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TOPICAL REVIEW

Unleashing the Power of Tomorrow: Exploration of Next Frontier With 6G Networks and Cutting Edge Technologies

INSHA ISHTEYAQ[1], KHALID MUZAFFAR[1], NAWAZ SHAFI[2], AND MOATH A. ALATHBAH[3]

[1]Department of Electronics and Communication Engineering, Islamic University of Science and Technology, Awantipora, Jammu and Kashmir 192122, India
[2]School of Electronics Engineering, VIT University, Vellore, Tamil Nadu 632014, India
[3]Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11451, Saudi Arabia

Corresponding author: Moath A. Alathbah (malathbah@ksu.edu.sa)

ABSTRACT As societal needs evolve, especially with the advent of demanding applications like remote surgeries in Smart Health, current communication systems struggle to meet the required latency and reliability for such use cases. Similarly, enhancing existing applications, such as increasing transmission rates in mobile networks to provide Quality of Service (QoS) and improved user experiences, presents complex challenges. The pursuit of higher data rates has been realized by 5G wireless communication networks, which have already been commercially deployed. Nevertheless, the proliferation of smart communication devices and the emergence of IoE (Internet of Everything) applications present challenges to existing 5G networks in meeting the escalating requirements for ultra-reliable, low-latency communication. To address these limitations, researchers are focusing on the development of the sixth generation (6G) of cellular systems. Consequently, the selection of enabling technologies is crucial for designing a suitable 6G architecture that can address these evolving demands. Herein the main aim is to provide insights into the significant technologies for the future 6G, including their operation principles, potential applications, current research status, and associated technical challenges. This article proposes a methodology to analyze the relevance of enabling technologies and leverage it for designing an optimal 6G architecture. The evaluation results offer a unique perspective on 6G enablers, pinpointing issues and stimulating research for future mobile architectures. Additionally, the obtained insights provide researchers with essential information to stay updated on emerging enabling technologies and their suitability for crafting new and optimized 6G architectures that are engineered with adaptability and flexibility in mind, highlighting cell-free massive MIMO, hierarchical cell structures, and network slicing to facilitate ultra-reliable, low-latency communication and cater to various applications, all while prioritizing energy efficiency and sustainability.

INDEX TERMS Alliance of network AI (6GANA), beyond 5G, beam forming, block chain, cell-free massive MIMO, edge computing, holographic teleportation, sixth generation (6G), Tera-Hertz, ultra-dense networking, wireless optical communication.

I. INTRODUCTION

A. EVOLUTION

Communication technologies are constantly evolving, bringing about revolutionary changes with each new generation. So far, there has been advancement in wireless communication systems through 1st up to 5th generation. These five generations, starting from the analog-based 1G (First Generation) to digital-based 5G (fifth Generation), have progressively incorporated higher band frequencies, data rates of high frequencies and wider bandwidths. Since 2019, 5G has been introduced officially into commercial use, utilizing Sub-6GHz and millimetre wave (mm-Wave) bands and achieving peak data rates up to 20Gbps [1]. From an architectural view point, wireless mobile systems have advanced towards employing more number of antennas with

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wider range of services and multiple-access technologies. The evolution is depicted as in Fig. 1.

5G base stations are designed to leverage technologies like massive MIMO (multiple-input multiple-output), UDN (Ultra-dense networking) and mm-Wave (milli-meter). They can support a large number of transceiver chains, with some capable of handling up to 64 transceiver chains and greater number of antenna elements. The base stations for 5G communication with 128 antenna elements are already commercially available and many companies have even introduced the base stations equipped with massive MIMO having 384 antennas [2]. Furthermore, 5G networks have capability to support IoE (internet of everything), AR (augmented reality) and VR (virtual reality), enabling wide range of immersive experiences and connecting various devices and systems. Overall the progression from 1G to 5G has brought significant advancements in communication technology, paving the way for enhanced data rates, increased capacity and the support of emerging applications and services.

While 5G has brought significant advancements compared to its predecessor 4G, it still faces certain limitations. The number of applications and services today require performance levels beyond the capabilities of 5G. These include global coverage, ultra-low latency, ultra reliable and secure connections, and high energy efficiency, less power consumption, ultra-high data rate transmission, high precision positioning and pervasive intelligence. Overcoming these limitations entails addressing several challenges. Achieving global coverage necessitates further exploration of maritime and satellite communications at higher altitude regions. The transmission of data at extreme high data rates needs substantial improvement to support services like tele-medicine and ultra-high definition videos, with peak data rates reaching terabits per second (Tbps) levels. E2E (end to end) latency should be under 1 millisecond at low transmission speeds and reach microsecond level at high speed. The connection density needs to support 108 devices per square kilometer, meeting the demands of densely populated areas and industrial equipment. Furthermore, for high precision positioning, the accuracy must be enhanced to achieve centimeter level accuracy outdoors and sub-centimeter accuracy indoors. Reliability becomes crucial for novel applications that include wireless data centers, tactile internet and V2X (vehicle to everything) communications. For more number of intelligent applications, the communication systems of higher intelligence levels are of utmost importance. The novel features of 6G communication encompass leveraging terahertz frequencies to attain unparalleled data rates, ensuring ultra-reliable low-latency communication (URLLC) for mission-critical applications, integrating artificial intelligence (AI) algorithms for dynamic network optimization, and facilitating seamless connectivity across heterogeneous communication technologies. Furthermore, advancements in energy-efficient designs, exploration of quantum communication protocols, and implementation of robust security mechanisms constitute distinctive aspects of 6G communication.

B. LATEST ADVANCEMENTS

Wireless communication systems' progression occurs approximately in cycles of a decade. Currently, investigations into 6G are in the initial phases, with numerous countries and standardization bodies globally revealing their intentions for 6G research. The government of Finland initiated the world's foremost extensive 6G research program in 2018. The FCC (Federal Communications Commission) of USA inaugurated discussions on the subject. The Federal Communications Commission (FCC) has initiated the exploration of the terahertz (THz) spectrum aimed for the future 6G communication. In March 2019, they have recommended the concept of constructing sixth generation (6G) using a combination of "mmWave + THz + satellite". Subsequently, in October 2020, the NextG Alliance was established which specializes in overseeing the advancement of 6G within North America. In November 2019, China formally commenced the 6G research. They also established the IMT-2030 campaigning group to drive the development of 6G technology. The Communications Ministry of Japan unveiled its strategy for 6G in April 2020. Meanwhile, South Korea introduced a 6G timeline in January 2020, aiming for commercialization by 2028. Germany joined the 6G research endeavour in April 2021, outlining investments in a 6G Platform and Research. In the broader European context, 6G-IA (Smart Networks and Services Industry Association) emerged to foster the growth of next-generation networks and services. In February 2020, the ITU has issued the preliminary road-map for the developing research in 6G, on account of international standardization front [3].

Significant initial efforts have been undertaken in the pursuit of 6G development. A succession of publications and associated review documents are published. These papers outline the envisioned prerequisites, usage scenarios, crucial performance metrics (KPIs), and delve into topics such as network structure and pivotal enabling technologies for 6G. For instance, Finland's flagship 6G organization issued its inaugural 6G white paper in September 2019. This document introduced the concept of "pervasive wireless intelligence" which concentrated mainly on primary catalysts, obstacles, and pertinent subjects of research within the 6G domain. Subsequently, a sequence of white papers encompassing various aspects like networking, applications based on machine learning (ML), business implications, edge intelligence and security were released. Rohde & Schwarz contributed to the discourse with a white paper that investigated the progression from 5G to 6G, offering insights into anticipated 6G key technologies. Additionally, Ericsson emphasized the pivotal role of artificial intelligence (AI) in forthcoming intelligent networks, pinpointing five distinctive challenges associated with the incorporation of AI in the realm of 6G. The NGMN alliance meticulously examined the driving

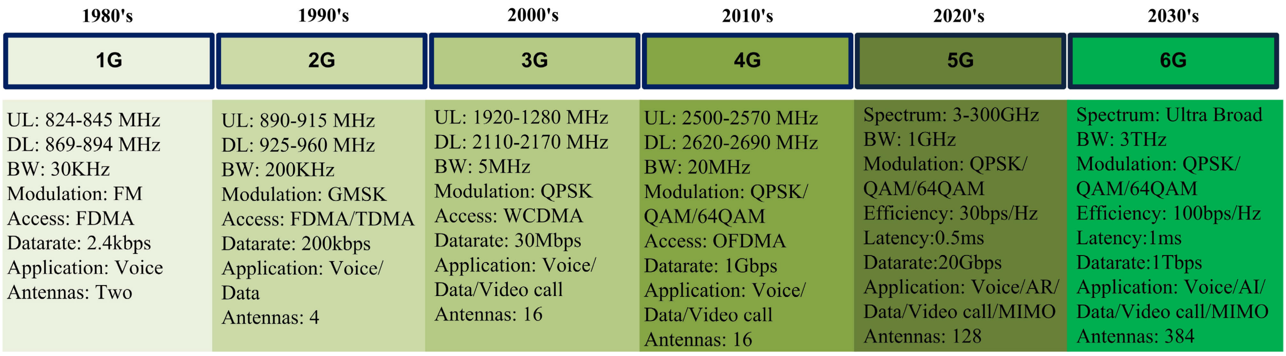

FIGURE 1. Evolution of antenna's, technologies and services from first generation (1G) and advancing to sixth generation (6G).

forces behind 6G, considering societal objectives, market expectations, and essential requirements. Their analysis also encompassed the transition from 5G to 6G, framed within a 6G vision [4]. On a similar note, the 5G-IA (5G Infrastructure Associations) issued a white paper [36] that projected into the future, outlining the impetuses, necessities, key technologies, and architectural considerations for 6G. Moreover, the 6G Alliance of Network AI (6GANA) is dynamically engaged in the exploration of implementing AI network and establishing internally intelligent 6G networks. These forward-looking evaluations of 6G have also acted as catalysts for various investigations into potential technologies geared towards the 6G landscape [5].

