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6G Ecosystem: Current Status and Future Perspective

JAGADEESHA R. BHAT[1], (Member, IEEE), AND SALMAN A. ALQAHTANI[2], (Member, IEEE)
[1]St. Joseph Engineering College, Mangalore 575028, India
[2]Research Chair of Pervasive and Mobile Computing, King Saud University, Riyadh 11543, Saudi Arabia

Corresponding author: Salman A. AlQahtani (salmanq@ksu.edu.sa)

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ABSTRACT Next-generation of the cellular network will attempt to overcome the limitations of the current Fifth Generation (5G) networks and equip itself to address the challenges which become obvious in the future. Currently, academia and industry have focused their attention on the Sixth Generation (6G) network, which is anticipated to be the next big game-changer in the telecom industry. The outbreak of COVID'19 has made the whole world to opt for virtual meetings, live video interactions ranging from healthcare, business to education. However, we miss an immersive experience due to the lack of supporting technology. Experts have anticipated that starting from the post-pandemic age, the performance requirements of technology for virtual and real-time communication, the rise of several verticals such as industrial automation, robotics, and autonomous driving will increase tremendously, and will skyrocket during the next decade. In this manuscript, we study the latest perspectives and future megatrends that are most likely to drive 6G. Initially, we describe the instances that lead us to the vision of 6G. Later, we narrate some of the use cases and the KPIs essential to meet their performance requirement. Further, we highlight the key requirements of 6G based on contemporary research such as UN sustainability goals, business model, edge intelligence, digital divide, and the trends in machine learning for 6G.

INDEX TERMS 6G, artificial intelligence, cloud computing, sustainability goals, digital divide, healthcare, machine learning, Tera hertz communication, cellular network, 6G architecture.

I. INTRODUCTION

Recently after the launch of Fifth Generation (5G) mobile networks, several data-intensive applications and verticals which require specific network parameters have undergone a deep sense of relief due to the availability of high data rate, bandwidth, and reliability. In 2020, the 5G deployments by different network providers either as Non-Stand-Alone (NSA), or as Stand-Alone (SA), will address the need for mobile internet by high data rate (e.g., enhanced Mobile Broadband (eMBB)), ultra-reliable low latency (uRLLC), and connectivity between massively dense deployment of smart devices (e.g., massive Machine Type Communication (mMTC)) [1]. Further, 5G networks can reduce the network scale-up time drastically due to its virtualized core. Consequently, the cost reduces. All these features have made 5G networks predominantly different from its predecessors in terms of network capacity, and range of applications it would support [1].

It is envisioned that by 2030, there will be 97 billion machine type devices, resulting in an astonishing increase in the global mobile generated data traffic to 5.016 Zeta Bytes (ZB) per month from 0.062 ZB as in 2020 [2]. Further, a survey has anticipated that by 2030, the number of people living in 43 megacities across the globe will increase to 10 million [19]. Consequently, information communication technologies (ICT) should be agile and robust with respect to the massive data generated by the mobile devices due to urbanization and from smart city ecosystems such as smart transportation, smart healthcare, and smart buildings. Moreover, the data generated will be fueled by the emerging applications in the area of Artificial Intelligence (AI), Robotics, Industry 4.0, and Internet of Everything (IoE) to name but a few, that generates a colossal amount of data. In such a context, cellular network infrastructure will be one of the key drivers to support extreme data

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rate, high bandwidth, and quality of service (QoS) for these verticals [3], [4].

Let us consider a few future internet applications such as self-driving cars with simultaneous communication capability. In such a case, each communication link demands extreme network parameters, for instance, connectivity with a delivery drone to assist in the delivery of emergency medical facilities that requires extremely low latency (<1ms), on the other hand, with the roadside infrastructure (V2X) that requires high reliability (~99.9999999%) to prevent accidents [48]. Similarly, remote robotic surgery in a smart hospital, remote holographic image transmission of a live public concert, data communication from ultra-high dense IoT (uHDIoT) and wearable devices, haptic online games, and haptic meetings are some other scenarios. In 2030, these use cases will be the key thrust areas which require a high degree of automation and intelligence to address diversified requirements [5]–[8]. To address these requirements, we need data rate up to 1 Tbps, ultra-high reliability of $10^{-9}$and ultra-low latency of 0.1 ms or less [2]–[4]. It is evident from the above facts that 5G telecom networks will drastically fail to meet the said requirements, as 5G's capacity is relatively lower and unified [8]. As a result, there is a definite need for a next-generation system that support new services, and technologies while maintaining backward compatibility. Altogether, the new technology components and architecture for beyond 5G (B5G) networks is necessary to address a plethora of user applications [3]–[9].

Several experts have articulated the speculated features of Sixth Generation (6G) networks which are considered to be the successor of 5G networks [1]–[9]. As expected, 6G network shall overcome the major limitations of the predecessor networks; alongside, it will further extend the three key features of the 5G network. In Fig. 1(a), the intersection of these factors (classes of use cases) is shown. Certain scenarios may require multiple use cases to be met simultaneously (uRLLC and mMTC) as shown in Fig 1. (a) with intersecting circles. Specifically, 6G network will further enhance Ultra-Mobile Broadband (feUMBB), ultra-High Sensing Low Latency Communications (uHSLLC), ultra-High Density Data (uHDD) services, ultra-High Energy Efficiency (uHEE), ultra-High Reliability and Sensing (uHRS), ultra-High Reliability and User experience (uHRUx), ultra-Low Latency Reliability and Secure (uLLRS), ultra-High Security (uHS), ultra-High Sensing and Localization (uHSLo) and several other combinations of these Key Performance Indicators (KPIs) and use cases [9], [10]. Refer Fig. 1(b), for an exemplary use case of 6G for different verticals. As shown in the figure, certain verticals require a combination of use cases which is indicated by the blue arrow at the intersection. For instance, distance robotic surgery will require low latency (uRLLC) and high security of the data (uHS). This interdependency between multiple use cases is shown as uLLRS (low latency, reliability, and security) by an arrow in Fig 1(b). In the similar way, the other arrows at the intersection (uHRS), (uHRUx) of multiple use cases are shown.

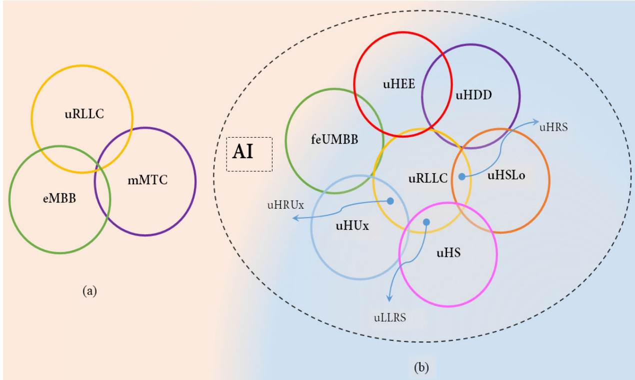

FIGURE 1. A comparison of 5G and 6G using support for verticals (a) 5G and (b) 6G.

Currently, 5G network is yet to be fully deployed worldwide; as a result, its real-time performance on every use case is not well studied. Nevertheless, when we see the evolution of the telecom industry, it is evident from the keen observation that each generation took a decade from setting a vision, R&D, standardization to market launch. Expecting the same trend, the next generation (i.e., 6G) shall be made realizable for customers' use around 2030. At this juncture, academia and industry may only have the visionary groundwork regarding 6G networks, as it is too early to realize the full potential of it. Motivated by the current research on 6G networks and its technological components, in this manuscript, we will discuss various aspects of future networks. Several kinds of literature have shed light on vision, requirements [1]–[9], technologies [10]–[15], use cases [96]–[98], of 6G networks. In this article, we outline the key points from the previous research and provide insight into the future research trends in 6G networks.

The *main contributions* of this manuscript are as follows:

(i) First, we discuss the expected key features of future networks to give a direction to the research community.
(ii) We highlight most of the KPIs for 6G networks as applicable to different use cases (Table 1) and we provide an outline of the 6G ecosystem by considering all the stakeholders.
(iii) We provide an *exhaustive categorized survey* of exclusive literature on 6G and discuss their research directions (Table 2).
(iv) Unlike the existing literature, we discuss various architectures for 6G networks from the literature. Moreover, we proposed network architecture for 6G with a layer-wise approach for simplicity; and improved latency, reliability through AI-enabled distributed cloud features.
(v) Further, we summarize the future megatrends in 6G networks, namely, UN Sustainable Development Goals, Digital divide, Edge intelligence and Machine learning, and Business models.

The remaining part of the manuscript is organized as follows:

Section II illustrates the scope of the future networks, KPIs, and use cases of 6G networks. In section III, we classify the recent literatures, and highlight their contributions to the research community. Section IV discusses various technology components of 6G networks and their main features. Furthermore, section V presents the architectures of 6G networks, while section VI provides the future trends in 6G networks. In section VII, the global research initiatives are highlighted, and section VIII narrates the open research areas for future exploration. Finally, section IX concludes this article.

II. SCOPE OF FUTURE NETWORKS

The study of future networks enables us to equip ourselves with necessary facilities for the industry verticals required during 2030. The in-depth analysis of the current mobile networks reveals the existence of a large gap between user application's expectations and services offered by the network providers [38]. For example, user expectations on immersive multimedia, personalized holograms, multi-sense haptic service, etc. remain as a gap which the current networks shall not support [12]. Further, technology components including hardware, software and overall ecosystem (devices, spectrum and standards, security, data management algorithms, cloud-based core and access solutions, and applications) need tremendous upgrade [19]–[23], [28].

A. TRANSITION FROM 5G TO 6G: GAPS AND RECOMMENDATIONS

Implementation of 5G has escalated in most of the mega-cities worldwide due to 5G's ability to support current industrial use cases. Albeit, there would emerge several use cases, societal requirements, and technological evolution in the future requiring exploration beyond the abilities of 5G. Currently, terrestrial communication is one of the key requirements in 5G networks; however, it would extend in 6G networks, say from terrestrial to underwater and aerial in several folds of 5G's capacity [12]–[14]. This degree of freedom in all-round connectivity will encourage the rise of several verticals such as flying cars, ultra-real human-computer interactions, holographic telepresence, and underwater recreation having challenging constraints. To address the demands of these verticals such as 3D connectivity, multi-dimensional video (∼16K resolution) [46], extremely high data rate (Tbps) and bandwidth (∼10GHz) [9], and so on, the communication networks must be much more *intelligent than now*. Also, the existing internet cannot support these requirements. Therefore, a new KPIs will be necessary to handle the use cases with *integrated performance* requirements. For instance, real-time remote robotic surgery will need *simultaneous* ultra-low latency, massive data rate, and security to work effectively [17], [18].

Furthermore, user applications do not have direct control in terms of latency, security, congestion, and reliability, leading to poor user experience. Similarly, a state of unpreparedness exists to launch holographic data that requires several Gbps to Tbps data rate with extremely low latency and ability to connect to millions of users in real-time. The time difference between the occurrence of events and generation of response should be minimal which is lacking in the existing cellular networks. For instance, in a remote robotic surgery sending a command to control the robotic limbs and the video transmissions of the surgery must have a time precision (latency) of a fraction of milliseconds. Again, sparse infrastructure and interfaces for all-round network connectivity for a packet to traverse when we consider air, underwater, and terrestrial communication. Further, intelligence has been merely considered at the network edge (as in 5G), but we lack intelligence at individual layers of network or when network elements are distributed.

1) RECOMMENDATIONS FOR FUTURE NETWORKS

We recommend the following key point for the future networks:

- (i) *End-to-End connectivity*: Future networks shall provide sufficient assistance such as virtualization, intelligent decision, network automation, and slicing to applications in order to make them attain reliability, security, network capacity along with guaranteed and timely delivery from the origin to the destination. Therefore, a holistic approach toward full end-to-end connectivity and integrity of data transfer is necessary to make the future applications a reality [23], [38], [49].
- (ii) *Interoperability*: The network will interoperate between heterogeneous, small/ large, and private/ public networks where each mobile node will have multiple radio interfaces to provide all-round connectivity.
- (iii) *Compatibility*: It should allow new protocols, network architectures, nodes, and services to coexist with the existing technologies. The data transfer protocol must be agile to send packets over different network interfaces with the vision of end-to-end realization of services.
- (iv) *Dedicated timely service*: There should be autonomous services such as Industry 4.0, autonomous driving, and robotic surgery to improve the service quality and scale up the production, time plays a critical role. Therefore, the network must have exclusive support for time-critical services [22]–[24].
- (v) *Edge computing capability*: To reduce the delay during media-rich services and provide local services efficiently at a closer location to the user devices, the data from the user will be processed at the edge instead of only at the cloud. This increases reliability, scalability, and privacy [42], [97].
- (vi) *Intelligent network*: Starting from the physical layer to the applications, the AI will be predominant and distributed across different network entities such as core, access network, and terminal users. Thus, 6G will transit from smart network (as in 5G) to an intelligent network [36], [81].

(vii) *Ultra-smart devices*: The existing hand-held smartphones will become obsolete and they will be replaced by either smart glasses that would deliver ubiquitous XR experiences or the phone functions that will integrate a smart wearable device/ smart patch offering high resolution, and holographic experiences [19]. We also envision that the features of the phone will be found in a distributed connected intelligent device. Thus, alleviating the need for a hand-held dedicated device.

(viii) *Cell-free networking*: The mobile device shall connect to the radio access network seamlessly without depending on a specific type of access point to provide infinite mobility and QoS [31]. The network should be flexible enough to allow devices to connect through a range of access networks such as THz, mm-wave, and visual light communication (VLC). In addition, a user may get served by multiple antennas mounted on various base stations without the restriction of cell boundaries; thus, reducing the inter cell interferences [28], [40].

(ix) *Support diverse media*: Even if 5G supports diverse multimedia such as text, image, video, voice, augmented reality, and multi-dimensional holograms, in 6G the applications would demand the multimedia at lowest latency, precise location, high data rate, etc., which requires much improved KPIs than 5G [106].

(x) *Amalgamated sensing, communication, and positioning*: Some verticals need a combination of ultra-high-speed, ultra-low latency, exact positioning, along with precise sensing of the surroundings all being met together. To realize such requirements, future networks shall provide resources, energy, hardware, and computational support [108].

(xi) *Multi-level architecture*: The storage, communication, and computing should be distributed at the user, edge, and cloud levels, which will operate as a centralized or as a distributed model to support scalability [108], [114].

B. 6G ECOSYSTEM

The 6G ecosystem consists of all stakeholders ranging from an equipment manufacturer to application developer. A brief diagram of the 6G ecosystem has been presented in Fig. 2. The 6G chipset manufacturers will deal with the design of new hardware and electronic components such as radio, modulator to accommodate new technology. Next, the mobile manufacturers and network equipment vendors (radio access network installer) will base their products to support the underlying technology from the chipset manufacturers. Next, all these technologies will assist the mobile network operators to launch their mobile services to users. Moreover, the edge devices at the boundary of radio access and the core network, cloud servers, data centers, software modules such as core network virtualization, slice providers, content delivers, will exchange data and services with the application developers. Since 6G will be centered around the users, the mobile devices, network operators, and other service providers of the network shall also revolve around the users. The discrete arrows indicate that the mobile users (or IoT devices that need service) will directly be supported by the network provider, device manufacturer, and applications. However, all the remaining components of the ecosystem will coordinate the services. Such coordination, and interdependency/ interplay between each component of the ecosystem is shown by the bold arrows.

Further, as shown in Fig. 2, security, and intelligence will be pivotal in the 6G ecosystem. The security, and AI as shown, shall be a part of every component such as at the device level, at the mobile operator, user, software, edge or cloud level, and at the applications.

C. VISION AND KPIs OF 6G

V*ision and quest for 6G network*: After discussing the technology gaps and recommendations for 6G networks, we highlight the crux of the vision and the need for 6G networks. There are several reasons we put forward, which necessitate the need for 6G networks.

First, considering the broad scope of United Nation's Sustainability Development Goals (SDGs) for 2030, there is need for several essential technologies that will satisfy the objectives, communication challenges, and new application requirements of the SDGs [44]. Second, 5G network has matured enough to address the performance requirements of the existing verticals. However, when these verticals or market demands grow to the next level, say Industry 5.0, Society 5.0, Transport 4.0, and many more that are human-centric, ubiquitous, fully automated, and driven by AI, will demand specialized resources which burden 5G networks [19]. Third, considering the business models for 2030 and beyond, the technologies like telepresence, holographic and haptic communications, Brain-Computer Interface (BCI), 4D imaging, Extended Reality (ER), and Internet of Everything (IoE) will drive the telecommunication industry [39]. The requirements of the aforementioned industries and applications cannot be met by 5G networks. Thus, leading to the contemplation of 6G networks as an ultimate *ecosystem* of communication technology solutions [34]–[37]. It should be noted that the 6G network is not just about exploring new frequency bands, architecture, and access schemes to support high data rates.

Even though 5G network covers the requirements of future networks to a minimum extent, the 6G network must comply with the requirements such as extreme reliability, real-time ultra-low latency, and massive connectivity, simultaneously. The authors in [9] have categorized the 6G vision as four types, namely, intelligent, ubiquitous, deep, and holographic connectivity. In general, we suggest that as an ecosystem, 6G networks must envision to support the new application requirements of industry and society, especially with regards to the following seven metrics during 2030.

