signal processing and stands at the interface between analog (physical) and digital world. Traditionally, for efficient transmission, flexible processing, noise immunity, security inclusion (using encryption and decryption), low cost, etc., Nyquist sampling theorem has been used. According to this, for a bandlimited signal, if the samples are taken at a rate greater than equal to twice the highest frequency of that signal then the exact replica of the signal can be reconstructed using these samples. Sampling is usually followed by compression process where the sampled data is compressed to maintain some acceptable level of quality [225]. As pointed out in [226], with the increase in the transmission bandwidth with 5G and future 6G mobile networks, the continued used of Nyquist sampling technique will result in numerous challenges like significant overheads, large complexity and higher power consumption. In this context, CS has been proposed as an

intriguing solution that has potential to overcome the limits imposed by traditional sampling. CS, which is at times also referred as compressive sampling or sparse sampling, is basically a sub-Nyquist sampling framework that states that provided a signal is characterized by sparsity and incoherence, it can be sampled at a rate smaller than the Nyquist rate and the resulting (smaller set of) samples are sufficient to reconstruct the original signal [226]. This is achieved in computationally efficient manner and by finding solution to underdetermined linear system. Moreover, in CS both the sampling and compression is carried out at the same time.

1) IMPORTANCE TO 6G

In nutshell, sampling rate in CS depends on sparsity and incoherence characteristic of the signal being sampled, and does not depends on the bandwidth of the signal [14]. This property of CS opens the door for it applicability to 6G networks. In general, CS is proposed to be used for reducing the data generated by IoT devices for mMTC [227]. Another proposed use of CS is to enable NOMA at the transmitter in the landscape of mMTC scenario [228]. This is carried out by assigning non-orthogonal spreading codes to devices and applying CS based MultiUser Detection (CS-MUD) technique since very less percentage of total devices are active at any given time. The advantage is this scheme incur no control signaling overhead. Yet another use of CS along with deep learning techniques is to overcome the issues pertaining to the expected intensive usage of Large Intelligent Surfaces (LISs) in the next generation networks [68].

2) RELATED WORK

Gao *et al.* [226] surveyed various CS techniques that are useful for next-generation of wireless communications. Authors explained different CS models, and in particular discussed how CS can play an instrumental role for the three different technical domains vis higher spectral efficiency, larger transmission bandwidth and efficient spectrum reuse. Liang *et al.* [229] proposed to solve the problem of BS getting overwhelmed by the estimates of downlink CSI. These estimates are necessary for efficient working of FDD-MIMO systems and are computed at UEs to send to BS. Thus, the authors propose CS-ReNet framework where the estimates at UEs are compressed using CS and then uncompressed at the BS using deep learning based CS reconstruction mechanism. Another interesting work [230] focuses on how to validate the sparsity assumption that underlies the application of CS techniques. In this direction, authors present an algorithm that utilizes learned dictionary and ML prediction for inferring level of sparsity. Further, the authors report that the proposed algorithm is able to make quality estimates for sparsity levels in wireless channels and in cognitive radio spectra. Yet another work by Li *et al.* [231] applies CS for encryption of high resolution images that will proliferate in 6G era. The idea there is to compress and encrypt the images simultaneously. Furthermore, a method to use multiple estimates of signals with existing sparsifying bases

to reconstruct signals from compressive measurements to improve reconstruction performance is given in [232]. This method reduces the decoding complexity as it does not bank on heavy learning techniques for dictionary creation.

Summary: CS is expected to be an important enabling technology for 6G since it is way to reduce the data that need to be exchanged for required communication. The signal with sparsity and incoherence characteristics can be reconstructed with lesser number of samples in CS than required as per Nyquist sampling theorem. However, to gain the maximum benefit, it is important to ensure that signals have the required level sparsity.

Thus, efficient techniques are required to ensure the sparsity assumption. If used with proper estimation, CS has potential to support other technologies like LIS, MIMO and NOMA.

D. BLOCKCHAIN/DLT

The last couple of years have witnessed the rise of DLT, in particular, the Blockchain technology. DLT is envisioned to unlock the doors to the decentralized future by overcoming the well-known impediments of centralized systems [233]. Blockchain is a type DLT which maintains a digital ledger in a secure and distributed way. This ledger holds all the transactions in a chronological order and is cryptographically sealed [234]. Blockchain technology has received all-around attention equally by industry as well as by academia since it offers numerous advantages like disintermediation, immutability, non-repudiation, proof of provenance, integrity, and pseudonymity [235].

1) IMPORTANCE TO 6G

Many sectors have already acknowledged the pragmatic use of blockchain technology and its efficacy as they are running/offering blockchain-based technological solutions [236]. Examples of some of these business sectors are finance and banking, industrial supply chain and manufacturing, shipping and transportation, medical health care and patient records, and educational processes and credentialing. The world of mobile communications is not an exception to this list [28], [237]. Blockchain can play a cardinal role in improving (i) management and orchestration in terms of interference, resource, spectrum and mobility management [238]–[241], (ii) operations in terms of cell-free communication and 3D-networking, and (iii) business models in terms of decentralized and trustless digital markets involving various stakeholders like Infrastructure Providers (InPs), network tenants, industry verticals, Over-The-Top (OTT) providers, and edge providers [237], [242]. Further, blockchain has an immense potential to strengthen the existing service arena of mobile networks as well as set the floor for futuristic applications and use case of 6G.

2) RELATED WORK

Blockchain has been identified as one of the key enabling technologies for 6G. Numerous efforts are being made to

leverage its potential to improve both the technical aspects of 6G as well as use cases of 6G ecosystem. For instance, author in [238], have presented the use of blockchain for decentralized network management of 6G. In particular, the work showed the blockchain plus smart contract for spectrum trading. In [243], authors proposed blockchain-based Radio Access Network (B-RAN) that allows small sub-networks to collaborate in trustless environment in order to create larger cooperative network. Authors in [240] have presented how blockchain can be leveraged to remove intermediate layer (i.e., disintermediate) and develop a distributed Mobility-as-a-Service that is hosted as an application on edge computing facility. Improved transparency and trust among all the stakeholders are the manifested advantages of this work. Li *et al.* [244] advocated the use of blockchain for ensuring data security AI powered applications for 6G. Two applications focused by authors were indoor positioning and autonomous vehicles.

Summary: Blockchain being one of the prominent type of DLT has turn out to be very promising key enabling technology because of its builtin strong security nature. On the one hand, it can enhance the technical aspects of 6G like dynamic spectrum sharing, resource management, mobility management, and on the other hand it enables unforeseen applications like HT, XR, fully CAVs, Industry 5.0 and many more. Nevertheless, in order to harness best use of blockchain for 6G challenges like computational overheads, lightweight consensus algorithms, high transaction throughput, quantum resistance and storage scalability need to be mitigated.

E. SWARM UAVS

Numerous natural phenomena such as the how bees coordinate with each other to accomplish a critical task and flocks of geese coordinate to find efficient flight paths to achieve their migration, have inspired many fields of research. In general, swarm is a group that coordinates with each other to achieve specific goals and objectives [245], [246]. Recent developments in the area of UAVs has drawn significant attention towards UAV swarm networks for communication, surveillance, medical-care, disaster management, etc. UAV swarms use wireless communication to interact and share information among UAVs, where each UAV acts as a node in a multi-hop communication network. UAV swarms consist of heterogeneous UAVs that govern themselves while moving in a coordinated way [247]. UAV swarms are capable of overcoming any limitations of UAVs operating as individual node that needs to be controlled continuously, that has a limited payload, a limited flight time, and a limited communication range [248]. UAV swarm network model includes three scenarios. They are (i) swarm topology model using scale free networks, (ii) swarm damage model to minimize the damage at each threat event, and (iii) swarm recovery model to configure network nodes to ensure the connectivity [249].

1) IMPORTANCE TO 6G

6G is expected to incorporate swarms of UAVs, robots, and edge devices due to their collaborative nature [250]. Swarm UAVs are envisaged to be an integral component of 6G [30], [104], [237]. Aerial Base Stations (ABS) deployed using UAV swarm can provide on-demand broadband, and seamless connectivity in a reliable, cost-effective and agile fashion [251]. The dawn of 6G will raise the demand for connecting massive number of IoE devices which may be located outside the coverage area of terrestrial cellular networks and may be difficult to be connected using conventional IoT technologies such as NB-IoT and Long Range Radio (LoRa). Moreover, providing connectivity using satellites is also challenging due to the inherent latency and limited data rate. Thus, swarm UAVs are expected to be utilized to connect wide-area IoT networks in 6G [45]. UAV swarms are also expected to be widely deployed to facilitate cell-free communication and massive MIMO systems [252].

2) RELATED WORK

Increasing popularity of UAVs is due to their easy deployability, configurability, and comparatively low implementation cost. Authors in [247] present a blockchain-based softwarized multi-swarming UAV communication scheme for a 6G networks. This scheme combines THz spectrum together with intelligent connectivity and virtualization of communication links. A flexible and easily configurable communication infrastructure is achieved through softwarization while data security is ensured by the use of blockchain. Liu *et al.* [45] investigated a wide-area IoT-oriented cell-free cognitive satellite-UAV network to address possible issues in implementing a hybrid satellite UAV network. This work also addresses opportunistic spectrum sharing for satellite-UAV networks. UAV swarms can employ FL models to execute various tasks such as monitoring, target recognition, and power allocation and scheduling [15]. Bai *et al.* [249] propose a model and a resilience metric that can be used to evaluate the resilience of a UAV swarm. This model and the metric can be used for mission planning and designing of a UAV swarm. Gao *et al.* [253] consider the uplink transmission between a MIMO ground station and UAV swarm to study the positioning of UAVs in the 3D space such that the channel capacity of the MIMO system is maximized using decentralized UAVs channel capacity learning. Attacks performed by malicious UAVs, which attempt to enter into UAV swarm networks can be mitigated using blockchain to protect networks against either intruders or spoofing attempts [254]. Swarm robotics is another area of swarm networks, as reviewed in [255]. Swarm robots may also contribute toward establishing swarm networks in situations where UAVs cannot be deployed, such as in underground and underwater communication.

Summary: Swarm UAV represents fleet of UAVs that coordinate with each other to accomplish a common goal. Their role as flying or aerial BS will enable to extend the coverage radio coverage in remote areas as well as

areas which less population. Swarm UAVs can be integrated with terrestrial networks and satellite networks to realize 3D networking with cell-free communications. Nevertheless, there are numerous challenges like interoperability, energizing, physical security and channel sensing in drastic environments.