To meet the ambitious performance objectives, 6G may introduce novel technologies as crucial enabling factors such as:

1) Terahertz radio technologies to achieve ultra-high data rates.
2) Flexible networks designed for situational adapted network availability.
3) Fully integrated, precise localization and environmental sensing capabilities.
4) Optimized network architecture aimed at delivering superior service quality and reliability.
5) Integration of artificial intelligence for orchestrating the high flexibility features of the 6G network, ensuring robustness, self-organization, self-healing, and self-optimization of wireless networks.

The identified Key Performance Indicators (KPIs) of 6G primarily focus on technical performance, with "Network Energy Efficiency" being the sole metric directly addressing sustainability concerns. Regarding the comparison between 5G and 6G in terms of "Energy Efficiency," various values are reported in the scientific literature, ranging from a factor of 2 to as high as 300. This variability indicates that quantifying this feature is currently challenging and immature. Factors like network load and scenario intricacies significantly influence the outcome, highlighting the complexity of this metric. Given the innovative nature of future mobile networks, featuring concepts like cell-free architecture, dynamic clustering, and channel charting functions, discussions are ongoing across different bodies and

TABLE 1. Targets for 6G system performance.

Performance Objectives	5G	6G
Frequency Bands	Sub-6GHz and mm-Wave	Tera-Hertz
Peak Data Rates	2 - 20 Gbps	1 Tbps
Latency	1 ms	0.1 ms
Peak Spectral Efficiency	30 bits/s/Hz	60 bits/s/Hz
Reliability	10^{-7}	10^{-9}
Resolution	-	1 - 3 mm
Energy Efficiency	10	100
Mobility	500 km/h	1000km/h
Connection Density	10^6 device/km^2	10^8 device/km^2

committees to define appropriate metrics and measurement methods for assessing "Network Energy Efficiency."

C. POTENTIAL OF 6G TECHNOLOGY

The frequency ranging from (0.1-10) THz is emerging as a critical technology in meeting the escalating demands for data traffic in 6G and beyond wireless networks. These demands involve faster data rates and better coverage. In the context of 6G, the aim is to achieve around 1Tbps peak data rates and 60 bps/Hz peak spectral efficiency and to ensure end-to-end reliability with packet error rates of 109, and maintain end-to-end latency at 0.1 ms, as illustrated in Table-1. This next-gen wireless technology also aspires to enhance energy efficiency by a factor of 100 compared to 5G, while simultaneously enabling sensing resolutions of 1 to 3 mm in the expansive realm of the Internet of Things, accommodating billions of devices [6]

Although millimetre-wave (mm-wave) communications (30-300 GHz) have been incorporated into recent 5G cellular systems up to 100 GHz, the drive for even higher carrier frequencies poses challenges for achieving Tbps data rates and meeting stringent Quality of Service standards. These challenges arise due to the limitation of mm-wave systems under 100 GHz, constrained by a total consecutive available bandwidth of less than 10 GHz. Achieving spectrum efficiency of 100 bps/Hz within this limited bandwidth proves to be remarkably demanding, despite advanced physical-layer techniques. The THz band emerges as a potential solution for addressing the demands of 6G wireless systems. It stands out for several reasons: First, it offers contiguous bandwidth ranging from tens to hundreds of GHz. Second, it features symbol duration's at the picosecond level. Third, it enables integration of thousands of sub-millimeter antennas. Lastly, it easily coexists with other regulated and standardized spectrum, enhancing its usability. Traditionally, the THz frequency band has remained largely unexplored in the electromagnetic spectrum due to the absence of efficient and practical THz transceivers and antennas. Nevertheless, significant advancements over the past decade [7] have paved the way for practical THz communication systems, bridging this gap.

Amidst the rapid evolution of the mobile communications sector, there's an imperative to surmount the limitations posed by 5G and propel the progression toward 6G. Drawing from a series of forward-looking 6G initiatives, we present an exhaustive exploration and synthesis of the 6G landscape. The primary objectives of this paper are twofold: to establish a comprehensive understanding of 6G encompassing prevailing consensus and to delve deeply into the most recent advancements in 6G. The unique contributions and novelty of this survey can be encapsulated as follows:

1) An evaluative assessment of the global 6G vision, performance metrics (KPIs), and envisaged application scenarios is undertaken, encapsulating the prevailing currents in 6G research.
2) An extensive examination is conducted into the trajectories of development, research status, and standardization strides within the 6G network architecture. Moreover, we propose a promising blueprint for the 6G network architecture.
3) Embarking from the worldwide 6G vision, the survey uncovers a spectrum of open research directions and pivotal challenges in the 6G domain. It culminates with insights gleaned from meticulous evaluations of an extensive body of referenced literature.

Subsequent sections of the survey are structured on the foundation of delineating the comprehensive state-of-the-art, bolstered by more number of authoritative citations and succinct summary tables. This is then coupled with recognition of critical gaps in knowledge. Existing concepts are critically scrutinized, appraising their merits, drawbacks, and trade-offs. This groundwork serves as the Launchpad for tackling open research conundrums through a spectrum of promising avenues, while prudently avoiding potential pitfalls.

D. RE-IMAGINING THE FUTURE: THE VISION OF 6G

Envisioned as a trans-formative leap from existing wireless communication systems, 6G networks are poised to elevate service quality and cater to immense data traffic demands. Their goals encompass maximizing data rates, curbing energy consumption, expanding broadband connectivity, fortifying communication security, bolstering link reliability, reducing latency, and enabling intelligent communication. The aspiration for 6G is to achieve an extraordinary data rate exceeding 100 Gbps, coupled with end-to-end delays under 1 ms [8]. Moreover, 6G is anticipated to meet exceptional levels of communication reliability, ushering in an era of unparalleled connectivity. Anticipated as part of the ultra-era, future 6G networks aim to facilitate wireless communication with ultra-low latency, ultra-high reliability, and ultra-fast mobility. The advancement towards this era involves leveraging ultra-large scale MIMO systems and ultra-high frequencies to support high-speed wireless data transmission. Concurrently, these networks are geared to provide ultra-high broadband connectivity, enabling ultra-high-definition video streaming, as illustrated in Fig-2.

Realizing the ambitious requirements, of 6G hinges on novel and intelligent communication techniques. Concepts like re-configurable intelligent surfaces, extra-large MIMO, spectrum innovations, holographic radio communications, full-duplex wireless communication, diverse access and modulation approaches, and energy harvesting techniques are crucial for maximizing data rates and energy efficiency. Employing cell-free massive MIMO systems and integrating terrestrial with non-terrestrial communications contribute to enhanced connectivity and comprehensive coverage. Quantum communication and block chain enhance security and privacy, while holographic teleportation, edge computing, and the prowess of artificial intelligence and machine learning ensure ultra-reliable and low-latency communication.

6G's grand design is to seamlessly amalgamate diverse wireless networks, spanning terrestrial, airborne, underwater, and satellite communication systems. This integration establishes a powerful communication platform offering extensive broadband connectivity with universal coverage. Unlike its predecessors, 6G networks are designed to adeptly cater to delay-sensitive applications such as the Tactile Internet, holographic teleportation (tele-presence), the Internet of Smart Things (IoST) and multi-sensory extended reality (XR) involving augmented reality (AR), mixed reality (MR), and virtual reality (VR). IoST applications encompass domains like smart cities, smart radio environments, healthcare, grid management, transportation, manufacturing, agriculture, and home automation, all poised to be robustly supported by the capabilities of 6G wireless communication networks [9], [10].

E. RELATED WORKS

In recent years, there has been a significant surge in publications related to the THz band. This surge is not limited to technical papers alone; it also encompasses numerous tutorials and review articles that have surfaced in the academic literature. In the following section, we aim to provide an overview of these publications in Table-2.

II. RESEARCH METHODOLOGY, CONTRIBUTION AND HIGHLIGHTS

The review paper on 6G technology is based on a structured and systematic methodology in order to ensure a comprehensive and well organised review. We began the survey with the literature review on the appropriate academic databases

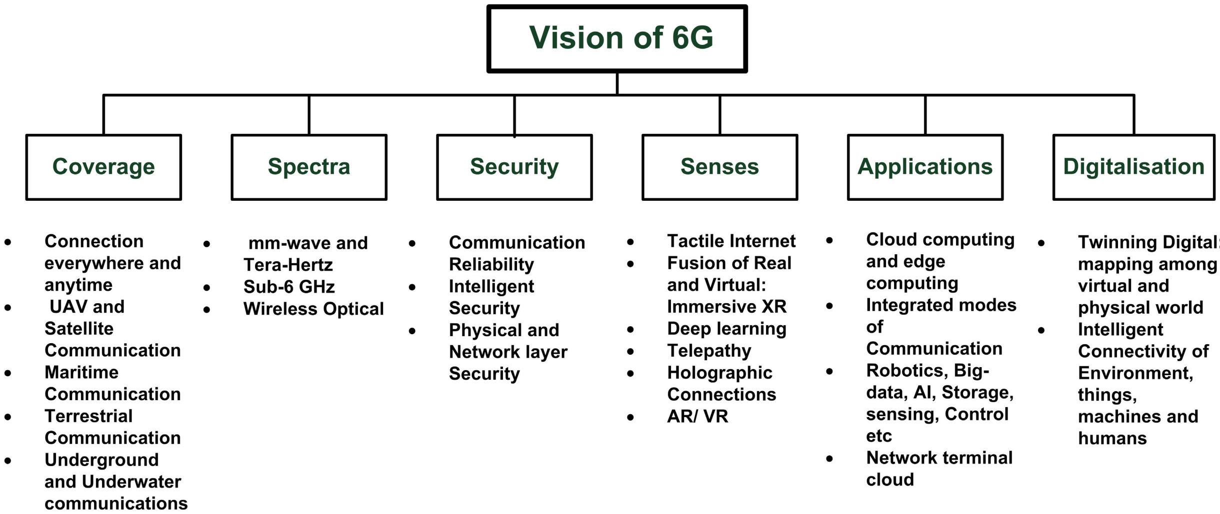

FIGURE 2. Vision of 6G: Re-imagining the future.

