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Software-Defined UAV Networks for 6G Systems: Requirements, Opportunities, Emerging Techniques, Challenges, and Research Directions

MD. ABU BAKER SIDDIKI ABIR[1] **(Member, IEEE),**
MOSTAFA ZAMAN CHOWDHURY[2] **(Senior Member, IEEE),**
AND YEONG MIN JANG[3] **(Member, IEEE)**

[1]Institute of Information and Communication Technology, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
[2]Department of Electrical and Electronic Engineering, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
[3]Department of Electronics Engineering, Kookmin University, Seoul 02707, South Korea

CORRESPONDING AUTHORS: M. Z. CHOWDHURY and Y. M. JANG (e-mail: mzceee@ieee.org; yjang@kookmin.ac.kr)

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ABSTRACT The ever-increasing demand for wireless communication has driven the development of innovative technologies to address the issues that conventional communication networks meet. To support autonomous devices in the sixth-generation (6G) and provide seamless wireless connectivity in inaccessible and hard-to-reach areas, the combination of software-defined networking (SDN) with unmanned aerial vehicles (UAVs) has already shown promises. As the traditional UAV-based cellular network encompasses challenges such as lack of centralized supervision, robust decision-making ability, and dynamic network management, the SDN platform could be an excellent alternative to offer aerial networking for future 6G ecosystem. However, the SDN-assisted UAV paradigm faces a set of challenges and critical issues. For instance, the network management and orchestration, resource allocation and optimization, handover mechanism, spectrum management, energy efficiency, integration of heterogeneous networks, and reliability, thus causing the decrease of quality of services of the SDN-enables UAV networks. To effectively address all these issues and identify the trends of software-defined UAV (SDUAV) networks, more research activities are needed. Unfortunately, there are not any specific guidelines in the literature that address each of these requirements, enabling technologies, emerging techniques, and future research directions in the context of SDN-based UAV networks to enable next-generation 6G systems. Therefore, motivated by this fact, this paper offers a comprehensive evaluation of the state of the SDUAV network and architecture, highlighting its various requirements and different prospects and applications in 6G systems. Besides, this paper also addresses why the combination of SDN and UAV-enabled networks is becoming essential in the 6G networking context and how it can offer more flexibility, scalability, reliability, and efficient connectivity than the conventional approaches to provide features like intelligence, automation, programmability, and centralized controllability. This paper furthermore outlines the difficulties of implementing SDUAV networks, such as security, adaptability, interference management, interoperability, and lack of standardization. Finally, to accomplish the goals, this article provides a roadmap for future trends and research directions in SDUAV networks to support the 6G systems.

INDEX TERMS 6G, aerial base station, SDN, SDUAV, UAV-based cellular network.

I. INTRODUCTION

THE growing trend of emerging technologies, such as artificial intelligence (AI), augmented reality (AR), virtual reality (VR), extended reality (XR), automated vehicles, electronic health (e-health), cloud computing, Internet of Things (IoT), and Industry 4.0, is culminating a massive amount of data every day [1]. Recently, the International Telecommunication Union (ITU) estimates that traffic volume will be 5016 EB/month, with traffic volume per person reaching 257.1 GB/month [2]. As a result, there will be 97 billion machine-to-machine (M2M) subscriptions and 622 EB/month of total M2M traffic [3]. Therefore, to support these next-generation communication and networking trends features such as high bit rate, high bandwidth, high energy efficiency, increased spectrum efficiency, new spectra, intelligent networking, mesh computing, enhanced security, and high network availability are required [4].

Fifth-generation (5G) communication systems, however, have recently been associated with trade-offs of several kinds of issues, including lack of virtualization and intelligence management, delay, throughput, heterogeneous hardware complexity, energy efficiency, and reliability [5]. Most likely, 5G will not be able to keep up with the current trends in future networks [6]. Therefore, researchers from all over the world are attempting to predict what the next-generation network will be. As a result, the sixth-generation (6G) wireless communication system is the outcome of user requirements expanding beyond what the 5G networks can provide [7]. It is expected that 6G networks would bridge the gap between current networking requirements and 5G [8].

Along with the current key performance indicators (KPIs) of the 5G networks, it is projected that the 6G network will require several kinds of additional KPI drivers [9], [10]. The initial phases of 6G KPIs can be broadly separated into two distinct categories [2]. The first set of KPIs are productivity and technology-driven KPIs, and the second set is sustainability and science-driven KPIs. The first category covers mobile broadband, three-dimensional (3D) mapping, greater availability, link budget, and energy-saving technologies [2], [11]. On the other hand, the second category includes characteristics like standardization, open-source everything, virtualization, intelligence, automation, confidentiality, and security [2].

To support the technology and productivity-driven KPIs of the 6G system, a robust, dynamic, flexible, cost-effective, and fast-deployable network infrastructure is needed. In this regard, the unmanned aerial vehicle (UAV)-assisted cellular network has already demonstrated some promising characteristics [12]. Due to their special abilities to operate in difficult, disaster-affected, and distant areas as well as their capacity to provide momentary on-demand coverage, UAVs have recently been recognized as a promising 6G communication platform [13]. By utilizing the improved line-of-sight (LOS) connections with ground users, UAV-based aerial base stations (ABSs) can be easily relocated which can improve coverage area [14]. In addition, to meet the quality of service (QoS) requirements based on user intensities, desired data rate, and interference or blockage effects, these UAV-enabled base station (BS) also can swiftly adjust their height in the 3D direction. As a flying autonomous mobile platform, the UAV-based BS can enhance not only throughput but also spectrum efficiency, reliability, and efficiency of 6G networks [15]. Therefore, to provide ubiquitous 3D connectivity to the 6G wireless network, UAV-based ABS can play a crucial role [16].

In order to enable the sustainability and science-driven KPIs of future 6G-enabled systems, it is anticipated that self-organizing capability will be one of the most fundamental features [17]. Employing these self-organizing features, the 6G network aims to establish an autonomous, intelligent, centralized control, virtualized platform that can support all aspects of future applications and services [7]. Therefore, a programmable, centrally regulated, intelligent, and highly flexible networking architecture is required to ensure this type of self-organizing network (SON). In this context, the emerging software-defined networking (SDN) can empower the 6G communication systems with centralized control, intelligence, and programmability features [18]. By separating the controlling features from the data plane, SDN can enable centralized controllability, robust adaptability, and programmability over the network infrastructure. In addition, SDN can enhance network administration and monitoring mechanisms, enable effective resource allocation, offer swift deployment, and provide more intelligent decision-making abilities. These features are essential for enabling autonomous systems, satisfying the numerous 6G services and applications, and facilitating massive IoT connections [19].

Conventional UAV-based cellular networks in 6G wireless communication systems have limitations and challenges that prevent them from reaching their full potential [20], [22]. For example, conventional UAV-based aerial networks lack efficient resource management systems, making dynamically allocating and optimizing resources such as spectrum, power, and connectivity challenging [23]. Additionally, they struggle with seamless mobility and handover management for UAVs, resulting in disruptions and service degradation during transitions [24]. Moreover, the conventional technique lacks centralized control and intelligence, making it difficult to adapt to the various requirements of 6G applications. Without an integrated control plane, network functions suffer from inconsistencies in traffic routing, load balancing, and QoS management. Furthermore, integrating heterogeneous networks creates challenges in terms of interoperability, seamless connectivity, and efficient resource allocation [25].

To meet the diverse and evolving demands of contemporary aerial communication, SDN integration into UAV networks offers a pivotal solution [30]. SDN improves UAV network's flexibility for dynamic situations by centralizing control and management functions and optimizing resource allocation and traffic flow [21]. On the other hand, incorporating UAVs into the SDN ecosystem enhances the capabilities of network infrastructure by utilizing the UAVs' mobility, enabling rapid provisioning of network services as well as information assembling in difficult-to-reach regions [18], [19]. Hence, this symbiotic relationship empowers both SDN-assisted UAV networks and the overall SDN infrastructure to perform more efficiently and responsively.

With the increasing complexity and scale of 6G networks, efficient resource management becomes crucial [20], [26]. Moreover, 6G networks are expected to handle highly dynamic and heterogeneous traffic patterns and services, including real-time applications, massive machine-type communications (mMTC), ultra-reliable low-latency communications (URLLC), on-demand services, and high-definition multimedia streaming [11]. Therefore, to meet the KPI-associated services of the 6G networks, like ubiquitous mobile ultra-broadband (uMUB), ultra-high-speed with low-latency communications (uHSLLC), and ultra-high data density (uHDD), a software-defined UAV (SDUAV) network can be a good solution [21]. SDUAV networks are expected to operate in 6G environments with high mobility, extremely dense heterogeneous networks, and minimal backhaul and access network congestion. Additionally, the centralized control and programmability of SDN enable efficient handover decision-making, resource allocation, and network reconfiguration. As a result, SDUAV networking concepts can enable seamless mobility management, ensuring uninterrupted connectivity during UAV transitions between different network cells or handovers between ABSs and GCS.

The SDUAV framework effectively addresses the limitations and challenges that traditional UAV-based cellular networks meet in 6G wireless communication systems [26]. By leveraging the centralized control and programmability features offered by SDN architecture, the SDUAV network can extend the coverage of the networks and can offer a "connectivity from the sky" feature to the 6G networks [27], [28]. Additionally, the SDUAV networks can provide dynamic network orchestration, seamless mobility, and effective resource management. Through optimized intelligent decision-making ability and resource allocation, the SDUAV networks can adapt in real-time to meet the specific requirements of different applications, resulting in enhanced overall network efficiency and performance [29]. At the same time, centralized controllability of the SDUAV networks can simplify the integration of heterogeneous networks, ensures seamless connectivity and enhances interaction routes from end to end [30]. Moreover, to boost the network's intelligence, the SDUAV network also can utilize advanced technologies like machine learning and AI. In 6G wireless communication networks, this intelligence advances several types of features, such as network effectiveness, security, and reliability. With such features, the SDUAV network certainly can support the 6G services like mMTC, uHDD, uHSLLC, and uMUB.

A. COMPARISON AND OUR CONTRIBUTIONS

To the best of our knowledge, to support the 6G services like uMUB, mMTC, uHDD, and uHSLLC, there is not a single comprehensive review article on the SDUAV networking system. Though several works have been carried out on UAV-based cellular networks and SDN as well as their related technologies, these survey articles focus only on different UAV technologies which are not sufficient. Some survey articles, however, either concentrate on SDN or UAV networks individually. The majority of the associated survey papers cover various aspects of UAV networks, such as routing protocols, security considerations, channel modeling, security, and other UAV-assisted 5G approaches. When it comes to the implementation of SDN and UAVs for communications, there are several research gaps. One of the main challenges is ensuring the development of effective and cost-efficient architectures as well as algorithms for the deployment of UAVs in an SDN framework to support the 6G requirements. In order to achieve optimal coverage, UAV placement must be optimized, and UAV interference must be kept to a minimum. Another research gap is the establishment of new networking protocols that can support the unique characteristics of UAVs, such as mobility and limited energy resources. Further investigation is required into the security and privacy ramifications of deploying UAVs in an SDN system, as well as advancing the development of secure communication and authentication protocols in 6G domains. To establish more sophisticated and effective communication systems for SDUAV networking, a further investigation needs to be conducted on the integration of SDN and UAVs with different revolutionary technologies such as AI, blockchain, massive multi-input multi-output (MIMO), optical wireless communication (OWC), mobile edge computing (MEC), intelligent reflecting surface (IRS), proactive caching, and backscatter communication systems. Therefore, some of the most important research questions are:

- What is the proposed structure and communication technique of the SDUAV network, and how does it enable seamless integration and communication between UAVs and SDN controllers?
- What specific service requirements must SDUAV meet in order to provide 6G services, and how can the network be effectively designed to fulfill these requirements?
- What innovative technologies offer promise for enhancing SDUAV networks, and how could possibly they be employed to boost the system's overall effectiveness, efficacy, and scalability?
- What are the challenges and possibilities in providing seamless integration and interoperability, and how does the SDUAV system interact with different communication and networking technologies?
- What are the expected SDUAV-enabled applications and future possibilities, and what are the specific requirements for successfully enabling 6G features and applications?
- What are the challenging issues and possible constraints associated with the SDUAV system, particularly in supporting 6G-enabled systems, and how could they be addressed to ensure seamless and efficient operation?
- What are the potential future study directions for SDUAV networks, and how can they be substantially refined and improved to meet the changing requirements and complexities of 6G wireless communication systems?

In this paper, we offer an article that comprehensively covers all the areas of SDN-enabled UAV systems. For better illustration, we present the related survey/review of the SDUAV networks and their related topic as well. Being one of the in-depth surveys, our paper focuses on the implementation of SDUAV networks to enable 6G services. It covers different kinds of issues related to various SDN-based UAV systems that comprise UAV-assisted networks. In addition, we consider different emerging networking technologies such as digital twin networking (DTN), time- sensitive networking (TSN), cognitive swarm networking (CSN) as well as radio frequency (RF) technologies, e.g., cognitive radio network (CRN), cell-free communication, terahertz (THz) communication, and microwave/millimeter wave (mmWave) links for the possible combinations of hybrid solutions in 6G domain. We also identify all the possible prospects and opportunities of the SDN-enabled UAV networks. Besides, we discuss the enabling technologies for SDUAV networks, including AI, blockchain, network function virtualization (NFV), quantum technologies, big data analytics, MEC, and so on. The key contributions of this paper can be summarized as follows:

- The architecture, as well as the communication mechanism of the proposed SDUAV network, are presented.
- To support the 6G services, the service requirements for SDUAV are addressed.
- Possible emerging technologies that can be utilized for SDUAV networks are summarized.
- The interaction mechanism of SDUAV systems with different communication systems and networking is discussed.
- The role of different communication technologies in SDUAV networks is discussed.
- Expected SDUAV-enabled applications and prospects with their requirements to support the 6G features are presented.
- Recent works on SDUAV communication systems are surveyed and research trends are addressed.
- To support the 6G-empowered systems, the possible challenging issues systems related to the SDUAV framework are discussed.
- Future research directions for SDUAV networks are outlined.