F. ZERO TOUCH NETWORK AND SERVICE MANAGEMENT

Zero touch network and Service Management (ZSM) is an evolving concept that aims to provide a framework for building a fully automated network management, primarily driven by the initiative of ETSI. The idea of ZSM is to empower the network so that they can perform self-configuration to carry out autonomous configuration without the need of explicit human intervention, self-optimization to better adapt as per the prevailing situation, self-healing to ensure correct functioning, self-monitoring to track its own functioning, and self-scaling to dynamically engage or disengage resources as per need [256]. To stress the importance of ZSM framework, ETSI in [257] has identified list of scenarios that are grouped into seven different broad categories which are as follows: (i) End-to-end network and service management category talks about the automation of operational and functional tasks involved in end-to-end lifecyle management of different types of network resources and services that are part of core network, transport network and radio access network; (ii) Network-as-a-Service (NaaS) presents the requirement of exposing some of the service capabilities from all the parts of the network to enable zero-touch automation; (iii) Analytics and ML scenario emphasize the need of integration of ML and AI capabilities for realizing ZSM; (iv) Collaborative service management category emphasizes on the need of collaborative management spanning domains of multiple operators; (v) Security highlights the need of strong security and privacy mechanisms for ZSM framework; (vi) Testing scenario points out the need of automated testing of resources as well as services; (vii) Tracing scenario needs are driven by requirement for automated troubleshooting and root cause analysis. In this direction recently a framework named as Self Evolving Networks (SENs) [258] has been proposed that aims to automate the network management with self-efficient resource utilization, coordination and conflict management, inherent security and trust, reduce cost, and high QoE.

1) IMPORTANCE TO 6G

Future 6G networks are going to heterogeneous networks with multi-tenancy, multi-operator, and multi-(micro)-services features. To make such networks work at their best and at low cost, they are envisioned to be fully automated. Thus, ZSM becomes highly important. Use of AI/ML capabilities within the framework of ZSM has indeed potential to add many new capabilities (as mentioned above) and set the floor for AI-enabled autonomous networks. However, security remains the high concern. This is because ML techniques

are vulnerable to attacks like poisoning attack or evasion attack [259]. Here, the use of blockchain as common communication channel can do the required. Further, enabling automated service updates without affecting service interoperability as well as end-user experience is another challenge when using ZSM [260].

2) RELATED WORK

In light of the use of AI/ML solutions proposed by ETSI [257], the work [261] highlights the limitations and potential risks involved when using these techniques. Authors projected limitations broadly under two categories; (i) limited AI due to lack of labeled datasets, interoperability of AI/ML models and significant training time required and (ii) security issues mainly because AI/ML techniques are prone to attacks like poisoning attack during training and evasion attack during testing. Further, in [259] authors discussed potential attacks on ZSM that includes attacks on open API, treats on intent-based interfaces, vulnerabilities of closed-loop automation, and attacks on AI/ML techniques. The work also proposed possible solutions that talks about adding various security features by adding control information, proper authentication and authorization controls, traffic monitoring, validation of inputs and more. In another related work, Darwish *et al.* [258] proposed the SEN framework for future networks that utilizes the Intelligent Vertical Heterogeneous Network (I-VHetNet [262]) as the base architecture. Authors presented five different scenarios where SEN can contribute significantly to automate the network management. In particular, for the case of distributed data offloading and computation authors showed that SEN outperforms SON (Self Organizing Networks which was proposed by 3GPP for 4G and 5G) in terms of data offloading and computation delays.

Summary: With the initiative of ETSI, ZSM is an evolving framework that aims to instill automation capabilities in terms of configuration and optimization, monitoring and healing, and testing and scaling. To have zero touch automation active collaboration and intelligent decision will be required. AI/ML are the highly sought after solutions to effectuate ZSM, nevertheless, security guarantee of AL/ML models is the challenge. Moreover, the aspect of conflict resolution also need to be dealt since 6G will allow the coexistence of several stakeholders and various automated components.

G. EFFICIENT ENERGY TRANSFER AND HARVESTING

Energy harvesting has been the much sought area of research when it comes to future sustainable way of energizing the growing number of connected devices. The aims of energy harvesting is to replace the conventional ways of powering devices and sensors by tapping the energy from ambient environment. The two broad class of sources for energy harvesting are natural sources and man-made sources [263]. Natural sources include renewable energy sources like solar, mechanical vibrations, wind, thermal, microbial fuel cell,

and human activity powered [263], [264]. Man-made energy harvesting happens through Wireless Energy Transfer (WET) where dedicated power beacon is used to transfer energy from source to destination [263], [265]. Since the natural sources of energy harvesting suffer unpredictability and periodicity they fail to offer guaranteed QoS, thus WET is the hot research area [264].

1) IMPORTANCE TO 6G

With the vision of universal communication system and providing solid underpinning to IoE, the future 6G networks will be proliferated with large number of connected devices. The conventional way of powering these devices with rechargeable or replaceable batteries might not efficiently scale in 6G era. The reason being such solutions are, in general, costly, inconvenient, risky, and have adverse effects when the devices are operating inside the body [264]. Thus energy harvesting technologies are considered to be an efficient alternative solution for next generation mobile networks [263]. In this context, much of the excitement revolves around the idea that the radio signals can simultaneously transfer energy as well as information [266]. This at times referred as Radio Frequency Energy Harvesting (RF-EH) [267]. Nevertheless, to have the pragmatic use of such techniques and to gain the maximum benefit the challenge lies in efficient integration of both wireless information transfer and wireless energy transfer provided that their hardware and operational requirements are different [263]. The other open issues are high mobility, multi-user energy and information scheduling, resource allocation and interference management, health issues, and security issues [264], [267].

2) RELATED WORK

To improve both the spectral and the energy efficiency of IoT devices in 6G era, authors in [268] used the combination of cooperative spectrum sharing and Simultaneous Wireless Information and Power transfer (SWIPT) techniques. To overcome the interference issue, which is a significant challenge in wireless information and energy transfer, this work makes use of orthogonal subcarriers. Authors in [43] propose the applicability of Extended Kalman filtering (EKF) to forecast the power that can be harvested. The work [269] reveals that Channel State Information (CSI) acquisition is an important impediment in utilizing WET to massive IoT scenario and thus propose CSI-free multiple-antenna strategies — One Antenna (OA), All Antennas at Once (AA), and Switching Antenna (SA) — for WET. To access the performance of the proposed CSI-free strategies, the authors uses two metrics which are Average Harvested Energy per node (AHE) and Average Energy Outage probability per node (AEO). Their results show decreasing AEO probability when Distributed Antenna Systems (DAS) (aka Distributed Power Beacons (DPB)) is used in conjunction with CSI-free strategy.

Summary: Using WET for both information and energy transfer is seen as way to energize the connected devices in

future. Though, RF-EH can be consistent source of energy than natural sources, however, the challenge would be to have efficient and simultaneous transfer of information and energy provided the requirements for the two are different.

H. LARGE INTELLIGENT SURFACES

The emerging paradigm for controlling the propagation environment via smart and intelligent surfaces has been referred with numerous names like LIS, IRS, RIS, Software-Defined Surface (SDS) and many more [163], [270]. LIS can play a vital role when direct line of sight (LoS) communication is either not feasible or degrades in quality such that it hampers the sensible communication [163]. LIS provides a way to transform man-made structures (for, e.g., building, roads, indoor walls/ceilings) to an intelligent and electromagnetically active wireless environment [271]. This transformation is performed by augmenting these structures either with large array of small, low-cost and passive antenna or with metamaterial (aka metasurfaces), such that they help in controlling the characteristics like reflection, scattering and refraction of propagation environment [270], [272]. Although, changes can be made to different characteristics of the incident electromagnetic signals by LIS, however, as mentioned in [163], most of the work focus on change in phase of incident signal.

1) IMPORTANCE TO 6G

LIS have been identified as key technological enabler for 6G since it is going to operate at higher frequencies and is expected to go beyond the massive MIMO [12], [272]. Various advantages of LIS over conventional massive MIMO, as highlighted in [271], includes reduced noise, lower inter-user interference, and reliable communication. Interestingly, LIS would allow the use of holographic Radio Frequency as well as holographic MIMO [12]. Moreover, in 6G realm, LIS can be used to better sense wireless environment by capturing CSI [273].

2) RELATED WORKS

Taha *et al.* [68] deals with the two contrasting problems. First, the requirement of large training overheads when all the LIS units are passive, and second the need of higher power consumption and higher hardware complexity when all the LIS elements are active. To resolve these issues, the authors proposed LIS architecture where merely few LIS elements are active and then presented two different solutions; one using CS and another using deep learning. Further the authors manifested that although both the solutions showed to achieve near-optimal data rate incurring negligible training overheads, the approach with deep learning needs lesser number of LIS active elements and does not need the knowledge of LIS array geometry. Nevertheless, sufficient dataset is required as input for deep learning approach. Jung *et al.* [271] carried out analysis of System Spectral Efficient (SSE) of an uplink LIS system considering a practical LIS environment and reported asymptotic analysis can correctly indicate the performance of the LIS system

and thus extensive simulation is not required. Further, the authors proposed optimum pilot training length which can help achieve maximum SSE irrespective of the pilot contamination. The work [272] proposed to integrate LIS (or RIS) to Index Modulation (IM) to achieve higher spectral efficiency even at very low SNR for future 6G networks. In particular, the author put forward two schemes RIS-space shift keying (RIS-SSK) and RIS-spatial modulation (RIS-SM). The works [163], [274], [275] highlighted the importance of LIS (or RIS) for 6G networks. In particular, [163] primarily focused on the categorization of the recent works concerning LIS and [274] provided significant list of open challenges besides discussing state-of-art RIS hardware designs. The work [275] explains integration of IRS with latest transmission technologies like mmWave communication, NOMA transmission, and PLS system.

Summary: By covering the man-made structures with either antennas or metasurfaces, the propagation of environment can be controlled thereby turning them into intelligent surfaces. Majority of the work so far focused on changing the phase of the incident signal, though other characteristics can also be acted on. Integrated use of techniques like ML and deep learning are looked up to achieve the required intelligence for LISs.