TABLE 2. Targets for 6G system performance.

Reference	Contribution
Zaman et-al [11]	The work has given the vision towards future 6G communications including the network architecture. It has provided the description of newly emerging technologies e.g. terahertz communication, cell-free communication, intelligent reflective surfaces, holographic beam-forming and many more. Most importantly the work has described the main challenges and directions for pursuing research towards achieving the goal of 6G.
Alsabah et-al [8]	The survey provides a forward looking perspective on the realm of 6G and its critical technologies. More specifically, it aims to furnish a comprehensive review regarding pivotal technologies for 6G networks. The survey encompasses an exploration of basic principles of operation of each technology, their important applications, cutting-edge research technologies along with technical limitations.
Hosseinzadeh et-al [12]	A comprehensive survey has been provided on the 6G how its related with Internet of Things (IoT). It has provided the technical hierarchy of 6G enabled IoT, mainly focusing on energy efficiency, security and organization of systems. It has pointed out towards future directions and challenges mainly including data off-loading, data storage, data sharing, scalability, user experience, authorization etc.
Mohsan et-al [13]	The review of key technologies and areas highlighting 6G networks and 6G prospectus has been given. The article has highlighted the historical outline of generation of communication technologies, prospective challenges and desirable solutions towards 6G.
Wang et-al [2]	The paper has provided a thorough depiction of 6G vision, going into its technical pre-requisites and important application scenarios. It has enlightened with a critical assessment of architecture of 6G networks along with in-depth of key technologies. The work has for the first time presented an exploration of test-beds and advanced platforms used for the characterization of 6G systems.
Farhad et-al [14]	This work has conducted an in-depth analysis of AI's application within the domain of Tera-hertz communications, exploring the challenges, potentials and limitations associated with its integration. In addition, the survey has entered into the available platforms, solutions, experimental test-beds and easily available simulators for Tera-Hertz communications
Alsharif et-al [15]	The main contribution of this work centers on the exploration of pivotal issues and identification of key attributes of 6G communications. The review mainly encompasses the envisioning of main technicalities, addressing challenges and potential remedies and comprehensive research endeavors.
Akyildiz et-al [16]	The main aim of the paper is to cast a retrospective gaze upon the past decade, re-examining previously encountered challenges and elucidating the accomplishments made within the research community so far. In addition, it focuses on the identification and presentation of on-going challenges and novel research avenues awaiting exploration within the realm of THz bands communication systems.

IEEE, Elsevier etc. the extensive research was done and certain specific aspects of 6G were defined for the review. The review began with the evolution of 6G from 5G with the latest advancements outlining the 6G platform. The research was also done on some key concepts including Tera-Hertz communication, cell-free massive MIMO, RIS (reconfigurable intelligent surfaces), Holographic communications, Edge computing, Block chain, Quantum communication, Artificial intelligence and Machine learning etc. The design flow of 6G wireless communication networks with associated performance parameters is depicted in Fig. 3.

The second step was to visualize the technical pre-requisites and the application scenarios for 6G communication. The major requirements of 6G were to identify the key performance indicators and the quantitative analysis of these KPI's. The number of research papers have been analysed for the detailed visualisation of the KPI's for efficient 6G communication. The critically targeted technical scenarios mainly included the key concepts of wireless data centre,

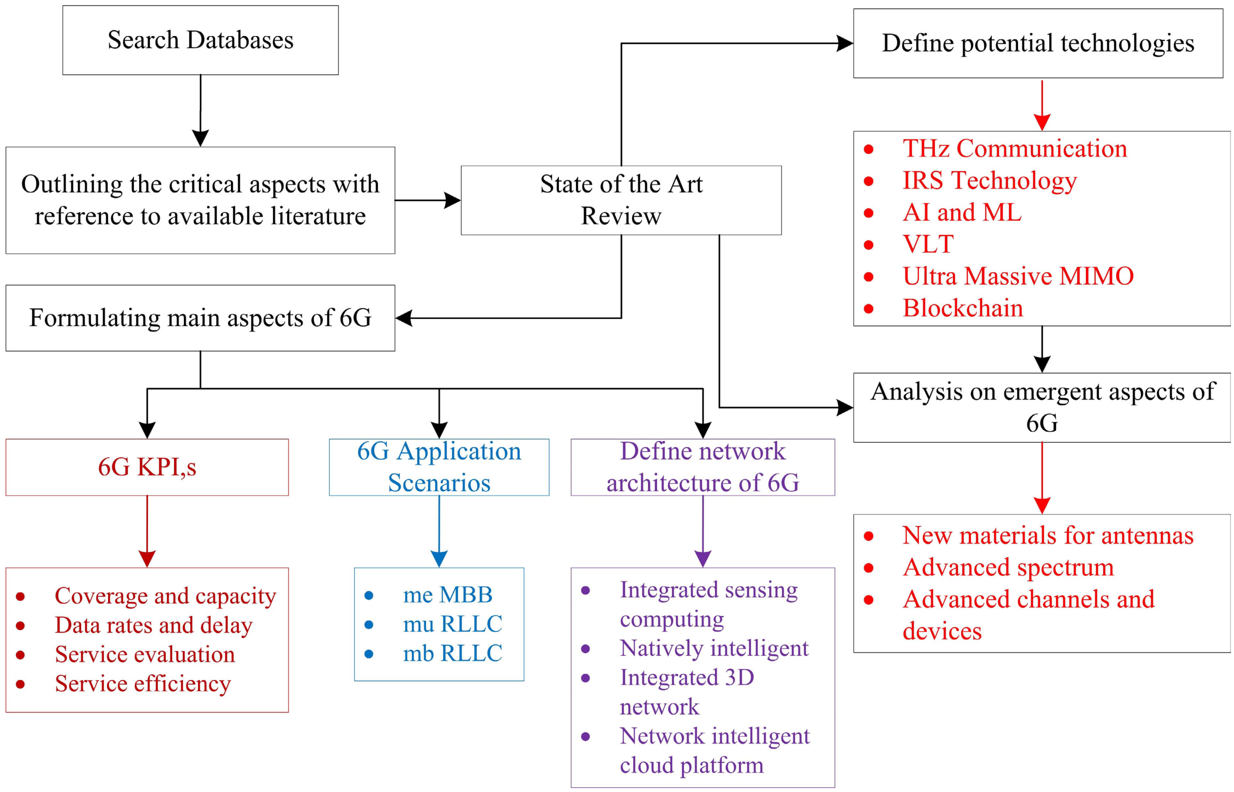

FIGURE 3. Design flow of 6G wireless communication networks with associated performance parameters.

digital twin, tactile internet, immersive XR etc and are comprehensively explained in Table 3. To address the high demand requirements for 6G communication, the three scenarios are explained: meMBB, muRLLC and MBRLLC.

For the 6G technical survey, we formulated a strategy starting from the basic 6G communication, KPI's for visualizing performance parameters, state of art literature, technical requirements, and network architecture emerging trends in the evolution of 6G architecture. The survey continued with the potential technologies for 6G viz THz, VLT, IRS technology, ultra-massive MIMO, AI, Block chain, ML, semantic communication etc. These technologies were then reviewed with emerging aspects for 6G that included the main features of new spectrum, new materials and antenna's. All the main technical aspects of 6G have been explained in the sub-sections respectively. The methodology involved in the survey is outlined in Fig. 3

III. TECHNICAL PRE-REQUISITES AND APPLICATION SCENARIOS FOR 6G

The number of application scenarios visualized in the 6G vision impose diverse performance demands on 6G communication systems. This section will provide a detailed vies of the 6G technicalities required and its application scenarios.

A. REQUIREMENTS OF 6G

The ITU-R initially identified eight key performance indicators (KPIs) for the assessment of International Mobile Telecommunications 2020 (IMT-2020). However, as mobile communication networks have rapidly evolved, these metrics are no longer sufficient to address the important use cases and applications anticipated for 2030 and beyond. While the eight KPIs originally employed to evaluate 5G remain relevant for 6G, their specific values must be updated to accommodate advancements in technology and the emergence of new applications. Additionally, the evaluation of new services in the 6G era necessitates the introduction of fresh indicators, encompassing aspects such as sensing, positioning, intelligence and security. The major KPI's for 6G have been shown in Fig. 4 and the quantitative analysis of Key point indicators of 6G in comparison to 5G have been broadly summarized in Table-3. The numerical values of 6G Key Performance Indicators (KPIs) are derived from an analysis of various literature sources, as elaborated in the text and explained in brief in Table 2.