B. STRUCTURE OF THE SURVEY

The rest of the paper is organized as follows: Section II presents the direction of the review methodology of this paper. Section III outlines the preliminaries about the SDN framework. After that, Section IV provides a brief discussion on UAV-based cellular networks, their architecture, and how they can be employed as ABS. Next, Section V offers an in- depth overview of the proposed SDN-enabled SDUAV networking system. Following that, Section VI provides the communication approaches which can be deployed in the SDUAV networking system. Then, Section VII sets out the opportunities as well as the application scenarios and Section VIII presents the enabling technologies for the SDSUAV systems. After that, Section IX provides the possible emerging communication and networking technologies. Following that, in Section X, some recent research activities by various sectors, countries, and universities on SDUAV networks are addressed. Before, the last session, Sections XI and XII illustrate the future directions and trends for SDUAV networks and the challenges in this area, respectively. Finally, in Section XIII we reach the conclusions. In addition, Table 1 summarizes the abbreviations employed in this paper for ease of reference. In addition, Fig. 1 illustrates the summary and the organization of this paper.

II. REVIEW METHODOLOGY

In this section, the selection criteria and research activity on SDN-integrated UAV networking technologies are discussed. Initially, the selection steps of this article have been described in the selection criteria segment, as well as a complete summary of the information selection in this paper is listed in Table 2. On the other hand, some previous and current investigations, main focusing areas, and significant contributions are presented in the section on research activity on SDN-based UAV networks.

A. SELECTION CRITERIA

This section summarizes the selection methodology for this paper. Following that, the method of identifying the appropriate databases, search strategies, how the title and abstracts are investigated, and the evaluation method for this topic are also highlighted.

1) *Identify pertinent databases:* The first and most important task before getting started the review process is to identify the relevant databases, such as IEEE Xplore, Google Scholar, ACM Digital Library, ScienceDirect, ResearchGate, and SpringerLink. These databases provided us access to academic study in the fields of networking, computer science, engineering, wireless communication, and other related fields.
2) *Develop a search strategy:* The search strategy and databases utilized for this study are created to find pertinent studies that satisfy the inclusion criteria and to give a thorough overview of the field's most recent research. A combination of keywords, as well as Boolean operators, were deployed to find suitable and relevant works in this field, and filters were also used to refine the search criteria and assess the quality and relevance of the studies.
3) *Briefly go through the title and the abstract:* To efficiently find relevant research, we employed several kinds of approaches, from scanning paper titles for keywords like “SDN-enabled cellular networks,” “UAV-based communication networks,” “Aerial networks,” and “UAV-assisted non-terrestrial networks” to exploring relevant topics like architecture, various applications, network security, enabling technologies, challenges, ongoing researches, and possible future developments of the SDUAV networks.

TABLE 1. List of acronyms.

3D	Three-Dimensional
3GPP	3rd Generation Partnership Project
4G	Fourth-Generation
5G	Fifth-Generation
6G	Sixth-Generation
ACR	Advanced Cognitive Radio
AI	Artificial Intelligence
AR	Augmented Reality
ABS	Aerial Base Station
BS	Base Station
CRN	Cognitive Radio Network
CSN	Cognitive Swarm Networking
DL	Deep Learning
DT	Digital Twin
D2D	Device-to-Device
DNC	Dynamic Network Coding
DMR	Dynamic Multipath Routing
DNS	Dynamic Network Slicing
DSA	Dynamic Spectrum Access
DSS	Dynamic Spectrum Sharing
DTN	Digital Twin Networking
E2E	End-to-End Delay
ENN	Electromagnetic Nano-Networking
eMBB	Enhanced Mobile Broadband
FSO	Free Space Communications
IBN	Internet Based Networking
ICT	Information and Communication Technology
IoE	Internet of Everything
GCS	Ground Control Station
GNN	Graph Neural Networks
IR 4.0	Industrial Revolution 4.0
IRS	Intelligent Reflecting Surface
IoT	Internet of Things
IoS	Internet of Storage
ITU	International Telecommunication Union
IIoT	Industrial Internet of Things
IoV	Internet of Vehicles
LiFi	Light Fidelity
LED	Light-Emitting Diode
LOS	Line-of-Sight
LTE	Long-term Evaluation
LoRa	Long-Range Low-Power
FANET	Flying Ad Hoc Network
MR	Mixed Reality
M2D	Machine-to-Device
M2M	Machine-to-Machine
MEC	Mobile Edge Computing
MIMO	Multi-Input Multi-output
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
NFV	Network Function Virtualization
NLP	Natural Language Processing
NTN	Non-Terrestrial Network
OWC	Optical Wireless Communication
QoS	Quality of Service
QKD	Quantum Key Distribution
RF	Radio Frequency
SDA	Software-defined Antenna
SDN	Software-defined Networking
SDR	Software-defined Radio
SDS	Software-defined Storage
SD-IoT	Software-defined IoT
SD-RAN	Software-defined Radio Access Network
SD-WAN	Software-defined Wide Area Network
SDUAV	Software-defined Unmanned Aerial Vehicle
TI	Tactile Internet
THz	Terahertz
TSN	Time-Sensitive Networking
UCS	UAV Communication System
UAV	Unmanned Aerial Vehicle
UAM	Unmanned Aerial Management
UAS	Unmanned Aerial System
UWC	Ultra-wideband Communication
uHDD	Ultra-High Data Density
uHSLLC	Ultra-High-Speed with Low-Latency Communications
uMUB	Ubiquitous Mobile Ultra-broadband
URLLC	Ultra-Reliable Low-Latency Communications
VR	Virtual Reality
VLC	Visible Light Communication
WBS	Wireless Base Station
WBAN	Wireless Body Area Network
WiFi	Wireless Fidelity
XR	Extended Reality

TABLE 2. Overview of the selected topics.

Property	Category
Publication	Journal articles, international conferences, research articles, and scientific magazines.
Year Consideration	2000-2023
Paper election evolution criteria	Initial overview paper title and the abstract. After that, select the proper paper and go through its full text.
Paper selection classification	The architecture of the SDN, SDN-based aerial networking concept, application scenario, vision, and design goals.
Inclusion	Focus on the SDN-based UAV networking process, scenario, protocols, applications, challenges, and the integration with different networking infrastructures.
Exclusion	Similar papers that had recently been released in the journal were also available on the ArXiv and other preprinted servers.

4) *Evaluate the studies:* To evaluate studies on "SDUAV networks," the appropriateness of the research design, sample size, data sources, and analysis methods for the research questions and goals are taken into account. Additionally, the reliability of the study's conclusions is investigated to make sure that the evidence and analysis support it. Deploying these criteria, the quality of the studies and their relevance to the review subject are determined. Following that, a choice regarding inclusion as well as exclusion for writing selection was made. Similar articles that had recently been published in journals and available on ArXiv were also excluded. Table 2 covers the review technique, search criteria, database, exclusion and inclusion criteria, and further information.

B. RESEARCH ACTIVITIES ON SDN-ENABLED UAV NETWORKS

Across the world, numerous ongoing research efforts, projects, and experiments focus on the integration of SDN

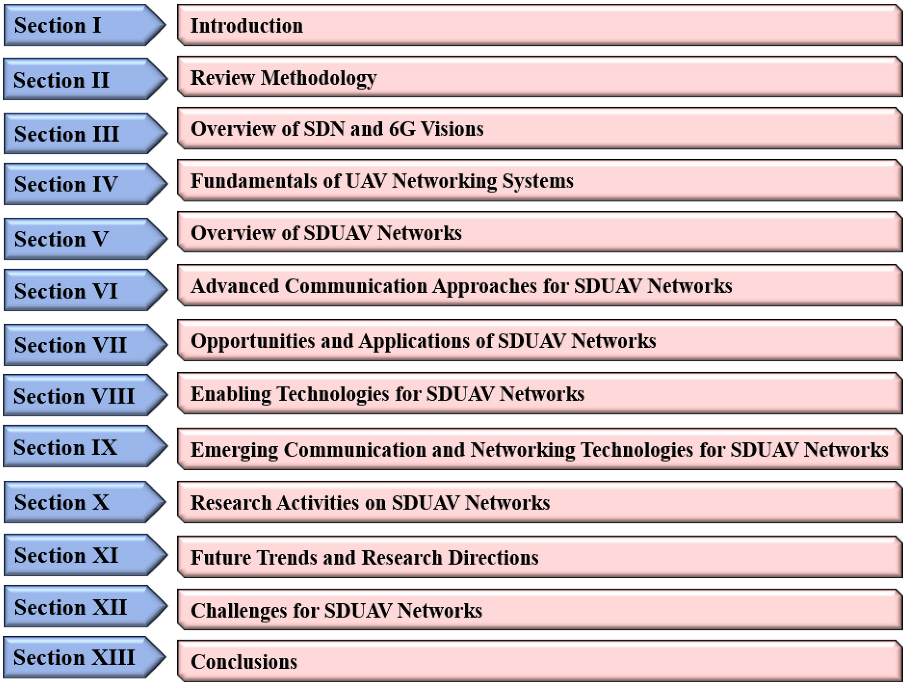

FIGURE 1. Summary and organization of this paper.

and UAV technologies. For instance, in [31], Sliva et al. present SDN-based topology management for flying ad hoc networks (STFANETs), an SDN-driven topology management framework for flying ad hoc networks (FANET). With the help of this technology, UAVs can establish a reliable networking platform that can stay stable in variable environments. In multi-path UAV networking circumstances, Secinti et al. offer a path routing methodology to reduce end-to-end (E2E) delay in [28]. Additionally, to prevent collusion as described in [32], Latif et al. describe a load-balancing technique tailored to SDN-enabled UAV networks. On the other hand, Zhao et al. provide a distributed approach that aims to determine the optimum number of UAVs required and their precise location [33].

To enhance the security of SDN-powered UAV networks, Hu et al. offer an approach based on blockchain technology [34]. Similarly, Hermosilla et al. introduce an SDN-based NFV scheme with the goal of providing security orchestration within the SDUAV infrastructure [35]. Furthermore, Usman et al. develop a lightweight challenge-response authentication method to address issues with elliptic curve encryption in an SDN-centered UAV networks [36]. In another study, Tran et al. present an mmWave embedded placement technique using the NFV concept [37].

Utilizing the positive aspects of the SDN concept, certain researchers have additionally broadened the prospective applications of SDUAV networks across various kinds of domains. As an illustration, Gupta et al. develop a blockchain-based multi-swarm UAV model in response to the challenges raised by COVID-19 [39]. Additionally, Guan et al. provide an SDN-integrated UAV system that focuses on global optimization in the context of softwarized industrial deterministic networking [40]. Al-Turjman et al. explore the integration of SDN with UAV networks for IoT frameworks in [42].

To establish an air-to-ground collection scheme, Zhang et al., on the other hand, develop a Q-learning-based edge scheduling routing method [43]. Zhu et al. additionally present an optimization model for SDN-based FANET in [46]. Additionally, Ali et al. demonstrate an SDUAV network that can coexist with existing RF-based WiFi networks [47]. Apart from these efforts, Oubbati et al. perform an extensive analysis of the softwarization types and applications of UAV networks in [48]. However, they did not address few crucial factors like deployment challenges and security concerns. Table 3 addresses a few recent research works on SDN-enabled UAV communication systems. To incorporate the potential of advanced technologies like AI, NFV, computer vision, quantum communication, IRS, and so on, proper guidelines and further researches are required. Moreover, the integration of different emerging communication and networking technologies also can improve the overall efficiency of the SDUAV networks. Hence, to facilitate future 6G services, this article seeks to offer an in-depth analysis of the emerging SDUAV networks.

III. OVERVIEW OF THE SDN AND 6G VISIONS

In this section we discuss the basic of SDN technology. Then we compare the SDN concept with the conventional networking architecture. After that, we demonstrate the

TABLE 3. An overview of recent studies on SDN-based UAV communication systems.

Reference	Year	Research direction and contribution	Area of main focus
[23].	2017	A handover management scheme for SDUAV networks is proposed.	SDN and UAV
[31]	2019	A protocol named is demonstrated for flying ad hoc networks that can offer communication for UAVs in dynamic circumstances.	SDN and FANET
[30]	2018	For multi-path UAV networking, a routing approach is suggested that can reduce the average end-to-end (E2E) outage rate compared to the other conventional multi-path routing algorithms.	Aerial vehicular network, SDN, and routing techniques
[32]	2023	To prevent collisions due to UAVs' high dynamics, a flight control mechanism is offered.	SDN, load balancing technologies, and UAV networks
[33]	2018	A distributed algorithm is developed which can be employed in the scenario of using a certain number of UAVs to cover UEs while knowing their precise positions.	UAV-based airborne network
[34]	2021	A blockchain-integrated self-organizing adjustable network is demonstrated for an SDN-enabled UAV network.	SDN, blockchain, and UAV
[35]	2020	An SDN-based NFV aware UAV networking system is developed, implemented, and evaluated in a real testbed with real drones.	NFV/SDN, security orchestration and enforcement techniques, and UAV networks
[36]	2022	A lightweight challenge-response authentication scheme is developed to address the elliptic curve cryptography issues in an SDN-based UAV network.	SDN, elliptic curve cryptography, and UAVs network
[37]	2022	The mmWave embedded placement method in the multi-UAV scenario is suggested that can provide an increased data rate in multi-UAV communications using the NFV/SDN.	mmWave technology, UAV, and NFV/SDN
[38]	2021	A blockchain-integrated and 5G-enabled softwarized UAV networking framework is developed to detect eavesdroppers and anomalous data.	5G, blockchain, UAV, and SDN
[39]	2021	A blockchain-based multi-swarm UAV model is offered with the support of SDN to tackle the COVID-19 scenarios.	Blockchain, swarm intelligence, SDN, and UAV
[40]	2021	An SDN-adopted UAV system to accomplish global optimization for softwarized industrial deterministic networking.	SDN, UAV, IoT, and Industrial automation technologies
[41]	2022	To mitigate the attacks in virtual network topologies for the SDN-enabled UAV, a topology deception scheme is developed.	SDN and drones
[42]	2020	For a software-defined IoT scenario, an SDN-based UAV solution is designed.	UAV and software-defined IoT
[43]	2021	A Q-learning-based edge scheduling routing algorithm and a forwarding strategy are developed to enable the dynamic air-to-ground distributed data collection system.	SDN-based Internet of UAVs and Q-learning
[44]	2019	A virtualized environment for a multi-UAV network is being created.	Network virtualization and UAV
[45]	2020	The path-planning model is proposed which can efficiently reduce the amount of time required to travel to any targeted territories for SDN-enabled vehicles.	SDN and UAV
[46]	2023	An optimization model for an SDN-based FANET had been designed.	SDN and FANET
[47]	2020	An SDUAV network is suggested that can coexist with the current WiFi	SDN, UAV, and WiFi technology
[48]	2020	Different types of softwarization of UAV networks as well as their applications and future trends are reviewed.	UAV and SDN
[49]	2022	A wireless architecture for UAVs is presented which is based on the 6G radio spectrum in the unlicensed band area.	6G and UAV

visions of 6G networks and how SDN can enhance the performance, efficiency, and reliability of it.