(*i*) *Data rate*: This is the ability to provide quality service for verticals ranging from autonomous high precision industry to immersive virtual/mixed reality applica-

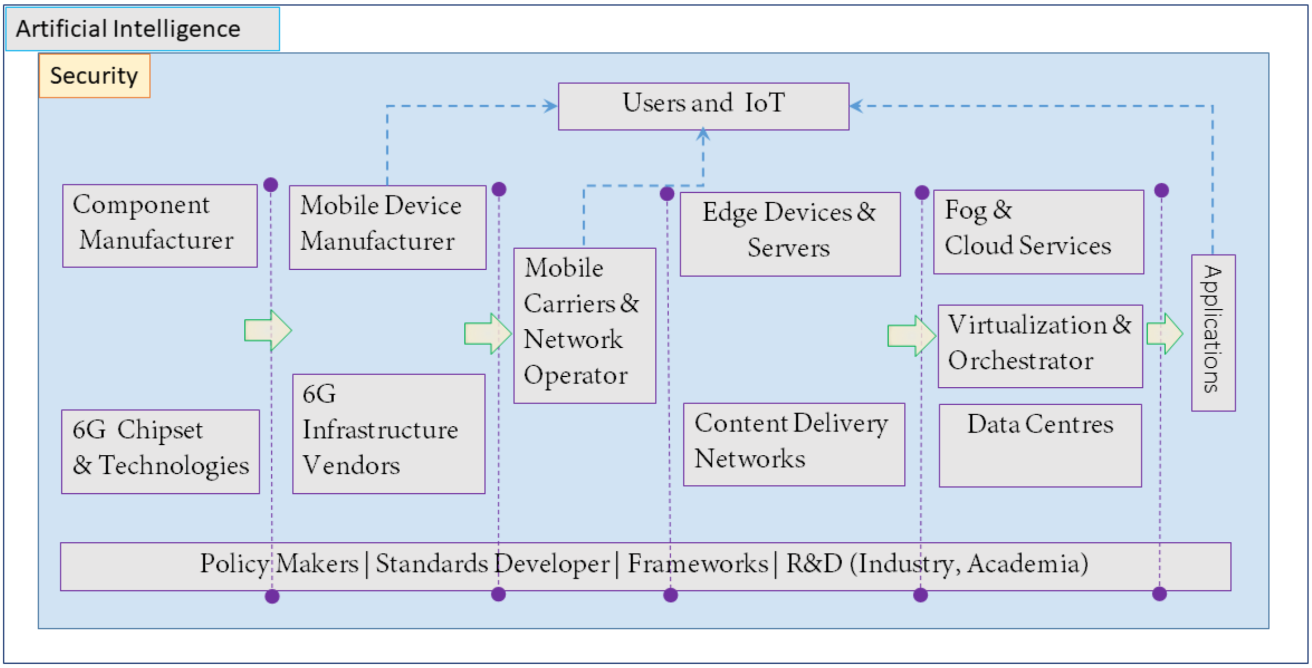

FIGURE 2. 6G ecosystem.

tions, (*ii*) *Latency*: This is the time-sensitive data delivery, (*iii*) *Super Coverage*: It means a three-dimensionally covering infrastructure that encompasses aerial, terrestrial, and underwater connectivity, (*iv*) *Sense of Feel*: This involves the support for holographic personal communication to tactile internet applications, (*v*) *Extremely low power consumption*: This stands for mobile devices that operate for a long time without requiring to charge, (*vi*) *high network density*: It means connecting of devices ranging up to 10 million/ sq.km, and (*vii*) high security with precise location information ranging from 10cm to 1cm [39], [53], [55].

TABLE 1 shows the KPIs that mandate the various verticals and use cases that will be supported by 6G.

D. USE CASES OF 6G NETWORKS

Let's look at some of the prime use cases of 6G networks along with the KPI requirements, as shown in Fig 3. These use cases will require a combination of KPIs simultaneously to deliver their services. Hence, they are challenging. The following scenarios will be more realistic in 2030.

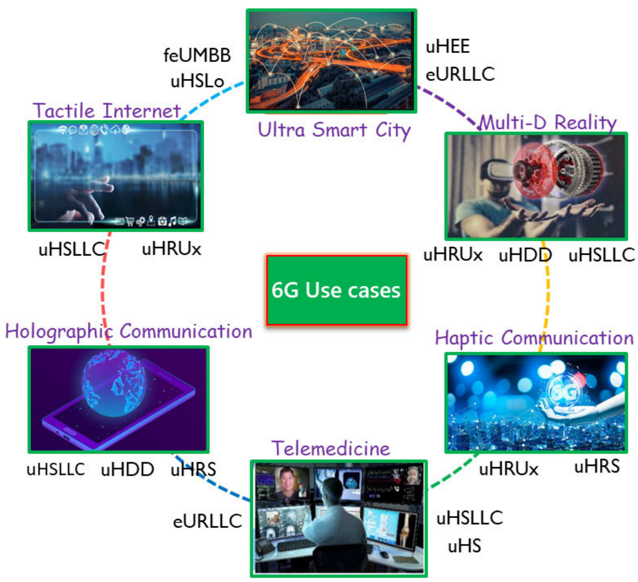

FIGURE 3. Use cases of 6G.

1) ULTRA SMART CITIES

5G networks will provide the user and application-specific QoS and quality of experience (QoE) through many verticals. For instance, telemedicine, smart agriculture, and smart industry can get the data service at specific data rate, latency, or priority. However, when we contemplate the future scenarios in an ultra-smart city, that may require, for example, a data rate of the order 1Tbps, 3D connectivity, localization within 1cm, and reliability of 99.99999999% for automated transportation, smart healthcare, or smart industry [46]. The KPIs needed for these applications in a smart city cannot be addressed by 5G networks [48], [108]. We shall consider a few more examples to visualize the scenarios. The mobility support requirements of 6G will typically vary from 240km/hr to 1200km/hr. A self-driving car needs to communicate with roadside sensors and other vehicles in the adjacent lanes to coordinate while moving at high speeds. Furthermore, the delivery drones on the fly may need to communicate with the ambulance on the ground to collect the medical supplies in the urban setting and transport it to remote locations.

TABLE 1. List of Kpi for 6g and typical values [46], [48], [96], [118].

KPI Category	KPI Values	Use cases
Peak data rate	1Tbps: DL/ UL Use experienced data rate: 10 Gbps/m^3,	uMBB uRLLC
Frequency Spectrum	4G, 5G (mm wave), THz, VLC	uMBB
Traffic Capacity	1–10Gbps/m^3	uMBB, uMTC
Network density	Devices: 10000000 /km^2	uMTC
Traffic density	100Tbps/km^2	uMTC
Data Generation	5 ZB/month, Data per device: 5GB/day.	uMTC, uMBB
Connectivity	3D connectivity	uMTC, uRLLC
Energy efficiency	Nominal ~High, 1 pJ/b	uHEE
Peak Spectral Efficiency	(100bps/Hz/m^3), 60b/s/Hz	uMTC
Localization, Sensing	<1cm- 10cm [3D], ~1 degree	uRLLC, uHSLo
Capacity per gNB	1Gbps~1Tbps/ m^2 [46]	uMTC
Availability	100%	uRLLC
Battery Life	20 Years	uHEE
Mobility Interruption Time	0 ms	Always available
Mobility	240km/hr~(1200km/hr)	Mobility
Processing delay	10ns	uRLLC
Bandwidth	At least 100MHz (at 3GHz), 30GHz (at 300GHz), and 300GHz ~1THz (at 3THz–750 THz VLC band)	uMBB
Latency	1 ms~ 100us	eURLLC [46]
Latency *	Control plane (<1 ms), User plane (<0.1 ms)	eURLLC
Link Budget	+10dB~+40Db	mMTC Industry
Jitter	1us~100us	eURLLC
Security	Nominal~ High	Smart Health, uHS
Coverage	1 m~50Km	mMTC, Smart Farm
Trust	High	Smart farm, eLearning
Privacy	Nominal ~ High	EBanking
Reliability	(99.99999% ~ 99.99999999%,	Eurllc
Synchronicity	<100ns	Eurllc
Satellite link	Exists	uMTC, long range
Slices Count	10000 slices/ operator	Support verticals

In another instance, drones may have to follow the cars to act as floating base stations or as relays to communicate the information as a part of inter-vehicular communication. It is worthy to note that the two scenarios involve radio communication between multiple entities under high mobility (say 500 km/hr). The 6G networks should support extremely low latency communication in the above scenarios, which is one of the key requirements of autonomous driving and decision making. These examples cover a few scenarios of future smart city and their communication requirements. But in general, high energy efficiency, high data rate, reliability, latency, precise sensing, and localization are essential for a smart city, as shown in Fig 3.

2) MULTI-DIMENSIONAL REALITY

Human-computer interactions that deal with the ultra-high-definition graphical contents such as online games based on Augmented Reality (AR) or Virtual Reality (VR), generates a massive amount of data. We would soon witness 3D games or multi-dimensional video that interacts with all the five sense organs of the body to create an illusion of real-world by combining VR and AR to render a true virtual gaming experience. These applications will be tangible within a decade as the computer technology, computing power, and storage space of the mobile devices multifold in their capacity. Nevertheless, when these augmented data to be transmitted through a wireless channel, we need extreme bandwidth, reliability, and data rate that 6G networks will offer. In other words, we need ultra-high reliability, low latency, ultra-high data density, and user experience, as shown in Fig. 3.

3) HAPTIC COMMUNICATION

Let us consider a smart healthcare system where an injured patient can only express her emotions by visualizing in her mind. In that situation, a smart headband can reconstruct the brain signals and represent it as a 3D video of the patient's imagination and communicate to the caregiver in real-time through mobile networks. In addition, a group of people who do not have a common language to communicate can use their imaginations, and disabled people get access to open the door, or to control the gadgets can use haptic communication. These haptic ways of communication will enable them to express the information by the sense of touch. It is one of the expected use cases of 6G networks, where the network supports high data rate which is much greater than 5G could support. The other scenarios of haptic communication include the brain-controlled computer interactions where people interact with their surroundings through haptics and control the environment through digital gadgets such as brain-embedded wireless chip that respond to human emotions [5], [105].

4) REMOTE SURGERIES AND TELEMEDICINE

5G networks can provide ultra-low latency of nearly 1 ms to critical applications. However, remote surgeries are extremely sensitive, with a latency requirement of much less than 1 ms (nearly 0.1ms) [149]. The remote robotic surgeries will require ultra-high precision and reliability of the data, high data rate to exchange data, and control signals between two remote health care facilities through the mobile network. The emergence of 6G networks will be a game-changer when telemedicine and remote healthcare will be taken into account by diminishing the space and time constraints [31]. Since 6G's vision is to provide at least 99.99999% data reliability and a 1 Tbps data rate, it will be the most suitable candidate to meet the above requirements. The main concern in the case of remote surgeries is the latency requirements. The 6G should target both minimum and maximum latency requirements, unlike the previous generation networks. That is because, during the remote surgery, some aspects of the transmitted data must arrive at the destination within a specified maximum latency, whereas some events should follow minimum arrival latency. These minimum and maximum latencies together will render coherent data at the receiver, which is the key requisite for remote surgery [31].

5) HOLOGRAPHIC COMMUNICATION

With the maturity of AR/VR applications, we will soon realize that the virtual experience is not serving us all the aspects of reality, and we need more. Recently, due to the outbreak of COVID'19 pandemics, virtual presence (telepresence) has gained high prominence over real physical meetings. This kind of task requires advanced VR techniques, bandwidth, and computations to project an object or a person in real-time remotely. As a future trend, each mobile phone will be equipped with more than five ultra- high definition cameras to capture an event and render multiple dimensional videos that give an immersive experience of the event being captured to all the human senses. In other words, a video may be a multi-dimensional real-time projection with the audio-visual effect of the person or object being telecasted in a virtual meeting. For instance, videos of 16 K resolution, 240 Hz scanning rate, and spherical coverage (360°) need to be transmitted as a hologram for a fully immersive VR experience [46], [115]–[117]. To transmit these videos or holograms that require several Gbps data rates, the existing 5G's KPIs such as data date, bandwidth, and reliability becomes insignificant [12], [39]. These transmissions involve a large volume of data. Besides, the angle of projection, response time are critical as well. For instance, if the audio or video response from the site of holographic projection has to be sent back to the source, then a precise and well-coordinated synchronization between the source and destination with respect to different layers of the image is essential. In another instance, consider a public concert where a remote artist can be rendered as a holographic presence (virtual presence) to entertain people from his local existence. Similarly, remote and hard to reach areas such as mines and deep ocean terminals will benefit from holographic applications where excavation activities and workforce training can be undertaken through holographic communication.

6) TACTILE INTERNET

In 6G networks, connectivity between various devices will be highly interactive in real-time (responsive), including the transfer of data, control, and feedback in real-time with a sense of touch [71]. Here one could transmit touch, feelings (sense), along with the information to give a live experience of the things virtually related to the information being communicated. To be specific, tactile internetworking involves a feeling of touch or taste along with an audio, video, or other forms of responses [9]. For instance, training the astronauts on space facilities, accessing underwater vessels/containers, and remote surgeries with the help of virtualized holographic models requires even a sense of touch to execute remote training and perform repairs with ultra-low latency. Furthermore, the transmission of smell and taste to enhance users' experience will be a major target of food industry to digitize users' experience of food access. As an example, while transmitting an advertisement of a particular type of food, its smell, texture, and taste shall be transmitted together with the help of advanced sensor technology and Apps to give a real feeling of the food. The 6G network will serve the need of these verticals due to its ultra-high data rate and low latency [18], [75], [88].

In summary, when we consider holographic tactile internet communication, different aspects of the hologram in the case of remote transmission may require varying amount of latencies (the minimum and maximum latency requirements), reliability, and user experience which need to meet by 6G networks to render a synchronized immersive effect to the human senses.

III. LITERATURE REVIEW

In this section, we will review the most recent literature that motivated our research. First, we categorize the publications based on the topic of research, and later, we present their contributions. Altogether, we have considered 158 recent articles, specifically on 6G networks and its components. For easy reference, we have listed them categorically in Table 2.

6G vision, technology, prospectus, and challenges: First, the vision statement of the 6G networks, as defined by all researchers, pointed out that 6G networks will be a breakthrough in transforming the smart cellular network into an intelligent network. These studies have anticipated the emergence of 6G networks by 2030 and have listed several interesting technologies, applications, and use cases that will benefit from the 6G networks [1]–[5], [9], [19], [31]. The technologies such as AI, Intelligent surface, holographic radio, blockchain, three-dimensional connectivity, cell-less architecture, quantum computing, and wireless power transfer will revolutionize future networks [19], [28], [31], [43]. Furthermore, the authors elaborated on the targets and features necessary to meet the requirements of the use cases. In general, most of the technology components of 6G networks are in the infancy stage. Therefore, there will be several challenges, such as training the AI models, security issues, lack of architecture, signal modeling, and computational facilities [96]–[98]. In addition, the authors have proposed several KPIs for future networks, compared them with 5G networks, and listed several technology gaps in the inception of 6G networks [35], [39], [40], [107].

Next, we review *photonics and* VLC. We noticed that VLC and photonics will be the primary components of 6G's terra hertz communication [10]. Consequently, authors in [12], [17] have drawn a roadmap to VLC for its inception in 6G networks. Another key aspect of 6G network will be the *AI and edge intelligence*. AI will be used by 6G networks at all levels starting from the PHY for channel selection, MAC for achieving power efficiency, and at the application level for context awareness [13], [42], [47]. Moreover, AI will spread across various network entities in 6G ecosystem, such as the sensing, edge, and cloud devices, in a distributed way to manage the *small data* generated locally and *big data* to be processed centrally to minimize the latency to the minimal level [36], [60], [61], [72]. In addition, the authors at [13], [34], [42] have discussed various ML algorithms that would benefit from the 6G networks at the various operational levels of the network. During 2030 and later, 6G networks will open doors for several verticals and markets due to its performance metrics. These business models for selected verticals have been discussed in [16], [23], [24], [50].

Another technology component of 6G networks that will revolutionize wireless communication will be *reconfigurable intelligent surfaces* building using meta- materials or smart objects [29]. These surfaces will essentially direct the data toward the destination using their electromagnetic reflection property to achieve high-quality reception without any external power sources [59], [70]. Similarly, another category is *machine type communication* and ultra-dense IoT networks.

The authors in [7] have exclusively discussed the machine type communication and its components for the 6G networks. The other category in our review is an interesting technology component, i.e., *quantum communication* (QC). In [71], the authors detailed a state of the art work on QC for 6G networks, including the scope of machine learning in QC.

Furthermore, we have discussed, all the architectures and their key features, the issues involved with the digital divide, and rural connectivity, the scope of business models and THz communication, cell-less architecture, ecosystem and its components, etc.

Please see Table 2, for a detailed discussion on the various literature on different categories of 6G technology, and their contributions.