B. APPLICATION SCENARIOS

For 5G, there were mainly three application scenarios that included eMBB, uRLLC and mMTC that were designed to address specific high demand requirements including substantial bandwidth and higher data rates, extensive device connectivity, minimal latency with exceptional reliability. Numerous research papers have presented their visions for 6G application scenarios but there is a requirement of detailed survey for determining the most important application scenarios along with justifiable classification [17]. 6G applications

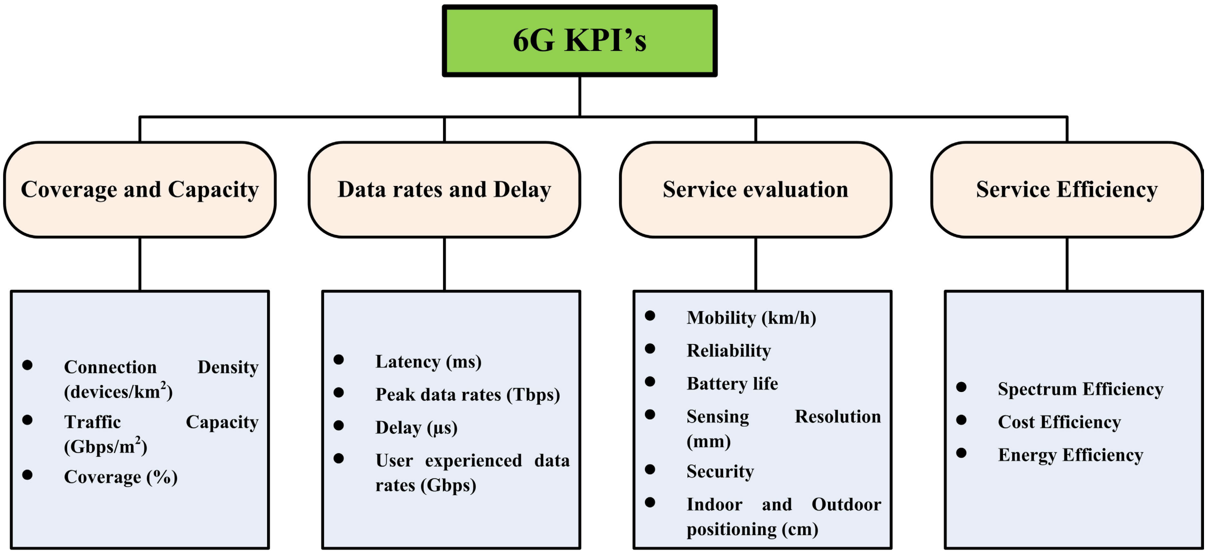

FIGURE 4. 6G Key point indicators, fundamental aspects for understanding the vision, development, and deployment of 6G technology.

Scenarios where 6G systems can be utilized to provide specific services, features, or benefits are presented in Fig. 5.

In the evolution to 6G, the existing application scenarios will undergo further enhancement and expansion. These enhancements include further enhanced mobile broadband (feMBB), ultra-massive machine-type communications (umMTC), and enhanced ultra-reliable low-latency communications (euRLLC). By 2030, the following three scenarios will not only encounter traditional Key Performance Indicators (KPIs) like data rate, connection density, and communication system latency but will also encompass new KPIs related to imaging, positioning, sensing, security capacity, and intelligence levels. Additionally, 6G will harness the integration and development of various technologies to introduce hybrid application scenarios that combine attributes from different categories. Beyond the three scenarios built upon the foundation of 5G, 6G is expected to introduce several new application developments that mainly include meMBB, muRLLC and MBRLLC. The potential 6G application scenarios are shown in Fig. 5.

1) **meMBB (Massive Enhanced Mobile Broad-Band)**
Massive Enhanced Mobile Broadband (meMBB) refers to a key application scenario and capability envisioned for future wireless communication systems, particularly in the context of 6G networks. meMBB aims to provide significantly higher data rates compared to previous generations including 4G and 5G. It seeks to enable ultra-fast internet access and data transfer, stream high-definition content, and engage in data-intensive applications seamlessly. To achieve the high data rates, meMBB requires access to a wide and substantial portion of the spectrum [2]. It may involve the utilization of previously untapped frequency bands or the aggregation of multiple frequency bands to provide ample bandwidth for data transmission. meMBB is expected to support a massive number of simultaneous connections, accommodating the proliferation of devices in an increasingly connected world. This includes not only smartphones and tablets but also a wide range of IoT devices and sensors. Dense scene communications scenario is particularly relevant in crowded or densely populated areas where a multitude of devices require high-speed data connectivity. It may find applications in urban environments, sports stadiums, concerts, conferences, and other venues with concentrated user activity.
meMBB is among the various envisaged application scenarios for 6G networks, with the goal of advancing wireless communication by providing exceptional data speeds, substantial bandwidth, and the capacity to support a multitude of concurrently connected devices. meMBB applications encompass delivering immersive augmented and virtual reality (AR/VR) encounters, enabling real-time high-definition video conferencing, supporting autonomous vehicles and drones, and facilitating advanced cloud-based gaming and entertainment services.

2) **muRLLC (Massive Ultra-Reliable Low Latency Communications)**
Massive Ultra-Reliable Low Latency Communications (muRLLC) refers to a key application scenario commonly used in the context of 5G and beyond wireless communication technologies. Massive mainly refers to the ability of the network to handle a massive number of devices simultaneously. In the context of the Internet of Things (IoT), this could mean connecting a vast number of devices, including sensors and machines, to the network. uRLLC is a category of communication services that prioritize ultra-reliable, low-latency communication [18].

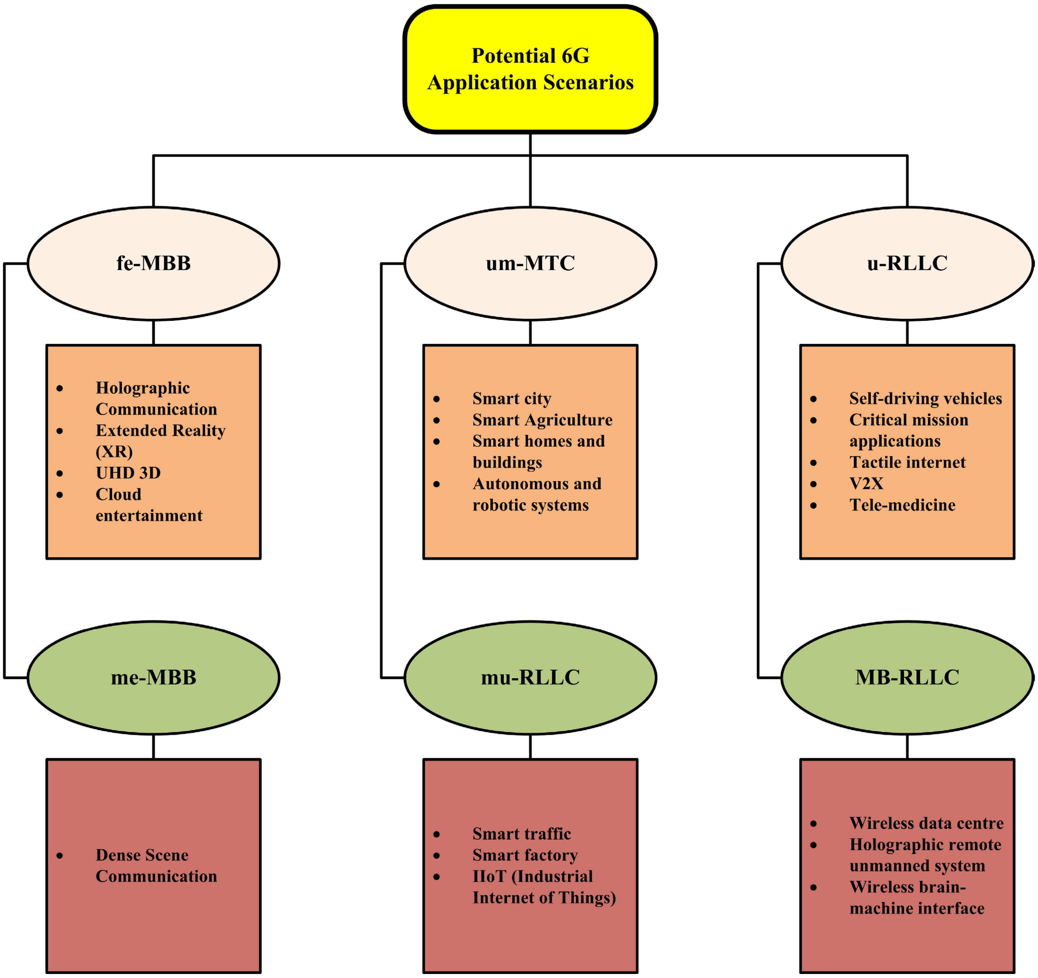

FIGURE 5. 6G applications scenarios where 6G systems can be utilized to provide specific services, features, or benefits.

It's designed for applications where extremely low latency and high reliability are critical. This includes applications like autonomous vehicles, remote surgery, and industrial automation, where even a slight delay or error in data transmission could have severe consequences.

3) **MBRLLC (Mobile Broadband Reliable And Low Latency Communication)**
Mobile Broadband Reliable and Low Latency Communication" (MBRLLC) is a term that combines the features of reliability and low latency related to mobile communications particularly 6G. Mobile broadband allows users to access internet, stream media and use various online services while on the move. In the context of MBRLLC, reliability likely means that users can expect a stable and consistent connection [5]. Low latency is crucial for applications like online gaming, autonomous vehicles, video conferencing and real time industrial automation. MBRLLC technology emphasizes both reliability and low latency ensuring a dependable and responsive connection for various applications and use cases.

Additionally there are various other scenarios that represent a diverse range of communication needs and applications and mainly include:

1) Communications with exceptionally low power requirements.
2) Applications related to digital twins.
3) Integrated networks encompassing space, ground, air and sea..
4) Long distance communication solutions.
5) Communication systems designed for high mobility environments

In Table-3, an overview of some new representative scenarios is given with respect to the upcoming 6G technology.

IV. NETWORK ARCHITECTURE OF 6G

To facilitate an energy efficient network with low cost, it's essential to transform the architecture of entire communication network. The network architecture of communication systems is constantly developing as going from 1G to 5G in number of aspects like virtual and cloud platforms including many more. In 5G, the main network architecture included SDN (software defined network), SBA (service

TABLE 3. Targets for 6G system performance.