A. WHAT IS SDN?

SDN is an innovative method of networking that has completely transformed the way networks are designed, deployed, and managed [50]. As a result, the network can be controlled centrally, which makes it more accessible to manage and more effective. Besides, the interoperability of SDN has produced an expanding network of open-source projects and vendors, encouraging creativity and collaboration [51]. Moreover, SDN enhances network security, reducing the risk of security breaches, and network agility, allowing networks to rapidly adjust in changing traffic

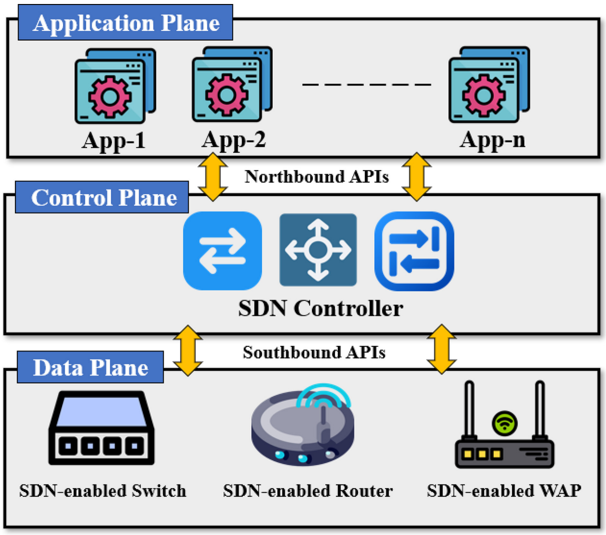

FIGURE 2. Architecture of the SDN.

patterns. For modern data centers, service providers, and enterprises, it is rapidly dominating over the encouraged network architecture [52]. SDN is therefore regarded as the networking technology of the future because of its ability to improve security, flexibility, and effectiveness.

In SDN paradigm, the networking devices are divided into control and data planes. Hence, it allows a greater degree of control over network traffic and better automation [53]. The data plane is formed by different data forwarding devices, such as routers and switches that forward information following the controller's commands, whereas the control plane is handled as a centralized controller that interacts with network devices as illustrated in Fig. 2. On the other hand, the application plane is the layer of SDN that contains applications, e.g., control and manage network behavior. It acts as an interface for applications and network administrators to communicate with the underlying network infrastructure via the SDN controller [53], [54]. Apart from these, the application plane is alsoresponsible for executing network policies, QoS enforcement, traffic optimization, security measures, and dynamic network configuration. Through the utilization of precise network configurations and policies, such as virtual networks and traffic engineering, SDN framework can create programmable, autonomous, and scalable networks [54]. Therefore, SDN is a significant improvement in the networking industry since it can lead to greater adaptability and technological advancement, and it is rapidly gaining prominence in contemporary networks [55].

B. WHY SDN IS THE FUTURE OF NETWORKING?

By offering greater management, flexibility, scalability, automation, and security, SDN has the potential to fundamentally transform networking. As enterprises trying to develop flexible, scalable, and effective networks that can adapt to the dynamic needs of contemporary applications and technologies, such features make SDN the networking technology of the future [56]. How the network traffic is managed is one of the main differences between traditional and SDN networking. In a conventional network, switches and routers are in charge of deciding how to forward following pre-established rules and configurations. On the contrary, in an SDN, a central supervisor controls the network and decides how traffic should be forwarded based on an extensive overview of the network and real-time information [57]. As changes can be made quickly and effortlessly through the controller instead of having to configure each device, this enables more agility and adaptability in managing the network [55], [56].

The distinction between the control plane and the data plane in SDN and conventional networking is an additional significant difference. Since these two planes in a conventional network are closely coupled, both the control and data tasks are carried out by the network's hardware. While the data plane is still managed by the network devices, the SDN separates the control plane and gives it to a centralized administrator. Indeed, this enables more efficient and adaptable system administration considering the SDN controller is capable of handling challenging tasks like load balancing and traffic engineering while network devices only are concerned about forwarding traffic [58].

SDN additionally can offer network programming capability, which makes automation, less complicated, and less error-prone. Traditional networks, on the other hand, depend on device-level automation, which can be tedious and ineffective. Moreover, SDN can able to expand more effortlessly compared to traditional networks since the single controller can handle and configure a large number of network devices in a coordinated manner, which can be challenging in traditional networks [61].

In terms of security, SDN provides additional features like the capacity to dynamically segment the network and manage data flows, which is frequently challenging to accomplish in conventional networks [59], [62]. The implementation of SDN requires a significant initial investment in terms of hardware and software, which is a consideration for organizations planning to adopt this technology, even though SDN has the potential to be more cost-effective than conventional networks in the long run. The fundamental distinctions between SDN and traditional networking technologies are shown in Table 4.

C. 6G ROADMAP AND SDN

The 6G system's roadmap addresses the anticipated development and implementation strategy for the next generation of wireless communication technological advances. Despite being in its initial stages, the 6G roadmap intends to address the changing requirements and challenges of a more interconnected community [63]. It also envisions a future in which ultra-high-speed data transfer, ultra-low latency, massive device connectivity, and intelligent network capabilities. In addition, the vision of 6G also covers several significant domains like enhanced mobile

TABLE 4. Difference between SDN and traditional networking systems [59], [60].

Features	SDN	Traditional Networking
Network control	Centralized	Distributed
Forwarding decisions	Decided by the central controller	Performed on switches the routers
Network visibility	Full	Limited
Scalability	Highly scalable due to centralized control and management	Limited scalability due to device-centric architecture
Configuration management	Automated through software-based management	Manual
Innovation potential	High potential with open-source architecture	Limited
Control plane	Centralized control plane which is implemented on a dedicated controller	Distributed control plane which is implemented on each network device
Network intelligence	Advanced network intelligence because of the global view of network state and traffic	Limited network intelligence as each network device has its logic
Network programmability	High programmability since it provides open APIs, automation, and orchestration	Limited programmability due to vendor-specific APIs and limited automation
Configuration and management	Network-wide configuration and management through a single interface	Device-specific configuration and management Network-wide
Security level	Advanced security due to programmability and proactive security measures.	Limited security due to static and reactive security measures
Network monitoring	Advanced monitoring due to centralized control and real-time traffic analysis	Limited monitoring due to device-centric architecture
Network performance	Advanced performance due to dynamic and proactive traffic management	Limited performance due to static and reactive traffic management
Network customization	High customization due to programmability and network-wide configuration	Limited customization due to device-centric architecture
Network agility	High agility due to programmability and centralization	Limited agility due to device-centric architecture

broadband (eMBB), URLLC, uMUB, uHDD, uHSLLC, mMTC, holographic communication, and immersive media experiences. Furthermore, it underlines the significance of sustainability, energy efficiency, security, privacy, and reliability in the design and implementation of 6G networks. Fig. 3 illustrates the basic service requirements of the 6G communication systems.

To enable the intended visions of the 6G systems, automation, and virtualization are the two crucial features that can play a vital role [64]. The automation and virtualization features of a 6G network will allow billions of devices to be shared on a physical infrastructure. The development and implementation of 6G communication systems are expected to heavily rely on SDN as automation and virtualization are the key enablers of the 6G networks. One of the key advantages associated with SDN is that it enables a high level of network flexibility and programmability, allowing network operators to quickly install and scale new services and applications [65]. This is particularly essential in the context of 6G, which is predicted to bring in a wide range of new application and service scenarios that need highly tailored and flexible network infrastructures.

Another promising advantage of SDN in 6G communication system is its ability to support intelligent network slicing, which allows different essential for addressing the distinctive requirements of different 6G application scenarios, such as URLLC, mMTC, and uHDD services. To ensure the safety and confidentiality of 6G networks and services like uMUB and mMTC, SDN can play a crucial role. By splitting the data plane from the control plane, SDN enables the development and deployment of centralized security policies and protocols, which can minimize the risk of vulnerabilities and attacks. Furthermore, advanced technologies such as machine learning and blockchain also can be deployed in SDN-assisted 6G networks like UAVs, IoT, and Internet of vehicles (IoV) to create a secure and transparent mechanism for communication and exchange of information among devices. Hence, SDN is expected to be a key technology in the establishment of 6G communication networks, offering the flexibility, intelligence, and security required to handle the different and complicated requirements of next-generation 6G-based application scenarios and services.

IV. FUNDAMENTALS OF UAV-BASED COMMUNICATION SYSTEMS

To enable the intended visions of the 6G systems, cell-free networking and seamless connectivity are the two crucial features that can play a vital role [64]. By deploying UAVs as cellular wireless base stations (WBSs), these two crucial features of 6G networks can be achieved. In addition, these two features can allow billions of devices to be shared on a physical infrastructure. Moreover, one of the key advantages associated with UAV-assisted WBSs is that it enables a high level of network flexibility and adaptability, allowing network operators to quickly install and scale different services and applications [65]. This is particularly essential in the context of 6G, which is predicted to bring in a wide range of new application and service scenarios that

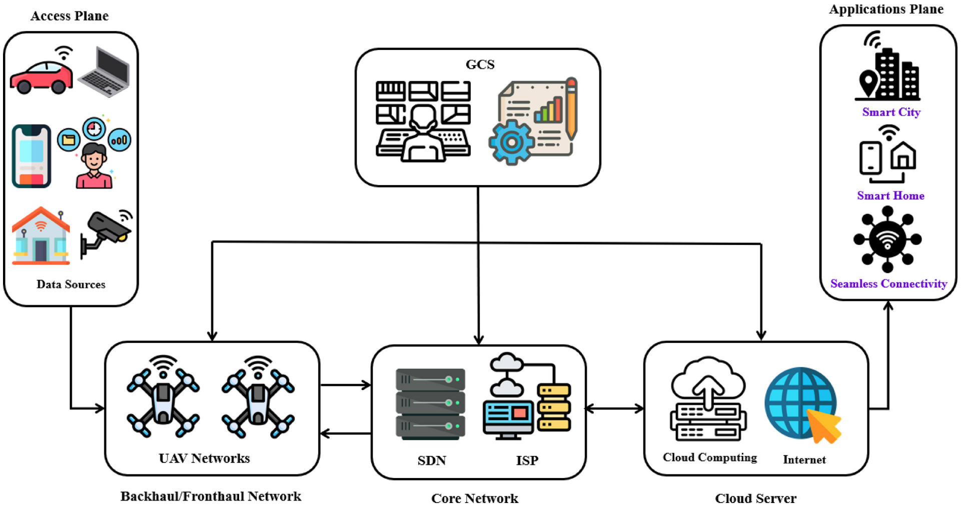

FIGURE 3. Block diagram of an UAV-enabled communication system.

need highly tailored and flexible network infrastructures. This section outlines the basic UAV-based ABS concept, their architecture and working principles, and fundamental requirements.

A. WHAT IS UAV-BASED COMMUNICATION SYSTEMS?

UAVs are aircraft that can operate autonomously or under remote control. Unmanned aircraft are outfitted with real payloads like cameras, radar, sensors, etc. UAV communication systems (UCSs), on the other hand, refer to a combination of techniques and processes employed to transmit information between UAVs, GCSs, and UAVs to UAVs (U2U) [66]. To operate these UAVs autonomously, the UCSs play a vital role. UCSs enable the transmission of several kinds of information such as telemetry, video, images, and sensor measurements across wireless communication lines [67]. Therefore, UCSs are essential for not only regulating and managing UAVs and providing remote monitoring but also for carrying out missions requiring real-time data transmission. For UAV communication, RF, OWC, acoustic technology, and non-territorial network (NTN) can be utilized as communication mediums [68]. However, RF signals are the most commonly employed form of communication for UAVs since it provides real-time data transmission and is dependable and economical as well. On the other hand, satellite communication can be utilized when the UAV is beyond the range of conventional radio transmission. Besides, optical communications use lasers or LED lights for interaction between UAVs or between the UAV and the GCS [69].

In UAV communication systems, the process of directing and supervising the UAV's mobility and functions from the GCS is referred to as command and control (C2) [70]. The GCS provides commands to and receives information from the UAV, allowing the operator to control the UAV's movement, payload, and other operations. Radio communication is the primary means through which UAVs interact with their controller and GCSs. In addition, ultra-high-frequency, very-high-frequency, and even high-frequency bands can be utilized for the RF links [71]. To connect with the GCS, the UAV normally utilizes a small transceiver, while the GCS typically communicates with the UAV using a bigger transceiver. To communicate information from the UAVs to the GCS, a communication link must be established with the UAV communication equipment. The UAV transmits telemetry data, which includes its altitude, location, and other operational data, to the GCS. On the other hand, the GCS transmits instructions to the UAV such as flight direction, payload operations, flight control, monitoring, and management. The block diagram of UAV-based cellular system is shown in Fig. 3.

B. WHAT IS UAV-BASED ABS?

An airborne antenna system that serves as a hub between the access network and the backhaul and fronthaul network is known as a UAV-assisted BS or an aerial base station (ABS) [72]. On the other hand, when more than one ABS collaborates in such a relaying procedure, then it is called a flying ad hoc network (FANET). One of the most innovative features of the 6G wireless networks is to offer "sky-based seamless connectivity". Due to the inherent capabilities of mobility, flexibility in 3D space, adaptive altitude, and symmetric rotation, ABSs strategically differ from the static conventional network architecture in that they can establish on-demand networks at specific locations [73]. These unique features of the ABSs enable superior services with high-quality wireless networks, minimal degradation, large bandwidth, and limited interference compare to the conventional BSs [74].

From an industrial perspective, many kinds of applications have been developed for the implementation of the ABS network to provide seamless connectivity and handover management during short-term events and emergencies in various areas without established network infrastructures. Hence, ABSs can offer several advantages over fixed ones.