IV. 6G ENABLING TECHNOLOGIES

In this section, we will discuss the prime features, their types, need, challenges, etc., of various technologies that enable 6G communication. In Fig. 4, we have depicted these technologies. We reckon that 6G will integrate three aspects namely physical, biological, and digital world as shown in Fig. 4. This intuition shall be elaborated as in the case of 6G networks along with the typical radio frequency communication, it will include robots, digital twins, artificial intelligence, emotion-driven devices, smart communicating surfaces, communication through brain implanted chips or brain-machine interface [136] to enable all-round cyber-physical-biological communication experience. Consequently, 6G will be much more than the present *smart* connected networks, where the network components will largely integrate *intelligence* to bring in a paradigm shift from smart to intelligent network as shown in Fig. 4. Further, we have discussed eight enabling technologies for 6G namely, artificial intelligence, THz communication, 3D connectivity, Visible light communication, blockchain, quantum communication, intelligent surfaces, and digital twins.

A. ARTIFICIAL INTELLIGENCE

Why AI for 6G: In 5G networks, the network orchestration functions lead to a flexible network slicing feature. Consequently, the specific requirements of most of the verticals could be met without depending on AI to a greater extent. However, we address the applications that are beyond the service limits of 5G networks in 6G networks. We reckon that due to the following reasons, AI is essential for the 6G networks [60]–[61].

(*i*) We anticipate that in 6G networks, there will be a plethora of heterogeneous network components that interconnect via multiple numerologies (3D connectivity) to serve diversified verticals, process a large amount of data, and they demand varying levels of QoS. Addressing these tasks require efficient analysis, optimization, and decision skills. Therefore, at every level of the communication system, say user terminal nodes to edge processor, and core network, *intelligence* has been deeply embedded and integrated to offer end-to-end services.

In addition, in such contexts, relying on existing architecture or time-consuming mathematical models for optimization of performance metrics may not lead to feasible solutions [7], [56]. Moreover, these user applications give the idea that the 6G network is much complex in terms of network structure and dynamics than the earlier generations. Consequently, it requires assistance from smart, adaptive, and intelligent AI agents to self-learn from the network inputs to adjust the offered services with dynamism and optimize. Generally, this scenario suggests that 6G architecture must target automation through AI. Precisely, those tasks such as resource allocation, reaching the targeted KPIs, mobility management and handover, policy and billing, services for various verticals, orchestration, and quality of service ought to be AI-driven by considering the volume, the heterogeneity of data, and its analysis to improve the performance [2]. Thus, making the network self-operative, manageable, and self-sustained under any network conditions [36], [61].

(*ii*) Similarly, at the physical layer, sensing and detection from sensors require the spectrum sensing to address spectrum scarcity problem, whereas interference detection requires a dynamic and massive volume of data collection. In this context, AI techniques such as Support Vector Machine (SVM) for real-time spectrum sensing and Convolutional Neural Network (CNN) for cooperative sensing would be proved to be effective solutions [36]. In addition, when we consider physical layer modeling in the presence of channel non-linearity, AI methods perform better than simple mathematical models, which may have unacceptable time complexity. For instance, Deep Neural Network (DNN) and CNN-based supervised algorithms have been proved to better than traditional methods [61].

1) CURRENT TRENDS IN AI

There are different types of AI systems (say ML) for wireless networking, which seems promising for 6G networks, namely, supervised, unsupervised, and reinforcement learning. Currently, a large body of research focuses on the use of AI and its derivatives, such as deep learning and machine learning to optimize the wireless networks' performance of [13], [34], [72]. AI will be pivotal in Radio Access Network (RAN) and the virtualized core network of 6G networks, including edge computing, resource allocation,

TABLE 2. List of literatures on 6G and their key contributions.

Reference	Category	Research Direction and contribution
[1,39] [98,108,112,124-125,149,151,157]	**6G Vision**: Technologies, Opportunities, Challenges.	▪ A state-of-the-art from the First Generation networks to 5G networks is discussed. Further, the article narrates the need of 6G, compare them with 5G network and predecessor technologies, and its vision from the user and service classes' perspective and taxonomy. Moreover, the literatures have foreseen the future directions in the development of 6G networks, such as zero-energy networking, secure business models, next-gen IoT, and unified services.
[2,40,133,96-97,140,115]		▪ Foreseen applications of 6G networks, such as smart city, extended reality, haptic communication, remote healthcare, robotics, and human computer interaction are presented. Next, technology requirements of these applications, plausible technology enablers, and its challenges were discussed. ▪ Some specific vision requirements for healthcare [97], haptic communication, autonomous driving [140], security, latency, data rate, resilience, computation were reported.
[3,43,115,120,127]		▪ The authors discussed the key enablers such as pervasive AI, cell-free networks, meta materials, wireless power transfer, and quantum communication along with their merits, while providing a generalized vision of 6G networks and its use cases.
[4]		▪ The articles discuss the generalized new architecture of 6G networks w.r.t infrastructure view (terrestrial, underwater, and space), control view (AI at the edge, physical layer, AI for distributed components), and network view (components at different layers).
[5,9,35,18]		▪ This article presents a new vision for 6G networks by integrating the anticipated applications, key features that promote these use cases, and technology components to support the features. It further throws light on multiple open research problems. ▪ Moreover, in [18], the authors highlighted several crucial human factors on which 6G networks depend, such as dependency on basic science, industries, health and social issues of users, social factors for worldwide connectivity, and business models.
[19,28,31,96]		▪ 6G networks were classified by a new vision of 6G networks as deeply learned, holographical connected, and ubiquitously covered network. It presents a detailed study of communication requirements, available technologies, and challenges of the next generation networks. They also presented a new KPIs for 6G networks to address various application requirements.
[117,152]	**Intelligent Healthcare**	▪ The authors proposed a framework for intelligent healthcare in the 6G network. The paper also studied the requirements of 6G networks for intelligent healthcare, including AI, Medical IoT, wearable devices, and augmented reality. ▪ The authors in [152] narrated the possible enhancements in smart healthcare due to the inception of 6G networks. It predicted that with the aid of Bio-Nano things, there would be three body communication patterns, namely, in-body, on-body, and off-body to communicate patient data to the intelligent processing systems, and 6G network will enable these services.
[10]	**Photonics and VLC**	▪ This article discusses the role of photonics in the 6G networks, in addition to AI, and holography. It presents a general framework of photonic for RAN, and cognitive radio for 6G networks.
[12,17]		▪ It describes the 2030 roadmap of 6G networks in general, and VLC in specific, while highlighting the technology mile stones. In [103], authors also provided a state-of-the-art of features, strength, and challenges of optical wireless communication for 6G networks.
[103,147]		▪ The authors proposed an algorithm for data security in VLC using watermark technique for 6G networks. In [147], several novel concepts such as hybrid-radio optical networks, interactive VLC, optical IoT, and their challenges were discussed.
[36,60,61,118,159]	**Artificial Intelligence:** AI for Edge, and Machine Learning (ML)	▪ These articles review the use cases of AI techniques for 6G networks, including applications of AI in mobile edge computing, handover management, and spectrum management. In addition, they discuss the key research directions and plausible solutions of AI in 6G networks communication scenario. ▪ The papers also propose a new AI architecture for 6G networks. They further explain the technologies to convert software-based network to an intelligent (AI) driven network.
[13]		▪ It envisions the role of AI for 6G network wireless communications, and signifies the role of AI agents in autonomous driving.
[34,42]		▪ These papers put forward a vision for distributed edge computing with AI targeting autonomy, learning capability, and context aware services. ▪ The white paper focus on edge computing, intelligence at the edge, training the intelligent ML algorithms, their challenges. They also provide a key for the intelligent edge computing system for 6G networks. Additionally, they consider the security, pricing, and user requirements from intelligent edge in the discussion.
[47,72,155]		▪ These white papers describe the various ML algorithms for the different layers of (Physical, medium access, and application) wireless networks, especially targeting 6G networks.
[14,30,99,150]	**Block chain**: and Security in 6G	▪ The authors presented the significance of block chain technology from the perspective of security and privacy in 6G Technologies. It highlighted the challenges and opportunities in the implementation of block chain. ▪ The authors in [99][150], pictured a broader scope of security in 6G networks, especially how different components like visible light, quantum communication, and block chain will contribute toward security.

TABLE 2. *(Continued.)* List of literatures on 6G and their key contributions.

[15,104,89-90]	**Cyber Twins**	▪ Authors present a cyber-twin-based cloud-centric architecture for 6G networks. Here, cyber twins reside in the edge device to offer end-to-end connection. They further recommend the use of cyber twins as communication assistant, network data logger, and digital asset owner, while highlighting their features.
[16,50] [23,24]	**Business Model**	▪ The authors here proposed a blockchain based decentralized resource configuration prototype for various verticals and business applications of the 6G ecosystem. ▪ The white paper enlightens the readers with the business scenarios for 6G in the next decade, its key trends and uncertainties. The authors mentioned three scenarios, namely, user experience, sustainability, and business, to propose their models. ▪ The authors narrate the performance attributes and value impact for the sustainability and efficiency of 6G network business models. Their study concludes that 6G business models can rely on scalability and sustainability.
[20,73,125]	**Resource Allocation** in B5G and 6G	• The papers investigate the multi-user resource allocation in WDMA for high data rate optical communication for indoor 6G network applications. They formulated a mixed-integer linear programming model to address the resource allocation issues in the diversity and imaging receivers. • The authors in [73], formulated a problem of radio resource allocation in massive machine type communication to meet the diverse QoS requirements. The design uses a grant-free access scheme as useful to the future 6G networks, which is also endorsed in [142].
[21] [22] [25] [122]	**Eco System:** Framework, and Life Critical Applications	▪ Authors presented a unique theoretical foundation for the 6G ecosystem, encompassing the eco system's structure, process, goals, outcomes, and contingencies. ▪ It analyzes the requirements for the 6G framework by comparing with 5G networks and studying the vision of the features of 6G networks. Further, the authors proposed a high-level capability enhancement framework for 6G requirements. ▪ Investigates the short-range life critical applications such as intra-vehicle, intra-body critical communication using 6G networks. The study proposed a subnetwork that operates as an underlay in the 30 GHz band, which coexist with other networks, and offer the requirements of extremely low latency and reliability. ▪ The article discusses the design aspects of Wireless Isochronous Real-Time (WIRT), a new use case of 6G networks, which requires extremely high reliability as applicable to life critical services. Further, this work evaluates the required bandwidth to achieve reliability in a densely deployed network.
[29] [59,70,91,119,130] [123,128,144] [138]	**Reconfigurable Intelligent Surface**, **Holographic MIMO**, Metamaterials, Intelligent Surfaces.	• The authors have envisioned that reconfigurable intelligent surface (RIS) will be one of the technology components for 6G networks to act as relays to intelligently modify the transmitted signal and offer a high data rate despite channel disparities. Further, they also discussed the challenges and future scope of this technology such as the design of metamaterials, beamforming for multi-user systems in RIS. • Describes the potential application of intelligent surfaces for holographic communication. Besides, it explains the future research directions and challenges of intelligent materials for holographic communication. • The work in [123], narrates a state-of-the-art study on back scatter communication and non-coherent detection for 6G networks to enhance the energy efficiency, and reliability by the usage of environmentally scattered signals. • Index modulation is the key for 6G networks. In [128], the authors investigated the use of index modulation and multiple-input multiple-output (MIMO) for intelligent surface transmissions. The proposed method is power efficient and does the beam scanning at a lower size, weight than the existing schemes.
[32]	**VANET**	• The paper investigates the throughput in 6G vehicular network scenario by the use of user channel quality sensing and network-based load estimation. The authors recommend sharing of traffic load information with the UEs to enhance the performance of the proposed method.
[7]	**Machine Type Communication**	▪ The authors discuss six enablers specifically targeting the machine type communication in 6G networks; namely, massive connectivity, security for MTC, distribute edge computing, wireless power transfer, AI and ML, and emerging verticals.
[71]	**Quantum Communication and ML**	▪ The article envisions that Quantum Computing, and Quantum ML (QML) will play a key role as technology enablers of 6G networks. Further, the authors provided a state-of-the-art study of quantum communication, application of ML to quantum communication, challenges, and future scope for the 6G networks.
[33,55]	**Trust Networking**	▪ Trust networking model, named customer edge switching model for 6G networks was proposed. They narrated the trust policy, regulations, and explains them with several use cases. ▪ This white paper narrates the need of trust model, and the challenges in 6G networks. Moreover, they described the use of trust models in PHY, network (i.e., crypto and post quantum security) layers in detail.
[37,38,44,93] [86,106]	**Future Networks**- 2030 and Scope.	▪ These white papers discuss the features, challenges, business models, technology components of next generation networks, especially B5G networks that would emerge in 2030.

TABLE 2. *(Continued.)* List of literatures on 6G and their key contributions.

		▪ The paper [44] gives a broader vision of 6G networks, including the key drivers and use cases by considering the 2030's sustainable development goals (SDG). ▪ In [86], the authors narrated the future of telecom network during 2030 under the light of 6G networks, and highlighted the significance of cyber twins, extended reality, and holographic communications.
[53,158]	**Localization**	▪ The white paper narrates the future localization and sensing opportunities for 6G networks. The authors illustrated the significance of localization in the future 6G networks use cases, and proposed various localization methods that are applicable to future technologies, such as intelligent surfaces, ultra-massive beamforming, and THz imaging ▪ Further, the authors in [158] presented tutorial on localization techniques, classifications, merits, demerits, significance of localization in different layers on 6G networks architecture, future trends in localization, and the role of wireless communication and localization in 6G networks.
[46]	**Validation and Trials**	▪ A clear roadmap for the development and commercialization of 6G networks is defined in [46]. Furthermore, software testing for different verticals that span from mobility, banking, to agriculture are discussed. It proposes the guidelines for trials and validation activities for various verticals.
[104,114,139] [140] [136] [102] [105] [108]	**New Architectures**	▪ In [114], a three-level intelligent deep learning-based architecture is defined for 6G networks. These layers encompass intelligence at the device (user level), at the edge (cell level), and in the cloud (network level). It mainly does user traffic prediction, scheduling, and user association at these levels, respectively. ▪ The authors in [140] defined a high-level 6G network architecture, where storage, compute, and networking are done at the same level. The architecture consists of three layers, namely, AI layer, user later, and control layer. The user layer is flat and is defined between the access network and the internet. The control layer and AI layers are distributed and virtualized for various services. ▪ An emulation of the human brain's intelligence to the 6G network was proposed in [136]. The new architecture defined how wireless implants in the brain shall communicate with surrounding 6G wireless infrastructure by amalgamating the theories from neuroscience and wireless communication. ▪ A cyber twin-based architecture for 6G networks as proposed in [104] consists of cyber twins at the edge devices between the user and cloud to act as a digital representative of the user to assist in data log, and in communication as an assistant.
[31,39-40,96,121,134]	**Cell-free 6G** Networking and 3D Connectivity	▪ The authors in [31,121,134] envisioned that 6G networks would have the aerial connectivity along with the terrestrial and underwater coverage to have communication in 3D space. Further, the aerial connection is easy to establish by the support of UAVs. ▪ In [39], cell-free architecture for 6G users was proposed. According to this concept, a user need not be attached to a single base station or a gNB for connectivity. Instead, a user will be sharing resources from multiple gNBs as if they belong to the same gNB or RAN. ▪ Similarly, in [40,96], the authors narrated the ideation on cell-free MIMO, where a user will be served by multiple gNBs' simultaneously to avoid interference, and the central coordinator will coordinate the communication.
[95,129,141,112]	**Power efficiency**	▪ These papers asserted that self-sustainability would be one of the key requirements of IoE devices in 6G networks. Therefore, the devices shall manage the power efficiency by the adoption of cell-free and intelligent surfaces in communication [95]. ▪ Furthermore, the wireless power transfer, solar cells, and outdoor devices were suggested for IoT devices, minimizing channel state information (CSI) in 6G networks [129,141]. The ambient RF signals shall be made to power the communication nodes in the surroundings to enhance their battery operation as a part of wireless power transfer [129].
[156-157,107,52] [48]	**Digital Divide and Broadband Connectivity**	▪ 6G broadband aims to support 1Tbps at extremely high mobility of 1000 km/h. To achieve the said goal, the authors in [48] suggested that sub-GHz, VLC, ultra-massive MIMO, holographic radio, and THz communication are required at the physical layer level. Furthermore, to achieve lower latency and higher reliability ML based optimization, a full-duplex radio, new modulation schemes, and rate-splitting will be necessary. ▪ A Digital device is one of the key concerns of the 6G networks as it has not been addressed effectively by the previous telecom generations. In [52,156,157], the authors proposed several solutions such as multi-hop service, recommendations for the front, mid, and backhaul, 3D coverage through drones and satellites, and spectrum co-existence to bridge gap in connectivity.
[111,113,153,132] [57,26]	**THz Communication**	▪ In [153], the authors reviewed the recent trends in THz communication, its challenges, and future research directions with respect to THz devices, THz channel, and space-based THz systems. In [57], the authors experimented with several aspects of THz communication B5G networks: measurement of propagation and partition loss, beam steering, and spatial consistency. Further, they have summarized several properties of THz communication. ▪ The authors in [111], defined different use cases of THz communication, such as THz IoT, THz-WiFi, THz-backhaul, and THz-space communication scenarios. In addition, they focused on challenges of THz communication for these use cases. ▪ An antenna model for THz communication is investigated in [26]. It studied a nano antenna model with the Plasmonic charge distribution principle for THz communication in 6G networks. The proposed mathematical model investigates the device model in THz and physical behavior in frequency and space domains.