S.no	Representative new scenarios	Explanation
1.	Digital Twin	It relates the real world systems to the digital world. The technology emphasizes on the digitization of the physical world with the help of smart technologies like AI. Digital twins find applications in industry, medicine, urban planning, transportation etc. Digital twin BAN (body area network) uses 6G to simulate a virtual body and can diagnose various diseases in advance and can also predict the effect of medication etc. on the virtual body [19], [20].
2.	Wireless data center	With the technological development like big data and AI, there has been enormous amount of data that plays a vital role in the developing recent societies. This much data needs much space for storage. Presently, the data centers are wired and consume high power, space and are very costly. So there is high demand for wireless data centers but there are many challenges to implement them because of transmitting high data rates. It is expected that THz spectrum in 6G and cloud technology will take through, to realize cloud based future wireless data centers. Cloud servers will be employed for massive data storage and THz spectrum will provide the medium for transmission by supporting the function of wireless data centers [21], [22].
3.	Tactile internet	It's a concept that represents the communication systems that aim to provide reliability and ultra-low latency for real time, touch based haptic interactions among devices and humans. With the onset of 6G, tactile internet allows collection, digitization and transmission of information over the available network. The major applications of tactile internet include remote surgeries and telemedicine, immersive / extended reality by using haptic feedback, robotics, gaming, training and education by facilitating hands on experiences. The TI concept is exciting and aims to bring touch based real time digitization of the world [23].
4.	Holographic Communication	It's an advanced technology wherein an individual can see as well as communicate / interact with the holographic images of others in a manner as is they are communicating with each other at the same place and time. It creates the realistic 3D images of remote things / individuals. Apart from real life examples it's expected that holographic communication technology will bring its users to experience their connectivity with past and future as well [24].
5.	Wireless Brain-Machine interface	The cutting edge technology allows its users to control the external devices through their brain without any need of external links or connections. In this, the electronic devices are controlled by the signals produced by the brain, wherein the device analyses the signals and converts them to certain commands in order to make the device operational. This technology can be better realized by 6G which makes it more reliable with high speeds, low latency, low power consumption and higher accuracy [24], [25].
6.	Immersive XR	XR-extended reality is a combination of virtual reality, augmented reality and mixed reality. VR refers to users connecting to digital environments (completely virtual). AR refers to users overlaying the content (digital) onto the real world. MR refers to the integration of VR and AR. Immersive XR aims to create a holistic environment by engaging multiple numbers of senses that mainly include vision, sound, and touch. 6G is going to achieve a completely immersive XR with its high speed, less delay, high data rates etc [24].
7.	Emergency Rescue Communication	It becomes one of the critical components of emergency services like natural disasters, human accidents etc. wherein the communication networks need to be very quick and fast. With the realization of 6G aiming at full space 3D coverage, the emergency rescue communication option will be a life saver for mankind [26], [27].

TABLE 4. Network architectures of 6G.

S.no	Network Architectures	Explanation
1.	NFV	Network functions virtualization technology is an architectural approach that virtualizes and abstracts the network services like routers, firewalls etc that were initially made to run on hardware appliances. The main aim of NFV is to replace physical network architecture by virtualized software based instances. In other words it aims at decoupling hardware and software [19], [29], [30].
2.	SDN	Software defined network is the networking architecture approach that employs controllers based on software to communicate with the said hardware of the network. SDN decouples the forwarding/data and control plane with the aim of separating control functions from forwarding functions. This architecture mainly includes application, data and control planes [31], [32], [33].
3.	SBA	Service based architecture consists of separate modules acting as network elements that are connected to furnish the services to the basic network. SBA tends to modularize the core 5G network by providing service functions using NFV. Similar to SDN, SBA architecture also provides two plane functions namely user plane function and control plane function for 5G network core [34].
4.	Network slicing	The major scenarios of 5G communication systems i.e. eMBB, uRLLC and mMTC have quite different network requirements. There is a need of flexible communication system to support the different scenarios. The network slicing concept has emerged which has taken into consideration all the required factors. The main aim of network slicing is to provide number of application services by multiplexing different networks virtualized on the same physical network [35], [36], [37].

based architecture), NFV (network function virtualization) and network slicing which has made 5G network more flexible in terms of services (cost) and energy. But for real world network applications, 5G is still facing challenges [28].

Keeping in consideration, the cost, application and technical requirements, 5G architecture is enhancing towards 6G networks. 6G architecture will be having core 5G network in addition to some more additional novel architectures. The

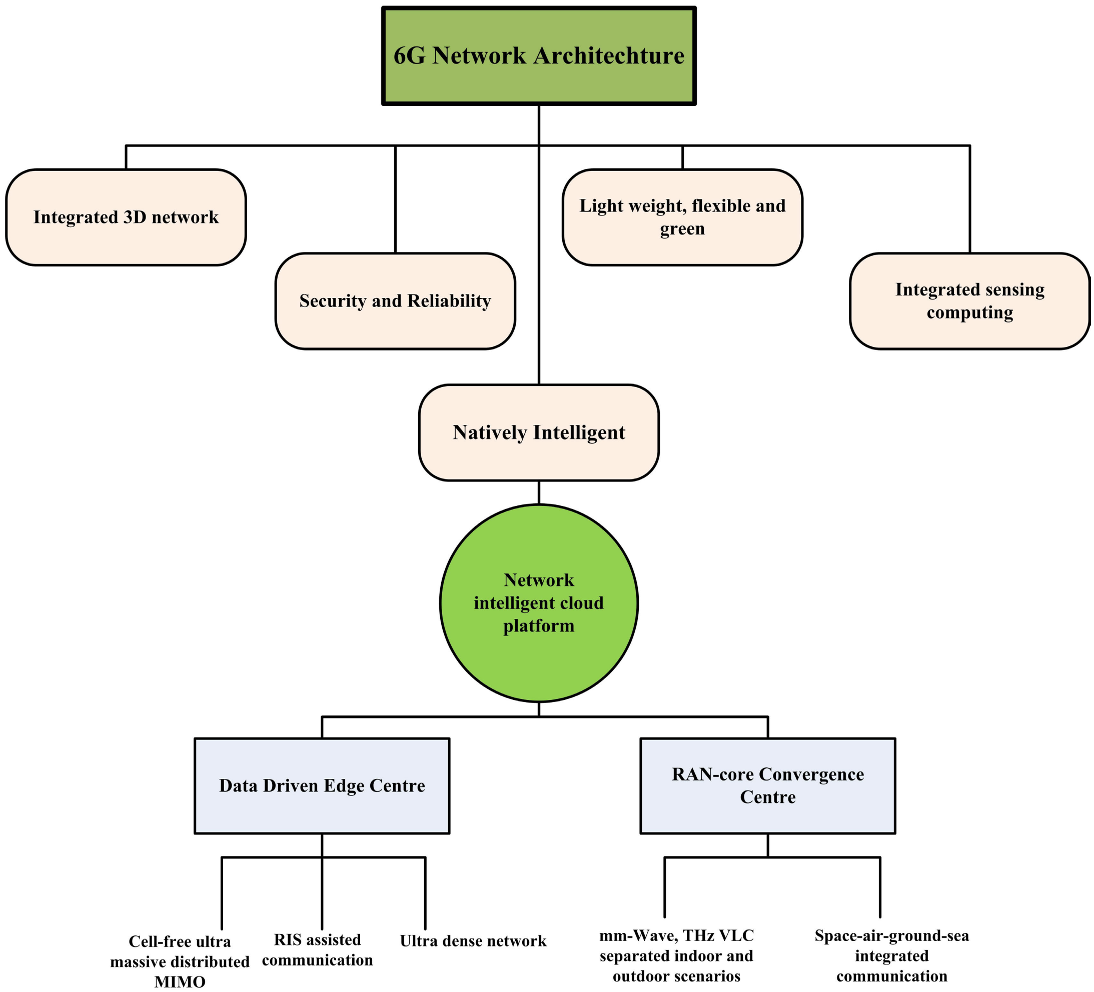

FIGURE 6. Network architecture of 6G, tailored to support wireless communication and connectivity.

network architecture for 6G is shown in Fig. 6. The most important parts of the network architecture include:

1) Integrated 3-D network
2) Security and Reliability
3) Light weight, flexible and green
4) Integrated sensing computing
5) Natively intelligent

The section first summarizes the evolved 5G network architecture and then developing architecture for 6G networks.

A. EVOLVED ARCHITECTURE OF 6G NETWORKS

The key considerations of the evolved architecture for 5G networks have been summarized in Table 4.

B. EMERGING TRENDS IN THE ADVANCEMENT OF 6G NETWORKS

1) Integrated 3D multi-network
All the existing and previous networks mainly provided the connectivity to the urban terrestrial areas. However, the rural areas were deprived of the good connectivity. Also, the terrestrial area networks lack robustness and on-time communication during the crucial times like disasters etc. This void is expected to be filled by 6G [38]. 6G is going to provide a full-space 3D network profoundly integrated with the heterogeneous dense terrestrial networks [39], [40].
2) Security and reliability
While it's essential to introduce the network architecture to cater the diverse needs of various applications in 6G communications network, the crucial aspects like security cannot be overlooked. The convergence of various communication technologies with virtualization, data and industrial technologies has posed a threat to the security in 6G technology. 6G networks are going to face number of security issues for example algorithms and models are prone to security risks in addition to software vulnerabilities and issues of privacy in data [41], [42]. In view of the above risks, the upcoming 6G architecture need to rely upon multi-lateral model that will take security risk into consideration right from the start of designing the new network. So, there is necessity of introducing some security technologies

like block-chain, physical layer security and quantum communication while designing the architecture of 6G network [3], [43].
3) Integrated sensing communication and computing
The edge computing service has been introduced in the network architecture of 5G in order to reduce the costs as well as service latency [43]. In 6G, the computing service can be realized by deep integrated sensing and data transmission functions. In order to ensure the efficient services for number of application scenarios of 6G, every node in the network will have to perform the function of data transmission, sensing and computing [44], [45].
4) Light weight, flexible and green
While designing the network architecture there has been a continuous trend for the networks to be flexible, green and light weight. It will be a boon for the flexible and dynamic allocation of network resources that will also reduce the operational deployment costs. By using cell-free architecture [46], fully decoupled RAN and Ran core convergence architecture [47], 6G architecture is going to be more flexible, greener and light weighted [48].
5) Natively intelligent
6G is believed to be more intelligent than 5G. NWDAF (network data analysis function) has been added to core 5G network, which has resulted in the improvement of collection of data and analysing capabilities of network. Because of limited data resources, privacy issue and external AI support [9], the NWDAF does not provide AI network support. With the fast development of AI and communication sensing and computing, 6G is going to support AI intelligence and other technologies like cognitive architecture, DEN2 (deep edge nodes and networks), SSN's (self-sustaining networks) will help 6G to be natively intelligent [49]. The concept of architecture is capable of connecting a number of promising network technologies into a single structure core. The architecture of 6G network with new flexible architectures that mainly include cell-free architecture and many more technologies for enhancing the intelligence of networks has been proposed.