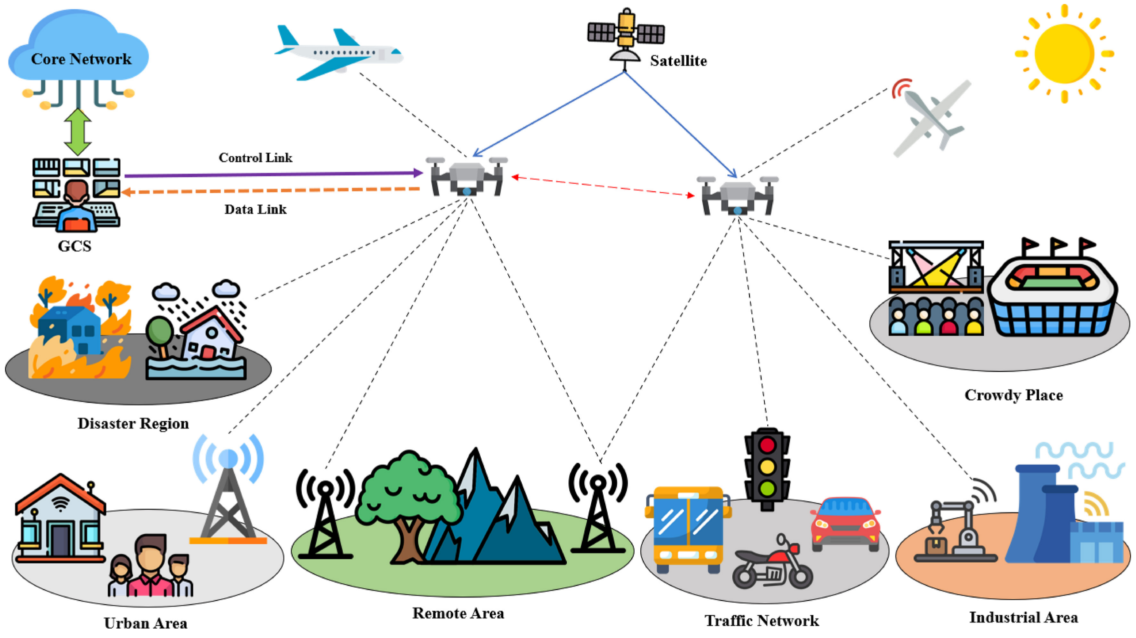

FIGURE 4. Application scenarios of the UAV-based ABS.

One of the prominent advantages is flexibility as ABSs can be deployed very quickly and easily to provide coverage for temporary coverage needs such as during special events or in disaster zones [73]. Another advantage of the ABSs is their ability to provide cell-free connectivity which provides coverage over large areas including remote or difficult-to-reach locations such as mountainous or hilly terrain [72]. This is particularly useful in emergency scenarios where there is no existing infrastructure. Additionally, ABSs can be less expensive to install and maintain than the traditional fixed BSs as they require less infrastructure like wiring, poles, or buildings, and can save on land costs [16]. Besides, ABSs can have a higher capacity to handle large amounts of traffic and data during peak usage times, than fixed ones. This can lead to faster connection speeds and fewer dropped calls [75]. Therefore, the ABSs offer a cost-effective and adaptive wireless coverage and connectivity solution. Fig. 4 illustrates some of the applications and prospects scenarios of the UAV-based ABS and Table 5 addresses some of the key differences between the ABS and traditional fixed BS.

C. NETWORK ARCHITECTURE OF UAV-BASED ABS

By carrying communications devices that include antennas, radios, power systems, and wireless AP (WAP), UAVs can serve as WiFi BS [76]. These components enable the UAV to establish connections with other equipment and ground-based networks, thereby expanding the cellular coverage area. In UAV communication systems, the network can be divided into three planes such as core plane, aerial plane, and ground plane as illustrated in Fig. 5. The three planes and their functions are briefly discussed below.

Core plane: The ABS is managed and controlled centrally by the core plane. It includes the network infrastructure, that regulates the data flow between the network's different nodes by switching, routing, and other means. Besides, the core plane also holds the responsibility for resource management, coordinating contact among various nodes, and maintaining network security. In this context, cellular networks, SDN, and optical fiber networks can act as the core network.

Aerial plane: Aerial plane is a network of UAVs which responsibility for providing wireless connectivity and the communication between UAVs and ground-based equipment. Therefore, to link the ground-based devices to the network, the UAVs in this plane serve as their WAP and BSs.

Ground plane: The transmission of data packets between the various network components is managed by the data plane. This plane includes the protocols and technical specifications for transferring data between the various nodes. In addition, it is also the responsibility of the data plane to make sure that data packets reach their intended destinations efficiently and dependably. For the ABSs connectivity, microcellular BS, satellite network, WAP, cable tv network, free-space optical (FSO) network, Internet service provider (ISP) network, and acoustic network can act as the ground plane infrastructures.

D. WORKING PRINCIPLE OF AN UAV-BASED ABS

The process of using UAVs as ABS involves a series of stages that enable the UAV the ability to provide network services and wireless connectivity. In the beginning the UAV launches and soars to a pre-set height and subsequently, it establishes a contact channel with the GCS or other network nodes, like other UAVs or ground-based equipment [76]. In order to maximize the coverage and signal strength of its wireless network, the UAV positions itself at a predetermined spot once the communication link is formed. After

TABLE 5. Differences between the ABS and fixed BS [72], [73], [74], [75].

Aspects	ABS	Fixed BS
Location	Mounted on UAVs	Fixed on the ground
Coverage area	Dynamic and adjustable	Fixed and limited
Deployment flexibility	High	Limited
Mobility	Mobile	Stationary
Network capacity	Scalable	Limited
Maintenance	More complex	Easier
Interference	Susceptible to aerial interference	Susceptible to ground-level interference
Range	Can be deployed anywhere, including remote or hard-to-reach locations	Typically provide fixed coverage area compared to ABSs
Infrastructure	Can be deployed without the need for extensive infrastructure, making them more cost-effective and easier to install	Requires significant infrastructure to be deployed, such as towers, buildings, and power supply
Antenna specification	Tend to have smaller antennas and lower power output, suitable for covering smaller areas or specific regions	Usually have a higher power output and larger antennas to cover a larger area
Coverage quality	May experience coverage disruptions or fluctuations due to their mobility and limited battery life	Provide consistent and reliable coverage within their range
Type of solution	Can be used for temporary coverage or emergency response scenarios, and can be quickly deployed and removed as needed	Typically provide a permanent solution for network coverage
Vulnerability	Less vulnerable to physical attacks or natural disasters since they can be quickly relocated or replaced	More vulnerable to physical attacks or natural disasters that can damage infrastructure
Backbone network	Can be used to extend network coverage beyond the reach of the wired backbone network	Require a physical connection to the wired backbone network

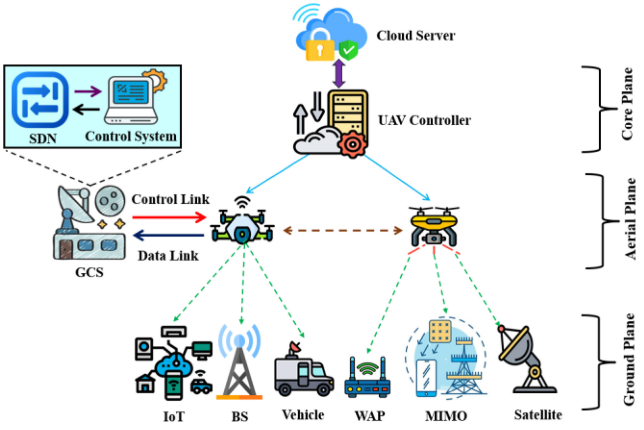

FIGURE 5. Architecture of an UAV-based ABS.

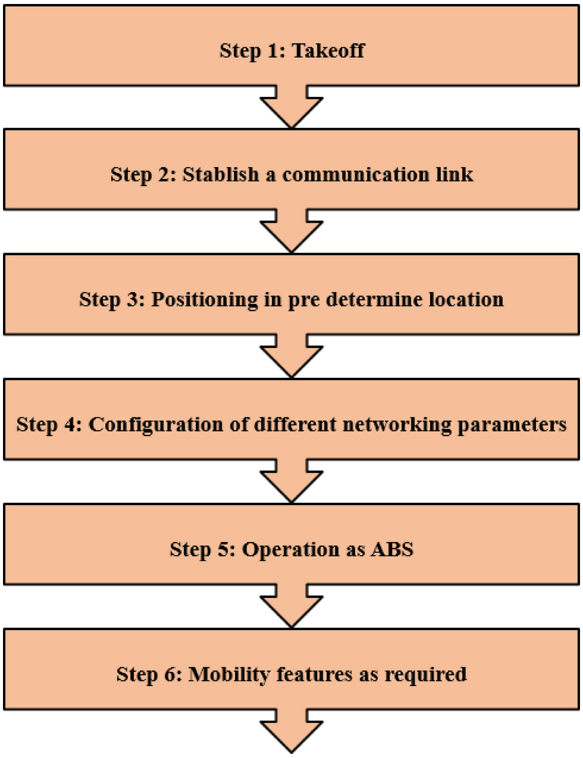

FIGURE 6. Steps and working procedures of an UAV-enabled ABS.

locating itself, the UAV sets up the parameters of its wireless network, including the channel frequency, power level, modulation type, and antenna orientation, to achieve the intended network effectiveness and reliability [77].

By offering wireless connectivity and network services to connected devices, such as data transmission, cellphone communication, video streaming, and sensor data gathering, the UAV then performs the function of an ABS [78]. To adjust with changing network circumstances or mission requirements, the UAV can relocate if necessary. After finishing the mission, running out of battery power, or returning to the GCS for maintenance and recharging, the UAV securely lands. For precise positioning, guidance, and attitude control during these procedures, the UAV's onboard instruments, including GPS, altimeter, compass, and gyroscopes, are used [79]. In order to guarantee the security, steadiness, and dependability of the ABS, the UAV's flying controller, and autopilot software can also be extremely important. Fig. 6 presents the holistic working procedure and the key steps of ABS by UAVs.

E. FUNDAMENTAL REQUIREMENTS OF AN UAV-ASSISTED NETWORK

To effectively employ UAVs as wireless networking platforms, several crucial service prerequisites must be satisfied. The UAV must first be able to reliably cover the targeted area with adequate signal strength and bandwidth to satisfy user requirements [80]. To ensure adequate bandwidth and connectivity, this could require specialty antennas, radios, and electrical infrastructure. Second, the UAV must be capable of operating securely and dependably in the intended environment, including in adverse weather or the presence of obstacles such as buildings or trees. For secure operation, it might be mandatory to implement advanced sensor technology and flight control systems. The UAV also needs to be able to interact with ground stations (GSs), other UAVs, and conventional cellular networks, as well as other wireless networks. Hence, to guarantee seamless integration and interoperability, this calls for smart communication protocols and software. To prevent unauthorized access or data breaches, the UAV must be able to offer users security and privacy, including encryption and authentication methods. Realizing the full potential of UAVs as wireless networking platforms, allowing better connectivity and communication in various applications requires meeting these service requirements [81]. The most significant service prerequisites for such networks are briefly addressed below.

Network programmability: As an ABS, UAV networks require to be programmable in order to dynamically design and optimize network resources, functions, and services based on changing circumstances as well as application requirements [82]. For low-latency, high-bandwidth communication networks between UAVs and ground-based stations, this is essential. With greater flexibility and agility to support dynamic UAV-based operations, network programmability enables swift adaptability to diverse scenarios and requirements [48].

Network automation: When serving as an airborne BS, UAV networks must include network automation capability as it can make network operations less complicated and more efficient [48]. In order for UAV-based applications and services to function, real-time, low-latency, and high-bandwidth communication channels must be established between the UAVs and GSs. By automating common processes like network configuration, device management, and security policy enforcement, network automation allows network operators to lower the likelihood of errors and increase the effectiveness of network operations. Furthermore, network automation can decrease downtime and increase network reliability by allowing for the quick identification and correction of network flaws. In order to ensure the seamless and effective operation of UAV-based networks, network automation is required [82].

Network intelligence: In order to perform advanced analytics and to make decisions that will boost the performance, efficiency, and reliability of the network, UAV networks require the network intelligence function [48]. To allocate the network resources, optimize routing, and strengthen security, operators can utilize the network intelligence feature to monitor and evaluate the network's traffic, performance, and security in real-time. This is particularly important especially when it comes to UAV-based applications and services, as the network must support a number of real-time and mission-critical functions like surveillance, inspection, and emergency response. The UAV network can adapt to changing network conditions and application requirements by leveraging network intelligence, resulting in highest levels of performance, efficiency, and reliability.

Centralized controllability feature: The centralized controllability feature must be preserved for UAV networks since it enables administrators to have one point of view and control of the network [48]. As a result, users can manage and coordinate all of the network's resources, features, and services from a single location, thereby increasing the efficacy and efficiency of network operations. As a result of real-time network circumstances and application requirements, centralized control also enables operators to dynamically distribute and optimize network resources and services. Therefore, this is crucial in the context of UAV-based applications and services as successful mission completion depends on quick response times and dependable communication channels [48].

QoS and service differentiation: In terms of QoS and service differentiation, the key criteria of UAV-assisted aerial networks include high scalability and reliability, minimal latency and delay, extensive bandwidth, and significant rates of data transmission [48]. Therefore, such networks must have the capacity to support several UAVs while retaining unwavering reliability in order to respond seamlessly to shifting mission requirements. Particularly in crucial applications like emergency response, low latency, and minimal delay are required to enable real-time control and feedback [82]. On the other hand, high data rates enhance communication between devices and decision-making abilities, while high bandwidth implies the efficient transfer of massive volumes of data required for applications like high-resolution video streaming and remote sensing. Even in complex and dynamic aerial circumstances, key activities are further prioritized through service differentiation mechanisms so they obtain the resources required to complete their objectives effectively [48], [82].

Energy efficiency: Considering that batteries are frequently utilized for powering UAVs, the network needs to be designed to consume as little energy as possible in order to prolong battery life and maximize flight duration [82].

Location awareness: To support location-based services and enable applications such as AR, the network must be able to provide accurate location information.

Spectrum sharing: To make better use of the available spectrum and enable new applications as well as services, the core network must be able to cope with dynamic spectrum sharing [83].

Mobility management: In order to ensure uninterrupted communication between the UAV-to-UAV and UAV-to-GCSs, and also minimize data transmission interruptions, the core network must be able to perform error-free handovers between BSs. In addition, the core networking infrastructure need to have the capability to supervise the mobility of UAVs while they travel across airspace [48], [82].

Privacy and security: UAVs are vulnerable to attacks and interference due to the fact they often transport sensitive data or equipment [18]. Security is therefore a crucial prerequisite for SDUAV networking. To avoid unauthorized access or interference, the network infrastructure which will be employed for managing UAV operations must be able to offer adequate safety. In order to safeguard against unauthorized access and guarantee the confidentiality and integrity of data, the network must also have robust encryption, authentication, and authorization systems [18].

Network orchestration: Network orchestration is critical for controlling the network resources and making sure that SDUAV networking is operating smoothly [48]. So, the core network must be capable of dynamic resource allocation depending on demand, traffic prioritization, and network performance optimization [82].