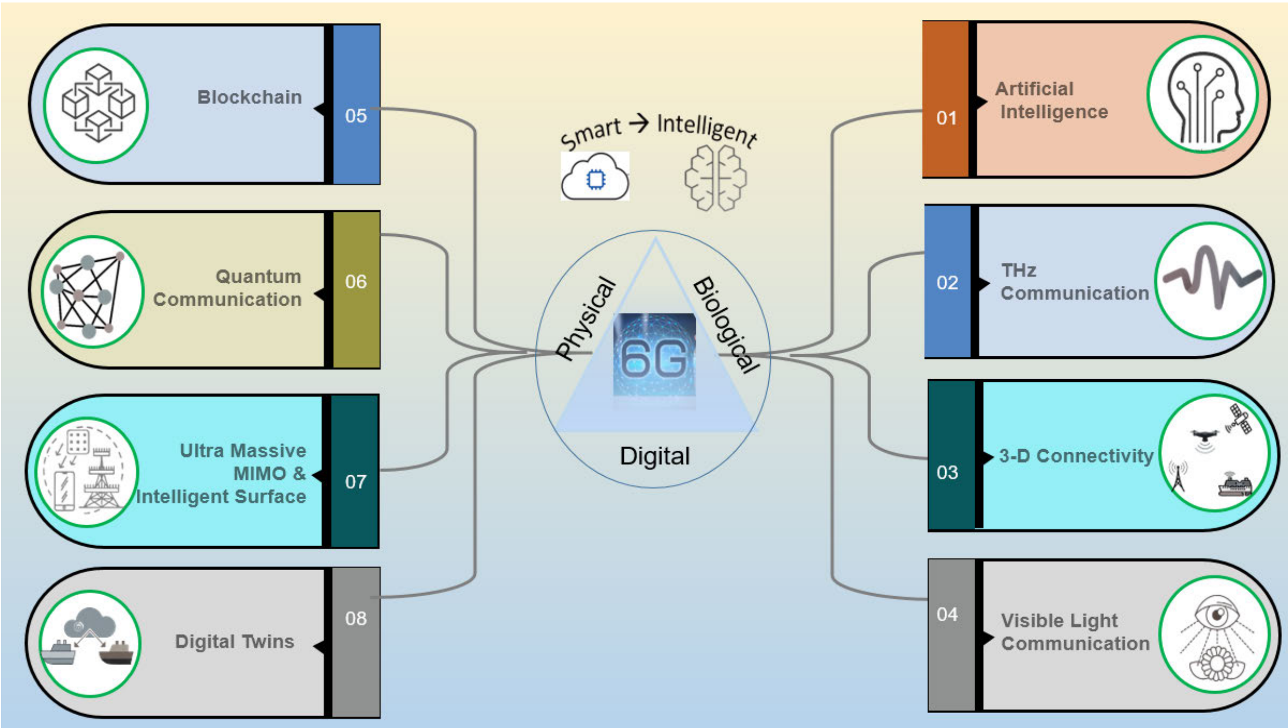

FIGURE 4. Technology enablers of 6G.

slicing, control, and applications. However, how exactly AI would support the core 6G networks has to be realized in the future as a finalized architecture for 6G networks is yet to be devised.

Tariq *et al.* [3] has opined that AI will be pervasive in distributed 6G architecture, where various network components would adopt federated learning. AI will be operating in distributed training agents at different network entities that will support individuals and the overall network's benefit by a collective operation. The AI scenarios, specifically deep learning algorithms, will suit the analysis of big data generated by several IoT nodes when processed centrally in the network. In addition, to enhance network performance, the wearable sensors will incorporate the computing and data aggregation features locally along with sensing and communication. That means 6G networks necessitate another context, where data processing is done locally at the edge/fog devices in a distributed way for delay-sensitive applications, which could be done using reinforcement techniques [5], [42]. The authors in [60] have endorsed that locally generated data by various subnetworks of the 6G network might be processed locally using AI techniques to attain efficiency in terms of reduced latency and overhead. Furthermore, AI could be integrated into the radio access network to infuse cognitive capabilities for efficient channel selection from the physical channels such as THz band, visible light communication, Wi-Fi, satellite link, transmission power, and modulation scheme selections. AI at the application layer can manage various smart processes such as automated driving, smart healthcare, and improved performance by suitable data learning methods. On the same note, the study in [4] has identified three categories of AI systems for 6G networks. (i) AI at the *network edge* supports low latency applications with real-time data processing capability instead of a cloud-based centralized AI system. (ii) AI-enabled radio that decouples *physical* hardware (i.e., transceiver) from the software with control functions to enable AI-driven dynamic and intelligent decision making using the data received from the transceiver. For instance, interference avoidance, cell selection, channel estimation, etc. (iii) Distributed AI, where each network entity will be capable of running the AI algorithms in parallel, using the local data in a distributed manner before being sent to the centralized cloud [43], [102].

2) AI ARCHITECTURES 6G

In the literature, there exist two AI models for 6G network architecture. We will review both of them briefly in the following paragraph.

AI Model 1: Let us consider how AI finds its place at different levels of a network. An AI-based layered architecture for 6G networks, as defined in [36], has the following realizations.

a) *Layer 1*: This first layer occurs at the RAN, where several sensors such as robots, cameras, mobile devices, and connected vehicles sense real-time data and communicate to the Access Point (AP). In this context, efficient environmental data collection, intelligent channel estimation and interference management (including the scenario of cognitive radio), ultra-low latency, and high reliability shall be possible by enabling AI techniques in these devices. Otherwise, data collection in a rapidly varying environment and channel selection during multiple devices' simultaneous operation will pose challenges. For efficient real-time sensing, SVM, DNN, and CNN methods are recommended.

b) *Layer 2*: Next, as the data arrives at the Access Point (AP) level from layer 1, the massive data collected from the sensors require analysis (temporal or special), processing (to reduce the redundancy), computing, and storage. In particular, data analysis and mining filter the redundant content to tailor the data set to a reasonable quantity. At this point, well-known AI techniques such as Principal Component Analysis (PCA) and Isometric Mapping (ISOMAP) can now be employed to compress the raw data. With intelligent data analytics, critical network data patterns can be studied to improve the overall performance.

c) *Layer 3*: In the third level, data from the AP, or e-NB is sent to cloud computing and storage. These clouds or edge computing facilities will be NFV and SDN controlled virtualized network entities. At this level, the controllers equipped with intelligent agents will make decisions regarding learning and decision making by the knowledge obtained from layers below it. It includes resource allocation functions, power control by considering the network slicing requirements of various applications. Further, AI agents control handover and optimize the physical layer parameters such as deciding the precoding matrix, rank index in massive MIMO transmissions, and edge computing by learning from the knowledge obtained from the previous lower levels to meet the high-quality service requirements. The main AI methods for efficient decision making regarding optimal parameter selection in massive MIMO or smart reflecting surface (polarization, precoding matrix, phase, and rank indicator, etc.,) in 6G network can be performed through the Markov decision process, reinforcement learning methods.

d) *Layer 4*: Finally, at the application level, AI will assist in delivering specific services based on the needs of each application or verticals. For instance, data service for the 6G eMBB user and ultra-low latency for robotic-assisted smart healthcare can use AI techniques to automate the network functionality, self-management, and self-organizing features [36].

AI Model II: Now, let us see the O-RAN Alliance, which is an Open RAN alliance formed by five global telecom operators for B5G networks, though not specifically for 6G [61]. Albeit, it provides a framework for integrating AI into the future cellular network. We summarize the key points as follows. Here RAN is coupled with AI features to handle *non-real-time* (latency less than 1 s) and *near-real-time* (latency 10 ms–1 s), and *real-time* services. This architecture has a multi-radio protocol stack to support heterogeneous radio interfaces.

i) At the physical layer, deploying AI will enhance channel estimation for MIMO, receiver symbol detection without much regard to channel state information (CSI), and channel decoding. As discussed earlier, AI techniques such as learning-based DNN for channel estimation, and detection will prove fruitful.

ii) Further, at the MAC layer, spectrum access in the outset of multiple radio interfaces will be the key requirement. However, employing spectrum access schemes for individual access technologies (as in existing practice) will prove inefficient as 6G networks will have heterogeneous access technologies. Therefore, to facilitate distributed channel access for multiple radio access technologies, learning based dynamic spectrum access technologies, such as deep reinforcement learning-based distributed spectrum access method shall be adopted [61].

This architecture defines two interfaces, namely, A1 and E1 to support non-real-time and near-real-time access layer, respectively.

iii) Similarly, at the network layer in 6G network, the resource allocation and management tasks are herculean task by traditional methods due to the high density of connected devices. Therefore, it is recommended to use methods such as AI-driven trouble shooting, knowledge data for fault recovery, and root cause fault analysis by an AI model. Second, the management of virtualized network functions at different virtual networks, tuning the MIMO parameters for setting the beam width during mobility can be achieved with reinforcement learning algorithms [61].

Additionally, the authors in [60], have proposed an intelligent radio for 6G networks that enables the future upgrade of radio receiver, introducing an operating system between transceiver hardware and its software. The operating system will be capable of reconfiguring its algorithm to improve the performance by sensing the transceiver parameters and other inputs with the help of an interface. The DNN-based implementation of the intelligent radio will be low cost, and flexible.

B. THz COMMUNICATION SPECTRUM

The 6G communication will span across microwave (300 MHz–300 GHz), infrared (300 GHz–400 THz), and visible light (400–800 THz) frequencies, ranging from long distance to short distance coverage, while coexisting with the previous generations. However, 300 GHz–3 THz expanding up to 10 THz which is popularly known as *Terahertz* (THz) spectrum is a new frequency band for cellular communication, which 6G networks will exclusively target to offer extremely high data rates [4], [75].

1) NEED OF THz SPECTRUM

Spectrum is the fundamental and sparsely available resource for wireless communication. From the discussion of 6G's plausible use cases, and expected KPIs, it directly boils down to the point of bandwidth and spectrum resources to support these data applications. The 5G network will explore sub-GHz, and frequencies up to 30 –300 GHz, (with a maximum bandwidth of 400 MHz) to offer millimeter wave communications. However, the offered bandwidth may not suffice to meet the services that have dual requirements like ultra-low latency combined with high data rate or vice versa, because that strains the bandwidth [10], [57]. Anyway, 6G network being the successor of 5G network, will continue to use the microwave, mm-wave frequencies along with the future THz frequency bands, where tens of GHz chunk of frequency (spectrum) are available [9]. Recently, along the same lines, 6G research has been triggered by the US Federal Communications Commission (FCC) by announcing an experimental license for 95 GHz to 3 THz spectra, along with granting 21.2 GHz of spectrum for unlicensed communication [24]. This major step will motivate many researchers to explore THz band in-depth.

The need for a new spectrum arose as the lower GHz band will be much occupied (5G family). As a result, providing a large chunk of frequencies to next-generation networks to support high data rate will not be feasible. Therefore, ITU-R has foreseen the need for an exclusive spectrum for B5G networks and has recommended 275 GHz - 3 THz frequencies that include the microwave and optical frequency bands. This Terahertz frequency band will offer a nearly 60 GHz unoccupied spectrum, sufficient to provide a Tbps data rate [3].

2) OPPORTUNITIES

THz communication offers several opportunities due to its unique properties. As a result, 6G networks will prefer it for short-range high-speed communication and space communication between satellite and ground stations. Meanwhile, the availability of wider bandwidth in THz frequencies makes the high data rate feasible. Next, high-frequency communication leads to miniaturization of the circuit (device). As a result, multiple antennas, an array of antennas can be accommodated into the user devices. This facilitates the use of efficient multi-antenna MIMO schemes, beamforming, and interference suppression to enhance the quality of communication [107]. Furthermore, these high-frequency signals will follow the line of sight (LoS), and are highly directional, resulting in less susceptible to jamming and are secure. In addition, the frequencies above 100 GHz are least affected by rain/moisture. The THz range will give rise to extremely tiny cells (say 10's of meters) to support a high data rate mobile broadband communication in local space for special applications in the future. Short wavelength and pulses with well resolute time make it an ideal candidate for super-precise positioning [24]. With regard to the space communication, certain wavelengths like 600–870 micrometer are well suited for long-range communication at low noise and low power [111], [120], [122].

3) CHALLENGES

THz waves will significantly affect large-scale fading and shadowing. It has been reported that signals below 100 GHz face large attenuation due to moisture in the air [120125]. Further, it has a relatively higher free space loss compared to lower frequencies. At 1 THz, the radio signal will experience high absorption from water molecules, oxygen in the air [28]. In addition, shadowing will immensely influence propagation. A study says the human body may attenuate the signal by 20–35 dB [9]. Another challenge will be at high frequencies design and fabrication of transceivers for mobile devices is extremely complicated [127]. Besides, the power required to handle the high frequency processing such as Analog to Digital Conversion (ADC) for sampling is yet to be known [28], [132]. There is currently a lack of study on the channel characterization of THz frequency signals, the support for inter-frequency mobility, handover and the physical layer protocols [5].

C. UBIQUITOUS 3D COMMUNICATION

One of the significant requirements of the 6G networks, as different from the previous generations is to have all round global connectivity such as high altitude, underwater, and terrestrial connectivity to adeptly accommodate a wide range of verticals. With this vision, 6G networks target to achieve extended and continuous communication between humans and smart things, machine-machine such as underwater vehicles, UAVs, or spacecraft, and robots [75], [121]. In 2030, communication between terrestrial, aircraft and satellites, and ships will become more obvious [9].

Let us see the scenario more in detail. Refer Fig. 5 where we have pictorially represented the scenario. Concerning the network densification, 6G networks is anticipated to see an un-presidential increase in the number of user terminals, where users will be capable of networking with other terminals either in the same level (terrestrial-terrestrial) or at different levels (terrestrial-aerial, terrestrial-underwater, or aerial-underwater) via multiple radio access networks. Furthermore, it will be a common scenario where a user will have network connectivity with multiple cells with resources being shared among those cells by mutual coordination. As a result, the concept of a cell will diminish i.e., the *cell-less architecture* will emerge to have infinite freedom with multiple RAN connectivity feature to endorse all round connectivity [134]. The emergence of cell-free in 6G networks will bring in the need of heterogeneous technologies such as satellite, UAV, submarine, and deep-sea connectivity to coexist and integrate with terrestrial THz RAN to enhance the data rate, coverage and seamless, flexible connectivity aspects. The proposed feature shall address the issues of present networks such as delayed handovers, mobility, data loss, etc., to offer better quality of experience to the users [31], [142], [124]. In the following paragraph, we will visit the various components that constitutes 3D networking.

1) SPACE COMMUNICATION

The three main patterns of space communication consist of (*i*) communication between the earth satellite transponders and low earth orbit (LEO) satellites, (*ii*) 6G cellular base station, cellular users, and UAVs, and (iii) UAVs, aeroplanes, and 6G base stations.

It is a well-known fact that the existing communication satellites mainly belong to the Geo Stationary Orbits (GEO)

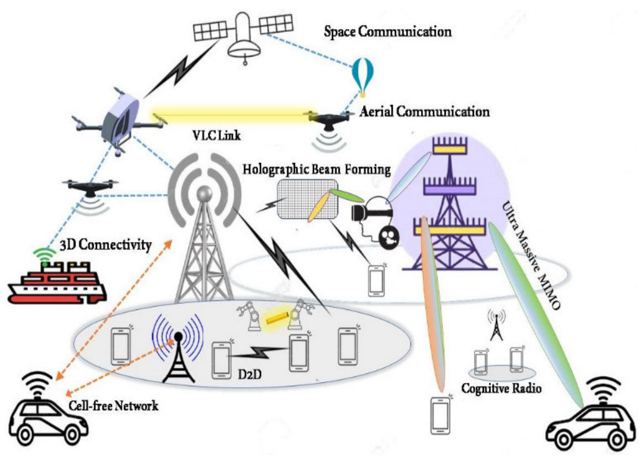

FIGURE 5. 3D communication scenario in 6G.

that impose large delay for terrestrial mobile communications. Consequently, theoretical studies in the literature have envisioned mobile broadband amalgamation with LEO satellites [121]. It has been reported that several countries like US, UK, and China have planned their satellite missions. For instance, China has planned to launch nine such LEO satellites (Hongyan) by 2025, into its cluster of 320 satellites [4]. These satellites may provide direct coverage to the terrestrial station (transponders) or to ships. This is the first pattern of space communication.

These LEO satellites will offer extended coverage, high-speed data, low latency communication support to terrestrial communication in conjunction with GEO satellites that acts as backbone network [22], [149].

2) UAV BASED COMMUNICATION

Recently, UAV's have been extensively used as relay nodes to extend cellular coverage. At a little lower altitude than satellites, UAVs functions as either mobile base stations while being afloat in space to cover a large footprint of terrestrial mobile users or act as relays (hotspots) to extend the coverage of base stations where the mobile infrastructure is hard to setup and thereby serve a greater number of users [18]. One of the foreseen applications of UAV communication in 6G networks will be to provide rural connectivity at a reduced cost [76], [151].