I. NON-TERRESTRIAL NETWORKS (NTN) TOWARDS 3D NETWORKING

In conventional ground-centric mobile networks the functioning of base stations are optimized to primarily cater the needs of ground uses. Moreover, the elevation angle provided to the antennas at ground base stations are focusing on the ground user for better directivity and hence cannot support aerial users [276], [277]. Such mobile network allows marginal vertical movement (i.e., above and below the ground surface) thus predominantly offers two dimensional (2D) connectivity. NTN expands the 2D connectivity by adding altitude as the third dimension [278]–[280]. NTNs are capable of providing coverage, trunking, backhauling and supporting high speed mobility in unserved or underserved areas through the integration of UAVs, satellites (in particular Very Low Earth Orbit (VLEO)), tethered balloons, and High Altitude Platform (HAP) stations [12], [278], [281]. The development of protocols and architectural solutions for New Radio (NR) operations in NTNs are promoted in 3GPP Rel-17 and is expected to continue in Rel-18 and Rel-19 [278]. 3D networking further extends the NTN paradigm allowing 6G to emerge as global communication system by extending its coverage from ground to air towards space, underground, and underwater [20], [282]. Interestingly, Aerial Base Stations (ABS) powered by UAV technology can offer on-demand, broadband, and reliable wireless coverage in cost-effective and agile way. Some of the promising characteristics of UAV-enabled ABS based on [251], [276], [282] are as follows:

- Intelligent 3D mobility and ease of maneuvering.
- Varying capabilities in terms of computation, storage, power backup, etc. to meet heterogeneous demands.
- LoS communication that allows effective beamformimg in three dimension.
- high flexibility in terms of number of antenna elements when UAVs are used to create antenna array for 3D MIMO

1) IMPORTANCE TO 6G

There has been exponential increase in number of connected devices in recent past and the trend will continue with higher rate of increase in future. In particular, future is expected to see significant increase in aerial users or aerial connected devices. Technological advancements in various fields, like electronics and sensor technology, high speed links, data communication networking, aviation technology, etc., provide necessary ecosystem for robust growth of UAVs (aka drones) which has in turn extended the horizon of UAV's applications. By 2022, the fleet of small model UAVs (primarily used for recreational purposes by hobbyists) is expected to reach a mark of 1.38 million units whereas small non-model UAVs (primarily used for commercial purposes) are forecast to be 789000 million units as per the Federal Aviation Administration FAA's report [283]. Moreover, by same year, i.e., 2022, the global market of UAVs is estimated to value at US$ 68.6 billion [284]. Hence, 6G mobile networks is expected to provide required connectivity to such increasing number of aerial users. To fulfil this expectation, 3D networking paradigm is going to play a key enabling role in 6G.

2) RELATED WORK

Authors in [276] have proposed a framework for UAV-based 3D cellular network for beyond 5G that provide a solutions for placement of UAV-ABS in three dimension (using truncated octahedron approach) as well as latency-sensitive association of UAV-based user equipment to UAV-ABS. In [285], authors have put forward 3D non-stationary Geometry-Based Stochastic Model (GBSM) for UAV-to-ground channels that are envisioned in UAV-integrated 6G mobile networks. GBSM is proposed to work well for mmWave and massive MIMO configurations. Strinati *et al.* [286] proposes to extend the intelligence to the edge 3D networks (i.e., beyong the premises of 2D networks) by leveraging edge computing paradigm. In particularly, the work envision to integrated flying base stations with ground stations by using technologies like MEC, SDN, and AI.

Summary: NTN evolved towards 3D networking to enable global radio coverage and capacity in three dimensions for future 6G networks. It represents a gamut of technologies like UAVs, HAPs, satellites, and other flying gadgets that are anticipated to work in harmony to offer seamless coverage over space, air, ground, underwater and underground. AI/ML based solutions are expected to play an important

role to overcome the limitations posed by physical absence of human beings.

J. VISIBLE LIGHT COMMUNICATION (VLC)

VLC is one of the promising Optical Wireless Communication (OWC) technologies that uses visible light for short-range communication [287]. The frequency spectrum for VLC is between 430 THz to 790 THz. Further, in VLC the most common devices used for transmission are Light Emitting Diode (LED) and Light Amplification by Stimulated Emission of Radiation (LASER) diodes, whereas, for reception photodetectors such as silicon photodiode, PIN Photo-Diode (PD) and PIN Avalanche Photo-Diode (APD) are used [287]–[289]. Some of the advantages of using VLC technology based on [287], [289], [290] are as follows: (i) visible light spectrum is free to use since falls under unlicensed band, (ii) very high bandwidth as compared to RF signals (visible light spectrum is 10^4 times higher than radio waves [289]), (iii) high spatial reusability since visible light is blocked by objects like walls, (iv) permits precise estimation of direction-of-arrival, (v) supports very high data rate (10 Gbps using LED and 100 Gpbs using LASER diodes [291]), (vi) low energy consumption with the use of LEDs, (vii) inherently secure due to unidirectional propagation, signal isolation and non-penetrating nature of visible light, (viii) less costly as compared to radio communication especially in mmWave and THz range, (ix) safe to be used for communication since it meets the eye and skin regulations [289]. Moreover, the existing radio frequency band and visible light band are well separated thus there is no electromagnetic interference [292].

1) IMPORTANCE TO 6G

VLC came into existence with the emergence of white LEDs and has matured over the last two decades for it to be considered as an enabling technology for 6G [23], [293]. The technology has been successfully used for various applications scenarios such as vehicular communications, underwater communications, indoor areas (homes, offices, hospitals, aircraft cabins), visible light identification system, and Wireless Local Area Networks (WLANs), underground mines [288], [294]. Since, VLC operates in THz range thus is offers ultra-high bandwidth which means it can well satisfy the capacity and data rate demands of 6G [295]. From the 6G point-of-view, a hybrid communication infrastructure can be developed leveraging the best of visible light communication and other conventional communications like RF, Wi-Fi, Infrared (IR), and Power Line Communication (PLC) [293], [296], [297]. For instance, to establish RF-VLC hybrid system use of RIS has been suggested. Here, RIS can control the propagation environment and ensure the LoS communication between base station and mobile device equipped with photodetector [298].

2) RELATED WORK

Some of the related work pertaining to the use of VLC in 6G are discussed in this subsection. Soderi [292] aims to improve the physical layer security of VLC and proposed Watermarked Blind Physical Layer Security (WBPLSec) protocol. In particular, mitigating the confidentiality attacks in VLC was the prime concern of the author and to do so authors used RGB LEDs, spread spectrum watermarking technique, and jamming receiver. Author suggest the use of WBPLSec protocol based VLC can be used transact secret shared key between authentic receiver and devices in an indoor environment. Lee [299] also targeted to improve the security of VLC communication system tailored for smart indoor services in 6G ear. Author proposed the use of asymmetric Rivest–Shamir–Adleman (RSA) encryption for securing data communication and for exchanging secret key. Further, the work studied the optimum key length for public or private encryption codes and performance of VLC system for these key lengths. Cui *et al.* [300] have pointed out that VLC transmission may also results in spill over transmission in side channels which lead to security issues. Even though an adversary is not present in the same area (i.e., blocked) it can still sniff this side channel leakage and can gain access information. Authors designed low-cost VLC sniffing system that can tap information simultaneously from multiple VLC systems which are few meters away even with the presence of concrete wall as an obstacle.

Summary: VLC, in general considered to be highly secure communication technology, can still be compromised and prone to vulnerabilities. Hence, for the wide adoption of VLC in 6G ecosystem efforts are required to design efficient systems (with minimum leakage) and at the same time techniques (and equipment) are required to crosscheck the efficacy of VLC systems [300]. Furthermore, though the use of sophisticated encryption techniques enhances the security of VLC systems, however, the cost is paid in terms of high computational overheads. Thus, lightweight encryption techniques specifically designed for visible light systems will be required to better meet the needs of 6G services. Also, so far the VLC system have been mostly used for indoor environment, nevertheless, more research is required to explore its use in outdoor scenarios.

K. QUANTUM COMMUNICATION

As per [260], the role of quantum systems for telecommunication and networking fall under two different categories; quantum communication and quantum computing. Quantum communication, as put forward by Gisin and Thew [301], is a way to transfer a quantum state from a sender to a receiver. It can enable the execution of the tasks that either cannot be performed or inefficiently performed using classical techniques [260], [301]. Some of the interesting offerings of quantum communication are Quantum Key Distribution (QKD), Quantum Secure Direct Communication (QSDC), Quantum Secret Sharing (QSS), quantum teleportation, quantum network (quantum channel, quantum repeaters, quantum memory and quantum server) [302]. One of the promising use of quantum communication is the secure distribution of cryptographic keys referred QKD. The techniques that

use quantum entanglement for this purpose are called as entanglement-based Quantum Key Distribution (QKD) [303]. Any kind of man-in-middle attack while using QKD can be detected easily as the attacker disturbs the quantum (shared joint) state and this disturbance can be known by examining the correlations between the communicating entities [303].

1) IMPORTANCE TO 6G

Quantum communication is foreseen to play a crucial role in realizing secure 6G communications. In particular, the underlying principles of quantum entanglement and its non-locality, superposition, inalienable law and non-cloning theorem pave the way for strong security. The next generation of services that are going to be increasingly supported by quantum communication are HT, tactile Internet, BCI, extremely massive and intelligent communications [260], [304]. This QKD protocols have shown the most progress and numerous practical implementation of such protocols have been shown which reflects their potential applicability in 6G networks [30], [260]. Yet another interesting use of quantum communication is its applicability for secure long distance communication [30]. This, in particular, would be interesting since it is envisioned that 6G will have special focus on LDHMC that would deal with extremely long distance communications.

2) RELATED WORK

Nawaz *et al.* [53] surveyed various paradigms like quantum communication, quantum computing assisted communication, and quantum assisted machine learning based communication that utilizes machine learning and quantum computing in a synergetic manner. The advent of quantum computing facilities poses a significant treat to traditional cryptographic techniques that are used to encrypt data in current wireless communication systems. Thus, the work [305] exploits QKD mechanism for key generation and management in 5G IoT scenario. Authors named the proposed protocol as Quantum Key GRID for Authentication and Key Agreement (QKG-AKA) and analytically showed that security cannot be broken in polynomial time. Abd EL-Latif *et al.* [306] proposed two hash functions (for 5G applications) that utilizes Quantum Walks (QW), namely, QWHF-1 and QWHF-2 (Quantum Walk Hash Function 1 and 2). Further, QWHF-1 was in turn used to develop Authentication Key Distribution (AKD) protocol and QWHF-2 was used to develop Authenticated Quantum Direction Communication (AQDC) protocol for Device-to-Device (D2D) communications. Zavitsanos *et al.* [307] studied applicability of QKD for securing fronthaul that offers low-latency connectivity to myriad of 5G terminals. In particular, the authors investigated fronthaul link that integrates BB84 and QKD and supports AES encryption. Their work paves the way towards quantum secure fronthaul infrastructure for 5G/B5G networks.

Summary: Quantum communication is very promising application of the principles of quantum physics in the world

of communication. Some of the techniques provided by QC are quantum teleportation, quantum network, QKD, QSDC and QSS. Various upcoming applications of QC are Quantum Optical Twin (QOT), HT, tactile Internet, BCI, and long distance intelligent communication. In spite of the hype, the establishing synergy between QC and classical communication will be challenging. So far most of advancements are limited to QKD.

Table 5 presents in nutshell the importance of each technology in the sense that what the technology is and what it offers to 6G. Further, the table tries to map the level of importance each technology serves for six identified broad future directions. Moreover, Table 6 highlights the key challenges related to 6G technologies and possible solutions.

VI. 6G PROJECTS AND RESEARCH ACTIVITIES

Several 6G research and development activities are already initiated at global level. This section summarizes such leading 6G research activities for the moment.