F. UAV COMMUNICATION SYSTEMS FOR 6G NETWORKS

The capability, reliability, as well as effectiveness of communication networks in the 6G era, can be enhanced through the deployment of UAV communication systems. Therefore, to overcome the challenges faced by the traditional networking approaches, UAV communication can play an essential role in 6G communication systems. As UAVs can operate at higher altitudes than ground-based communication systems, the ABS can provide better coverage as well as more robust connectivity. Furthermore, UAVs are easily deployable for establishing a temporary communication infrastructure in various locations. In addition, the unique characteristics and features of UCSs make them crucial for the development and implementation of the 6G wireless communication network, allowing it to handle the various and demanding requirements of future services and applications. Hence, UAVs can support the 6G's KPIs such as uMUB, uHSLLC, mMTC, and uHDD because of their distinctive capabilities and attributes [49]. The key services requirements for 6G systems and how the UAV communication networks will meet them are briefly discussed below.

uMUB: By offering dependable and low-latency communication links between user equipment (UE), ground-based IoT devices, and cloud-based applications, UAV networks can support uMTC in 6G. In order to minimize latency and provide direct LOS communication links, UAVs also can serve as flying BSs or relays. In areas where the networking infrastructures are inadequate such as disaster zones or isolated locales, UAVs can be deployed very swiftly and rapidly to provide coverage. Moreover, UAVs can serve as a platform for uMUB by providing the mobility needed to access remote locations, disaster situations, or various challenging environments [84].

To support high-speed data transmission in the 6G networks, UAVs can be equipped with high-performance communication hardware such mmWave transceivers [49]. Additionally, by dynamically adjusting the orientation and transmission circumstances in response to network conditions, UAVs also can utilize their mobility and agility to improve the performance of the network. For instance, network analysis and evaluation can be employed by UAVs to identify locations with inadequate coverage or significant amounts of interference, and then they can modify their positions and power correspondingly to provide uMUB to enable the 6G features. Hence, by providing mobility, adaptability, and high-performance communication capabilities, UAVs can help uMUB in 6G networks and enhance the overall efficiency of the network [85].

uHSLLC: In order to enable the 6G network, UAV communication networks can support uHSLLC by offering a flexible and dynamic communication platform. Because of UAVs' unique mobility and altitude advantages, they can be deployed as ABSs to extend the coverage and capacity of existing terrestrial networks. Additionally, UAVs can function as a relay to improve QoS for delay-sensitive applications including VR and AR, autonomous vehicles, and industrial automation. Such relays can also improve communication between users and GSs. Furthermore, the deployment of UAVs in uHSLLC can enable technologies like network slicing, edge computing, and AI technologies to optimize network performance, minimize energy consumption, and improve communication safety and confidentiality. Hence, integrating UAV communication networks with uHSLLC can enable the 6G vision of seamless, ubiquitous, and intelligent connectivity and provide new opportunities for next-generation wireless communications [86].

mMTC: UAV communication networks can support mMTC by offering affordable, low-power, and low-complexity solutions for device-to-device (D2D), M2M, and machine-to-device (M2D) connectivity to allow 6G functionalities. Being one the most prominent pillars of 6G technologies, mMTC aims to connect thousands of devices as well as sensors for IoT, IoV, and industry 4.0 [74]. In locations where there is not enough terrestrial communication infrastructure, UAVs can serve as ABSs that can connect an extensive number of devices.

By offering effective routing algorithms and flexible resource allocation plans, UAVs also can play a crucial role in mMTC [87]. To avoid interference and ensure optimal communication, UAVs can utilize the machine learning algorithms to predict network congestion and modify the transmission power and bandwidth allocation accordingly. Besides, the signal-to-noise ratio (SNR) and coverage area of UAVs can be increased by utilizing innovative beamforming and antenna technologies. Moreover, UAVs are capable of providing mMTC devices with flexible and on-demand connectivity services like real-time monitoring and low-latency data transmission [75]. By collecting information from sensors and transmitting it instantaneously to a remote GCS or cloud server, UAVs can enhance precision agriculture in 6G scenarios.

uHDD: Due to the high-speed data transfer ability, large-capacity storage, and real-time information processing, UAV communication networks can cope with the uHDD features of 6G. UAV networks can effectively manage the huge quantities of information generated by the multiple devices and sensors in the network by utilizing sophisticated communication technologies including SDN, NFV, and AI. Applications that require extremely high data densities and low-latency connectivity such as driverless vehicles, smart cities, and industrial automation, can all benefit from such information [88]. Additionally, modern sensors like LiDAR and cameras that can capture and send high-resolution images and videos for instantaneous monitoring and analysis can be included in UAVs [89]. Therefore, the uHDD features of 6G, which have the potential to completely change the way we live, work, and communicate, can be made possible by UAV communication networks [90].

V. OVERVIEW OF SOFTWARE-DEFINED UAV NETWORKS

Integrating the SDN and UAVs can revolutionize the wireless networking by enabling more efficient and flexible wireless connectivity [47]. As the demand for UAV-based applications continues to grow for 6G systems, SDN will likely become an increasingly important technology for enabling the next generation of UAV cellular networks to support the uMUB, uHDD, uHSLLC, and mMTC services [91], [92]. Therefore, to support the services in 6G systems, the SDUAV networks is very essential. Besides, the centralized control and programmability feature of the SDN can be utilized to control the deployment and behavior of UAVs equipped with various wireless technologies [93]. Hence, this SDN integrated UAV networks can offer several advantages over the conventional UAV-based networks, including dynamic resource allocation, rapid deployment, scalability, improved coverage, and reduced costs [47], [48]. The fundamental distinctions between the SDUAV and conventional UAV communication networks are summarized in Table 6. On the other hand, in an SDN-assisted UAV network, wireless resources can be dynamically allocated where they are needed most which can allow more efficient utilization of resources and reducing network congestion [82]. Moreover, by deploying multiple scaled up or down to meet changing needs in 6G environments. Furthermore, the utilization of UAVs as the ABSs can significantly reduce the need for expensive and complex fixed infrastructure, leading to lower deployment costs [48], [94]. Thus, the integration of SDN and UAVs can provide a flexible, efficient, and cost-effective solution for wireless networking to support the 6G systems. Fig. 7 illustrates the basic technologies which are required for the SDUAV networks. In addition, the visions, design goals, proposed architecture, are discussed briefly in below.

A. VISIONS

To support the next generation future 6G networks, the visions for SDUAV networks should include the following:

Seamless connectivity: By employing UAVs as WBSs, SDUAV networks aim to deliver seamless connectivity. Hence, these SDN-assisted UAVs are going to offer a flexible and dynamic network infrastructure that will guarantee ubiquity and dependable connectivity even in off-the-grid and underserved locations. In order to increase network coverage, especially in places with sparse terrestrial infrastructure, they

TABLE 6. Differences between the SDUAV and conventional UAV communication networks [48], [82], [94].

Aspects	SDUAV Communication Network	Conventional UAV Communication Network
Architecture	Centralized	Decentralized
Scalability	High scalable	Limited
Control	More granular	Limited
Interpretability	High	Limited
Adaptability	High	Low
Performance	Dynamic	Static
Network configuration	SDUAV communication networks enable dynamic and adaptable network configuration that is simple to update or change as required	The network configuration of conventional UAV communication networks is fixed and challenging to modify or update
Configuration type	Fieldable and automated	Fix and manual
Network management	In order to increase scalability and resilience, SDUAV communication networks adopt a centralized network management strategy	Conventional UAV communication networks employ an administrative network management strategy, which can result in single points of failure and restricted scalability
Network monitoring	SDUAV communication networks feature advanced network monitoring capabilities that can offer real-time visibility into network operation and help in the rapid identification and resolution of network-related problems	It is challenging to identify and resolve network problems in conventional UAV communication networks due to their poor network monitoring capabilities
Traffic control	A comprehensive traffic management approach is employed by SDUAV communication networks to enhance network performance, provide traffic priority, and prevent congestion	Conventional UAV communication networks employ a best-effort traffic control strategy, which may end up resulting in congestion and an overall decrease in network performance
Network security	SDUAV communication networks consist of advanced technology security measures such as network segmentation, access control, and encryption to defend against threats from the internet	The security protects implemented on conventional UAV communication networks tend to be inadequate leaving them vulnerable to cyberattacks

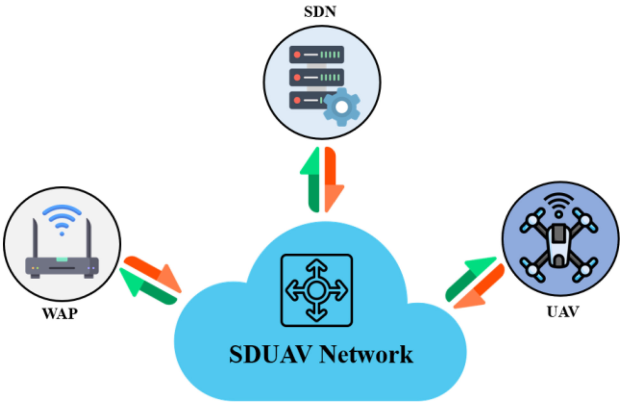

FIGURE 7. Required technologies for SDUAV communication network.

are going to establish ad hoc wireless communication links and coordinate.

Dynamic resource allocation: The goal of SDUAV networks must be dynamic resource allocation, facilitating effective and flexible utilization of network resources [95]. Based on service demands, traffic patterns, and network circumstances, sophisticated resource management algorithms can reallocate bandwidth, computer resources, and storage space in real-time [96]. Therefore, the aim is to maximize resource utilization, meet the diverse requirements, and optimize network performance of uMUB, uHDD, uHSLLC, and mMTC applications in 6G networks.

Edge intelligence: SDUAV networks must embrace the concept of utilizing capabilities for intelligent analysis and edge computing [97]. UAVs will function as edge nodes at the network's edge, processing localized information, analyzing data, and doing AI-driven work. This concept enables low-latency processing, real-time decision-making, and less reliance on centralized cloud infrastructure, resulting in more rapid responses and better application performance [98].

Autonomous and self-organization feature: SDUAV networks have to possess the notion of self-organization and autonomous adjustment features. To do so, UAVs need to have the intelligence to coordinate, configure, and optimize their activities depending on broad objectives and awareness of the surrounding environment [18]. To maintain effective network operations and provide seamless services, they need to constantly adapt to changing network circumstances, optimize their flight paths, and collaborate together with other UAVs.

Resilience and fault tolerance: The emergence of fault tolerance and resilience techniques is part of the SDUAV network goal. To recognize and recover from network issues on their own, UAVs are expected to possess self-healing capabilities [99]. Redundancy techniques, such as placing several UAVs in the exact location, will provide uninterrupted operation even if a single UAV malfunctions. With regard to URLLC services in particular, which demand high dependability and low latency, the objective is to ensure stable and robust connectivity [100].

Mobility support: The ultimate objective of SDUAV networks will be to ease UAV mobility by facilitating seamless handoffs and ongoing connectivity as UAVs move throughout the network. This consists of effective mobility management protocols, flexible routing designs, and sophisticated handoff techniques that guarantee constant communication and reduce service interruption during UAV movement [82]. In order to maintain reliable interactions with users on the ground and other network components, it is envisioned that UAVs would be able to dynamically modify their vantage points and network interactions.

Collaboration and interoperability: SDUAV networks are intended to promote cooperation and compatibility among multiple UAVs, network components, and heterogeneous networks in the 6G environment [101]. With additional communication systems, including terrestrial networks and satellite networks, the ultimate objective is to enable seamless integration and cooperation [102]. Due to the flawless handover, roaming capabilities, and global connectivity provided by this interoperability, UAVs are able to collaborate with different networks in order to offer and all-encompassing service coverage.

User-centric design: A user-centric design strategy for SDUAV networks is necessary, considering end-user demands, preferences, and experiences into account. This vision requires user-centric network optimization, individualized service provisioning, and flexible delivery methods that address the requirements of the user and their experience first. Therefore, establishing SDUAV networks with seamless, tailored, and context-aware services is the objective in order to increase user engagement and adapt to the demands of different clients [103].

B. DESIGN GOALS

To support services such as URLLC, uMUB, uHDD, uHSLLC, and mMTC in 6G systems, SDUAV networks should aim for the following design goals.

Low latency: To fulfill URLLC and uHSLLC service criteria, SDUAV networks need to emphasize on reducing latency. To accomplish this, communication protocols must be improved, processing delays must be reduced, and edge computing capabilities must be deployed.

High reliability: SDUAV networks must guarantee high reliability and fault tolerance for URLLC services. To ensure uninterrupted connectivity, swift failure recovery, and seamless handovers, redundancy, and failover methods must be in place. This could include utilizing robust routing protocols, deploying multiple UAVs to provide redundancy, and having redundancy for network infrastructure aspects.

Scalability: To cope with the huge number of devices and connections anticipated for 6G networks, especially for services like uMUB and mMTC, SDUAV networks need to be scalable. In order to facilitate seamless resource expansion and contraction in response to demand, the network development should support the dynamic scaling of resources. This

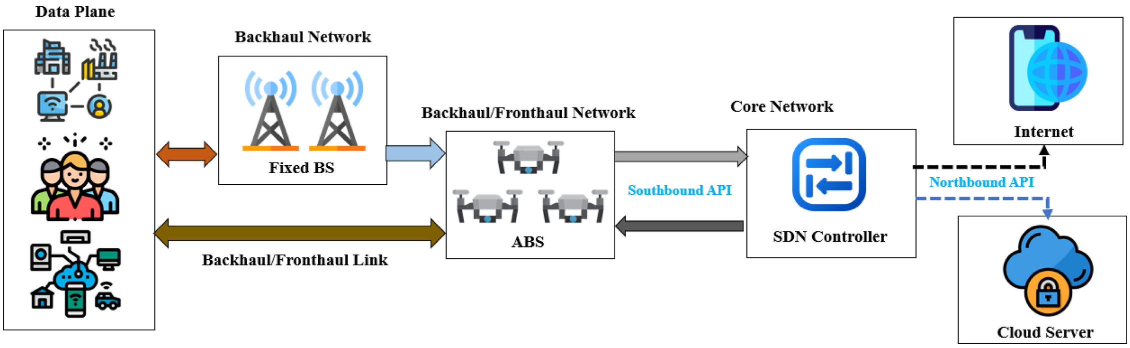

FIGURE 8. Block diagram of the proposed SDUAV framework.

can be accomplished by virtualization, network slicing, and efficient resource allocation techniques.