3) FEATURES OF UAV COMMUNICATION

Easy deployment and network setup are critical features of UAV to enable flexible range extension or coverage enhancement of wireless communication. For instance, during a calamity, hurricane, tsunami, desert, where the existing infrastructure has damaged or does not exist, the UAV may function as a floating base station. However, there are challenges when 2D communication has to be extended to 3D due to the altitude and added degree of freedom [31]. The aerial channel modeling study should attain maturity before UAV can be integrated as a part of 6G [9], [113]. Further, optimization of route, power, number of UAV's to provide coverage requires special attention as these devices have power constraints [76].

4) UNDERWATER COMMUNICATION

Let us consider a scenario of deep-sea exploration, for instance, the study of underwater habitats, deep water ecosystems, natural resources, or recreational tour, and military communication; all these activities involve the transmission of video, data to a ground station. Furthermore, the communication during any rescue operation through a submarine or UAV, far from the coast are challenging due to an unpredictable underwater environment, where RF, visible light, and acoustic signals should provide communication. Later, it has to be integrated into the terrestrial or at times to space communication [112]. Incorporating this challenge as a part of 6G network with different frequencies to communicate for underwater (low frequency) and terrestrial will meet the key requirement of the future networks. The acoustic communication mainly spans between acoustic waves, RF, and optical wireless frequencies; a thorough channel modeling for all three cases is an intricate task [127], [9].

In general, to provide 3D coverage, 6G network will virtualize its hardware access (i.e., physical and medium-access) to enable the network service for more users and verticals.

D. VISIBLE LIGHT COMMUNICATION

In earlier telecom networks, connectivity between cell tower and mobile switching centers were either microwave (RF) or fiber optic links (non-RF). However, since 4G onwards, free-space optical (FSO) links have started to attain prominence to connect the backhaul due to its simplicity, license-free operation, high data rates, and security. Due to these features, VLC will be on the main contender for backhaul networking in 6G network, along with RF links [2]. In dense 6G networks, a very high bandwidth technology will be mandatory at the backhaul to manage the data due to the massive amount of data generation. In this regard, the VLC and THz communications will be the two main candidates for 6G cellular communication at the physical layer [31]. The VLC as a complementary technology to RF occupies the higher scale of THz frequency ranging from 400 THz–800 THz. Note that VLC offers hundreds of THz bandwidth (unlicensed), meanwhile, the THz frequency communication has only up to a hundred THz bandwidth (licensed) available [4]. Even though 5G networks did not consider VLC in its ecosystem, VLC deployments for short-range communications offer several Gbps data rate [9]. Thus, in the next decade when LED technologies mature, especially with the advent of micro-LED sources, and laser diodes, 6G's data rate requirements can be met.

VLC as a family of FSO has several merits over RF communication. First, the optical spectrum is license free. Second, the VLC in the frequency range 430–790 THz uses white light LED as a source to transmit the encoded data. The data encoding is much simplified in VLC, where by modulating the brightness of the light emitted by LED, different encoding levels can be achieved easily. Third, it is anticipated that VLC link will offer several THz bandwidths and up 100 Gbps data rate, and may grow to Tbps in future [4]. As a result, the use of multi transmission links can offer enough data rate for 6G use cases [3]. In particular, laser diode which has higher efficiency and illumination than LEDs, can offer a 100 Gbps of data rate for critical applications of the 6G networks [28]. In general, even indoor communications remain secure within a confined space as light sources cannot pass through the obstacles [17]. VLC will be the most suitable candidate for the line of sight inter-UAV communication in 6G networks. Since the communication system is simple and flexible, two or more aerial vehicles can communicate through optical frequencies generated by the LED sources without being distracted by the obstacles above the ground level. In addition, the interference issues in VLC are also minimal. As a result, underwater communications between submarines, personal healthcare devices, or industries susceptible to electromagnetic radiation are the other scenarios that will find VLC the most suitable [9].

Nevertheless, VLC is challenging in the outdoor setting, as external light (ex: sunlight) will influence the communication beam. So, aerial communication requires a very strong light beam to overcome this limitation. Thus, VLC is more suitable for indoor short-range communication without this constraint.

E. BLOCKCHAIN SECURITY

Blockchain is a distributed ledger that will play a pivot role in the maintenance of data security and transparency when numerous devices share the data in a decentralized way in B5G networks.

1) WHY BLOCKCHAIN FOR 6G

We know that 6G networks will have a massive network of IoT and MTC devices that connect homes, cities, and factories with several data transactions between the networked entities. Moreover, a survey predicts that there will be 50 billion connected devices IoE during the 6G network era [3]. In that context, there should have trust among the devices to facilitate secure data transfer. To build such trust and security, the blockchain allows maintaining a sequential ledger (chain of blocks) by each node wherein if any user does the modification of data within a block, it will be visible to and shall be authenticated by everyone else to prevent falsification.

2) FEATURES OF BLOCKCHAIN

These modifications are imprinted into the data block with a private hash key, and data remains unaltered without the consent of the other devices [2]. That means, when a data block is created, it must be *verified* with respect to the previous blocks by the other participating users to maintain transparency. In this way, the *reliability* factor is introduced among all users; however, with the compromise of privacy, as modifications will be visible to all [14]. The decentralized operation of blockchain brings flexibility with reduced management cost. The blockchain even offers several advantages in a highly connected mesh network, such as security, reliability, trust, and scalability [2]. One of such instances of blockchain in 6G networks could be a video conference call, or mixed reality-based video streaming, where the network along with providing connectivity, also requires all the parties to authenticate themselves and the data being communicated through dedicated blockchains. This will bring in the knowledge of data properties to analyze the abnormal behaviors in real-time [42]. However, there are other challenges in 6G networks besides the massive device connections for blockchain implementation, such as resource restrictions on the devices limit the scope of use of cryptographic security algorithms on the device. Similarly, data packets must undergo an intensive audit to evaluate the risk, which becomes a herculean task when the number of devices is very big. Due to the lack of third party verification, security attacks are more accessible by compromising half of the total participants. The authors in [14] have suggested using cryptographic and quantum computing based algorithms for privacy issues in blockchain. Altogether, the blockchain has a major role contributing to security, scalability, and reliability factors in the 6G network [30].

In the future, for 6G, blockchain shall provide security to mobile edge computing nodes when several devices wish to store their data in the edge device. Similarly, in case of device-to-device communication, the cooperative data caching among the users also shall use distributed security. In addition, when we consider network virtualization, it is obvious that the network capacity will enhance due to provisioning more slices. In this regard, while implementing blockchain, it will provide authenticity of data in every slices along with immutability features to efficiently manage the virtual network [33], [14].

F. QUANTUM COMMUNICATION (QC)

It is one of the enablers of the 6G network; especially, it will support 6G network in achieving (*i*) extremely high data rate requirements at the backhaul, (*ii*) data security, and (*iii*) long-range transmissions [3]–[5]. In general, the existing protocols of mobile networks can be significantly enhanced by utilizing the principles of quantum theories to attain higher degrees of freedom [71], [18]. Foreseen by the role of QC in the 6G and future networks, the Government of UK, and New York University have invested heavily on the research of quantum communication and computing [78].

In the case of QC, data that encoded using photons which cannot be decoded or copied (cloned) without tampering as quantum particles (photons) will be highly intertwined and correlated. In addition, data will be represented as ‘qubits’ a unique notion of multi-level description of data, where qubit is the fundamental unit of quantum data [4]. Therefore, the underlying principle of QC, includes quantum superposition, quantum entanglement (no-cloning) theorem [71].

However, when we move our attention toward data rate improvement in QC, we use the concept of a quantum superposition of qubits. Basically, it does the parallel processing of multi-dimensional large-sized data to offer seamless data rate, unlike the binary data processing in conventional computing systems. For instance, a qubit can represent binary '0' and '1' simultaneously. In addition, n bits can represent 2^n bit patterns at the same time, instead of anyone combination of n bits as in digital communication. In the case of QC, communication security is another key feature to mention by randomization. The communication is impossible for eavesdropping as the data will be represented in an encoded quantum state using photons and cannot be meddled without the intertwined patterns. Here, QC makes use of quantum entanglement, or the no-cloning principle [3]. One of the future applications of QC in security is the quantum key distribution (QKD). This application provides vast security to physical layer due to quantum mechanics based key distribution in future networks [19].

Furthermore, long range communication is supported with the aid of quantum repeaters (relay) that retransmits the photons. It has been reported that QC can be integrated with satellite communication to offer global coverage [4]. Meanwhile, quantum repeaters and switches are difficult to build due to no-cloning theorem [71]. An interesting paradigm for the future networks will be combining QC with ML to solve classification and regression problems more efficiently than the classical ML solutions, which is termed *quantum machine learning* [40]. Here, quantum supervised and unsupervised learning, quantum deep learning, and quantum reinforcement learning techniques would satisfy the complex computation requirements of 6G networks [71]. All these features make QC a suitable candidate for 6G networks.

G. ULTRA-MASSIVE MIMO AND INTELLIGENT COMMUNICATION SURFACES

Due to the availability of large bandwidth in THz frequency, by the use of MIMO transmission technique, large spectral efficiency can be achieved. MIMO technique which exploits the spatial diversity of the communication medium several antennas at the transmitter and/or the receiver, and offers enhanced spectral efficiency and gain with the given channel bandwidth [9]. For instance, in a 64-beam array plane, there are 64 unique predetermined angular directions. During transmission to a user, a single angular beam will be chosen to expect each user to be well apart from the rest and should have a line of sight path [48]. This limitation of 5G massive MIMO should be overcome in 6G networks, where each antenna array creates a beam in multiple directional vectors with each beam having different angular directivity [48]. The massive MIMO transmission will enable the receiver to overcome the degradation effect on the THz waves caused due to rain and atmosphere in dense urban settings [9]. However, looking at challenges, such as energy efficiency of massive MIMO and inter-cell interference, efficient solutions are yet to be determined [28], [40].

In the context of 6G networks, it is more appropriate to use the term *ultra-massive* MIMO. To fill the gap concerning the physical layer, the combination of THz and several antenna arrays (massive MIMO) shall be used in 6G networks to support user's mirage of data hungry applications. One of such use cases will be beamforming, where multiple antennas are pointed toward a user with the help of directional beams for complete utilization of spatial dimensions. Therefore, 6G networks must target physically large panels accommodating more antennas, and narrow the beam width (increased spatial resolution) to increase the beamforming gain. The efficiency of beamforming can be achieved using continuous aperture antennas where each antenna is discretely spaced. This increases the cost and power consumption. In this context, holography radio is a solution that uses meta-materials on which antennas can be densely spaced on a small area [48]. In 6G, we will overcome the limitations of 5G networks by using large antenna reflecting surfaces and holographic communication, where holographic beamforming with the help of Smart antennas renders holographic 3D videos [28]. Unlike the 5G massive MIMO, 6G networks would use smart intelligent surfaces (IRS) which reflect the data received from a base station toward the receiver [59].

1) INTELLIGENT COMMUNICATION SMART SURFACES

The existing massive MIMO technologies for 5G networks provide spatially, efficient ways of enhancing communication performance. However, the complex signal processing, increased power consumption, hardware design, and THz wave's propagation properties (ex: blockage due to obstacles) pose a real challenge. Furthermore, at THz frequencies, due to low scattering very few scattering paths exist. Thus, using antenna arrays becomes a challenge due to the shrinking size of the antenna elements. Therefore, an alternative to ultra-massive MIMO is essential.

As we know, the hardware components will be driven by *intelligence* to adapt to the changes in the surrounding environment in the 6G network. For instance, the performance of the cognitive spectrum access, modulation, and coding, beamforming can be modified as the environment changes [70]. One such intelligent component that enables wireless communication is an *Intelligent surface*. The intelligent surface is also known as Reconfigurable Intelligent Surface (RIS). An intelligent surface will act as a boon to enhance overall communication between transmitter and receiver in a cost effective and energy-efficient manner [28]. An intelligent surface is a passive reflective surface of electromagnetic signals without requiring a dedicated power source. These are generally made of reflective arrays, liquid crystals, or software defined meta-surfaces. These surfaces will manipulate and reflect the incident RF signal from different sources and direct them toward the receiver to assist in wireless communication [40], [48]. The modification of the incident RF signals is done by *programming* these meta-material surfaces, similar to a software defined radio. Therefore, the RIS is also denoted as software-defined surface (SDS) [59], [119].

2) FEATURES OF INTELLIGENT SURFACES

Since these surfaces are passive and do not use power amplifiers or analog for the digital converter, they prove to be power efficient than massive MIMO technology as the latter uses active elements to re-transmit the signal. Further, the amount of radio wave reflection depends on the surfaces area of these intelligent surface. Another key property of the intelligent surface is that they intelligently reconfigure the modulation or phase of the reflected signal with respect to the channel condition such as fading and path loss. Further, the intelligent surface can aggrandize beamforming of massive MIMO in the 6G networks due to the software programmable feature [28]. With the help of reflecting surface elements, it is easy to mimic the effect of beamforming at a reduced complexity. Studies have investigated the potential of intelligent reflecting surface for index modulation for 6G networks [59].

3) HOLOGRAPHIC MIMO

Holographic MIMO is an interesting paradigm of intelligent surface enabled communication [70]. Here, a large intelligent surface can be configured to act either as transmitter, or as receiver using the principle of *optical holography*. When there is a power source used for the operation, i.e., in the *active mode* of operation it is explicitly termed as H-MIMO surface. However, in *passive mode* (no power source) it is majorly a reflecting surface that modifies and reflects the incident RF signal as a intelligent reflecting surface [70], [43].

Now, let us consider the challenges associated with the Intelligent surfaces: (*i*) In a wireless communication system assisted by RIS, the surface should acquire enough CSI feedback from the transmitter and the receiver. However, acquiring the CSI is a burden for passive devices which cannot transmit the pilot signals for channel estimation, as in the conventional systems. (ii) The passive surface needs to transfer information, such as control signals to synchronize with the transceiver and real-time environmental parameters. (iii) Resource allocation issues such as lack of analytical models and computation cost [29].

These H-MIMO surfaces have a benefit of reusability, easy customization, and lower latency due to software programmability of the meta materials. In passive modes the thermal noise is absent. It is also spectrum efficient. Furthermore, intelligent surfaces will act as range extenders when there is no direct link from the transmitter (gNB) to the user. Due to simplified beamforming, the RF signals can be focused to the desired location that reduces the change of eavesdropping, loss of signal due to attenuation, and facilitates wireless power transfer along with the information to the intended receiver [70]. In 6G network, RIS will find its applications apart from physical layer communication, as RIS enabled Edge computing, wireless power transfer, device-to-device communication, and positioning and localization [2991].

H. DIGITAL TWINS

A digital twin is a digital representation of a real world object, person, place, or event projected virtually in a cyber-physical world, without regard to time or space restrictions [90]. It is expected that with the digital twins, we will experience the reality (i.e., of the original object) virtually (as a twin) [86]. The advancements in sensor technology, AI, and communication has led to several applications of digital twins. To render the twin of an object digitally at the remote site end, the system must process a high definition data of the original object, analyse, and decode to reproduce it virtually. In this context, AI's supervised or unsupervised algorithms will be much suitable as they can accurately analyse the data from the surroundings.

Digital twins have several use cases, as mentioned in [89], [90]. For instance, in Industry 4.0, a digital twin of a machine will help the operator to predict future failures or malfunctions much earlier by analyzing the twin data as there will be continuous feedback between the original machine and the twin for better performance analysis. A similar intension has been exploited by the automotive giant Tesla company in their digital twin of the cars. Another foreseen application will be for e-healthcare. With the aid of the digital twin of a human, it will be easy to analyze the body parameters in real-time or shall study the impact of a drug, pre-surgical study of the area to be operated [89].

Samsung has expressed that digital twins will be one of the technology components that will drive 6G networks [86]. In [15], authors have proposed the digital twin model for the 6G network architecture. Since 6G networks will have extremely high network density, the network will have distributed its architecture for better management. These digital twins (a.k.a. cyber twin) can become part of the network by acting as assistant, data logger, and digital asset owner of the objects. In this scenario, the 6G's network architecture shall consist of four entities, namely, (i) *end entities* (human, things) who receive the service, (ii) *edge to cloud* entity that connects the end-user to the core cloud through the edge devices, and does initial edge processing. (iii) *Cyber twins* located at the edge server which are the replica of an end-user that provides services such as communication, data logging, and even act as the owner of assets. It will replace the end-to-end communication model with an end-to-cloud model. (iv) The *cloud network* where edge clouds and different other clouds will be interconnected. This architecture will provide scalability, security, and flexibility to future generation networks.

1) CHALLENGES

To replicate an object or human in real-time requires extremely high data rates and perfect synchronization (say 1Tbps and 100 ms). Besides, there are issues such as privacy, security, ethical issues, and cost of development. The technical community is hopeful that by 2030, digital twins will very well support 6G networks when there will be more advancements in technology [90].

I. CHALLENGES OF 6G ENABLERS

Even though 6G enablers will enhance the performance of 6G networks several times more than the 5G networks, the path

TABLE 3. Technological challenges of 6G.