V. STATE OF THE ART: A COMPARATIVE STUDY

In response to the swift evolution of the mobile communications sector, addressing the constraints of 5G has become imperative, necessitating the on-going advancement toward 6G. This comprehensive exploration builds upon existing forward-looking 6G initiatives, presenting an extensive discussion and consolidation of the current state of 6G. The objective of this paper is to propose a definitive definition for 6G, encompassing prevalent perceptions, and to meticulously examine the latest advancements in 6G technology. A comparison between this survey paper and other existing 6G survey papers is provided in Table 5.

The distinctiveness and contributions of this survey can be outlined as follows:

1) Thorough evaluation of the global 6G vision, Key Performance Indicators (KPIs), and application scenarios, providing a critical analysis of the prevailing themes in current 6G research.
2) In-depth examination of the development trends, research status, and standardization progress related to the 6G network architecture, along with key technologies. Additionally, a promising 6G network architecture is proposed based on the findings.
3) Pivotal scrutiny of existing 6G materials, encompassing 6G-style wireless channels, crucial 6G components and new antennas marking the comprehensive review of these elements in the context of 6G.
4) Starting from the global 6G vision, this survey delves into a set of open research directions and key challenges inherent to 6G. The discussion culminates by drawing insights from the critical assessments of an extensive body of literature cited, providing valuable lessons learned in the process.

VI. POTENTIAL TECHNOLOGIES FOR 6G

The vision of 6G has set a path for this future wireless system. With the aim of using all the spectra and offering a global coverage to its users, there is going to be the expansion of communication systems towards intelligent secure services integrated with sensing and computing. In view of this, it's expected that 5G is not going to fulfill support the 6G vision in terms of intelligent systems. A part of 6G technologies are the expanded versions of 5G technology. In 5G data rates were increased by using mm-Wave technology while as 6G is going to use THz, optical wireless technology and more advanced spectrum's to meet the demand. Interfacing technologies like massive MIMO, OFDMA, half-duplex etc. of 5G are going to be developed further in 6G [61]. The current world technology, AI is going to enhance the wireless communication by providing the intelligent solutions for all network layers of the communication system [52], [62]. Block-chain is another technique for providing reliable and secure communication systems [63]. To overcome the bottleneck in transmission part of the communication systems, a promising way to extract information is represented by semantic communication. The potential 6G technologies have been briefly shown in Fig. 7. The developmental concepts, applications and the challenges of the further evolved 6G technologies are explained in this section.

1) THz Communication
It's one of the promising areas for research as it's going to offer number of advantages which are anticipated for the requirements of 6G. The problems of spectrum congestion have made 5G systems insufficient for realizing the demands for increasing data services by 6G systems. In between the optical and mm-Wave frequency range, the recent spectrum is 0.1 to 3THz.

TABLE 5. Outlook on the perspectives of reported works based on vision, KPI', applications, architecture, key technologies and challenges.

Ref.	Reported Content					
	Vision	KPI's	Application Scenarios	Network Architecture	Key Technologies	Challenges
[50]	#	#	@	#	#	@
[51]	#	N. R.	@	#	#	@
[52]	#	N. R.	@	#	#	@
[53]	*	N. R.	N. R.	#	#	@
[11]	*	N. R.	#	@	N. R.	#
[54]	*	#	#	@	#	#
[55]	#	#	#	@	#	#
[56]	*	N. R.	#	#	#	@
[57]	#	#	#	#	N. R.	@
[19]	#	#	#	#	#	@
[24]	#	#	#	@	#	@
[28]	*	#	#	@	#	#
[17]	*	#	#	#	#	@
[58]	*	#	#	N. R.	#	#
[59]	#	N. R.	#	N. R.	#	@
[9]	*	N. R.	N. R.	#	#	#
[60]	N. R.	N. R.	#	#	*	#
This paper	#	#	#	#	#	#

Note: The symbol '#' indicates that perspective which is explained in detail, '@' indicates that aspect which is mentioned in brief or in comprehensive manner and '*' represents those references where only outlook for where only outlook for 6G is given without complete vision for 6G whereas 'N. R.' indicates that aspect which is not not reported at all.

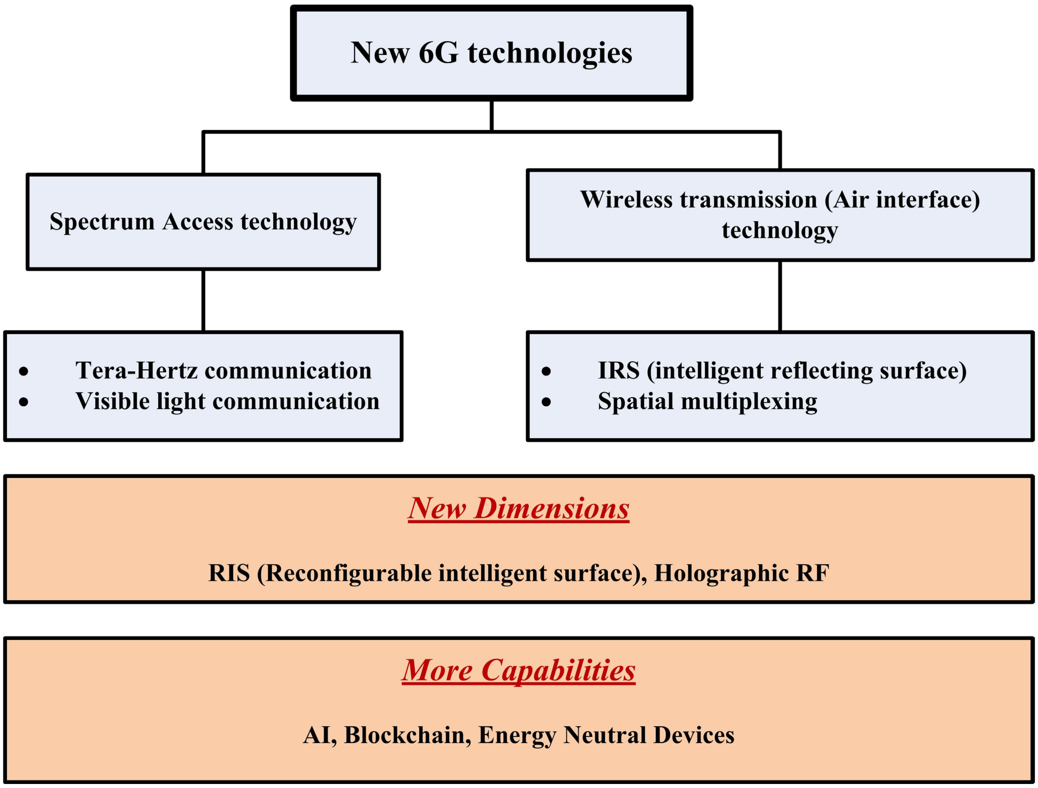

FIGURE 7. New technologies for 6G.

The THz frequency range is characterized by large bandwidth and high frequency, narrow beam, high molecular absorption etc [64]. THz communication is going to play a significant role in positioning, sensing, imaging and so on. With reference to Shannon's equation, THz can offer fast data services in Tbps meeting the essential requirements of XR (AR/VR). Having narrow beam, directivity THz communication will be highly secure with short distances [65], [66].

2) Visible Light technology
Besides THz spectrum, optical wave communication is going to provide the services of highly dense broadband

communication with no electromagnetic interference, high network security, very low latency, cost efficient, easy deployment and makes the use of unlicensed free spectrum. The optical band mainly consists of 10-400nm (UV), 760nm-1mm (IR) and 360-760nm (visible light) [67]. In addition to providing services of wireless communication, visible light is a good source of energy and it provides illumination also. VLC is a potential application for vehicular, indoor and underwater communication in addition to localized systems. Some of its applications like WiFi, Lifi are capable of providing multi-user communication as well as illumination at the same time [68].

3) IRS technology
In this technology, the reflection of the signals is controlled by certain software. The power of the signal can be improved by using IRS technology [69]. In addition to this, intelligent reflection surface technology is used to reduce the interference and chances of data theft by controlling the phase and amplitude of the signals [70].

4) Ultra-massive MIMO
The concept of MIMO has proved very important for 5G technology. In massive MIMO, the number of antennas per user should be greater than 10 [71]. For 6G, the concept of ultra-massive MIMO has been initiated which refers to hundreds and thousands of antenna elements forming larger antenna arrays. It enhances the spectrum and energy efficiency, provides high position accuracy with diversity in frequency range and flexibility in network coverage [72].

5) AI
The great learning and understanding ability, robustness and capability for reasoning has made AI applicable for potential scenarios and number of applications [73]. In this era, there have been various limitations on the on-going traditional algorithms of wireless communications because of the emerging technologies that has created the demand for intelligent services. It's expected that Artificial intelligence can be applied throughout the 6G network layers, thereby simplifying the optimization and management of networks making them more reliable and efficient [74].