High data density: To satisfy the uHDD requirements, SDUAV networks need to handle massive quantities of information produced by multiple applications in 6G systems. The ability to process, store, and transmit information effectively is a prerequisite for this. To manage the increased information density, lower data transmission latency, and ease network congestion, edge computing, distributed storage, and intelligent data caching techniques can be deployed.

Flexibility and adaptability: To meet different kinds of service requirements, SDUAV networks should be programmable and flexible. It is essential to have the capacity to allocate and reallocate network resources on an as-needed basis. SDN principles, such as network programmability and virtualization, enable the network to adapt and customize services in real time based on individual application requirements.

Security and privacy: With an increased dependency on connection, SDUAV networks must prioritize security and privacy. To secure network communications, information about users, and infrastructure, robust security mechanisms should be implemented effectively, including encryption, authentication, access control, and intrusion detection. Privacy-preserving technology, such as secure data aggregation and anonymization, should be employed to safeguard user confidentiality.

Energy efficiency: To facilitate sustainable operations, SDUAV networks should be designed with energy efficiency in mind. Energy-efficient UAV concepts, power management techniques, and intelligent resource allocation can play a critical role to minimize energy consumption and increase flying time. Energy harvesting and optimization techniques can be employed to maximize energy utilization.

Network management and orchestration: For SDUAV networks, effective network management, and orchestration are very critical. The effective monitoring, configuration, and optimization of network resources are made feasible by centralized control, network automation, and intelligent analytics. Hence, to ensure a reliable and efficient network operations, management and orchestration can offer real-time visibility, performance monitoring, problem detection, and automated network recovery [104].

By emphasizing these design objectives, SDUAV networks can offer the necessary features and infrastructure to meet every aspect of URLLC, uMUB, uHDD, and uHSLLC services in 6G networks, while providing reliable, productive, secure, and scalable wireless communication.

C. ROLES OF SDUAV NETWORKS IN 6G

In order to support the future 6G systems, SDUAV can play a pivotal role. Firstly, to provide robust and low-latency connectivity for URLLC, SDUAV utilizes its wireless capabilities, ensuring that critical applications operate without a hitch. Secondly, in the context of uMUB, an SDUAV network can employ its mobile communication potential to enable seamless and rapid connectivity, providing ubiquitous access to bandwidth-intensive services Additionally, in order to facilitate the efficient transfer of information and administration for uHDD applications, SDUAV networks leverage built-in wireless communication features. Furthermore, to support the uHSLLC and mMTC services of the 6G networks, SDUAV's intelligent and autonomous functions can ensure fast and reliable connectivity as well as can provide real-time and massive-scale data exchange.

The proposed block diagram in Fig. 8 illustrates the basic structure of an SDUAV network. In this framework, the SDN controller is responsible for making decisions on forwarding and can make utilization of cloud computing technologies to meet the specifications of 6G systems. First, user equipment (UE) can transmit data directly to the UAV, which serves as both the fronthaul and backhaul networks. Alternatively, the BS serves as the backhaul network and distributes the data from the UE to the UAV. The data is subsequently sent to the SDN controller after arriving at the UAV. Based on the information received, the SDN controller takes impose of making decisions on forwarding, such as switching and routing. Therefore, by managing and coordinating the data flow, it functions as the network's central control point. Furthermore, the controller of the SDN architecture is also capable of communicating with the Internet which allows connectivity to external networks and services. Besides, to fulfill the needs of 6G systems, it could utilize the advantage

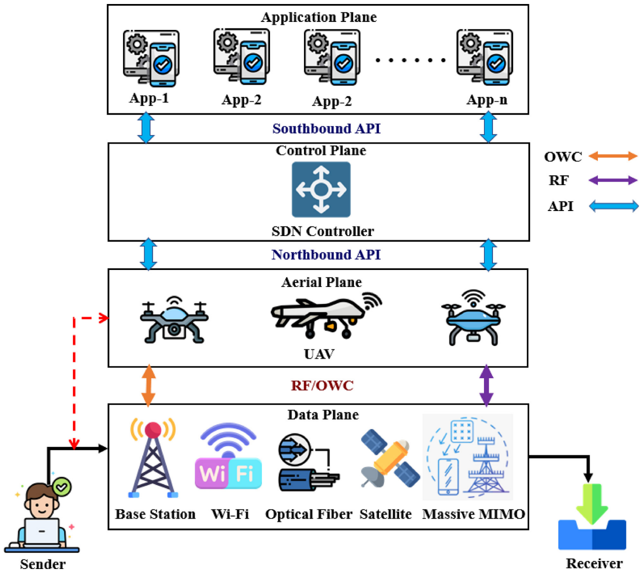

FIGURE 9. Architecture of an SDUAV network.

of cloud computing features including resource scalability, virtualization, and sophisticated computational capabilities.

D. PROPOSED ARCHITECTURE OF AN SDUAV NETWORK

The architecture of an SDUAV network is a complex system that involves several different components working together to provide a flexible, scalable, and reliable network infrastructure. The SDUAV architecture is designed to provide a flexible and dynamic network infrastructure that can adapt to the unique challenges of UAV communications, including limited bandwidth, high mobility, and intermittent connectivity [82]. By leveraging SDN and virtualization technologies, SDUAV enables more efficient use of network resources, improved network performance, and enhanced security. However, an SDUAV network can be divided into three planes such as data plane, control plane, and application plane as illustrated in Fig. 9. The description of the four planes is summarized below.

1) *Data plane:* In an SDUAV network, the data plane functions as the backbone for communication between multiple components by utilizing various technologies including cellular BSs, WiFi, optical links, massive MIMO, and satellites acting as relays or establishing a fronthaul network [52]. Between UAVs, GCSs, and different network components, the data plane is responsible for transmitting and receiving data packets. While WiFi offers communication with higher data rates, cellular BSs can provide wide coverage and connectivity in widely distributed regions [52]. Conversely, optical networks can offer fast, low-latency connectivity over short distances in SDUAV-based networks. In addition, by employing multiple antennas for concurrent data transmission, massive MIMO can improve spectral efficiency and spatial capacity for SDUAV networks. Additionally, satellites can operate as fronthaul connections or as relays in SDUAV architecture to increase network reach to inaccessible or remote areas [59]. In order to select and manage communication channels, the SDUAV network's data plane implements the SDN concept while considering signal quality, congestion levels, and QoS needs into account. As a result, this ensures seamless communication across the various technologies employed and facilitates effective interconnectivity.
2) *Aerial plane:* In SDUAV network, the aerial plane is responsible for forwarding data packets between various network devices. In SDUAV, this can include devices such as switches, routers, and access points, as well as UAVs themselves, which can act as network nodes [52]. The data plane is programmable and can be configured by the SDN controller to enable dynamic network routing and traffic management. Moreover, utilizing a multi-hop relay network, a communication link between UAVs and the receiver can be established [126]. This kind of architecture enables UAVs to send and receive signals before it reaches the receiver.
3) *Controller plane:* The SDN controller is the core component of the architecture, responsible for managing the network infrastructure and configuring network devices [52]. It receives input from the network administrator or applications running on the network, and translates these inputs into network policies that are implemented by the network devices.
4) *Application plane:* The application plane in SDUAV is one of the essential planes in the proposed framework [52]. It refers to the layer where network services and applications are set up and executed. For the purpose of defining network policies, traffic management, and service provisioning, the application plane communicates with the control plane. Moreover, it enables the deployment and maintenance of several network applications by utilizing the programmability and centralized control features of SDN.

E. COMMUNICATION LINK ESTABLISHMENTS BETWEEN SDN CONTROLLER AND UAVS

In an SDUAV architecture, packet processing and communication mechanism are done via the OpenFlow protocol and different type of control messages [93]. In an SDUAV framework, the controller act as the central manager which also can be considered as the brain of the architecture and the UAV nodes are responsible for gathering the data or information from the uses and create backhaul link for the UEs. To establish a communication link in an SDUAV network, five types of communication messages such as hello_message, packet_in, packet_out, administrative_role, and feature_request is utilized as shown in Fig. 10. The main objectives of each of these messages are briefly outlined below.

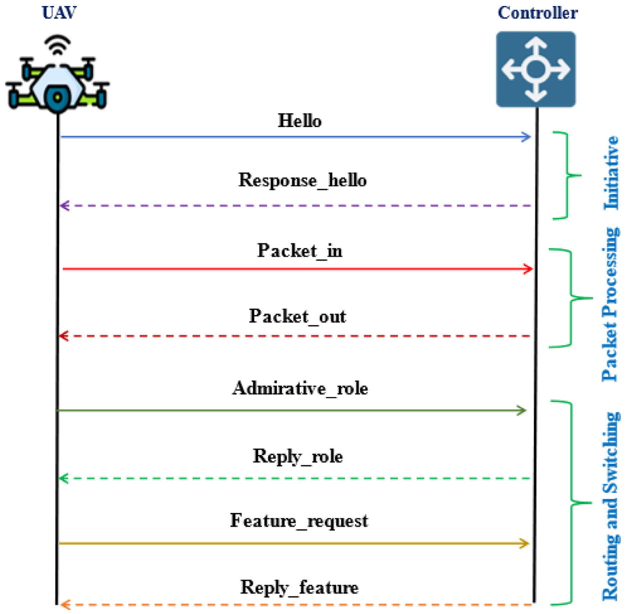

FIGURE 10. Working flow diagram between the UAV and SDN controller.

1) *Hello message:* This is the initial message sent by both the SDN controller and the UAV node once the transmission control protocol (TCP) connection is established. To ensure that two devices can communicate with one another, this hello_message information are exchanged.
2) *Packet_in:* When the UAV node gets a packet that is not compliant with any current flow rules, it transmits a notification to the SDN controller. The message contains the packet information as well as metadata, like the switch identity documents (ID) number and port number.
3) *Packet_out:* To direct the UAV node to forward a packet, the SDN controller sends this message. In addition to the packet data, the message also contains metadata like the output port number and switch ID.
4) *Administrative_role:* To grant or withdraw administrative access, the SDN controller broadcasts this message to the UAV nodes. Access to sensitive configuration information or network resources can be restricted using this.
5) *Feature_request:* The UAV node receives this message from the SDN controller inquiring about the node's OpenFlow capabilities. The features that will be provided by the communication link are negotiated utilizing the message.

Together, these components form a comprehensive UAV network management system that enables efficient and effective operation of the SDUAV networking architecture as shown in Fig. 11. By providing a centralized view of the network and automating different management tasks, the system helps to reduce complexity and improve reliability, scalability, and performance.

F. FEATURES PROVIDED BY SDUAV NETWORKS IN 6G

SDUAV communication networks offers a flexible, efficient, and cost-effective solution for providing connectivity in a wide range of settings. As the technology continues to evolve, it is likely that we will see more and more applications of SDUAV networking in both traditional and emerging settings. Some of the most essential features provided by the SDUAV networking are briefly described below.

Robust traffic management: In SDUAV networks, traffic management is done using SDN principles, which decouples network management from hardware and centralizes it in a software controller. SDN can increase the performance of UAVs by enabling more efficient use of network resources, reducing network congestion and latency, and optimizing communication pathways. Besides, it can dynamically allocate network resources based on the real-time needs of the UAVs and help ensure reliable and low-latency communication between UAVs and their GSs. SDN is especially important in UAV networks, where the communication links can be highly dynamic and subject to interference from the environment.

Handover management: To guarantee seamless communication transfer between APs as the UAV moves between coverage areas, handover management in SDUAV networks is carried out using SDN the basic concepts [21]. By using a centralized controller to manage load balancing, dynamic path switching, and handover choices, SDN can allow handover management, enhancing the performance of UAVs by ensuring dependable and low-latency communication links. In mission-critical applications where uninterrupted communication is crucial, such as surveillance and crisis response, SDN plays a crucial part. SDN additionally has the ability to optimize the handover process and minimize its effect on network performance, improving wireless networking performance by managing handover decisions and dynamically switching communication paths. As a result, the efficiency of UAVs and the network as a whole is enhanced by SDN's seamless handover, dynamic path switching, and load balancing specifications [21], [105].

Dynamic load balancing: Dynamic load balancing in a SDUAV network is the ability to distribute traffic across the network to prevent network congestion and ensure reliable and low-latency communication links. SDN enables a centralized controller to manage traffic distribution using predictive and reactive load balancing techniques to balance the load across available links and access points. This improves the performance of UAVs by ensuring they have access to the resources they need to complete their mission and extends their range. SDN also helps prevent network congestion and improves wireless networking performance.

Dynamic routing: Dynamic routing in an SDUAV network is the process of selecting the best path for a UAV based on real-time network conditions. SDN enables a centralized controller to manage the network's routing by programming the forwarding tables in each network device to direct traffic along the optimal path. This can improve the

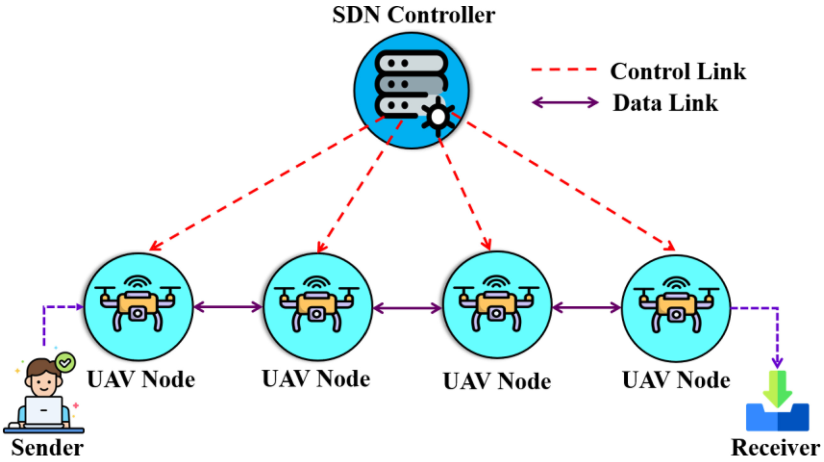

FIGURE 11. Communication link between the SDN controller and the UAVs.

performance of UAVs by reducing latency and packet loss and improving network reliability [21]. Additionally, SDN concept also accelerate the performance of the conventional wireless networking by ensuring that UAVs have access to the resources they need to complete their mission.