Technology	Challenges
THz Communication	i. Atmospheric absorption and propagation losses. ii. Antenna design and operation at THz frequencies is yet to be determined.
Complex User device	Even though 6G network is said to be a device free (Smartphone) wearable patch, in case for designing a hardware that operates at several frequency bands (RF, Optical), accommodating ultra-massive MIMO transceiver, while being power efficient, miniaturization, and supporting AI will be highly a complicated design. ii. Supporting AI, XR, Holographic, and tactile requires additional sensors and need a tradeoff with price, device size, and features.
3D communication	i. In an all-round connected network, providing suitable multiple access mechanism and resource management are complicated. ii. Deployment of 3D access network (Access points, balloons, drones, underwater receivers) and minimizing the interference in a dense network is a real challenge. Similarly, a precise aiming of the receiver by beamforming, and tracking in case of underwater and special purpose communication are difficult.
Blockchain	i. User privacy will be compromised due to transparent transactions on which blockchain rely. ii. Decentralized transactions requires a lot of time (delay). As a result, achieving tradeoff between secure communication and maintaining the computational complexity practical is another challenge.
Artificial Intelligence	i. Deep learning algorithm requires large data set offline, and when the data is complex, it becomes difficult to manage the system's operation. ii. Obtaining more practical and credible training data for physical layer analysis is challenging in a cellular world. iii. For DNN model, labeled training data is required, and system has to be trained under no mobility, which is not the scenario in mobile networks.
Edge Intelligence	(i) Due to heterogeneous nature of 6G network devices, computing, caching, and communication at the edge (resource constrained) will be challenging without proper coordination among the cloud, edge, and the user terminal. (ii) AI- algorithms that run at the edge shall be light-weight and flexible.
	Otherwise, will degrade due to hardware limitations performance, which is a real challenge.
Reflective Intelligent Surfaces	(i) Deployment of RIS for optimizing the transmission range, coverage, and efficiency requires detailed analytical study which we lack at the moment. (ii) In case of holographic MIMO, channel estimation is challenging due to the constraints associated with the hardware.

TABLE 3. *(Continued.)* Technological challenges of 6G.

Quantum Communication	(i) Quantum computing repeaters and switches for long range communication are difficult to build with the available technology. (ii) With regard to implementation of quantum communication in 6G networks, a long distance quantum channel is necessary. However, for long distance photon transmission without much loss requires photon repeaters. This area requires in-depth research in future.

to achieve the gain is arduous. In this subsection, we describe the various challenges associated with the 6G network technology components, as given in Table 3.

V. ARCHITECTURES FOR 6G

While roadmap, and standardization activities are yet to be initiated, a few researchers have proposed new architectures of 6G networks. In this subsection, we describe briefly various architectures from the literature.

In the earlier section (IV), we narrated the critical features of two AI-based 6G architectures. Now, let us discuss the other architectures.

A. CYBER-TWIN ARCHITECTURE

The authors proposed two architectures for 6G networks, namely, (i) cloud-centric internet model and (ii) a decoupled RAN model [104]. In the cloud-centric internet model, the existing IP architecture is slightly retained with certain modifications. First, the users are connected to the RAN, and the data from the RAN enters the edge cloud layer where cyber-twins accept the data. These cyber-twins act as data loggers, assent owners, or virtual representation of the user. Edge clouds, in turn, are connected to the cloud layer, where multiple clouds are interconnected to form the center of the network architecture. The cloud layer consists of resource scheduler, orchestrator, communication, computing, and caching functions. This cloud layer enables applications to provide services in the edge and cloud at reasonable cost and QoS.

B. DECOUPLED RAN ARCHITECTURE

Here are distinct APs for handling the *control* and *user plane* data different from the earlier cellular generations. The control plane BS will be a macro BS, which a user shall connect to exchange the control information. These control BSs will be connected to the user plane (data) BSs for high-level signaling. In addition, the uplink and downlink traffic are also decoupled and handled by separate BSs to the users. Here, the uplink BS can be a micro-cell dense deployment near the user to collect the user data at low power. The uplink and downlink base stations will have internal coordination for efficient communication [104], [105].

C. GENERALIZED ARCHITECTURE FOR 6G

A generalized 6G architecture for IoT and vehicular networks is presented in [139]. It consists of three levels, namely, *user level* composed of smart devices with caching ability. These devices send the sensed data to the base station level, where base stations or APs have edge servers to perform scheduling and resource allocation. Finally, a central server will do the slicing, handover actions at the network level. This architecture will reduce the delay for critical services (autonomous cars) by processing and storing at the edge level. However, due to its partially centralized control plane, some non-critical tasks still use cloud processing.

D. A HIGH-LEVEL ARCHITECTURE OF 6G

A three-level 6G network architecture consists of AI plane, user plane, and control plane [140]. In this case, storage, compute, and networking are done at the same level (in user plane) to eliminate the hierarchy. The user plane is flat and it is defined between an access network and the internet. The control plane and AI planes are distributed and virtualized for various services. Further, the transport network is virtualized and isolated from the rest by software defined virtualization. The core network functions are made as micro-services and accessible by server-less systems.

E. MULTI-LEVEL ARCHITECTURE FOR 6G

A three tier architecture of 6G consists of smart users, edge devices, and the cloud [114]. The users implement intelligent decision making techniques such as data-driven or model-based techniques to predict mobility and traffic patterns. At edge intelligence level, the mobile edge devices use deep reinforcement learning, or deep neural networks to optimize the scheduler for resource allocation to mobile users based on the CSI. Moreover, at the cloud level, having a high capacity central control can train the system with a numerical platform that presents the labeled samples for optimization algorithms. These can be used to train deep neural networks and later be implemented in the control plane.

F. THREE-DIMENSIONAL 6G ARCHITECTURE [4]

The FG-NET 2030 has envisioned a 3D architecture for 6G networks, covering three key aspects, namely, communication (infrastructure view), intelligence (control view), and management (network view). It has different communication layers at the infrastructure view ranging from terrestrial, underwater, aerial, and satellite to enhance the range of communication in 6G networks. In addition, the authors at the control view presented how 6G networks will include intelligence to control and optimize the overall functions of sensing, spectrum access, communication, storage, and processing with the help of AI, deep learning, and ML. It recommends that the intelligence will be distributed across various network entities. Finally, in the network view, the functions of the overall network have been divided as sublayers. They include the application sublayer, routing, management, spectrum access, and physical medium, which resembles the layered IP stack. A simplified version of the same architecture for 6G has been proposed in [108].

G. NEUROSCIENCE BASED 6G ARCHITECTURE

This architecture is more of a framework that tries to integrate neuro signals to emulate the wireless signals to be applied in 6G networks [136]. Here, human brain's intelligence and radiating properties of wireless signals shall be integrated to enable an intelligent communication between the human and computers. Recent advances in bio-IoT and implantable-communication devices have made us bold to envision short range 6G network communication, where wireless modules implanted inside the human brain acquire intelligence from the brain and communicate directly with the outer world wireless devices and base station or with another human with similar capability.

H. PROPOSED ARCHITECTURE

Our proposed 6G architecture consists of devices at the outer layer as shown in Fig. 6. The devices in this layer gather data, events in the network and communicate to the next level. Here, IoT nodes, cellular users, smart devices, etc., which have been connected to the radio access network may have a certain level of intelligence by default. Consequently, interference, channel selection, sensing shall be better managed. We have also depicted the paradigm of the cell-free network, small cells, and massive MIMO enabled by intelligent surfaces operating side-by-side as will be the scenario in 6G. The arrows in this layer indicate the wireless links. Further, in the next layer, we have edge devices and cloud that utilize AI for resource allocation, user management, and other optimization tasks. As proposed in [42], we considered a distributed edge intelligent architecture which provides process, store, compute and decision-making facility for independent physical networks. The intelligent agents at these edge devices learns from the devices to assist in better management of the network below it at layer 1. For instance, it could be the selection of wireless channel and tuning the parameters accordingly. Here, a centralized edge node provides backhaul service to all the physical networks through these edge clouds, that is shown by the discrete lines. It also includes cloud-RAN and backhaul resources for various use cases. However, all these resources are virtualized. Further, we have various clouds that interconnect the network elements. Finally, at the innermost layer, we have the applications for various verticals which either provides or receives services from the layers below it. Thus, the proposed network architecture in Fig. 6, provides the *abstract view* of 6G. However, several other features such as quantum computing, fog nodes, security, etc., have not been shown exclusively and shall be the potential candidates of 6G architecture.

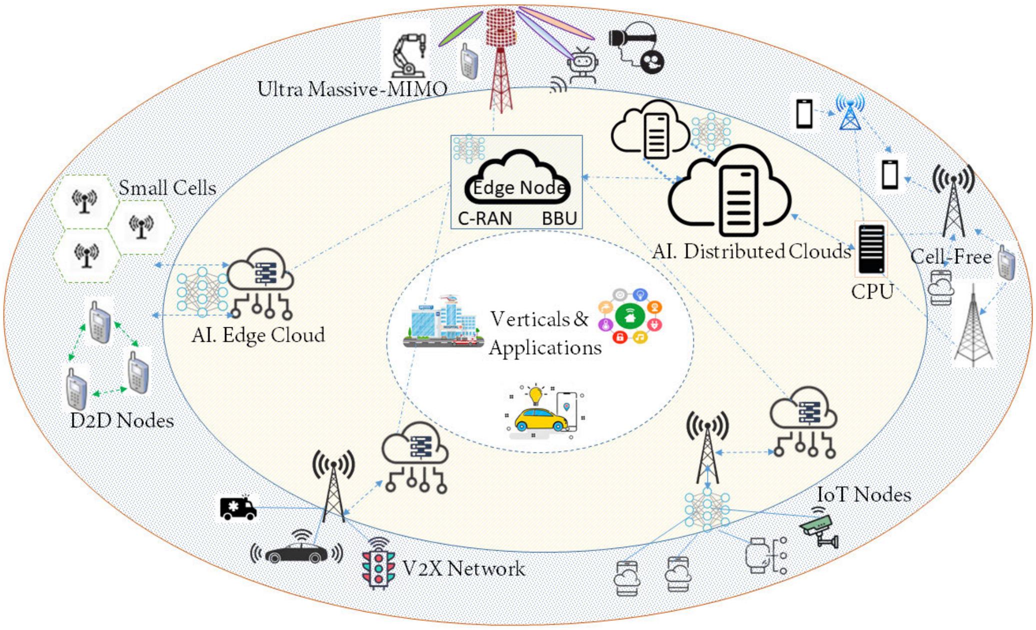

FIGURE 6. **Proposed network level 6G architecture.**

VI. FUTURE TRENDS IN 6G

The *6GFlagship* project has identified 11 key areas of 6G pilot project, and have published white papers in June 2020 [36], [42], [44]–[55], [107]. In this section, we summarize the overall ambition of some of the key areas such as localization and sensing, trust and security, UN sustainable development goals, rural connectivity and networking, edge intelligence, machine learning, and 6G business scope as shown in Fig. 7.

A. LOCALIZATION IN 6G

Traditional sensing and localization using GPS or cell coordination will become obsolete in future high dense smart urban settings. In 2030 future networks, KPI related to accuracy must include user's environment information to facilitate accurate positioning. For instance, a use case of 6G networks such as autonomous driving, where high resolution positioning at the cm level is necessary along the driving lane or track details to achieve traffic safety [19]. Similarly, mobile sensor-based applications that use location information should include power consumption per unit distance coverage; integrity and privacy-related KPI should include location details, malfunctioning nodes, and alarms [53]. These requirements ensure that future technologies or devices for 6G networks must be accompanied by additional information such as power consumption and types of alarms generated during any sensor failure for exact location sensing with emphasis on privacy. In addition, localization and sensing of information have several applications in future, including robotic surgery, contact tracing during pandemics, VR based games, social networking and dating apps, food delivery, context-aware marketing, autonomous driving, personal navigation, and animal tracking. Specifically, in the case of the context-aware services, 6G network will automatically learn user requirements by sensing the environment or location and providing the best QoS and other settings [124]. Consequently, 6G systems will integrate intelligence, pervasive networking, along with precision localization and high-resolution sensing to serve specific use cases that emerge during 2030, requiring accuracy being fine-tuned to cm level. This will enable seamless connectivity, localization, and sensing for context-aware services [19].

The 5G NR and mm-wave will offer localization and sensing features different from the previous generation of cellular networks. Moreover, 6G networks will further enhance the localization accuracy leading to high definition imaging by the use of THz communication, massive antennas, and RIS [53], [91]. As the beamwidth reduces at lower wavelengths (μm-wave), the positioning accuracy increases. Next, the inverse relationship between frequency and device size (antenna) will enable dense packing of multiple antennas, which facilities precise angular and direction estimation. In this regard, better channel estimation algorithms are necessary at THz frequencies to sense and localize. Further, a higher data rate of 6G network will enable the sharing of maps between the devices much easier. With the large IRSs, the reflected wave can provide better localization service by exploiting the near-field effect and analyzing the wavefront. In addition, it will remove the need of synchronization between reference stations. However, more precise methods are necessary for the real-time localization and positioning if the intelligent surfaces are smaller in size [91].

It should be noted that the existing localization techniques using ML heavily depend on fingerprinting, regression, and

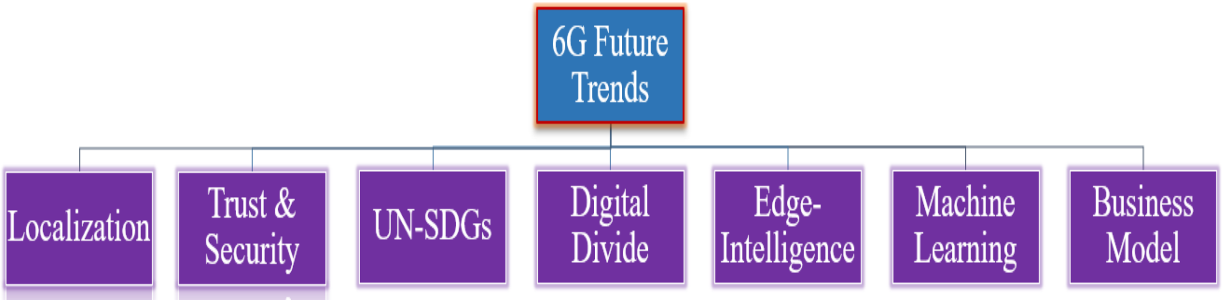

FIGURE 7. Disruptive future trends in 6G.

classification methods. However, more intelligent localization and mapping methods will be necessary for the 6G network [53]. By AI- and ML-based frameworks, the sensing system can be trained to learn from raw data, where vital information (time and space-based) present with the noisy radio signal, or weak sensor data can be extracted to analyse the location and sensing patterns for the 6G network system. Albeit, most of the ML- and DL-based techniques need a large volume of structured data for training, which may not be available (noisy, random) in tiny sensor-based applications. Therefore, advanced analysis methods should be introduced to assist in trained localization.

As mentioned earlier, localization is also associated with another set of tasks i.e., imaging and sensing which involves high frequency signals (60GHz). These signals when reflected by the objects, the size and dimension of the objects can be measured accurately [127]. Besides, localization also includes imaging using sensors. Here, passive sensors will capture the images and active sensors will transmit signals that represent range, angle, and Doppler with a high resolution and accuracy. For instance, in case of self-driving cars, radar imaging adds range and Doppler to the multi-dimensional image [53].

B. TRUSTWORTHY 6G

How security in 6G different from 5G: The number of connected devices (IoT, MTC, and mobile users) in 6G networks will increase at a galloping rate and density-wise ten million devices in a unit square km area [2]. These devices will inherit artificial intelligence and span across diversified applications such as banking, industry, healthcare, government, transportation, and many more. Due to the dependence on many verticals, 6G networks must enforce a higher-level security in every stage of its network to prevent all forms of security attacks. In another instance, we may imagine a hyper connected world, where a minor compromise in the security settings may lead to fatality in an automated industry, robotic surgery performing incorrect incision, etc., [55], [50]. Currently, in 5G networks, traditional cryptography will serve most of the needs to secure the data communication across cloud and edge architectures. However, a new era of security will begin by the inception of quantum computing in 6G network. For instance, QKD systems facilitate easier eavesdropping detection that classical cryptography. Furthermore, upgrading the level of security is possible with quantum secure direct communications (QSDC), which provides better security over the quantum channel than the QKD or classical methods [120]. In another view, automation of security functions with ML algorithms at different levels will be essential because of network densification. However, there is a threat of reversed ML based security attacks, as the network can learn all parameters minutely. Therefore, 6G network needs exclusive holistic network security architecture [55].

1) REQUIRED SECURITY FEATURES

The key features should include: especially, future SIM cards and their security aspects, and use of asymmetric cryptography, Transport Layer Security (TLS) using elliptic curve cryptography (ECC), software and AI-driven security as applicable to SDN and NFV. For example, the security model in 6G networks will consist of a deep learning enabled VNF gateway that monitors the ingress and egress traffic and apply filtering policies to detect and prevent potential security attacks. In summary, a trust model must define the rules to collect, process, distribute, and filter data in the network.