A. 6G FLAGSHIP (MAY 2018 - APRIL 2026)

The 6G Flagship [2] is a research project which is focusing of "6G-Enabled Wireless Smart Society and Ecosystem." It is a 8 year research project funded by the Academy of Finland. 6G Flagship aims at realizing 5G networks from the 5G standard to the commercialisation stage and the development of the new 6G standard for future digital societies. It will target areas such as wireless connectivity, distributed intelligent computing, security and privacy to develop essential technology components of 6G mobile networks. In addition, to communication between people, the research will focus on communication between devices, processes and objects. This will contribute to enabling a highly automated, smart society, which will penetrate all areas of life in the future. Finally, 6G flagship project will also carry out the large pilots with a test network with the support of both industry and academia.

B. HEXA-X: A FLAGSHIP FOR B5G/6G VISION AND INTELLIGENT FABRIC OF TECHNOLOGY ENABLERS CONNECTING HUMAN, PHYSICAL, AND DIGITAL WORLDS (JANUARY 2021-JUNE 2023)

Hexa-X [308] is the European Commission's flagship for realizing B5G/6G vision and developing intelligent fabric of technology enablers for connecting human, physical, and digital worlds. Hexa-X project is the first European Commission (EU) funded 6G project. This is a collaborative project between both European industries and academic institutes. The aim of Hexa-X project is to pave the way to the next generation of wireless networks by explorative research. It's vision is to connect human, physical, and digital worlds with a fabric of 6G key enablers. To realize this aim and vision, the Hexa-X project is focused on developing key technology enablers in the areas of:

TABLE 5. Role of different key enabling technologies towards six future directions.

6G Key Technologies	Importance in Nutshell for 6G Networks	Ultimate Mobile Experience	Hyper-Intelligent Networking	Harmonized Networks	Sustainable Networks	Extreme Global Network Coverage	Ultimate Security, Privacy and Trust
Beyond sub 6 GHz towards THz Communication	• Provides new frequency bands in THz range (0.3 THz to 10 THz) capable to deliver high data rates. • Offers intriguing alternate for backhaul connectivity, point-to-point links and for whisper radio applications.	M	H	L	M	H	M
AI and FL	• Provides a distributed (AI) framework for training models such that every participating device trains the model locally and shares the updated model instead of data. • Offers to overcome the issues like privacy leakage, huge overheads, and single-point-of-failure associate with the usage of AI/ML in 6G realm.	H	H	M	M	M	H
Compressive Sensing	• Provides a way to go beyond the traditional sampling, by sampling a signal at the rate smaller than Nyquist rate given that the signal is characterized by sparsity and incoherence. • Offers to reduce the volume of data generated by massive IoT devices and can help enable other technologies like LIS, MIMO and NOMA.	H	L	L	M	M	L
Blockchain/DLT	• Provides numerous advantages of immutability, disintermediation, auditability, and non-repudiation since blockchain provides decentralized and distributed management of cryptographically secure digital ledger. • Offers secure management including spectrum, resource, mobility and interference management as well as decentralized 6G business model.	M	H	H	M	L	H
Swarm UAVs	• Provides an intelligent and distributed paradigm to coordinate and achieve common goals. • Offers the most promising way to extend the radio coverage and supports 3D networking and cell-free architecture of communications.	M	M	H	H	H	L
Zero Touch Network and Service Management (ZSM)	• Provides a framework to empower the next generation of networks with self-configuration, self-optimization, self-healing, self-monitoring, and self-scaling capabilities. • Offers to transform future 6G networks fully automated and economical with utilization of powerful AI/ML techniques.	L	H	M	M	M	H
Efficient Energy Transfer and Harvesting	• Provides a new paradigm to energize massive number of connected devices by utilizing natural or man-made source thereby aims to replace conventional sources like rechargeable and replaceable batteries. • Offers WET as a means to transfer both information and energy using radio signals (aka radio frequency energy harvesting RF-EH).	H	M	L	M	M	L
Large Intelligent Surfaces (LIS)	• Provides a way to control propagation of radiated EM waves by covering structures within wireless environment like building, roads, indoor walls and ceilings with either antenna elements or meta-material. • Offers a way to go beyond massive MIMO and allows reliable communication with reduced noise and lower inter-user interference.	H	H	L	L	H	L
Non-Terrestrial Networks (NTN)/ 3D Networking	• Provides a paradigm to extend the radio footprints from ground to air, space, underground and underwater by considering altitude as third dimension to be covered. • Offers to leverage technologies like UAV, tethered balloons, HAPs, and satellites to provide seamless connectivity to everything in three dimensions.	H	M	H	L	H	L
Visible Light Communication (VLC)	• Offer the possibility to utilize the unlicensed frequency range for a long lifespan with low power consumption and reduced cost. • Offer fast, secure and safe communication with low EMR (Electromagnetic Radiation) and radio interference specially for indoor 6G applications.	M	L	M	H	M	M
Quantum Communication	• Provides various new concepts and techniques like QSDC, quantum teleportation, and quantum network. • Offers support to applications like holographic teleportation, tactile internet, BCI, extremely massive, intelligent communications as well as long distance communications.	M	L	L	M	L	H

H	High		M	Medium		L	Low

- New radio access technologies at high frequencies and high-resolution localization and sensing
- Connected intelligence through AI-driven air interface and governance for future networks
- 6G architectural enablers for network disaggregation and dynamic dependability.

C. TERAFLOW: SECURED AUTONOMIC TRAFFIC MANAGEMENT FOR A TERA OF SDN FLOWS (JANUARY 2021 - JUNE 2023)

TeraFlow project [309] is focusing on creating of a novel cloud-native SDN (Software Defined Networking) controller for beyond 5G networks. This novel SDN controller for

TABLE 6. Key challenges related to 6G technologies and possible solutions.

Technology	Key Challenges	Possible Solutions
Beyond sub 6 GHz towards THz Communication	- The design of THz transceivers - THz network modelling and deployment	- Investigating efficient resource allocation algorithms with both hardware and THz channel impairments - Exploiting directionality features of THz signals to design efficient medium and random access protocols
AI and FL	- New security, privacy and ethical issues - Hardware heterogeneity	- Leveraging emerging technologies like blockchain to design new security and privacy mechanism - Deploying edge AI to overcome the limitation and heterogeneity of IoT and mobile devices
Compressive Sensing	- Ensure higher level of sparcity - Higher computational requirement at the receiver due to higher decoding complexity	- Designing different dictionaries to achieve higher sparcity - Using fusion of multiple reconstructions to improve the decoding performance - Utilizing edge intelligence to perform computationally heavy tasks
Blockchain/DLT	- Additional computational, energy and financial overheads to operate the blockchain - Limited scalability due to requirements of high transaction throughput and growth of permanent storage - Lack of quantum resistance in Computation oriented consensus algorithms	- Design of quantum resistance lightweight consensus algorithms based on random processes in wireless communication - Develop AI-assisted storage recycling and transactions prioritization mechanisms
Swarm UAVs	- Interoperability issues use to different devices types, operating systems and platforms - Efficient energy and power management - Vulnerable for physical tempering and jamming	- AI based path planing and energy management algorithms - Computational offloading to edge networks - Global level standardization
ZSM	- Traffic control research which include self-organized networks, cognitive radio networks, mobility prediction, network flow prediction, and network traffic classification. - Scalability, Security, and Computational Complexity	- Advanced Deep Learning Techniques, Soft Computing, Auto-scaling mechanisms - Blockchain, Smart Contracts, AI and their Integration
Efficient Energy Transfer and Harvesting	- Hardware and operational requirements are different to integrate both wireless information transfer and WET - high mobility, resource allocation -multi-user energy and information scheduling	- Combination of cooperative spectrum sharing and use of orthogonal subcarriers - CSI acquisition is an important impediment for WET
Large Intelligent Surfaces (LIS)	- Most of the research work focus on changing only the phase of electromagnetic signals. - Analysis and improvement of spectral efficiency is an aspect that requires more efforts.	- Other characteristics and the effects of modifying them also need to be studied. - New channel models specific to LIS-controlled wireless environment are required and profitable integration of LIS with latest radio transmission technologies is required.
Non-Terrestrial Networks (NTN)/3D Networking	- Optimal placement of UAV ABS in 3D space - Real-time access to powerful computational resources	- Efficient modelling of UAV integrated 6G networks - Extend processing to the edge 3D network
Visible Light Communication (VLC)	- Security of VLC need to be ensured since it can be compromised due to possible spill over in side channels [300]. - Available off-the-self encryption techniques will result in computational overhead which might not be affordable for 6G KPI. - So far VLC has been confined to test use cases where most of them are related to indoor scenarios.	- Precise physical layer techniques and industry-grade equipment need to be designed to ensure negligible side channel leakage. - Lightweight and dedicated encryption techniques are required to secure VLC systems. - Collaborative efforts by industries and standard bodies can provide the required push to accelerate the advancements in VLC.
Quantum Communication	- Long distance quantum communication - Secure communication	- First second and third generation quantum repeaters. - Quantum key distribution protocols.

beyond 5G networks will be capable of integrating with current Network Function Virtualization (NFV) and MEC (Multi-Access Edge Computing) frameworks. In addition, it will introduce new features for traffic flow aggregation, management of service layer, network equipment integration at the infrastructure layer and AI/ML-based security and forensic evidence for multi-tenancy networks.

D. DAEMON: NETWORK INTELLIGENCE FOR ADAPTIVE AND SELF-LEARNING MOBILE NETWORKS (JANUARY 2021 - DECEMBER 2023)

DAEMON project [310] is mainly focusing on enabling high quality Network Intelligence (NI) for beyond 5G systems that will fully automate network management. The project will design an end-to-end NI-native architecture for beyond 5G

networks that can fully coordinate NI-assisted functionalities. DAEMOM project will systematically analysis each NI tasks which can be appropriately solved with AI models and also provide a solid set of guidelines for the use of machine learning in network functions. Moreover, DAEMON project will focus on developing beyond 5G networks specific AI methods which can extend beyond the current trend of plugging 'vanilla' AI into network controllers and orchestrators.

E. 6G BRAINS: BRING REINFORCEMENT-LEARNING INTO RADIO LIGHT NETWORK FOR MASSIVE CONNECTIONS (JANUARY 2021 - DECEMBER 2023)

6G BRAINS project [311] is focusing of utilizing AI-driven multi-agent DRL for 6G radio link. A novel

comprehensive cross-layer DRL driven resource allocation solution will be proposed to perform resource allocation for Sub-6 GHz/mmWave/THz/Optical Wireless Communications (OWC) mediums to enable massive connections over D2D assisted highly dynamic cell-free networks. This will enhance the capacity, reliability and latency for future industrial, intelligent transportation and eHealth networks.

F. SOUTH KOREA MSIT 6G RESEARCH PROGRAM

The South Korean Ministry of Science and ICT (MSIT) [312] is working on ambitious plan to be the first country to launch 6G networks. The government of South Korea expects 6G services could be commercially available in Korea between 2028 and 2030. First deployment of 6G networks will be available in 2028 and mass scale commercial deployment will happen in 2030. The Korean government will invest a total of KRW 200 billion ($169 million) during 2021-2026 period to fund the research and development related to the 6G technology [313]. The preliminary goal of this strategy to launch a 6G pilot by 2026. Five major areas (i.e., digital healthcare immersive content, self-driving cars, smart cities and smart factories) are identified for these pilot projects.