Intelligent decision-making: SDN enables intelligent decision-making in a SDUAV network through centralized network management that uses machine learning algorithms to analyze real-time data [21]. This allows for better routing, bandwidth allocation, and handover management through the use of QoS policies. By dynamically allocating network resources based on real-time needs, SDUAV network can enhance the performance of the UAV-based ABS by reducing latency, optimizing communication pathways, and reducing network congestion. This also ensures reliable and low-latency communication between UAVs and their GSs. SDN plays a critical role in enabling intelligent decision-making and improving the overall performance of the SDUAV networks [48].

Complex resource allocation management: To administer intricate resources in the proposed SDUAV networks, a self-learning channel selection mechanism can be integrated into the SDN-based networking architecture [21]. This mechanism combines information from several kinds of sources, including spectrum analysis, network load, and QoS requirements, in order to establish communication links between UAVs and GCSs, along with between UAVs and UAVs and SDN controllers [83]. At the same time, utilizing sophisticated algorithms that incorporate signal quality, latency, and bandwidth availability into consideration, it dynamically evaluates channel conditions, including interference, signal strength, and levels of congestion. On the other hand, the SDN controller can determine the optimal communication link for each scenario, enabling adjusting to changing traffic patterns and environmental circumstances. Additionally, SDN-enabled core network simplifies path selection by streamlining communication channels, lessening traffic, and boosting dependability through centralized control, thereby enhancing the performance of both the network and the UAV [105]. Furthermore, SDN concepts also increase bandwidth allocation more accessible by allowing dynamic allocation based on real-time UAV requirements and the application of QoS criteria, which is very crucial in applications that are mission-critical. Likewise, in THz-assisted SDUAV communication, SDN is particularly essential to beam management since it enables centralized control of beamforming to improve communication performance and lower interference, thus enhancing the effectiveness and performance of both UAVs and the overall network.

Heterogeneous hardware management: In a SDUAV network, heterogeneous hardware management is typically enabled using SDN architecture. SDN enables the network management to be decoupled from the hardware and centralized in a software controller, which provides a unified view of the network resources. This allows for more efficient management of heterogeneous hardware, including different types of UAVs and their associated SDN controllers [21]. SDN can help improve the performance of UAVs and the overall network by dynamically allocating network resources and optimizing communication pathways. This enables more efficient use of network resources, reduces network congestion and latency, and enables intelligent decision-making based on real-time data.

Interference management: In a SDUAV network, interference management is typically enabled using SDN principles. SDN allows for centralized network management, which enables intelligent decision-making based on real-time data. SDN enables spectrum and interference management by allowing the central controller to monitor spectrum usage and detect interference sources in real-time [83]. The controller can then dynamically adjust the UAVs' communication parameters, such as channel, modulation, and transmission power, to avoid interference and optimize the use of available spectrum [105]. SDN's ability to intelligently manage spectrum and interference can improve the UAVs' performance by reducing packet loss, increasing data throughput, and extending the communication range. It also improves the overall network performance by reducing interference and optimizing spectrum utilization. Thus, SDN plays a critical role in enabling interference management in SDUAV networks [83]. By dynamically adjusting communication parameters, SDN can help optimize the use of available spectrum and reduce interference, improving both the performance of UAVs and the overall network.

Frequency management: SDN enables frequency management in a SDUAV network by using intelligent algorithms to manage frequency allocation and avoid interference. A centralized controller can use real-time spectrum analysis to detect the availability of different frequencies and allocate them dynamically to the UAVs. Additionally, machine learning algorithms can be employed to predict interference and dynamically adjust the frequency allocation. This improves the performance of both UAVs and the overall network by ensuring reliable and interference-free communication [83]. SDN allows for dynamic and intelligent frequency allocation based on real-time data, optimizing communication pathways and ensuring a stable connection between UAVs and SDN controllers. As a result, SDN also can boost the wireless networking efficiency by reducing interference and optimizing communication pathways.

High-Capacity backhaul connectivity management: In a SDUAV network, high-capacity backhaul connectivity management is typically enabled using SDN concept. SDN makes it possible to centralize network administration, which enables the utilization of adaptive algorithms to control backhaul connectivity and enhance the performance of UAVs and the entire network. To guarantee efficient and reliable contact between UAVs and SDN controllers, SDN controllers can dynamically allocate backhaul resources, optimize routing paths, and handle network congestion. SDN can help increase the effectiveness and efficacy of UAVs as well as the network by optimizing the backhaul connectivity. The efficiency of wireless networking can be enhanced by lowering latency and increasing the bandwidth available for wireless communication.

Autonomous wireless system management: SDN concepts are typically implemented in SDUAV networks to enable autonomous wireless system management. The use of advanced algorithms to manage and improve wireless connectivity is made possible by SDN's centralized network management system. In order to increase network efficiency and reliability, SDN can automate administration of wireless systems, including automatic channel selection, power management, and antenna configuration. SDN additionally enables self-healing approaches to ensure that the network remains operational in the event of a failure or interference. The capacity of SDN to provide a high level of automation and intelligent decision-making based on real-time data is by far its most significant advantage in autonomous wireless system management. Hence, there will be less need for manual intervention and upkeep and both the efficiency and reliability of UAVs as well as the network as a whole will be improved.

High propagation and atmospheric absorption management: High propagation and atmospheric absorption control in an SDUAV network can be made possible by SDN framework. With the help of intelligent algorithms and centralized network administration provided by SDN, signal propagation can be managed and optimized while avoiding atmospheric amplification. By guaranteeing reliable and high-quality communication under various atmospheric conditions, SDN can enhance the performance of UAVs and networking. SDN can optimize communication channels and promises a steady link between UAVs and corresponding SDN controller by enhancing signal propagation and avoiding atmospheric absorption. The ability of SDN to dynamically modify signal propagation and frequency allocation based on real-time data is its key advantage in high propagation and atmospheric absorption management. By optimizing these factors, SDN can enhance the effectiveness of both UAVs and the entire network as a whole, as well as wireless networking performance by reducing interference and optimizing communication pathways.

G. COMMUNICATION MECHANISMS AND PROTOCOLS FOR SDUAV NETWORKS

An SDUAV network requires a combination of reliable mechanisms and protocols to ensure a secure and efficient network operation. These mechanisms and protocols must be carefully designed and implemented to meet the specific communication requirements and network conditions of different 6G applications. There are several mechanisms and protocols can be employed to ensure reliable and efficient network operation in SDUAV network. Some of the key communication protocols are listed below.

Advanced QoS technique: In an SDUAV network, QoS mechanisms can be employed to prioritize traffic and allocate the network resources based on the needs of different applications and users. For example, mission-critical applications, such as video surveillance or disaster response, may require high levels of bandwidth and low latency, while non-critical applications, such as email or Web browsing, may have lower requirements. Therefore, QoS mechanisms can be utilized to ensure that the network is providing the required level of service to different applications and users, which can also improve the overall efficiency and reliability of the uHSLLC service in 6G networks.

Cognitive radio: The cognitive radio (CR) technology is such a technique which can offers the UAVs to sense the wireless environment and adapt their transmission parameters, such as frequency, modulation, and power, to avoid interference and improve communication reliability. Hence, CR technology ensures that the UAVs are utilizing the most optimal wireless channels for communication to support the mMTC, uHDD, and uHSLLC features of 6G systems [105].

Routing and mobility protocols: Routing and mobility protocols, such as the mobile ad hoc network (MANET) and the dynamic source routing (DSR) protocol, enable the UAVs to communicate and establish network connections with each other. To establish and maintain communication links in a 6G domain even in environments where there is no pre-existing network infrastructure, these types of protocols can provide a secure link to the SDUAV communication systems.

Ad hoc networking protocol: Decentralized UAV communication can be accomplished with ad hoc protocols such as the ad hoc on-demand distance vector (AODV) or dynamic source routing (DSR) [106], [107]. With the help of these protocols, UAVs can instantly create communication linkages without relying on stationary infrastructure in SDUAV networks.

Multi-path routing mechanism: To utilize the multiple communication paths simultaneously to enhance network performance and reliability, the multi-path routing approach can play a vital role [105]. This is particularly essential in environments with limited wireless coverage, where multiple communication paths can improve the likelihood of establishing and maintaining communication links to serve the uHDD and uMUB services in 6G networks.

Satellite communication protocols: Using a satellite communication protocol like extension of digital video broadcasting satellite (DVB-S2X) or advanced satellite mobile systems (ASMS), UAVs can be connected to one another when they are operating in remote locations or outside of the LOS range [108]. Hence, for SDUAV networks, these protocols enable long-distance communication and global coverage.

Advanced security mechanisms: Security mechanisms, such as encryption, authentication, and authorization, are essential in SDUAV networks to protect against cyber threats and ensure the integrity and confidentiality of network traffic for 6G networks. Security mechanisms also prevent the unauthorized access to the network and protect against attacks that can disrupt or disable network operations [18].

Wireless mesh networking protocol: Wireless mesh networking protocols such as the optimized link state routing protocol (OLSR) or a better approach to mobile ad hoc networking (BATMAN) could be suitable for SDUAV networks [109], [110]. These protocols can enable the multi-hop communication and expand the network coverage by creating a mesh topology with UAVs serving as relays in 6G environments.

Intelligent network monitoring and management: To monitor network performance, identify potential issues, and implement corrective actions as needed, an intelligent network monitoring and management protocol can be integrated in an SDUAV network. Effective utilization of network resources and adaptation to evolving communication requirements to support the 6G networks can be facilitated by this approach [105].

Optimized power management protocol: By turning off the unused UAVs or adjusting transmission power based on communication requirements, power management mechanisms can be employed in the an SDUAV network. Therefore, this approach can provide a sufficient power to the UAVs to operate for the required duration, and also can extend the range and reliability of the 6G networks.

VI. ADVANCED COMMUNICATION APPROACHES FOR SDUAV NETWORKS

To increase the efficiency, dependability, flexibility and adaptability of SDUAV networks, the adaptation of innovative and advanced techniques is a must. Advanced communication techniques such as dynamic network slicing (DNS) and dynamic spectrum access (DSA), dynamic network coding (DNC), and software-defined radio (SDR) can not only increase the performance of the network but also can reduce the interference in ultra-dense heterogeneous 6G networks. Even in challenging circumstances, the UAV's communication link can be improved with the utilization of strategies like multi-user MIMO, beamforming, and network coding. A few advanced communication mechanisms that can improve SDUAV effectiveness are addressed below.

Dynamic spectrum access: In an SDUAV network, DSA mechanism can be employed by SDN controllers to dynamically assign spectrum that is accessible to UAVs. Unlike conventional wireless networks, DSA enables UAVs to receive real-time spectrum allocation based on criteria like their location and network demand [105]. By dynamically allocating distinct spectrums to different UAVs, this method optimizes network performance of the 6G systems as well as minimizing interference between UAVs. A further benefit of DSA is that it simplifies the utilization of the spectrum resources that are already in use, which eases congestion and boosts network efficiency [111]. On the other hand, in an SDN-assisted UAV network, the function of SDN controller is to provide centralized control and management of network resources. As a result, the controller can oversee the distribution of available spectrum to UAVs as well as various network resources like bandwidth and better QoS. Hence, to support the 6G services like uHDD, uHSLLC, and mMTC, an SDUAV network can reach high levels of performance, reliability, and efficiency by utilizing the DSA techniques.

Dynamic network slicing: DNS is a method of networking that enables network administrators to segment a single physical network into multiple virtual networks, each with a unique set of resources and capabilities suitable for the particular requirements associated with different services and applications in 6G networks [112]. Besides, the DNS technique enables the formation of distinct network slices, each with a unique set of network services customized to meet a wide range of 6G requirements. DNS has several essential advantages, including customization, adaptability, effectiveness, and confidentiality [113]. By employing programmable network devices and controllers to manage and coordinate the production and administration of network slices, network slicing could potentially be integrated into SDN. Moreover, DNS can boost network performance and efficiency by allowing different UAV services and applications to utilize the exact physical network infrastructure while ensuring isolation and security between distinct slices. Therefore, with the help of DNS, the SDUAV networks can distinguish the products and services they offer to their clients and optimize their utilization of network resources, maximizing performance, dependability, and efficiency. On the contrary, the role of SDN in this case is to provide a programmable network infrastructure that can dynamically allocate and manage the network resources based on the needs of the UAV applications [113]. By creating virtual network slices for different 6G applications, SDN can enable the efficient utilization of network resources and provide QoS guarantees for each 6G services. Therefore, the performance of the SDUAV networks can be enhanced by reducing latency, improving reliability, and increasing the bandwidth available for each 6G application.

Antenna beamforming: Antenna beamforming is an approach for directing signals in specific directions while minimizing interference as well as improving signal strength [114]. Moreover, antenna beamforming is also capable of enhancing communication between UAVs and the GCSs in SDUAV networking, leading to higher data rates, a greater communication range, and a more dependable connection for 6G networks [115]. To improve communication between various UAVs, antenna beamforming can be utilized to steer signals around the shortcomings of conventional omnidirectional antennas used in UAVs. Additionally, SDUAVs can communicate with several GCSs and several UAVs simultaneously with the assistance of directional antennas, establishing multiple communication channels immediately. By frequently adapting the network's configuration based on changing network conditions, SDN can improve the performance and dependability of the wireless network utilized by SDUAVs. On the other hand, the SDUAV networks can utilize SDN framework to prioritize various forms of network traffic, ensuring that critical information like telemetry and control signals are given precedence over less vital information including video streaming or file transfers.

Dynamic spectrum sharing: By maximizing the capacity of the available spectrum and minimizing interference between multiple wireless communication systems, dynamic spectrum sharing (DSS), a technique that enables multiple wireless communication systems to share the same frequency spectrum dynamically [116]. Interestingly, DSS approach can be deployed in an SDUAV network to access the underused or underutilized frequency bands. As a result, higher data rates, longer communication ranges, and more dependable connections between the UAVs and the BSs can be achieved in the ultra-dense heterogeneous networks [83]. Based on the network conditions and the spectrum's availability, SDN controller can control the frequency spectrum dynamically that can improve the performance and dependability of the SDUAV networks. Moreover, the ability of the UAVs to dynamically switch between accessible frequency bands based on network circumstances and spectrum availability provided by DSS also can be helpful during operation. Besides, by allowing several UAVs to operate in the same frequency range without interfering with one another, DSS can enhance the scalability of the SDUAV networks [117]. Hence, DSS is a potent method that can improve the SDUAVs network's performance, dependability, and scalability to support the 6G services.