C. 6G FOR SUSTAINABILITY DEVELOPMENT GOALS (SDG)

Digitization due to 5G networks will currently address many social issues such as education, environment protection, and hunger. Nonetheless, there exist several problems that require extensive urbanization and connectivity. Since 6G networks will bring in user experience-based hyperdata connectivity, several global issues especially, with regard to the United Nation's SDGs, shall be mitigated [86]. The 6G network through its multi-faceted communication capability (long and short-range, 3D connectivity), has the potential to promote global sustainability, which is mainly due to its seamless connectivity and support for a plethora of services. Let's see some of the future scopes of 6G networks as regards the promotion of sustainable development goals. For instance, online banking will enable anyone to access financial services with much ease, which will help to eradicate poverty. Similarly, online healthcare services will reduce the travel time and will easily reach the needy whenever necessary to promote better healthcare delivery. By having all-round network connectivity, farmers in rural places can make use of digital transactions for their agricultural, and home products. We shall implement IoT in food production to improve the yield and to obliterate hunger [93]. With the aid of 6G networks, all these issues shall be addressed on a massive global scale.

When we consider zero energy, 6G network will target miniaturization of the devices to increase the power efficiency and energy harvesting, thus improving environmental performance. For instance, these devices may sustain the power generated through everyday activities such as walking, jogging, and household work of the device user. This energy shall support the personal information devices like wristband, smart patch which monitor a person's vital body signs from time to time. In addition, in another scenario, these could cater to information and entertainment needs through over the top connectivity.

To support the United Nation's SDGs, 6G network has set its vision to provide an opportunity for the global society and economy to accomplish its digital dreams [44]. It includes data connectivity, a strong economy, facilitates smart healthcare, energy efficiency to name a few among the 17 SDGs. The 6G vision targets three underpinnings to implement SDGs through various services. They are as follows. (i) Addressing the problems of people and society by providing suitable *digital infrastructure* to empower them. (ii) Context-awareness based on the environment which is possible by highly precise *localization and sensing* capabilities, online monitoring of resources, and so on. (iii) All-round uplifting of the *ecosystem* of SDGs. Besides these requirements, the fundamental necessity to achieve the goal will be the *all-round connectivity* and access to the internet.

1) HOW 6G SUPPORTS UN-SDGS

Since SDGs spans all sectors of life, the vision of 6G networks should be multi-disciplinary. As a result, an open and co-innovation platform for 6G's technology standardization activities which support human life and environment is crucial to create an ecosystem that will benefit all stakeholders of the UN-SDGs.

The 6G ecosystem will contribute to the progress and well-being of various communities in society. For instance, 6G will provide wireless networking to connect patient, doctor, and medical equipment together in a remote smart healthcare system. With the aid of 6G network, several digital services could be extended such as education, food distribution services, banking, and industry to advance on a massive scale. These eventually result in the empowerment of human life toward achieving a better SDGs. Having said this, there will be concerns while targeting the SDGs such as inclusiveness, data security. For instance, when it comes to data collection, all stakeholders such as hospitals, society, and government must handle data with utmost privacy rules for the integrity of the system. Now, 6G networks play a role in addressing the privacy and security of data communication. In summary, 6G networks must implement actions that promote sustainability to different verticals, encourage growth with minimum energy consumption, and implement zero waste when people, machines, and resources are interconnected. Due to the prevalence of the *intelligence* in 6G network, it will improve efficiency and environmental sustainability by using low energy consuming technologies or devices that derive the energy from natural activities for their functioning. We have summarized the set of KPIs for all 17 SDGs and their possible use cases, as in Table 4.

2) OPPORTUNITY FOR 6G

The use cases of 6G networks must be aligned with the intentions of SDGs, especially the SDGs which can be well supported by ICT infrastructure. The common aspects such as online financial activities, including online banking and online business will promote economic growth. Furthermore, telemedicine, remote mapping of natural resources such as minerals and water bodies are some use cases that improves social and healthcare sustainability. When we look at 6G's diverse range of wireless connectivity, edge intelligence, localization, sensing, and ultra-low energy consumption will strongly support rural connectivity, environmental context, and energy aspects of SDGs. In Table 4, we summarize the KPIs with regard to the 17 SDGs and the use cases, as intended in [44].

D. HOW 6G WILL WIPEOUT DIGITAL DIVIDE?

There are several reasons for lack of connectivity in many remote areas of the world such as absence of infrastructure, low income, rough geography, and many more [92]. The 6G network has a strong vision on breaking the digital divide which will in turn promotes sustainability alongside the connectivity. It is estimated that nearly 3.7 billion of world population is far from reach of internet connectivity [44]. The digital divide gives rise to several other problems such as retarded economic growth, education and awareness, inhibits the adoption of remote, and advanced healthcare technologies. It also causes low growth in modern industrial and new age transportation sectors. The digital divide has not left any geographical regions untouched. In reality, even though, first world nations have high-quality mobile internet connectivity, there are remote areas of USA, and Europe that experience a low data rate of 0.4–1Mbps through wired/wireless connectivity. The situation is much worse in Africa, Brazil, and India [52].

1) SCOPE OF 6G IN RURAL CONNECTIVITY

Connectivity in tough terrains, away from the main cities should be simple, low cost, and easily achievable. Therefore, mobile broadband is the best solution when compared to wired internet [48]. Providing last-mile connectivity through the LEO satellite will cover a large area. However, it will not be a reasonable solution, considering the throughput, latency, and cost. Instead, usage of large power transmitters (mega cells) in low dense rural areas will be a viable solution. To achieve this target, new safety rules and power regulations will be necessary. Alongside, floating mobile base stations like UAV or balloons will promote mobile data services while acting as relays or data cache [52]. Since remote regions have financial constraints, while providing good QoS, special emphasis on affordability (cost-wise) is mandatory. The use of natural power sources such as solar and wind energy for power grids that operate the backhauls will enable cost reduction. In addition, cost reduction and resource efficiency could be achieved by confining the contents to the rural region generated within the locality. This requires caching the locally generated contents in local servers itself and provisioning network slicing. The local caching will enable cost reduction by minimizing the need for backhaul connections. Moreover, several data serving schemes can be brought into picture through network slicing to enhance connectivity with limited resources [76].

Regarding the backhaul connectivity, even though visible light or microwave seems to be the right candidates, they may face challenges in rural areas. Therefore, Integrated Access and Backhaul (IAB) seems much promising where the operator uses the part of the spectrum for backhaul and the remaining part for cellular access at a reasonably lower cost than the former candidates [52]. Thus, 6G networks shall rely on IAB to reduce the deployment cost and improve the resource utilization [107]. With IAB, only a subset of base stations will carry the backhaul traffic through connected links (fiber/wire); whereas, the remaining base stations will be connected through wireless links to transmit the backhaul traffic through multi-hop relaying. It is much possible in 6G due to the availability of large bandwidth in THz bands where access and backhaul traffic can be multiplexed by suitable scheduling schemes. Thereby, reducing the infrastructure cost. The IAB will provide service in sub-6GHz and mm-wave.

Similarly, Low orbit Satellites, UAV, and balloons find useful solutions to extend the range seamlessly. Based on the communication need, these terminals can be made operational (discontinuous trans-reception) as and at when required: thus, reducing the power consumption. Altogether, non-terrestrial communication will play a key role in 6G networks to reduce the digital divide [52]. In recent trends, edge computing and the caching of local data for local usage, installing micro telecom infrastructure and integrating it with mobile network operator, and their maintenance have attained prominence in rural regions. Albeit, all these have several challenges, such as financial models, frequency regulations, propagation delays, and co-existence issues [48].

E. WHAT IS THE SCOPE OF EDGE INTELLIGENCE IN 6G

The rise of edge computing and ultra-dense node deployment or mobile devices led to the emergence of mobile edge computing to optimize the computations and performance in the network. Further, the very nature of mobile devices requires the computations to be distributed.

A limiting factor of 5G network is the lack of intelligence in mobile edge computing, which will otherwise facilitate an easy transition into new verticals and services such as Industry 4.0, smart mega cities, and intelligent gadgets.

One of the reasons for the setback is that existing AI algorithms do consume enormous time and resources. Not only that, the production of hardware and AI solutions are yet to achieve synchronism. In total, when 5G network is considered to use cloud driven AI, 6G network will use edge driven AI [80], [81].

The Edge Intelligence (EI) is an extreme capability to process the data at the edge. Today, mobile devices have the high computational capability, storage space, and run petty AI applications. Subsequently, AI will become an integral part of the 6G network with distributed intelligence to run standalone and automated operations replacing most human interactions. For instance, verticals such as autonomous cars, ultra-smart healthcare, and modern industries involve complicated tasks with regard to data acquisition and computation. Therefore, distributed intelligence at different network entities will be required to offer optimized services. This forms the foundation for the 6G *internet of intelligent things* [86]. EI can be viewed from different directions:

(i) data analytics point of view refers to data analysis and development of solutions at or near the site where the data is generated.

(ii) the network perspective mainly targets the intelligent functions that are deployed at the edge of the network, comprising the user, tenant, or the network boundary [42].

1) NEED FOR SOFTWARE FOR AI EDGE

Currently, we lack software fluidity; without that, precisely locating intelligence in the network entity and sharing knowledge will be impaired.

EI will be useful in several verticals to offer better QoS. For instance, when we consider the scenario of self-driving vehicles, these vehicles need to compute and communicate many factors, such as inter vehicular distance, roadside entities, traffic signs, and vehicles in the nearby lanes. These data will be communicated to the EI enabled base station or access points located along the roadside to quickly (low latency) store and process the data and assist in deciding the load on available frequency bands (spectrum) to facilitate the data transfer from these vehicles dynamically. Noticeably, these EI units will also have access to the central cloud database, which maintains the overall data from several regional EI systems. Further, smart city applications, mobile extended reality (XR) which requires large data processing and computations, can be benefited by EI due to local data processing, reduced delay, resulting in higher data rate, task and sharing, and so on [42]. Nevertheless, the hardware technology to accommodate the intelligent processing capabilities on a small edge device with resource constraints is yet to mature. Similarly, software with intelligent, real-time, and independent decision capabilities with regard to training and learning from the data to meet the requirements of 6G networks will require time to evolve.

TABLE 4. Kpi for un sdg and their use cases.

UN SDG	Socio-Technical KPIs	Use Cases
1 NO POVERTY	Mobile coverage (area), % of population penetration, % of homes with internet access, security during online transactions (time to resolve, cost per issue).	Online banking, digital finance
2 ZERO HUNGER	% of population with internet penetration, % of smart phone users.	Smart farming, smart food delivery
3 GOOD HEALTH AND WELL-BEING	Latency, data rate, reliability; % of population with digital healthcare adoptions, achievable avg. uplink data rate.	Smart healthcare, Robotics Surgery
4 QUALITY EDUCATION	% of population with internet penetration, % of ICT ready institutes, % of learners skilled with online education methods, avg. speed of internet access (data rate).	Online education, MOOCs
5 GENDER EQUALITY	% of female population with internet penetration, % of female smart phone users, security of online communication.	Online education, Online community awareness programs, Remote healthcare
6 CLEAN WATER AND SANITATION	% of ICT ready cities and communities, no. of digital awareness programs organized on sanitization.	Smart water quality monitoring, Smart sanitation
7 AFFORDABLE AND CLEAN ENERGY	% of population adopted smart energy metering, energy efficiency.	Smart metering, smart grids, smart buildings
8 DECENT WORK AND ECONOMIC GROWTH	Mobile coverage, data rate, % of smart phone and ICT penetration, % of ICT skilled population.	Online business and trade, ICT based services
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Latency, throughput, connectivity, % of ICT ready cities, population, and communities. Cost of data.	Smart industry, Smart City, and
10 REDUCED INEQUALITIES	% of mobile broadband coverage in regions inhabited by disabled; refugees, low income, women population. Data rate.	Social networks, online education, online banking
11 SUSTAINABLE CITIES AND COMMUNITIES	% of ICT ready cities, population, and communities, energy efficiency, cost of data, coverage, reliability.	Smart cities, Smart education, smart transportation
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	% of population with internet penetration, % of homes with internet access.	Smart waste management, Smart grid and energy,
13 CLIMATE ACTION	% of ICT ready cities, data rate, coverage.	Smart air quality, water monitoring, Smart logistic, Green buildings
14 LIFE BELOW WATER	Coverage, Frequency, connectivity.	Marine environment monitoring,
15 LIFE ON LAND	Coverage, Frequency, connectivity.	Online environmental monitoring
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	% of smart phone and ICT penetration.	Online governance, online vigilance, and justice
17 PARTNERSHIPS FOR THE GOALS	% of internet penetration on trade, connectivity, and coverage, user experience.	Online collaboration for business

2) CHALLENGES

(i) When we consider a distributed environment, providing intelligence across the edge devices by gathering all parameters related to resource usage, training, and learning models will be a challenge. (ii) Furthermore, the optimum deployment of edge nodes in a high-density network and resource allocation is complex. (iii) At the edge devices, the action of AI is largely influenced by the type of precision of input data, especially when the available data is huge, vivid, and needs classification. Therefore, training models must consider these challenging factors and rely on synthetic data generated from generalized adversarial networks to manage the data consistency. (iv) With respect to the distributed edge devices that handle AI, say mobile phones, the AI algorithms must be lightweight, and applications must be partitioned between user devices and edge layer for efficient resource management. (v) The software packages for EI contain edge applications that are deployed on the edge devices along with virtualization infrastructure. In this context, the selection of system policies, billing, etc., play a key role. (vi) In EI devices, real-time feedback is essential to attain better performance. Consequently, it is necessary to re-define the real-time feedback by considering the online learning and pre-trained models. The training algorithms should be distributed instead of centralized and must adopt online training models by considering the edge device limitations [61], [42], [80].

F. HOW MACHINE LEARNING WILL RULE 6G

Machine Learning (ML) is a sub-branch of AI which assists in the prediction and classification of data based on the trained data. In 6G network, ML will find its application at different instances of the network, especially, at the PHY, MAC, Network, and Application layers. We shall discuss these applications briefly in this section. From the earlier discussions on use cases during 6G era, we realize that interconnected intelligent network components require ML as a fundamental network requirement to offer value addition to the services, zero-touch optimization, and improve the performance. This is because relying purely on mathematical modeling of the wireless system will make the whole system computationally complex. However, ML can efficiently model the wireless system that could not be wrapped under mathematical equations to suit the requirements of 6G networks. Interestingly, ML will act on the vast real-time data received from different use cases such as self-driven cars, holographic telepresence, and intelligently control 6G network [47].

At the PHY layer, many of the functionalities can be envisioned by mathematical models. However, certain non-linear phenomenon such as interference detection and channel prediction can be efficiently addressed with ML. Furthermore, the discrete modules such as modulator, demodulator, and the filter will optimize the performance as a whole by suitable learning methods in ML.

When we consider the channel coding process, the transmitter and receiver must implement certain coding schemes to safeguard the data against channel disparities. Deep learning is one of the promising methods for predicting the appropriate coding length by learning the channel codeword length. Next, synchronization is another aspect which certainly depends on the channel variations, mobility, and frequency deviations. In this regard, deep neural networks will prove to be beneficial. However, further research is necessary to comment more on this. Another aspect of ML is the use of deep neural networks for positioning. Since the existing positioning methods will popup accuracy issues when there is no line of sight path due to their dependency on pure mathematical modeling. In deep learning, fingerprint method uses CSI and received signal strength as learning data. Altogether, several physical layer optimizations such as beamforming, channel estimation, and throughput maximization are non-convex and do not yield a good performance with heuristic algorithms. Consequently, deep learning (CNN and DNN) appears as a boon to solve the physical layer optimization issues of 6G networks in real time, while achieving a good tradeoff between performance and computational time.

1) ML AT THE MAC

ML will find its application in optimal solutions to the MAC layer tasks such as resource allocation, modulation and coding scheme (MCS) selection, handover, and uplink power control. When the channel conditions vary due to user movement, channel variation the deep reinforcement learning methods could determine optimal solutions by learning from the varying inputs. (*i*) *ML for resource allocation*: In most IoT scenarios the data transmission is predictable as they follow a specific pattern. As a result, it is easy to predict such patterns and decide the resources to be allocated efficiently with the aid of ML. This reduces the network latency, and uplink random access for the devices. Similarly, by allocation of time, the frequency resources for cell users can be optimized with ML. It can predict the data traces in the cell, and network load and allocate time frequency slots in a flexible manner (flexible duplex) to optimize the resources and avoid interferences.

(ii) Power management: 6G network devices must have seamless battery management capacity. Since MAC layer controls the access to medium, the radio power is the key factor to be managed. ML can analyze the real-time traffic patterns inside the cell and data targeted for the neighbor cells to adjust the load. By this, the network can schedule users between transmission and sleep states in a power efficient way. (ii) *Security with ML*: Due to the high profile nature of the 6G network such as high data rate, all-round connectivity, and extremely low latency, the data generation will go skyrocket. As a result, to address the various security threats that would arise due to the massive data, the network security must be automated. In this context, proactive and self-adaptive features of ML will be promising solutions to automate the security.