6) Block-chain
The term block-chain has been initially coined for crypto-currency back in 2008. The traditional access control and authentication mechanisms will not be applicable in 6G because of frequently changing data and flatter structure [75]. Block-chain is regarded as fundamental technology in the context of 6G systems. It offers a good solution to address trust and security concerns that arise among distributed and diverse infrastructures and devices of networks [63], [76].

7) Semantic Communication
It's a method of communication where there is an exchange of content of the message. It puts an emphasis on conveying context, meaning and mainly understanding among the communicators. It's going to play an important role in AI, NLP (natural language processing) and most importantly human-computer interaction. Semantic communication is going to improve the quality of services, reliability and efficiency of communication and realization of connecting everything intelligently [77], [78].

VII. EMERGENT ASPECTS FOR 6G

Apart from the advancements in the past wireless technologies and in addition to overcoming the challenges required for the development of wireless systems, 6G is going to beset a number of a number new elements. These elements mainly include the new spectrum, devices, materials and channels. In the following section, the potential elements and the challenges [3] to be faced with every respective element will be discussed.

1) **New Spectrum**
The first and foremost resource for any wireless communication system is the availability of spectrum. To achieve higher data rates, more part of the spectrum is required. The allocation os spectrum is quite critical in terms of global economies and for convenient roaming around the globe. With the evolving generations of mobile technologies, the usage of spectrum has been expanding to the higher frequencies. The mm-Wave frequency were being first utilized in 5G, while as 6G is going to seek even more higher bands. Despite the fact that 6G will utilize high frequency bands but low and mid-bands are equally necessary for achieving the wider coverage. So 6g is going to have the framework of multi-layered frequency bands as shown in Fig. 8.

2) **The New Materials and Antennas**
Over the few recent years, there has been a remarkable advancement in the semiconductor device technology which has ultimately led to the revolution in the digital communication area. It is anticipated that the new material technologies will progress further enabling the use of new spectrum and novel antennas for the upcoming 6G.

   a) Use of Silicon towards THz
   The use of silicon technologies which are intrinsically cost effective, compact in size, high yielding and most importantly energy efficient play an important role in the communication, computing, imaging and beyond. The more advanced techniques are going to possibly integrate both electronic and photonic components more efficiently on the same compact silicon that could be practically realized in the near future. Due to the continuous progress in the semiconductor technology, THz circuits have been achieved. It has become possible to fabricate IC's upto 700GHz by using SiGe HBT (hetero-junction Bipolar) technology. Its estimated that this HBT

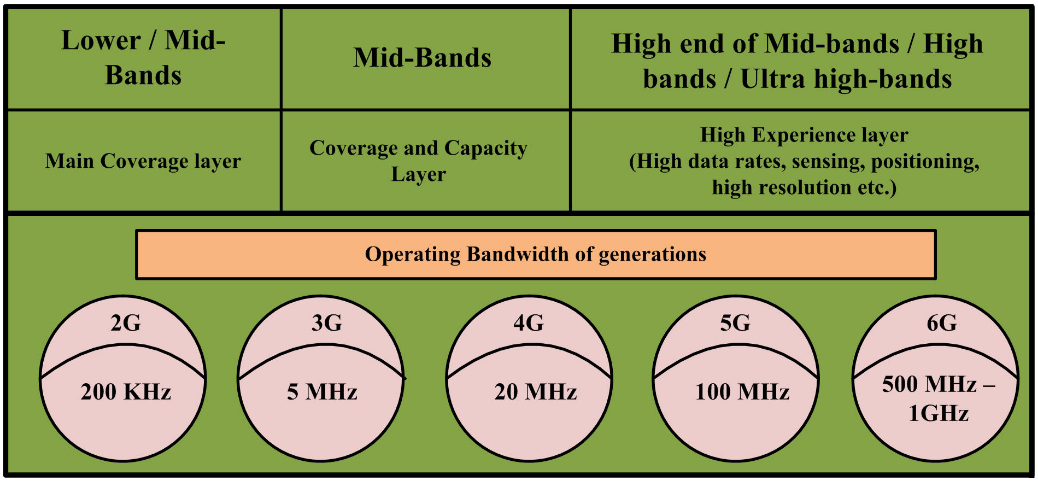

FIGURE 8. Framework of multi-layered frequency bands for 6G.

is going to reach 1THz mark. A THz antenna can be conveniently integrated with the silicon substrates having a front-end circuit. Although its very challenging to design on-chip antennas because of the generated surface waves in the substrates which can interfere with the radiation of antenna resulting in more losses. Its very desirable but challenging too to design the antennas having low loss and high efficiency at THz frequencies.

b) Intelligent and Re-configurable surface materials
The electrical properties of the materials can be desirably tuned for making the devices more functional with reduced dimensions and cost effective. For controlled flexibility, a number of tunable materials are proposed for the systems with this feature of tuning RIS (re-configurable intelligent surfaces) are enabled for the digital platforms. RIS have the ability to manipulate the incoming em waves and shape them to desired outputs by employing efficiently designed scatters called meta-atoms which can enable beam-steering and beam-forming functions. The materials can include liquid crystals, graphene etc. To enhance the multi-user performance, the base station beam-forming and the RIS phase control need to be optimized together. In those scenarios where there is no link between the base station and users/vehicles, RIS's can be employed to increase the indoor as well as outdoor coverage as can shown in Fig. 9.

3) **New Channels**
The propagation techniques are mainly represented by the channel models and are used for comparison and evaluation among number of different systems. There are mainly three broad categories of channel models: deterministic model, stochastic and hybrid model. The parameters of propagation are fixed in deterministic channels wherein the channels can be recreated by certain techniques like ray tracing, CEM (computational electromagnetics) and measurements etc. The stochastic models are constructed from randomly distributed clusters generated in accordance to specific probability distribution function. Hybrid models, sometimes referred as quasi-deterministic models and scattered elements from stochastic models [79]. In the transition from 3G to 5G, channel model research emphasized on enhancing the deterministic aspects but within some complexity limit. With the introduction of new scenarios, antennas and spectrum, channel modeling is facing new challenges in the 6G as discussed below:

a) There is a problem of increasing free space path losses with the spectrum going beyond 100 GHz i.e. in to the THz range. To overcome this more and more enhanced beam-forming techniques are required. One of the prominent challenges for THz range in the phenomena of molecular absorption [80]. For small-scale fading THz signals exhibit the properties of multi-path propagation like that of mm-Wave signals specially in case of indoor scenarios [81].
b) The development of new antennas like ELAA (extremely large aperture array), RIS, ultra-massive MIMO have prominently affected the channel modeling. So. some of the features like non-stationary channels, near-field spherical waves, rate of cross-polarization, phase shifters etc need to be re-modeled in accordance to the desirable outputs [82], [83].
c) The new scenarios like ISAC are more dependent on the environment and gets difficult to explain by stochastic models whereas some of the specific scenarios can be explained by deterministic models.

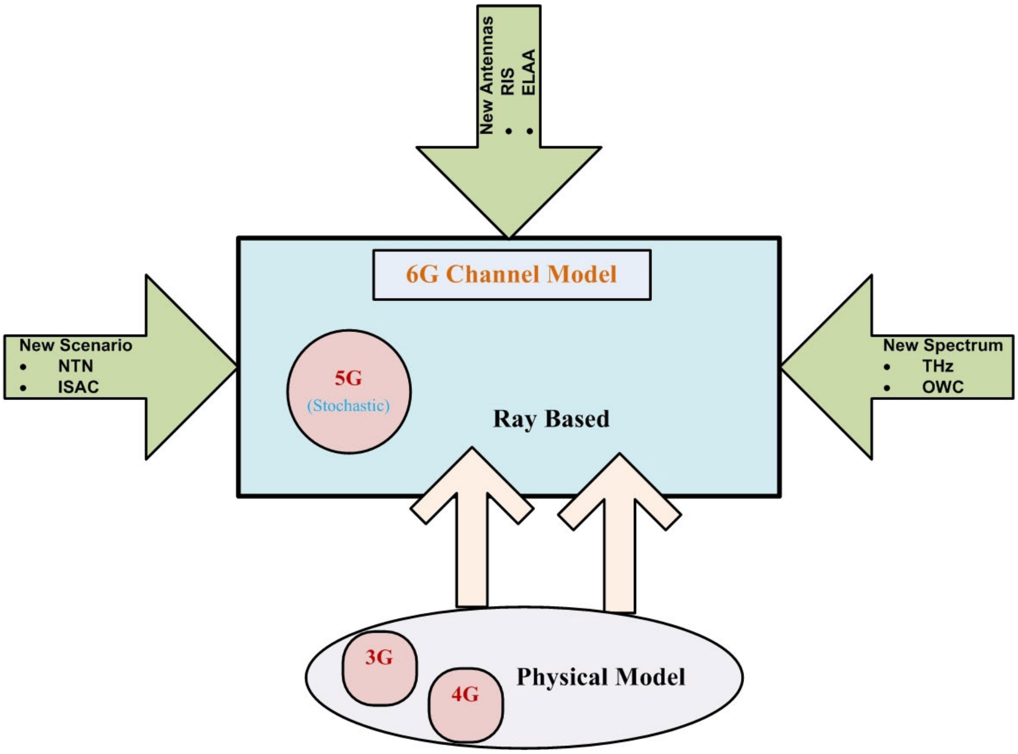

FIGURE 9. 6G channel modeling challenges.

4) **New Devices**
During the past 20 years, feature phones were replaced by smartphones, the same kind of revolution is expected during the 6G era. The devices in the future era are going to posses new possibilities that will include AI, imaging and sensing, holographic displays, haptic communications which will be the main targets of 6G communication systems. There can also be the perception at human level, human-machine interaction at multi-modal level, ambient sensing and energy harvesting etc as can be visualized from the Fig. 10. The development of new possibilities have become the driving force for the four major trend as explained below.