The MSIT has also formed the "6G R&D Strategy Committee" which will be responsible for management of 6G related projects. This committee consist of the three major mobile network operators, small and large sacele equipment manufacturers, government agencies and public universities in South Korea. The 6G research program is also call for proposals (led by 5G forum and 6G TF) to perform prolot projects to realize 6G vision.

The goals of the 6G research program are to,

- Reach the rate of 1 Tbps
- Reduce the wireless latency up to 0.1 ms
- Extend the connectivity coverage range up to 10 km from the ground
- Utilize AI with entire network to cover all the segments
- Use Security by design concept to protect the network.

G. JAPAN 6G/B5G PROMOTION STRATEGY

The Japanese government kicked off Japan 6G/B5G promotion strategy in 2020 to promote research and development on 6G wireless communications services [314]. The Japanese government invests ¥50 billion on this promotion strategy. A ¥30-billion will be used to establish a fund to support the research and development. Remaining ¥20 billion will be used to build a 6G test-bed facility to be used by academic and companies for testing their developed technologies. This funding scheme also plans to improve the collaboration between public-private sectors in 6G research and development. Moreover, this 6G/B5G promotion strategy is aiming to establish and showcase the core technologies for the 6G system by 2025 and put the new technologies into practical use by 2030.

H. 6TH GENERATION INNOVATION CENTER

By continue the research work started with 5G Innovation Center (5GIC), 6th Generation Innovation Center (6GIC) was launched by the University of Surrey in the U.K. in 2020 [315]. This research center is focusing on 6G related research activities under two themes.

1) **Ambient information:** Focusing on improving the fusion between virtual and physical environments by utilizing advance wireless technologies, high-resolution sensing and high-accurate geo-location methods. This will lead to better connection of human senses with ambient and remote data to offer new level of 6G digital services.

2) **Ubiquitous coverage:** Focusing on improving the network coverage quality and range of 6G communication systems. Research will be focusing on improving coverage indoors, utilization of intelligent surfaces and also use of satellite technology enable the worldwide availability of 6G services.

I. INDUSTRIAL 6G PROGRAMS

The leading telecommunication industries has already initiated several industrial 6G programs. Here we mentioned some of those research activities related to 6G.

- Sony, Nippon Telegraph and Telephone Corporation (NTT), and Intel have been working together in Japan on collaborative research activities on developing 6G technologies. These companies are expecting that 6G could be commercially available as early as 2030 [316].
- **Huawei**$'s$ Canadian research center is also focusing on research activities related to future 6G wireless technologies. Huawei is collaborating with 13 universities on their 6G research activities [317].
- **SK Telecom** is cooperating with **Nokia**, **and Ericsson** on a 6G-oriented project. Under this project, they will be conducting research on applying new technologies, e.g., uRLLC, Distributed MIMO, AI and 28GHz band communication technologies on commercial networks [318].
- In June 2020, **Samsung Electronics** has announced that they are launching a new 6G research center in South Korea. This activity will be followed by the formation of the Advanced Communications Research Center under Samsung Research [319].
- **LG** and **Korea Advanced Institute of Science and Technology** (**KAIST**) has opened a new research center which is dedicated to the develop the standards for 6G networks [320].
- **NTT** is working on demonstrating a 100 Gbps communication solution by using Orbital Angular Momentum (OAM) multiplexing at 28 GHz with MIMO [321].
- **Tektronix** and **French research laboratory IEMN** have also developed a 100 Gbps communication solution which is called as "wireless fiber." In 2019, they demonstrated a 100 Gbps single carrier wireless link which was operated from 252 to 325 GHz range by using the IEEE 802.15.3d standard [322].

TABLE 7. Contribution of global level ongoing projects and SDOs on 6G.

	6G Enabling Technologies										6G Applications										
	THz Communication	Artificial Intelligence and Federated Learning	Compressive Sensing	Blockchain/DLT	Swam Networking	Zero touch network and Service Management	Smart Surfaces	NTN/3D Networking	Visible Light Communication	Quantum Communication	UAV based Mobility	Holographic Telepresence	Extended Reality	Collaborative Autonomous Driving	Internet of Everything	Smart Grid 2.0	Industry 5.0	Hyper-intelligent IoT	Collaborative Robots	Personalized Body Area Networks	Intelligent Healthcare
6G Projects																					
6G Flagship	✓	✓	✓	✓		✓		✓	✓	✓	✓		✓		✓		✓			✓	✓
Hexa-X	✓	✓	✓		✓						✓			✓			✓		✓		
TeraFlow		✓		✓		✓								✓	✓						
DAEMON		✓	✓			✓					✓			✓	✓						✓
6GBRAINS	✓	✓	✓		✓	✓			✓		✓			✓	✓						
South Korea MSIT 6G	✓	✓			✓		✓		✓				✓	✓	✓	✓	✓		✓		✓
Japan 6G/B5G Strategy	✓	✓			✓		✓		✓	✓	✓		✓	✓	✓	✓	✓		✓		✓
6GIC	✓	✓	✓					✓					✓				✓	✓			
SDOs																					
ESTI	✓	✓		✓		✓			✓	✓	✓		✓	✓	✓	✓	✓			✓	✓
NGMN	✓	✓		✓					✓	✓	✓	✓	✓	✓	✓	✓					✓
ATIS	✓	✓	✓					✓	✓		✓		✓	✓	✓	✓	✓		✓	✓	✓
Next G Alliance	✓	✓	✓					✓	✓		✓		✓	✓	✓	✓					✓
5G-ACIA	✓	✓				✓					✓		✓				✓	✓	✓		
5GAA	✓	✓	✓								✓			✓	✓						
3GPP	✓	✓	✓			✓		✓	✓	✓	✓		✓	✓	✓		✓		✓		✓
ITU-T	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓			✓	✓

VII. 6G STANDARDIZATION EFFORTS

Standardization is important to define the technological requirements of 6G networks and also to select the suitable technologies to deploy 6G network. Thus, the global telecommunication markets are shaped by standards. Many Standards Developing Organizations (SDOs) are working or at least planning to work on 6G standardization. Table 7 maps both ongoing leading 6G projects and standardization activities with 6G enabling technologies and 6G applications.

A. EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE

ETSI [323] is a large telecommunication SDO with over 900 member organizations from 65 different countries. Since 6G related research are still is at very early stages, ESTI is currently focusing on 5G and 5G advanced standardization activities. ETSI is also expecting the first 6G services only appearing after 2030. Moreover, ETSI supports the 6G corresponding European Funding program, i.e., (Horizon Europe 2020 – 2027) which could generate impact research on standards. Preliminary funding suggests that technologies such as beyond mmW or THz Communications, smart surfaces, large intelligent surfaces, AI, SSN, energy harvesting/transfer and nanophononics (glass to radio) will be interested in 6G standardization.

B. NEXT GENERATION MOBILE NETWORKS (NGMN) ALLIANCE

NGMN [324] is an association which is focusing on mobile telecommunications standard development. It has members from different telecommunication stakeholders such as mobile operators, vendors, manufacturers and research institutes.

The NGMN alliance kicked off a new project called "6G Vision and Drivers." This project is focusing on providing early and timely direction for global 6G research and development activities. NGMN will work with all NGMN partners, i.e., Mobile Network Operators, Vendors/Manufacturers and Research/Academia across the globe on development of the mobile network technologies for the next generation mobile networks beyond 5G.

C. ALLIANCE FOR TELECOMMUNICATIONS INDUSTRY SOLUTIONS (ATIS)

ATIS [325] is a leading ICT solution development organization with 150 member companies globally. AITS is focusing on different technologies including 6G, 5G, IoT, Smart

Cities, AI-enabled networks, DLT/blockchain technology and cybersecurity.

ATIS launched a call to action promoting U.S. leadership on the path to 6G. It promotes innovative research and relies on 6G to position the U.S. as the global leader in 6G 6G services and technologies during the next decade and beyond. This call to action has later outgrown as the Next G Alliance.

D. NEXT G ALLIANCE

Next G Alliance [326] is an organization under AITS which is focusing on the supporting 5G evolutionary paths and 6G development in North American region. This is private sector-led novel initiative which is focusing on rapid commercialization of 6G technologies by supporting the complete 6G commercialization life-cycle including research and development, manufacturing, standardization and market readiness.

E. 5G AUTOMOTIVE ASSOCIATION

The 5G Automotive Association (5GAA) [327] is a global alliance which is working on better utilization of 5G for automotive industry. 5GAA is developing a cencepts called the Cooperative Intelligent Transportation Systems (C-ITS). The key enabling technology of C-ITS is wireless communication which is collectively referred to as Cellular vehicle-to-everything (C-V2X) communication.

The 5GAA is working of identifying the superior standards-based cost-effective and scalable 5G era and beyond wireless communication technologies for C-ITS and Connected Vehicle applications.

F. ASSOCIATION OF RADIO INDUSTRIES AND BUSINESSES (ARIB)

The ARIB [328] is a SDO based in Japan. ARIB is promotes R & D of new radio systems to achieve the efficient use of the radio spectrum.

ARIB is currently working on early nationwide deployment of 5G, promotion of Post-5G networks, and promotion of 6G R&D activities. ARIB is also supporting the Japanese government's vision on "Society 5.0," by developing wireless technologies which is expected to be the infrastructure to enable the Society 5.0 services.

G. 5G ALLIANCE FOR CONNECTED INDUSTRIES AND AUTOMATION (5G-ACIA)

5G-ACIA [329] is an alliance which is mainly focusing on applying 5G technologies within industries. It supports and guides the development of 5G technology to address the industrial requirements.

5G will managed to address many important aspects of Industrial Internet such as uRLLC, native support for LAN services, time-sensitive communication and non-public networks. Therefore, 5G-ACIA believes that next level of research should increasingly focus on the further evolution of 5G towards 6G.

H. 3RD GENERATION PARTNERSHIP PROJECT (3GPP)

3GPP [330] is united alliance of seven telecommunication SDOs, i.e., ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC. These SDOs are known as "Organizational Partners" of 3GPP. The main objective of 3GPP is to offer a platform for its organizational partners to define specifications and report that define 3GPP telecommunication technologies.

3GPP is continuously working towards the standardization of beyond 5G network and 3GPP Technical Specification Groups (TSG) are currently working on Release 17. From a standardization point of view, 3GPP will focus on concrete 6G standardization work from Release 20 onward. This is expected to happen around 2025.

I. INTERNATIONAL TELECOMMUNICATION UNION - TELECOMMUNICATION (ITU-T)

ITU-T [331] standardization sector assemble telecommunication experts across the globe to develop telecommunication standards. ITU-T has launched a Focus Group on Technologies for Network 2030 (FG NET-2030) which will be studying about the networks for the year 2030 and beyond. It will be focusing on different types of networks including 6G. FG-NET-2030 is also organizing a series of workshops to highlight the requirements for future networks.

J. INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS

Institute of Electrical and Electronics Engineers (IEEE) [332] is the largest professional association for electronic engineering and electrical engineering. IEEE Future Networks (FN) initiative is specially focusing on the development and deployment of 5G and beyond networks. It is working on establishing a 5G and Beyond technology Road map to highlight the short term (1-3 years), mid term (4-5 years) and long-term (6-10 years) research and technological trends. FN also organizes in technical conferences and workshops to promote beyond 5G research activities. Moreover, FN will work in collaboration with IEEE Standards Association to contribute IEEE standards related to beyond 5G networks.

K. OTHER SDOS
1) INTER-AMERICAN TELECOMMUNICATION COMMISSION (CITEL)

is an entity of the Organization of American States (OAS) which is focusing on the development of telecommunication and ICT solution in the American region [333]. CITEL is working together with ATIS and Next G Alliance on 6G development.

2) CANADIAN COMMUNICATION SYSTEMS ALLIANCE (CCSA)

is a SDO in Canada which is focusing on Internet, television and telephone technologies [334]. CCSA promotes the beyond 5G activities within Canada and participate the standardization activities with 3GPP.

3) TELECOMMUNICATIONS STANDARDS DEVELOPMENT SOCIETY, INDIA (TSDSI)

is a SDO in India [335]. It is developing standards for telecommunication systems to satisfy the India specific needs.

TSDSI is developing on Roadmap 2.0 of India's National Digital Communications Policy (NDCP) with telecommunication companies, mobile operators, academic partners, government R&D agencies and vertical operators. Roadmap 2.0 is mainly targeting beyond 5G and 6G networks by focusing spectral efficiency, new air interface technologies and new radio architectures.

4) TELECOMMUNICATIONS TECHNOLOGY ASSOCIATION (TTA)

is the South Korean SDO which is focusing advancement of telecommunication technologies and ICT services. TTA launched a 'Mobile Communication Technical Committee (TC11)' which will be focusing on the standard development for beyond 5G and 6G networks together with other global SDOs [336].

5) TELECOMMUNICATION TECHNOLOGY COMMITTEE (TTC)

in a non-profit SDO in Japan. TTC is contributing to the standardization activities related to the ICT domain. Together with other SDOs, TTC contributes to the 3GPP's beyond 5G standardization efforts [337].

VIII. FUTURE RESEARCH DIRECTIONS AND GENERAL CHALLENGES IN 6G

The present understanding of 6G provides a broad vision towards future research directions and key challenges in realizing 6G mobile networks [12], [338]. We formulate future research directions related to 6G under six main domains, as illustrated in Fig. 10.

They are:

- **Ultimate Mobile Experience:** The extreme connectivity provided by 6G is expected to deliver an ultimate mobile experience through a myriad of emerging applications, personalized services and gadget free communication.
- **Hyper − Intelligent Networking:** Large scale deployments of AI/ML enabled networks.
- **Harmonized Networks:** Smooth interconnection of multiple communication technologies, data storage and processing platforms, etc. at different scales and platforms.
- **Sustainable Networks:** Energy-optimized/energy-harvesting network infrastructure with minimal carbon footprint.
- **Extreme Global Network Coverage:** Digital inclusion through seamless global service coverage by connecting remote, rural, deep sea and even space locations.
- **Ultimate Security**, **Privacy and Trust:** Guaranteed data security, privacy, and trust in the digital world.
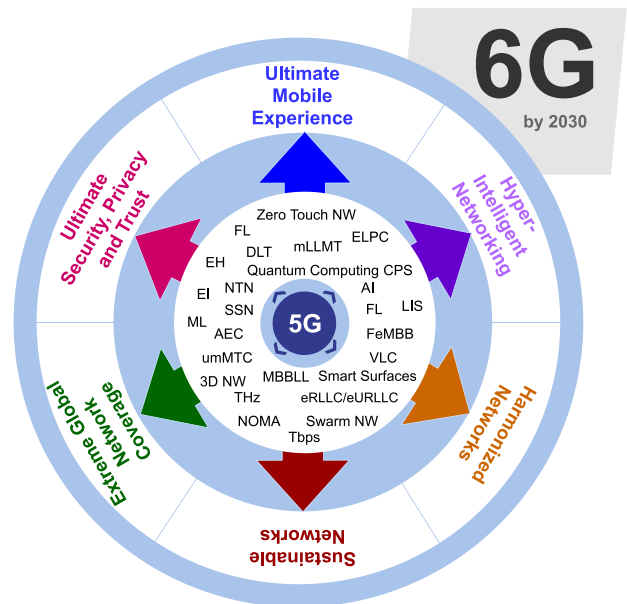

FIGURE 10. Towards 6G - Future Directions and Challenges [308], [339].

A. ULTIMATE MOBILE EXPERIENCE

6G is expected to provide an ultimate mobile experience by enabling many new applications. For instance, HT will project realistic 3D holograms of people and objects in real-time. Further, personalized BANs will be integrated with smart healthcare systems to provide better healthcare services. Also, digital services will be provided through gadget free communication models using tactile Internet, digital interfaces and sensors that are integrated in to the environment, and haptics [70], [71]. Many other applications including XR, IoH and CAVs are expected to provide an ultimate mobile experience to users. These applications will only be realistic with 6G that has FeMBB to provide Tbps data rates, extreme reliability to facilitate communication at a reliability of 99.99999%, ultra low latency below 1 ms, and ultra low processing delay in the range of 10 ns [12].

1) LESSONS LEARNED

5G evolved from 4G to provide eMBB with up to 10 Gbps peak rates, 1 ms latency, and 99.999% high availability and reliability to enable applications such as AR, ultra high definition video streaming, faster file downloads and remote operation of some industrial devices. However, the rapid growth of applications such as XR, HT, CAVs, IoH and UAVs, will require connectivity that surpasses 5G capabilities. Realizing applications such as CAVs and tele-surgery would require ultra-reliable and extremely-low latency connectivity beyond the capabilities of 5G [340]. Moreover, these applications will require powerful edge intelligence capabilities to process data in near real-time [341]. for instance, holographic communication requires the processing and transferring of large number of pixels in real-time to provide a ultimate user experience [30]. 5G network systems are also not capable of efficiently dealing with the dynamic

requirements of UAVs that will be utilized in diverse environments [342], [343]. The network reliability, scalability, low delay and fault tolerance in 5G networks are also not sufficient to realize a smooth UAV network [83]. CAVs also require unprecedented levels of reliability ($> 99.99999\%$) and low latency (< 1 ms) even in ultra-high mobility scenarios (> 1000 km/h) [17]. Furthermore, the lack of edge intelligence capabilities in 5G is a significant shortcoming that is expected to be addressed in beyond 5G communication systems [60].

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

Following are the key limitations and relevant research questions that needs to be addressed to realize the ultimate mobile experience envisaged with 6G.

- How to provide Tbps data rates to enable FeMBB, extreme reliability and availability in the range of 99.99999%, and ultra low latency below 1 ms?
- How can nearby devices cooperatively provide powerful edge intelligence capabilities to provide <10 ns processing delays?
- What are the way to integrate sensors and interfaces in to the environment to provide seamless gadget-free communication?
- How to connect and transfer data from up to 1 million connected devices per km^2?
- What is the way to ensure a smooth user experience in services such as HT and XR?
- How to manage SLAs for trillions of users while ensuring the required QoS, Quality-of-Experience (QoE) and Quality-of-Physical-Experience (QoPE)?

3) FUTURE WORK

6G communication networks are expected to provide peak data rates at the range of Tbps banking on the envisaged developments in technologies such as THz communication, ultra-high beamforming, better coding schemes and channel access schemes. In [344], authors present recent advances in low-latency and ultra-high reliable networks to propose a framework for modeling and optimizing uRLLC-centric problems at the network level. However, improving these technologies to meet the expected 6G KPIs requires further research work. The smooth amalgamation of wireless networks together with cloud/edge/fog platforms that provides data processing and storage facilities is essential to empower future 6G communication networks with edge intelligence capabilities. Furthermore, developing metrics such as QoPE, which is capable of combining QoS, QoE, and human perceptions, owing to the recent developments in machine learning is essential to provide services such as XR and holographic communication such that the human brain is able to perceive a realistic experience [12]. In addition, existing network security and privacy measures are also expected to see new developments to facilitate 6G networks and applications. For instance, novel approaches including secure
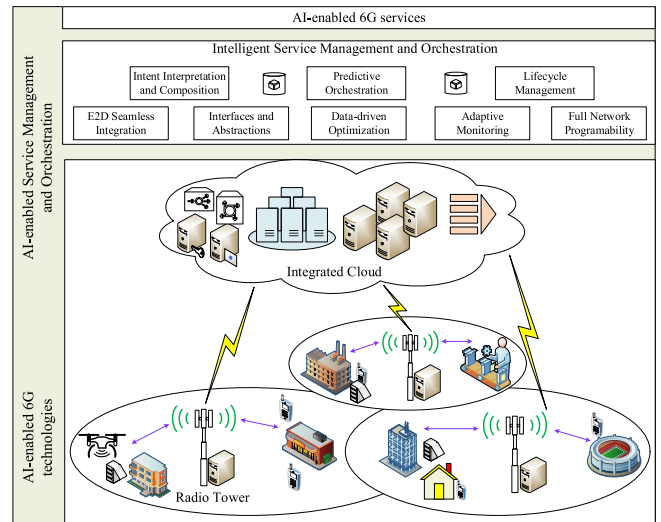

FIGURE 11. Dynamic instantiation and optimal placement of virtual micro services functions enabled by real-time AI/ML in the 6G era.

channel coding, channel based adaptation, quantum key distribution and quantum teleportation are being investigated to be used with future 6G communication networks [345].

B. HYPER-INTELLIGENT NETWORKING

The previous network generations, from 1G to 5G, have become more complex in many aspects. Moreover, the network has expanded in both horizontal and vertical dimensions. These reasons have motivated the use of intelligent and autonomous approaches to solving various design problems such as air interface, resource allocation, network orchestration and selection, intelligent radio signal processing, adaptive monitoring, interfaces and abstractions, and full network programability [346], as shown in Fig. 11. To enable hyper-intelligent networking in future 6G networks, there is a need for deeply embedding AI solutions to the network, especially when the solution cannot be obtained efficiently or in close-forms via conventional approaches.

1) LESSONS LEARNED

Many AI frameworks, including are machine learning [53], deep reinforcement learning [217], deep learning, distributed learning [68], FL [213], and computational intelligence [221], have been investigated to enable hyper-intelligent networking such as AI-driven air interface, intelligent orchestration, and node programmability. For example, the reconfigurability and adaptability of radio systems can be obtained via end-to-end learning design [347]. Since impairments, typically caused by analog radio hardware, can affect the network performance significantly, deep learning has been considered a promising solution [348]. To enable efficient modulation classification in fast fading networks, a deep convolutional neural network is proposed in [214] which can achieve very competitive performance in terms of classification accuracy and inference time as well as outperform various machine learning based approaches. The

potential application of swarm intelligence, a brand of AI, and machine learning for UAV-enabled VLC is considered in [349], where non-linear channel models in VLC are handled by a swarm intelligence approach effectively. More recently, a deep reinforcement learning approach is developed in [350] to maximize the minimum secrecy rate in an IRS-enabled multi-user multi-eavesdropper network. The use of deep reinforcement learning is to overcome the challenges caused by outdated/imperfect and highly-variant channel state information in IRS systems.