2) ML AT THE APPLICATION LAYER

6G networks will be intelligent by integrating context awareness to offer better user services and multi-agent reinforcement learning to enhance the overall efficiency. Using a rule-based approach to determine the context configuration for each service class will be tedious. However, ML can predict the context configurations meaningfully with the help of past service choices and modify the configuration to suit the new services from the applications. For instance, lets us consider an application that monitors the network parameters automatically. We know that KPIs need to be maintained within the threshold level. Therefore, ML can be used to detect anomaly with respect to network management, security, and many more.

Future network architectures must be end-to-end service providers, where there will be dynamic cooperation between network segments and communication entities. To ensure all-round ubiquitous connectivity, interoperability between heterogeneous networks is mandatory. Furthermore, efficiency in terms of cost, power, system performance, communication, and connectivity, spectrum usage are necessary.

The core network to provide on demand service deployment consists of SBA, where network functions (NF) will subscribe to network repository function and it offers services to one or more NFs. By, each NF can be independently upgraded or removed to provide network slicing.

G. BUSINESS MODEL FOR 6G

5G's market will revolve around, providing the three key metrics for various verticals. Furthermore, in 5G networks, business models changed from monopolized network operators to distributed local edge micro operators, virtualized and software network service providers, and slice managers. Unlike the 5G network, the 6G network will provide ultimate connectivity between cyber-physical world in real-time and several upfront KPIs. This will motivate numerous verticals, technology developers, product and application developers for the future society 5.0. These market advances will disrupt the conventional business and invite new stakeholders and investors with regard to 6G's communication, storage, and control applications [50]. In addition, 6G network will intertwine with intelligence, virtualization, local edge operation, spectrum sharing, and a variety of sensing services; altogether, it will influence our personal lives and will be an integral part of society in 2030. As a consequence, it will bring in several newer forms of business models and opportunities to generate revenue [16].

1) KEY TRENDS AND UNCERTAINTIES

Smart grid system for distribution of electricity, or internet will be foreseeing extreme connectivity and self-driven. Considering these applications, revenue models can be planned with the involvement of public-private-partnership. Next, over the top (OTT) companies will offer cloud storage and cognitive services (AI, UAV as a service, and context aware services) along with primary features such as calling and data connectivity to compete with the traditional MNOs. This trend will boost innovative business models to attract customers and improve their profit. The business models along with increasing the revenue must even target sustainability goals for the benefit of humanity. For instance, 6G's vision includes providing connectivity for all humans; in this context, at least providing mobile internet to everyone in rural areas will solve the problem of digital divide. When people around the globe are connected, they will have the digital identity that will enable economic growth [157]. In this regard, data services will attract monetization. Further, another interesting business opportunity will be industry automation. When we consider Industry 5.0 and beyond, all sensors and machines that communicate with each other or operated by robots, will require a private and secure communication network which will offer extreme reliability, zero touch assistance, and operate as standalone networks. More importantly, 6Gs spectrum sharing, and policy regulations will generate prime revenue to the government and agencies. In addition to this, digital twins, and FinTech industry will revolutionize the business pattern with 6G networks. This is because, 6G networks will use green, zero energy, and zero emission technologies such as intelligent reflecting surface and high lifetime wireless nodes in a manner that will bring new business around building these technologies [23].

2) SCENARIOS

It is anticipated that the following scenarios will open up new business opportunities for 6G [50]. Edge computing, IoT, Robotics, and AI will become the common technologies that every electronic gadget will incorporate and will be reasonably priced for customers to afford. Therefore, these devices could be used to collect a variety of data from users and process them locally before remote transmission. Next, network slicing will allow up to 10000 slices under a network operator. This will gear-up revenue generation [23]. Furthermore, the development of sustainable solutions will empower them to operate as standalone and simplify the lives of people. In this regard, to find locally sustainable and economical solutions, public-private partnership projects, distributed cooperative models, and peer-peer business models will be more suitable against the monopolized market at the local level [50]. In addition, due to the sparse spread of technology in rural areas, manufacturing cheap and inexpensive solutions at the micro level could be an acceptable approach. However, 6G will overcome the digital divide to promote technology sharing in which a 3D design of a machine can be shared in real-time with another underdeveloped city that is deprived of research facilities to manufacture it using its cheap labor and market locally as well as in the place of origin at a reasonable price than otherwise. This will support a circular economy and creates a better society both in the rural and urban areas.

H. ADDITIONAL TRENDS

1) CELL-FREE ACCESS

Cell-less architecture is a concept in future networks, where the existing paradigm of connecting a user to an access point (gNB) confined to a cell will no longer be the case. Instead, a cellular user will get connectivity from multiple BS without the restriction of cell boundaries. In a traditional cellular architecture, the users who are at the edge of the cell will have poor connectivity, which will be addressed in the cell-free architecture. This feature requires tweaking the traditional cell search, synchronization, random access, and resource allocation procedures, to suit the new cell-less access [107], [112]. Furthermore, in 6G due to the extremely high density of mobile users or intelligent devices that require high data rates, the coverage of the gNB will be limited since they operate at very high frequencies, which reduces the interference. In this context, cell-less architecture is very useful to provide seamless connectivity. The cell-less system consists of several gNBs distributed in a large geographical region provides connectivity to all users located using the same frequency. These gNBs will be connected to a central processing unit (CPU), which controls them. Normally, a cell-free system is associated with MIMO to improve the spatial connectivity. The cell-free architecture has several benefits, namely, (i) scalable signal processing, (ii) scalable power control, (iii) spectral and energy efficiency, and (iv) simple signal processing and economical system [120].

2) BACKSCATTER COMMUNICATION (BsC)

It is an interesting paradigm for 6G network to achieve extremely high energy efficiency (EHEE) of the network when there are an enormous number of connected devices. For massively dense distribution of wireless nodes, the use of the battery as a power source will not be feasible due to the challenges involved in recharging or replacing the battery. In this scenario, the wireless nodes shall receive radio signals from the ambience passively, leading to battery-free operation [123]. The fundamental idea is to use the RF energy that is incident from the ambience and reflect it back after modulation. This method in fact, reduces the burden on the constrained device and increases the spectrum efficiency. It has applications in short-range and low power communication scenarios.

3) WIRELESS POWER TRANSFER

While connecting the massive devices, obtaining the channel state information (CSI) to know their channel status becomes a tedious task and consumes a lot of energy. As a result, the quality of transmission may get affected if CSI is omitted. However, a tradeoff between data communication and power can be achieved by wireless power transfer (WPT) and CSI-free transmissions. Further, wireless power transfer will be a possible method to promote sustainability, low emission, and zero energy consumption among devices in 6G networks [112]. In this context, as applicable to massive IoT nodes, the nods can be made energy harvesting from the surrounding. It could be by the use of solar energy, wind, hydroelectric, or RF signals, etc. The wireless power transfer using RF involves remotely powering (charging) the wireless devices using the RF field. For instance, when BS transfer to a user, then the neighbor of that user may use the energy in the RF signal to charge itself. It uses far-field radiation properties of electromagnetic waves to transmit within a short distance. This has several benefits, such as significant increase in the durability and life time of the nodes, reduced energy footprint, auto-charging, and contactless charging.

A few well-known solutions for wireless energy transfer involve (i) energy beamforming, where a group of high beam antennas are focused to transmit the energy to a specific set of nodes using narrow beams. (ii) distributed antenna systems to replenish the energy loss during energy propagation toward the nodes by using power beacons. However, there are several challenges involved in energy transfer. They are (i) ineffectiveness of the support for non-line of sight energy transfer, (ii) power transfer for non-stationary (mobile) users, (iii) radiation hazards, to list a few.

VII. 6G RESEARCH WORLDWIDE HITHERTO

While the 5G network is being deployed worldwide, the research and development activities on 6G networks are gearing up both in industry and academia. In March 2020, 3GPP completed the 5G standard release 16, which will be followed by release 17 to support all three scenarios in 2021 [46], [99]. Therefore, in the next couple of years, 3GPP will initiate the 6G research. It is anticipated that by 2027, the 5G infrastructure market will increase to 47.75bn USD by 2027. The top five players in the 5G infrastructure market include Huawei, Ericsson, Samsung, Nokia, and ZTE. They have currently shifted their attention toward the 6G network due to the enormous potential and benefit that the 6G network is anticipated to offer over the 5G network. Along the same lines, FCC has decided to promote 6G network research and trials in the THz band by opening a 95 GHz -3 THz frequency band for research [99]. Samsung has anticipated that ITU-R will define the official vision of the 6G network in mid-2021, and the initial commercialization of 6G network will begin by the end of 2028 [86]. Recently, from the past 18 months after the first 6G wireless summit in March 2019, the academia has become aggressive in the early research on the vision, technologies, challenges, and the future directions of 6G networks. The global telecom companies have even endorsed this. In the following paragraph, we will list the major activities in the research and standardization efforts by various organizations worldwide.

A. FINLAND

The 6G Flagship program (6Genesis) of the University of Oulu in association with other industries and academic institutes such as Nokia, VTT research center, Business Oulu, and Keysight technologies are at the forefront of research groups. They have initiated two 6G network summits and have released 12 white papers on the key research areas of the 6G network [112]. Moreover, Mediatek has started its research on 6G chipset along with Nokia in Finland.

B. CHINA

The major players in the 6G network in China include Huawei and ZTE. They have their independent research units aside government-sponsored 6G R&D promotion and expert group. Their research mainly includes THz, AI, and blockchain for 6G networks along with other operators such as China Mobile and China Unicom.

C. USA

In Feb 2019, US President Donald Trump US telecom companies gave a call to intensify their research to launch 6G network at the earliest. From academia, The New York University wireless center, headed by Prof. T. Rappaport, has highly engaged in developing the THz channel modeling and has achieved a 100 Gbps data rates in its trials [57].

D. SOUTH KOREA

One of the key telecom players SK Telecom, has undertaken 6G network research in the areas of THz communication, ultra-massive MIMO, and aerial communication. Further, they have collaborated with Ericsson and Nokia in 6G equipment manufacturing technology development. Samsung has recently released the white paper on 6G vision emphasizing three aspects: holographic communication, truly immersive XR, and digital twins [86]. Moreover, LG and KAIST University have developed a 6G network research laboratory to jointly conduct research in the technology areas of the 6G network.

E. JAPAN

NTT-Docomo has released its white paper indicating the vision of future 2030 network (6G). It has focused its research on AI and Cyber physical system to promote 6G networks. In the process, NTT has demonstrated 100 Gbps at 28 GHz band. In addition, Japan Govt., released 2.04 bn USD to promote R&D. Apart from these, Toshiba and Tokyo University have initiated 6G networks research [149]. Similarly, Sony, Nippon, and Intel have planned to work together in different fields of 6G technology.

F. EUROPE

In Europe, besides Finland, several universities namely, University of Dresden and Deutsche Telekom (Germany) are involved in the research of Tactile internet, HCI technologies. Next, University of Padua, Italy and NYU wireless group are also involved in the 6G network research.

VIII. FUTURE EXPLORATIONS

After discussing the current trends and future directions, it is essential to lead the research community with hints for further exploration. In this section, we will ponder upon some key directions and opportunities.

A. HOW TO PROVIDE SECURITY

In 6G network, massive connectivity, heterogeneity, and multi-hop routing for communication of user data arises the question of privacy of data. This is because, in the said context, data will be exposed to multiple entities, while ML requires the use of private data for training the data, which increases the vulnerability of data. The proactive security mechanisms for dynamic networks (high mobility vehicular networks) will increase the cost of control signaling. However, 6G networks cannot afford to look for reactive security methods that are slower [159]. Therefore, cost effective proactive methods need to be invented. Even though, quantum security seems to be promising, a vibrant research in this direction is yet to be seen. Therefore, 6G networks research shall devote more efforts on these security aspects.

B. VIRTUALIZATION OF RADIO ACCESS INTERFACE

Even though 6G network is distributed, an intelligent supports SDN and visualization are needed. The crucial questions to answer, include Will every network element supports various simultaneous verticals requirements such as resources, latency, QoS, and cloud computing needs? and how do we achieve that? In addition, virtualization in 6G, needs to support all radio access interfaces such as THz radio, smart surface, and quantum radio, which is a great challenge to address.

C. VERTICAL EDGE CACHING

When we consider the terrestrial, aerial, and space networks (vertically), the satellite networks will introduce a large delay. Therefore, aerial network elements such as balloons or HAPs shall act as data caching and edge computing facilities between terrestrial and satellite networks to reduce the computations of satellite networks and support critical services from there itself at a reduced delay. This scenario has a wide scope for future research with regard to radio resource allocation, localization, power efficiency, etc.

D. MOBILITY AND LOCALIZATION

Similarly, cell-free networking requires precise localization and synchronization between heterogeneous networks along with beamforming and accommodation of reflecting surfaces, which opens another area for future research [158]. Next, high precision beamforming under high mobility is infeasible. Therefore, the location-based steering of the beam looks promising. Albeit, efficient location-based mobility tracking for beamforming requires research attention. Moreover, during the mobility between different access networks with various protocols, to maintain active communication and localization, an integrated protocol design is necessary, which we lack at the moment.

E. RURAL CONNECTIVITY

After the outburst of COVID'19 pandemics, the world has gone almost virtual. We noticed that the urban areas sparsely connect to the rural areas, and most of the rural areas have local networks without having connectivity to the backbone. Therefore, to bridge the gap of the digital divide, policy makers, technology developers, and service providers shall work together to facilitate the availability of modern ICT tools to the unconnected. Furthermore, there is a need for awareness among the people about using AI, XR, and cloud-based technologies to promote better living and healthcare. Next, with respect to optical connectivity to alleviate the digital divide, new standards are necessary for VLC, and the equipment shall have dual connectivity comprising of VLC and radio transceivers [147]. The VLC radio shall also target to provide cost effective services to suit the needs of the underprivileged population. By considering these potentials of VLC regarding the digital divide, major research is necessary to support long range communication, with relatively lower cost than the radio spectrum.

F. ANALYSIS OF META MATERIALS AND REFLECTING SURFACES

Undoubtedly, these reflecting surfaces form the key component of 6G networks due to their energy saving and harvesting features. Albeit, analytical and electromagnetic field modeling to study the non-linear behavior of the phase response, channel capacity, and spectrum efficiency of these smart reflecting transmitters, needs in-depth study in the near future [144]. Furthermore, the multicarrier modulation, multi-antenna transmissions, practical direct demodulation of the reflected wave at the receiver, and the prototype development are the key areas for future exploration.

G. EI

When heterogeneous devices are connected, and all the intelligence has pushed to the edge, managing various data types, address resource allocation, and modeling the network behavior that requires data-driven multi-level distributed algorithms shall be well studied. In addition, light-weight AI solutions will be necessary to enhance distributed operations. Moreover, another interesting domain to explore is selecting different machine learning models for various verticals as each vertical will have multiple KPI requirements.

H. SUSTAINABLE GOALS

One may readily agree that the 6G network will greatly support SDGs. However, measurement of social impact due to the penetration of the 6G networks requires an in-depth analysis and mapping between 6G KPIs and the 17 SDGs. First, KPI values for SDGs should be determined. Second, a tremendous amount of work is required to bring equality in society, gender roles, and data privacy to invent new use cases of the 6G network successfully in order to promote SDGs.

IX. CONCLUSION

This article discusses the trajectory of the 6G network and its network components along with the current status, merits, use cases, and challenges. Further, we highlighted the current research and areas for future explorations. The vision of the 6G network and the next-generation network requirements indicate that the 6G network will immensely outperform the 5G network due to its ability to serve the extreme needs of future use cases such as autonomous vehicles, tele healthcare, industry automation, and the rise of several verticals. With a positive outlook, we described some of the possible use cases of the 6G network that will largely influence the society in 2030 and later. Further, it is evident from the KPIs that every aspect of the 6G network communication will wisely support various verticals. The main outline of this paper's discussion stems from how 6G network being a 3D connected network, and an AI-driven network will bridge the contemporary technology gap to efficiently achieve the SDGs. In addition, we provided a brief discussion by highlighting the merits of the key areas of the 6G network mentioned in the 6GFlagship project. We envision that AI, Intelligent surfaces, cell-free architecture, digital twins, and quantum computing will likely become the 6G technology candidates. Albeit, these technologies are not market ready. In this regard, international collaborations in industry and academia for research, technology development, and commercialization are necessary for the early inception of the 6G network.

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JAGADEESHA R. BHAT (Member, IEEE) received the Ph.D. degree in computer science from National Tsing Hua University, Taiwan. He is currently an Associate Professor with the Department of Electronics and Communication Engineering, St. Joseph Engineering College, Visvesvaraya Technological University, Mangalore, India. His research interests include wireless networks, mobile computing, and next-generation networks.

SALMAN A. ALQAHTANI (Member, IEEE) is currently a Full Professor with the Department of Computer Engineering, College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia. He also serves as a Senior Consultant in computer communications, integrated solutions and digital forensics for few development companies, and government sectors in Saudi Arabia. His main research interests include radio resource management (RRM) for wireless and cellular networks (4G, 5G, the IoT, Industry 4.0, LTE, LTE-advanced, Femtocell, cognitive radio, and cyber sovereignty) with a focus on call admission control (CAC), packet scheduling, radio resource sharing, and Quality-of-Service (QoS) guarantees for data services. His research interests also include performance evaluation of packet switched networks, system model, and simulations and integration of heterogeneous wireless networks. His final research interest includes digital forensics.