1) Diverse
Diversity does not only confine to the smartphones but it also includes many different types of devices which can perform as sensors and actuators. A number of industrial and human-oriented devices are going to emerge in the near future. There will be advanced integrated sensors, Artificial intelligence, new display technologies e.g. medical implantable devices, smart equipment's, wearable devices automobiles and robots & cobots. The rapid outgrowth of diverse devices will demand heightened standards for connectivity. Central or anchor devices will play a pivotal role in ensuring a smooth and uniform user experience.
2) Versatile
In order to provide the new possibilities for future mobile systems, its going to offer sensing applications which are novel in addition to providing connectivity. For creating cybernetic organisms, multi-sensor capable devices might be integrated to the humans for advanced human race. These novel capabilities are going to support healthcare, spectroscopy, gesture recognition etc.
3) Cloud-based
The new models of business and privacy protection will be enabled by virtual devices in addition to the physical devices. The 6G devices are expected to have a virtual counterpart on the cloud acting as its proxy, that will be shared and used on demand. It will enable the users to use the desired services anytime and anywhere.
4) Smart
It does not only refer to make the smarter smartphones but to augment the reality for automating everything. The future mobile devices will be implementing the capabilities of AI and edge cloud computing. The future devices will be having more intelligence with AI/ML, thus automating the productivity and service experience.

There has been a shift in paradigm in the design of network architecture and the air interfaces [3].To accommodate the wide array of applications and to achieve the ambitious objectives of an era characterized by interconnected intelligence, we need to achieve groundbreaking innovations in the design of the 6G air interface. These innovations will instigate significant shifts in the fundamental design principles, as depicted in Fig. 11.

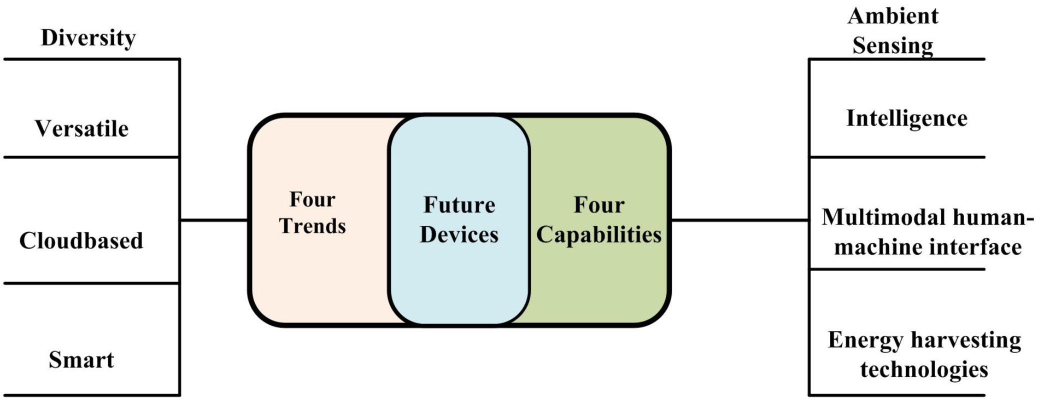

FIGURE 10. Trends and possibilities for future devices.

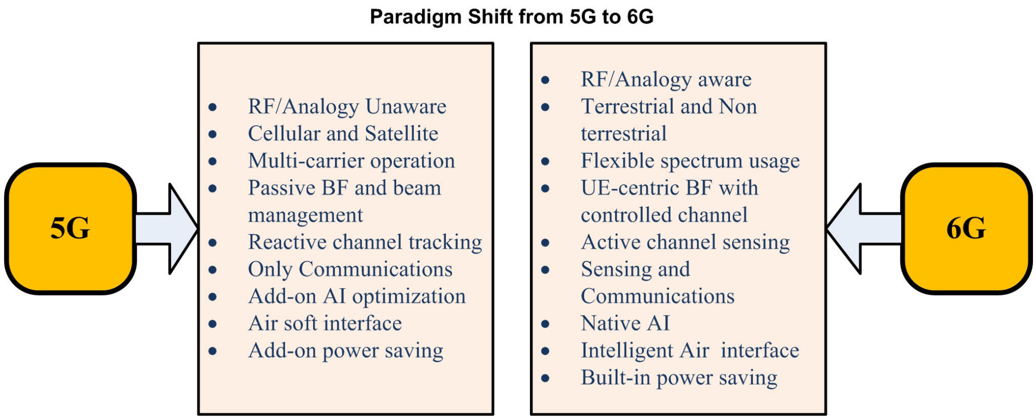

FIGURE 11. Shift of paradigm from 5G to 6G.

6G services will evolve from being solely about connectivity to encompassing connectivity, sensing, and artificial intelligence. In view of many aspects the paradigm shift has been summarized as follows:

1) Private networking will receive support through the integration of public networking and will be designed natively right from the outset.
2) Security, which relies on encryption, will shift towards technology-based trustworthiness, adopting a multilateral trust framework and post-quantum cryptography.
3) Algorithms within each layer of the communication system will transition from being solely analytical to being both model and data-driven, harnessing the power of AI and machine learning to adapt to practical conditions that are challenging to model analytically.
4) The level of automation in network Operations, Administration, and Maintenance (OAM) will advance further, moving towards full touchless "level 5" native automation.
5) To naturally support intelligence within the system and offer AI services to third parties, the networking infrastructure will become a converged platform for networking and computing.
6) With the deployment of mega-LEO (Low Earth Orbit) constellations, the networking infrastructure will expand from being exclusively terrestrial to being an integrated system that includes both terrestrial and non-terrestrial components.

VIII. CONCLUSION

The mobile communications sector, spanning from 1G to 5G, has reached a state of relative maturity, with its growth rate considerably slowing down. In this context, the significance of unified standards has grown immensely as they are key to achieving economies of scale. Just as with the previous transitions to 4G and 5G, the success of 6G hinges on a collaborative effort involving industry, academia, and various ecosystem participants. The worldwide standardization of 6G is unquestionably the roadmap to sustained success in the decades ahead. This paper has provided a comprehensive examination of the evolutionary path leading to future 6G wireless communication networks. In pursuit of this objective, we have identified the pivotal performance metrics for 6G networks. Furthermore, we have offered in-depth descriptions of the essential technologies that can facilitate the attainment of these performance indicators. For each technology, we have expounded upon its core concepts and operational principles. Additionally, we have outlined the fundamental benefits and potential applications associated with each of these technologies. Moreover, this paper has shed light on several persisting research challenges and has outlined new research avenues worthy of exploration in the future. It has also provided valuable insights and recommendations pertaining to the practical implementation of the considered technologies.bThe indepth of 6G research has been highlighted briefly as follows:

1) The vision of 6G has re-imagined the future as a transformative leap from 5G systems which has elevated the service of quality and cater to immense data traffic demands. 6G hinges on novel and intelligent communication concepts like um-MIMO, RIS, holographic communication etc.
2) The key performance indicators are explained in relation to the technical pre-requisites, and application scenarios were designed to address the specific high demand requirements.
3) The emerging trends in the advancement of 6G networks for facilitating the energy efficient network with low cost is highlighted for the transformation of entire communication networks.
4) The review has explained the potential technologies for 6G communication. The developmental concepts, applications and challenges of the evolved 6G technology have been further highlighted.
5) The main highlight of the review paper include the emergent aspects of 6G technology for overcoming the challenges required for the development of wireless systems.

The main elements include new spectrum, device materials, channels etc. There is a remarkable advancement in semiconductor device technology leading to the revolution in digital communication area.

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INSHA ISHTEYAQ received the bachelor's degree in electronics and communication engineering from the University of Kashmir, in 2013, and the Ph.D. degree from the Department of Electronics and Communication Engineering, Islamic University of Science and Technology (IUST), Jammu and Kashmir, India, in 2022, with a specialization in the development of 5G antennas for mobile and handheld applications. She is currently a Faculty Member of IUST. She has published a few papers in international journals and conferences. Her research interests include modern-day antenna design, millimeter-wave antennas, microelectronics, and related applications.

KHALID MUZAFFAR received the B.Tech. degree in electronics and communication engineering and the M.Tech. degree in communication engineering and IT from NIT Srinagar, India, in 2004 and 2006, respectively, and the Ph.D. degree from CARE, IIT Delhi, India, in June 2017. From July 2006 to July 2007, he was a Field and Maintenance Engineer with Ericsson India Pvt. Ltd. In August 2007, he joined the Islamic University of Science and Technology (IUST), Awantipora, as an Assistant Professor. His research interests include microwave antenna design and the applications of thermal imaging for microwave field imaging.

NAWAZ SHAFI received the bachelor's degree in electronics and communication engineering from the University of Kashmir, in 2013, and the Ph.D. degree from the Department of Electronics and Communication Engineering, Malaviya National Institute of Technology Jaipur, India. He is currently an Assistant Professor with the School of Electronics Engineering, VIT University, Vellore, India. His research interests include modeling, simulation, and fabrication of advanced semiconductor devices for RF and sensing applications, brain-inspired emerging neuromorphic devices, design, and development of semiconductor device-based hybrid sensor systems and sub-10-nm FETs with alternate conduction mechanisms, such as band-to-band tunneling, impact ionization, and the use of negative capacitance to surpass the Boltzmann tyranny or different device architectures, such as nanowires, nanotubes, and nanosheets to achieve enhanced electrostatic integrity.

MOATH A. ALATHBAH received the Ph.D. degree from Cardiff University, U.K. He is currently an Assistant Professor with King Saud University, Saudi Arabia. His research interests include the development of photoelectronic, integrated electronic active and passive discrete devices, the design, fabrication, and characterization of MMIC, RF, and THz components, smart antennas, microstrip antennas, microwave filters, meta-materials, 5G antennas, MIMO antennas miniaturized multiband antennas/wideband, and microwave/millimeter components using micro and nanotechnology.