AI will play a vital role in automatic conflict avoidance in 6G. As the 6G networks are pacing towards infrastructure less networks, thus, it is inevitable to neglect conflicts in terms of resource sharing and delay minimization tasks. Furthermore, service providers and operators might also create conflicts in order to maximize their profits, this phenomenon is termed as greedy behavior. These conflicts will affect the user experience as well as the service provision. Therefore, it is necessary to resolve conflicts while dealing with heterogeneous technologies in terms of networks, operators, and resources [258]. One of the ways to resolve conflicts is to use AI for deriving conflict management policies [351]. The policy will first detect the conflict if one arises and recommends an action that prioritizes the needs of a user to enhance the quality of service. It is highly recommended that a module comprising of policies for conflict detection and resolution be integrated within a 6G communication system network for seamless and user friendly services.

Although AI solutions have been shown to have outstanding performance if compared with conventional optimization approaches, there are still several limitations related to the use of AI in wireless communication networks. For instance, the performance of deep learning methods highly relies on the quality and size of datasets used for training. However, the requirement of a standard dataset of highly dynamic and complex networks is typically unavailable. Consequently, it may be difficult to compare the performance of different AI solutions for the same problem. Moreover, conventional methods still perform well in many cases, especially when closed-form and/or non-extract but high-quality solutions can be obtained. This requires holistic usages of both conventional and AI approaches to enable hyper-intelligence in future 6G networks.

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

There are several barriers and research questions that need to be solved for hyper-intelligent networking in 6G.

- How to create standard and high-quality datasets for learning tasks for networks with different characteristics (e.g., radio access technologies, densification level, and channel modeling)?
- How to devise a holistic design of both conventional and AI approaches so that wireless services can be provided in real-time?

- How to handle the explainability of the operation of underlying networks since almost all AI solutions in the available literature are implemented in a black-box manner?
- How to provide hybrid centralized-distributed AI solutions to exploit powerful computing capabilities of the central cloud servers as well as the computing resources available at massive IoT devices at the network edge?
- How to leverage AI solutions to enable the full network programmability so as to support flexible and software based implementation of 6G systems?
- How to develop predictive orchestration mechanisms to achieve the goals of supporting a few billion IoT devices, zero-latency services, and extremely large capacity.
- The use of transfer learning is necessary to reuse the learning models that have been well trained and well performed. Moreover, unsupervised learning is promising to reduce the labeling cost as well as exploit a vast amount of unlabeled data generated from massive network components in 6G. So a research question is how to effectively leverage transfer learning and unsupervised learning in future 6G systems?

3) FUTURE WORK

Future 6G wireless networks will guarantee global coverage and provide services with various QoS satisfaction levels. In this network, storage and computing capabilities are distributed over the whole network, from the central cloud to the MEC server at the network edge and wearable computing devices at the user side. Obviously, AI is a key enabler for hyper-intelligent networking in 6G networks. Explainable AI solutions should be investigated so that the underlying operations of the network can be explained well. Moreover, to exploit the computing capabilities and generated data from massive IoT devices, hybrid centralized-distributed AI solutions are very promising. In particular, the global server, deployed at central clouds and satellites, can be leveraged to build a learning model over multiple regions of the world. As transferring a large amount of data from massive IoT devices to a central server is not efficient and sometimes unavailable, the data can be processed hierarchically, from end devices to edge nodes (e.g., terrestrial and aerial base stations) and global nodes. Moreover, FL is a promising concept to design privacy-preserving solutions.

C. HARMONIZED NETWORKS

Similar to 5G networks, the 6G networks will also need to utilize both Stand-Alone (SA) and Non-SA (NSA) deployments leveraging both legacy networks and also future NR to enable new use cases, satisfy the new network requirements, provide extreme coverage and also support flexible deployment of network resources. Thus, the 6G will interconnect the different types of networks ranging from VLC to satellite by aggregating resources and technologies from IoT devices to core-network/cloud infrastructure. Specially, NTN

towards 3D networks are needed in 6G to achieve the global service coverage by offering full digital inclusion in the area such as deep sea and space. New 6G applications with enhanced human machine interaction and human cyber-physical interaction will be needed exploiting sensors/biosensors. In this context BCIs and other biosensors will be used. 6G should also support the communication related to this area as well.

1) LESSONS LEARNED

To enable harmonized networks, 6G should utilize new advanced networking technologies such as autonomous mesh networks [352], [353], nanonetwork or nanoscale network concepts [354], [355], scalable D2D communication [356] in addition to the legacy wireless technologies. Moreover, the spectrum bands used in 6G may be above 100 GHz. Moreover, novel and alternative computing paradigms, e.g., serverless schemes [357], [358], in conjunction with ultra-flexible splitting of functionality between end devices and edge nodes are also needed to satisfy the demand of new 6G applications. Moreover, 6G harmonized networks should be utilized both AI and network programmability concepts to automate the harmonization.

There are some limitations related to 5G system architecture. For instance, the 5G architecture is not optimally designed for integrating new features, such as managing nodes operating at above 100 GHz frequencies, interconnecting millions of sub- and mesh-networks, and network procedures exploitation by using AI. Therefore, it is needed in 6G to integrate and leverage these trends at 6G concept development phase to offer significant improvements in flexibility, cost efficiency and also reduced complexity.

Moreover, 6G network harmonization will cover various new environments such as modular flexible production cells, zero-energy sensors, solutions for on-demand connectivity in remote areas with different stakeholders. Since different networks have different network characteristics, the network harmonization in 6G will allows to provide required coverage and connectivity, dependability, and also satisfy the requirement of heterogeneous networking environments. Moreover, AI enabled network harmonization will allow 6G to deploy ultra-flexible resource allocation procedures in challenging environments, such as those populated by mobile devices with special requirements (e.g., reliability, energy-efficiency, security) and in need of coverage (e.g., in emergency scenarios or in remote areas).

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

Following limitations and research questions are required to be addressed to enable harmonized networks in 6G.

- What is the new 6G architecture which can harmonized networks to enable flexible network typologies and backward compatibility for legacy networks?

- How to harmonized different networks to achieve the convergence of the biological, digital and physical world ?
- What are the architectural options which can enable the allocation, instantiation and operation of AI processing functions over harmonized network deployments?
- How to tackle the large variations of available capacity at short timescales in 6G applications at architecture level?
- What are the possible global level optimization mechanism to increase the collaborative utilization of available resources at different networks?
- How to enable the cooperation between different networks in a trustworthy manner?
- How to create new services such as dynamic function placement, network programmability and processing of offloading at a global level in harmonized networks?
- What are the possible supporting protocols which can enable integrated and distributed AI to automate the network harmonization?
- How to design an automated and intelligent harmonized network equipped with distributed computing capabilities?
- How to develop technologies for new harmonized network requirements such as network function refactoring, run time scheduling of network resources and predictive orchestration?
- How to enable the integration in wireless networks with closely interacting BCI/human-machine interactions?

3) FUTURE WORK

The future 6G research should focus on harmonization by focusing on the integration of nodes using above 100 GHz spectrum (including optical), NTNs, nano networks, autonomous D2D and cell-free MIMO. One of the key enablers for such harmonization in 6G era will be the enhancement of radio access visualization methods. It will enable abstraction and programability which are essential to develop harmonized networks in 6G.

6G should evolve as new service-based network which can be enabled via network harmonization. Service based networks have optimal service independency, flexibility and re-usability. 6G can achieve this by evolving from fully cloud-native network functions in 5G to alternative compute paradigms such as serverless architectures. This approach will need redesign the signalling procedures and interfaces in legacy mobile architectures.

For a better realization, network harmonization should support crucial factors such as high reliability, accountability, availability and liability. The cross-layer technologies such as communication-control co-design [359], [360] and spatiotemporal network design [361], [362] and also novel computing techniques such as blockchain [237] can be used achieve above requirements. Moreover, the end results of harmonization can be further improved by using prediction or projection of trajectory, resource, and spectrum usage.

D. SUSTAINABLE NETWORKS

To meet global sustainability, energy efficient networks, zero energy network resource management, and green computing, needs to be achieved along with acceptable quality of service. The communication systems are exhibiting the aforementioned characteristics can be considered as sustainable networks. Together with 6G, AI can help in measuring network activity and identifying the demand requirement by analyzing trends and patterns from the acquired data. The system learned using AI can be applied for redirecting the energy resources in real-time so that the consumption of power can be reduced and efficiently utilized [363].

Recently, many works have been proposed for the realization of self-sustainable networks. Du [364] focused on reducing the computational complexity of data clustering algorithms for improving the energy efficiency of communication networks. Maddikunta *et al.* [365] opted for an optimization algorithm to reduce the energy consumption of the communication network when selecting the cluster head. Che *et al.* [366] highlighted the energy transmission problem in UAVs propagated through ground terminals. The study [28] have highlighted the importance of two-way sustainability when implementing 6G communication systems. The study suggest that 6G intrinsically supports green communication policies and relies on self-sustaining protocols. The realization of secure and end to end autonomous systems have challenges in terms of service classes such as ultrahigh data density, low-latency communications, and ubiquitous mobile broadband. Moreover, the provision of unlimited wireless connectivity necessitates the networks to be deployed in underwater, space, ground, and air respectively that entails the use of flexible materials.

1) LESSONS LEARNED

In order to attain sustainability in the communication systems, a holistic approach is required to be adapted rather than only focusing on the radio access or transmission part. Studies have suggested that the energy wastes and carbon footprints can be reduced by employing AI approaches that can adapt to the network traffic demands [367]. This process can be accomplished by employing schedule based mechanisms to turn the base stations ON or OFF. Alternatively, traffic steering or cell zooming methods can also be employed to improve the efficiency of resource utilization. Similarly, based on user's demand the services can be turned off or switched to low-resolution. In the context of energy utilization and weather conditions, the systems could use sensing approaches for scale the utilization in order to avoid outages and over-flows. The conventional base stations and new radios need to be offloaded or moved to the advanced 6G enabled edge computing facilities to achieve massive low-latency communications. This may result in energy barriers at the end of edge devices. In this regard, AI and 6G can be used in a combined manner to co-design energy-sustainable and cost-effective computing and communication protocols. Furthermore, Blockchain and optimization techniques can play a vital role in re-strategizing the resources while opting for decentralized systems to reduce bottlenecks, accordingly. To this end, we presume that the sustainable networks, in general, is the way forward for eco-friendly communication services.

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

There are still a lot of challenges that need to be explored and solved in order to realize a potential self-sustainable communication system. Some of the challenges are listed below:

- Advanced Power transfer and Energy harvesting techniques from heterogeneous devices for green communication.
- Network sustainability to users with varying levels of processing power.
- Super Energy efficient algorithms for a massive number of devices.
- Advanced handling strategies and designs for unstructured or semi-structured data from resource-constrained devices.
- Smart energy and resource management algorithms for 6G networks.
- Advanced 6G enabled reconfigurable intelligent surfaces for sustainable communication.
- Extended adaptive coding techniques for data compression.
- Improving network traffic, security and privacy issues with the fusion of distributed ledger technology and 6G.

3) FUTURE WORK

Attaining sustainability in communication systems is a challenging task and the efforts needs to be put in from all directions. Verma *et al.* [368] proposed the use of hybrid whale spotted hyena optimization to improve the selection of cluster heads in 6G to enable communication. Although, it is one of the components to be dealt with but in general other communication protocols and network resource management can also be optimized using the aforementioned strategy. Another challenge is to offload some of the centralized services to nearby edge computing facilities and that could be performed through federated and transfer learning approaches. Recently Liu *et al.* [369] proposed the use of FL approaches for 6G communications. However, the same can be leveraged for designing personalized systems, or using cached content for user-centric services that could reduce the burden from access networks. Previously, we also shed light on the use of scheduling services for base stations or new radios in 5G and 6G networks. In this regard, multiple domains including AI and optimization techniques integrated with 6G technology can help in reducing the number of transmissions or energy requirement by strategizing the sleep and wake schedule of base stations. For instance, Wang *et al.* [370] recently proposed hybrid energy powered cellular network that could plan the wake-up strategies

for base stations in order to balance the network resources and increasing energy efficiency. The same can be opted for selection of route strategies, network load switching and balancing, respectively.

E. EXTREME GLOBAL NETWORK COVERAGE

6G is conceptualized to go much beyond the maximum coverage that can be achieved by full-fledged deployment of 5G. In other words, by 2030, 6G energized telecommunication industry is expected to offer global services encompassing remote places (e.g., rural areas), oceans, vast-land masses with low inhabitants, air and space. The obvious advantages will be the minimization of digital divide by connecting everyone and everything, higher business opportunities in every part of the world supported by the continuous growth in local operators, and easy roll out of essential services like safety and basic governmental benefits.

1) LESSONS LEARNED

Even with 5G, originally conceived as terrestrial networks, it is presumed that considerable parts of the globe will be uncovered [26]. These parts of the earth mostly include oceans, desserts, deep forest, rural areas, mountains, and airspace. Thus, 6G is believed to overcome this shortfall of predecessor generations and emerge as universal communication systems offering ubiquitous global coverage. Some of the technologies that have been identified to play a vital role in driving the extreme coverage are UAVs as mobile and agile aerial base stations, satellites in particular LEO and VLEO for broader coverage, cell-free architecture based on distributed MIMO allows devices to avail multiple simultaneous connectivity to APs, Terahertz and VLC offer new resources to boost capacity, blockchain-integrated AI that can allow efficient spectrum management, and decentralized business ecosystem that incentivizes players of all sizes to participate in extending the radio footprints. Thus, 6G with its extreme global coverage is envisaged to be a key enabler for never-seen-before type of applications and will also minimize the digital divide. The latter is especially important in the emergency or global pandemic situations like COVID-19.

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

Following are the interesting research questions that need to be answered to realize the 6G's vision of extreme global coverage:

- How to intelligently manage the seamless 3D mobility while moving vertically up (in air or space) or down the ground level?
- How to efficiently manage and control swarm of LEO and VLEO satellites as well as enable them secure and cost-efficient inter-communication [26]?
- What could be the time-efficient solutions that can help overcome Doppler shift and Doppler variation issues that occur due to the relative motion of earth and LEO satellite [26]?

- How to optimize power radiation and improve system efficiency while achieving global coverage?
- What are the channel models that can be used for heterogeneous scenarios (for, e.g., UAV, maritime, satellite, and V2V) that will use different frequency bands like mmWave and THz band [174]?
- How to develop an automated, open and decentralized wireless market that motivates business entities of all sizes to participate realizing global coverage?

3) FUTURE WORK

Some of the important areas that need dedicated research inputs are presented in this subsection. In context of flying relays or base stations, we need optimized 3D localization and network planning [251]. These areas of research become even more important since UAVs can have resource constraint and are characterized by heterogeneous processing and storage capacities. Another area of future work concerning global network coverage would be secure interoperability among various operators and smart 3D roaming mechanisms applicable for heterogeneous networks utilizing different technologies. FL based optimization where different networks train locally the ML models and instead of sharing data these network share the updates on the model. Hence, FL has potential to globally optimize 6G ecosystem while ensuring ubiquitous network coverage. Yet another area of future work that can drive extreme global coverage is channel estimation and dynamic link optimization. Advance techniques are required in this area to provide efficient and cost-effective solutions for ubiquitous coverage.

F. SECURITY, PRIVACY, AND TRUST

6G is a great vision and it will bring new and life changing technology developments. These developments will guide the world towards vast enhancements with extremely ambitious goals such as, zero carbon footprint, climate ecosystems and so on, through the deployment of goal-oriented technologies, communications and applications. As discussed in Section III, few of applications are being and/or will be enabled by a trillion of heterogeneous devices. These devices will further collect sensitive data to support various services through the wireless centric computing in the digital world. Nevertheless, in this new trend of computing centric services and 6C convergence, cyber-attacks will present another but unavoidable issues for 6G security. For instance, detecting AI based attacks would be challenging in extremely massive network of networks. In addition, several stakeholders including consumers will be collecting and monitoring data through various devices and networks that may pose several privacy issues. In [371], the authors demonstrated the privacy threat in 3G, 4G and 5G. Such security and privacy issues may lead to the trustworthiness issues in 6G applications and networks, as discussed in [372], [373]. Therefore, it goes without saying that security, privacy and trust are worth studying before 6G planning, designing and deployments.

1) LESSONS LEARNED

It can be noticed from the deriving treads (refer to Section II), applications (refer to Section III) and enabling technologies (refer to Section V) that the 6G will be heavily relaying on the new paradigm of reliable communications, intelligent applications, and ubiquitous services. These new paradigms will open new attack vectors that may lead to security, privacy and trust vulnerabilities to the networks, systems and applications. However, the existing deployed 4G and 5G networks contain certain security holes that can lead to many attacks. For instance a recent report reported that existing 4G and 5G are vulnerable to the denial of services attacks [374], [375]. More precisely, the report revealed – the Diameter Signaling Protocol (DSP) that coordinates data through several Internet Protocols from different locations. Here it is worth to note that the DSP is unable to identify illegitimate and legitimate packets and thus it may lead to coordinated DoS attacks or other privacy issues. Furthermore, in [371], the authors demonstrated the security and privacy threat in 3G, 4G and 5G. Similarly, many other instances of security and privacy vulnerabilities are reported in IoT [376], Smart Grid [377], edge computing [378], and so on. In addition, detecting AI based attacks would be challenging in extremely massive network of networks. Therefore, the immediate lesson leaned from such vulnerabilities is that they can impact in many ways in 6G networks and applications, ranging from benign disruption to act of sabotage, threatening individual live to economic fraud and even more the national security threats. Another lesson learned from previous technologies is the data leakage (i.e., for individual's or community's privacy) threats. Malicious attackers can mount data extraction attacks that can fly under the radar, which can put individual's privacy at a risk within their application domains. Hence, security, privacy (along with trust) should be considered as a performance target of wireless computing in 6G.

2) RELATED LIMITATIONS AND RELEVANT RESEARCH QUESTIONS

As the scale of 6G networks, applications and services is massive (which is not finalized yet), deploying security, privacy and trust measures are challenging. Few of challenges are listed as follows.

- *Novel security architecture:* The benefits of 6G will be tremendous, however one of the naive challenges is how to deploy security and privacy measures in 6G architecture, which is not defined yet.
- *Security in on-demand 6G applications:* In the 6G distributed applications, software and hardware will be decoupled in device to device architectures. Another important challenge, how to perform security services (e.g., authentications) when new network elements may be instantiated on-demand in 6G applications.
- *Security and privacy in distributed AI:* Due to the fact that the scale of 6G network will grow unimaginably high. It is anticipated that 6G will be consisting of

several of decentralized and intelligent systems that will capable of taking autonomous and savvy decisions (through distributed AI) at various levels in many of applications. What security and privacy challenges and issues are related with such technologies are neither fully anticipated nor identified yet? Another issue associated with security and privacy is what if AI-based tools will be used for an attack purpose?

- *Security mechanisms in AI Algorithms:* It is very likely that the traditional AI mechanisms may vulnerable to security attacks. For instance, an attacker may pollute data during the model training and that may reduce the performance of an AI algorithm. However, how to detect such malicious attempts at first place is challenging.
- *Privacy mechanisms in AI Algorithms*: Privacy in AI enabled system has its own associated issues, such as legal, tech, moral and/or ethical challenges. There is a no guarantee that whether the collected data in AI models will not be exposed to other non-trusted model. Such non-trusted model may leak information or meta-data to unauthorized entities. This may lead to the security breaches. Therefore, AI based algorithms are privacy alarming situations as of today, with no potential solution that how to design and develop privacy enabled AI model that will protect the privacy of users while having the maximum usability of their data.

3) FUTURE WORK

As we progress towards the next decade or so, the 5G beyond/6G networks will be enabling (x times) faster technologies and services than the current technologies, to across the end-users, communications, businesses, governments, and so on. Such faster technologies will also open a huge attack vector that will bring high risk to societies, businesses, etc. In addition, the traditional security approaches of 4/5G may not be enough to secure ever evolving 6G network. However, the basic requirements, such as confidentiality, integrity, availability, authenticity that need to be fulfilled in the future network. Furthermore, privacy-by-design must be integrated and implemented that would guaranteed fulfill the demands of data privacy, location privacy, identity privacy and privacy of other meta-data. In summary, the future researcher must rethink about developing of new or innovative security and privacy solutions (enabling quantum computing based mechanisms) with affordable low-cost, and high security.

IX. CONCLUSION

In this paper, we provide a broad and exhaustive survey on the current developments of 6G. Societal and technological trends envisaged by the 2030 society highlight the limitations of existing 5G mobile networks. Driven by the heterogeneous demands of the hyper-connected 2030 world, a new network paradigm is envisioned to facilitate emerging applications. These applications require 6G networks to provide extreme data rates, extremely low delays, extreme reliability and

availability, massive scalability, extreme power efficiency, and extreme mobility. Realizing this 6G vision requires utilizing new technologies that are envisaged to act as enablers of 6G. We also highlight existing projects, research work, and standardization approaches focusing on the development of 6G. Consequently, we consider the lessons learned and limitations of prevailing research work to propose a roadmap for future research directions towards 6G.

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