Software-defined radio: With the use of SDR technology, UAVs can dynamically adjust their broadcast and reception characteristics in response to shifting network conditions [118]. By enabling UAVs to modify their radio parameters, such as frequency, modulation, and transmit power, to suit the current network conditions, SDR can boost the optimization of SDN-integrated UAV networks [119]. To prevent congestion, UAVs also can utilize the SDR approach to switch to alternate frequency bands and modulation schemes or reduce transmit power by recognizing interference and congestion [120]. At the same time, the centralized administration and control of network resources, including UAV radio parameters, is made feasible through SDN framework. To assess the current network scenarios and adjust the radio parameters of UAVs accordingly, SDN can take advantage of network telemetry and various information sources. Hence, the performance, efficiency, as well as efficiency of the SDUAV networks can be improved with the deployment of SDR.

Advanced cognitive radio: Advanced cognitive radio (ACR) can help SDN-based UAV networks by allowing UAVs to dynamically access and utilize available spectrum resources based on real-time network conditions [121]. ACR is a radio technology that utilizes intelligent algorithms to sense and adapt to changes in the wireless spectrum. In an SDN-enabled UAV network, ACR can improve network performance and efficiency by allowing UAVs to access and utilize the available spectrum resources more intelligently and adaptively. ACR enables SDUAV systems to sense and identify available spectrum resources and adapt their transmission parameters to use these resources [122]. For example, if a UAV detects that a particular frequency band is not in use, it can dynamically switch to that frequency band to avoid interference and improve network performance [123]. Similarly, if a UAV detects that the network is experiencing congestion, it can reduce the transmit power or switch to a different frequency band to reduce interference and avoid congestion.

Dynamic network coding: DNC is a technique used in communication networks to improve the efficiency and reliability of data transmission [124]. The basic principle of the DNC is to combine multiple data packets into a single packet, which is then transmitted over the network. As a result, this approach allows for more efficient use of network resources and can improve the overall performance of the network [125]. In traditional network communication, each packet is transmitted individually and independently. Contrarily, the DNC technique enables much simpler packets to be consolidated and encoded before transmission. This can improve the overall network efficiency for the 6G systems by reducing the number of packets that need to be transmitted, and can also increase the reliability of data transmission by allowing for redundant information to be sent.

In the context of SDUAV networking, this DNC technique can be utilized to improve the performance and reliability of data transmission between the UAVs and the SDN controllers. By combining and encoding multiple data packets, DNC can reduce the overall amount of data that needs to be transmitted, which can improve the efficiency of the network and reduce the risk of congestion [113]. DNC can also be utilized to improve the reliability of data transmission in SDUAV networks. By allowing redundant information to be sent, network coding can help to reduce the risk of data loss or corruption in the event of network errors or interference. Hence, this can be particularly important in SDUAV networks where reliable data transmission is critical to mission success. In addition, by combining and encoding multiple data packets, DNC can reduce the overall amount of data that needs to be transmitted, improve network efficiency, and increase the reliability of data transmission. Hence, this method can be an effective technique for improving the performance and reliability of SDUAV networks.

Multi-hop communication technique: Multi-hop communication is a wireless communication mechanism that transmits data across one or more intermediary nodes from a source to a target node [126]. Instead of using a single hop connection, this method sends the data through numerous wireless networks to the destination node. The fundamental principle of multi-hop communication is based on routing protocols, which allow nodes to choose the most efficient route for data transmission. Until the target node is reached, the intermediate nodes serve as relays, sending the data packets to the following hop. As a result, the network's range and coverage can be enlarged, and its dependability and redundancy can be improved [127]. However, multi-hop communication can also be deployed in the SDUAVs in a variety of ways [128]. First of all, it enables improved coverage and connectivity in regions where direct contact between UAVs and controllers as GCS is impractical because of obstructions or distance. Furthermore, multi-hop communication enables UAVs to communicate with each other and with the controllers over greater distances by passing data through intermediary UAVs. The capacity to transport information across many pathways ensures that communication is maintained even if one connection fails, and multi-hop communication likewise enhances dependability and redundancy. To further boost network performance and effectiveness, multi-hop communication also can be combined with various innovative networking strategies like network coding. Consequently, multi-hop communication is a potent networking approach that can substantially support the SDUAVs by supplying better coverage, reliability, and efficiency, improving performance, and ensuring the accomplishment of missions.

Multi-channel communication technique: Multi-channel communication is an approach that allows wireless communication between different devices via multiple channels at the same time [129]. A number of devices can share a single communication channel in a typical wireless communication system in a 6G network. By enabling devices to communicate across several channels, multi-channel communication solves this problem by expanding the bandwidth that is available and lowering the likelihood of congestion [130]. However, the performance and dependability of communication between UAVs and SDN controllers can be enhanced via multi-channel communication in the context of SDUAV networking. By applying multiple channels of communication, the UAVs can link with each other and the BS without interference or congestion, enhancing overall network performance. To assure that each form of traffic receives the necessary bandwidth and level of QoS, multi-channel communication can also be deployed to support several types of traffic, such as voice, data, and video, through separate channels. This can be particularly beneficial in UAV applications where real-time video and audio data may need to be sent over the Internet.

However, for seamless data and command interchange between the UAV-to-UAV, UAV-to-GSs, SDUAV network utilizes a multi-channel communication approach that is bidirectional. To operate and monitor the UAV's status in real-time as well as make swift decisions while flying, bidirectional communication is very essential for SDUAV networks. It not only enables the UAV to communicate telemetry data along with additional crucial feedback back to the controllers but also the ground to transmit mission-critical information to the UAVs. Moreover, bidirectional communication enhances situational awareness and overall operating efficiency, making it a crucial feature in SDUAVs.

As a result, SDUAV networks become more effective, dependable, and resilient by utilizing the crucial approach of multi-channel communication [131].

By utilizing a multi-layer graph model, the SDN controller can calculate transmission times and can employ an E2E resilient multipath routing mechanism. This enables the establishment of an E2E robust multipath routing approach, which assures reliable connectivity between user equipment (UE) and UAV nodes. Therefore, to provide effective and reliable transmission of data, the data plane utilizes the optimum use of multiple paths that can certainly enhance the overall network's effectiveness and resilience. Fig. 12 illustrates a typical block diagram of a multi-channel framework for the SDUAV networks.

Hydride networking technique: Utilizing different communication procedures, such as wired and wireless, to develop a single network infrastructure is referred to as hybrid networking [132]. The goal of this approach is to maximize the advantages offered by each technology to increase the performance and dependability of the network. However, when it comes to SDUAV networking, hybrid networking techniques can be deployed to provide UAVs the flexibility to switch between several communication technologies based on the suitability and availability of each infrastructure [132]. For example, a UAV can switch to a wire link or

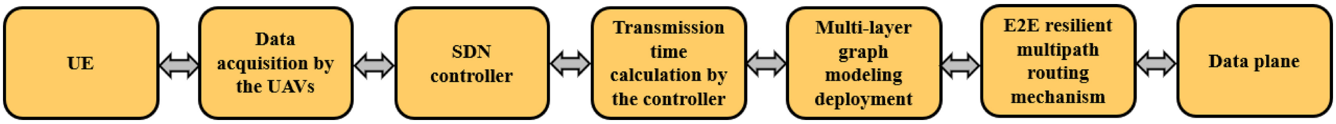

FIGURE 12. Block diagram of a multi-channel communication approach for SDUAV network.

another nearby UAV with a better connection if it loses contact with a GCS through a wireless link. Ad hoc networking, where UAVs can communicate with each other directly, and infrastructure-based networking, where UAVs rely on fixed network infrastructure, like APs or BSs, are two typical ways to implement hybrid networking in SDUAVs. So, to make the best use of available bandwidth and reduce interference amongst UAVs, hybrid networking can be deployed. In addition, several UAVs also can communicate simultaneously without interfering with each other if they are given different frequencies or channels.

Dynamic multipath routing: To increase both the effectiveness and dependability of wireless networks at the same time, a networking approach called dynamic multipath routing (DMR) can employ multiple paths for data transfer at once [133]. Based on current network conditions, it dynamically chooses the optimum path for data transmission, distributes network traffic across several paths, and offers network resiliency [134]. By employing programmable network components and controllers to regulate the selection and administration of various data transmission pathways, DMR can be integrated into SDUAV networks. In the context of SDUAV, DMR also can offer simultaneously transmitting data over numerous channels that can improve the efficiency and reliability of the UAV-based applications and services in 6G networks. As a result, the performance, dependability, and efficiency of the SDUAV networks can be enhanced by adapting this DMR approach.

VII. OPPORTUNITIES AND APPLICATIONS OF SDUAV NETWORKS

SDUAV networks can provide unparalleled flexibility and agility, making them well-suited for a wide range of applications. Their capacity to effectively handle network resources and dynamically rearrange them enables seamless integration with various sectors. SDUAV networks can be employed in agriculture for irrigation management, crop monitoring, and precision farming. They are also essential in disaster management due to their contribution to search and rescue efforts and provide real-time situational awareness. SDUAV networks additionally enhance connectivity and facilitate effective data collecting in communication and surveillance. Furthermore, they are useful in wildlife protection, environmental monitoring, and infrastructural inspection. SDUAV networks' adaptability and autonomy make them the perfect choice for solving the special requirements and difficulties of diverse applications, helping to produce safer, more effective, and innovative approaches in many different kinds of areas. The communication architecture scenario for the SDUAV communication system is demonstrated in Fig. 13. Additionally, a few major SDUAV network prospects and applications are briefly outlined below.

SDUAV-enabled IoT: The IoT is an interconnected network of physical equipment, automobiles, structures, and various objects that are embedded with sensors, software, hardware, and gateways [135]. These IoT devices can interact with one another, share information, and monitor and control different kinds of systems and processes. Hence, IoT has become an integral part of the 6G systems which can enable real-time information that improves decision-making ability, boosts efficiency, and minimizes costs across a wide range of industrial and domestic applications [135], [136]. IoT has an extensive variety of applications including smart houses, asset tracking, healthcare monitoring, environmental monitoring, and industrial automation. On the other hand, IoT networks rely on wireless transmission technologies like cellular networks, WiFi, Bluetooth, ZigBee, and OWC technologies [137].

To provide crucial 6G services like the uHDD, uMUB, uHSLLC, and mMTC to IoT, the SDUAV networks can play a significant role. SDUAV networks can offer a more secure, efficient, scalable, and flexible networking platform for the IoT which can increase the coverage area, better reliability, and minimum latency [138]. For instance, SDUAVs can act as a flying BS for the IoT networks to extend the wireless connectivity and range to regions that are challenging to access with conventional infrastructure [139]. Apart from these, real-time monitoring, control, and cloud-based data processing features can be made possible with the SDUAV-based networks. Furthermore, SDUAV networks can work independently, which can increase productivity and minimize the cost of IoT systems [140]. Moreover, SDUAV networks can support advanced security mechanisms like quantum technology, encryption, and, authentication which can improve the security of the IoT networks [141]. Through the centralized network management and orchestration, as illustrated in Fig. 14, SDN can also play a significant part in the IoT field which can allow dynamic and effective allocation of network resources as well as also can enhance the reliability, scalability, dynamic traffic planning, and advanced QoS mechanism for the IoT devices.

SDUAV-based Industrial IoT: The term IIoT describes the application of Internet-connected devices and sensors to industrial contexts like transportation, manufacturing, and energy production to boost productivity, efficiency, and security [142]. The ability to monitor and analyze operations in real-time results in more informed decision-making and expense savings, making it crucial

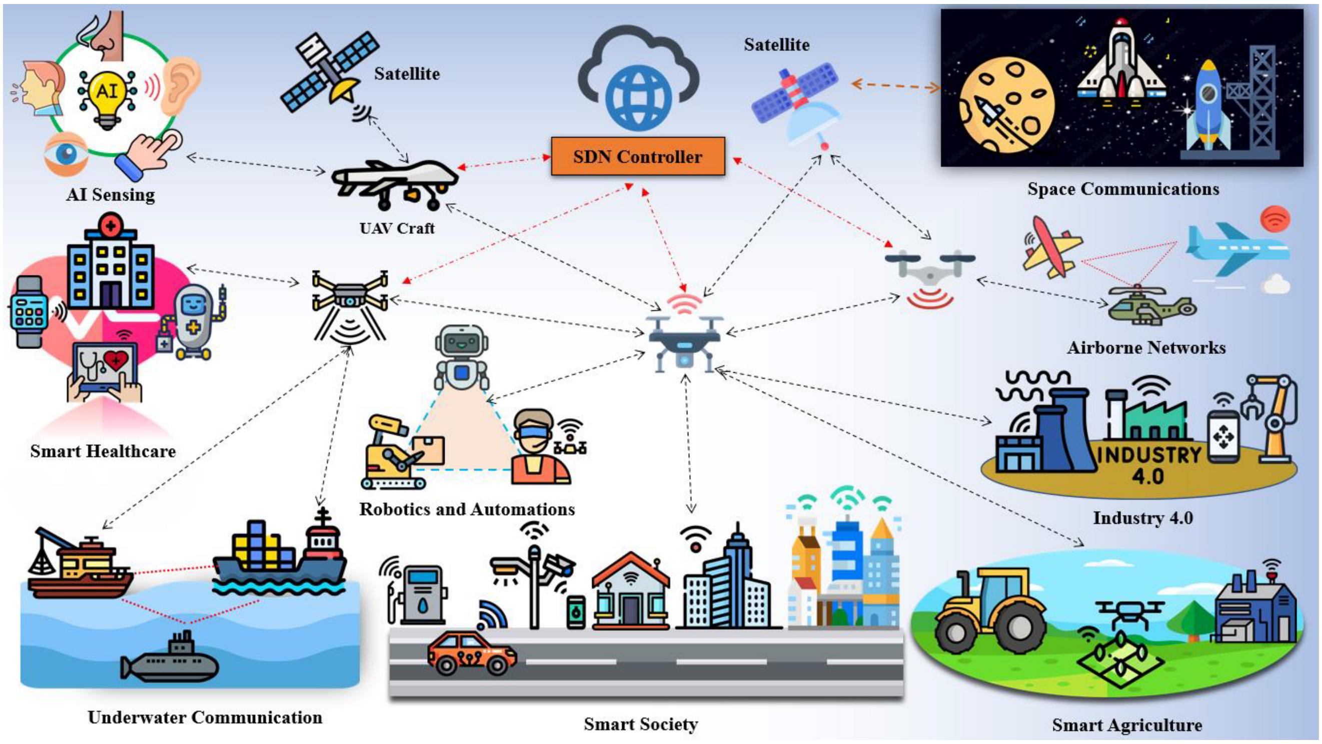

FIGURE 13. Application scenarios of SDUAV networks.

for 6G services and applications [143]. Besides, the IIoT has multiple applications, such as predictive maintenance, asset monitoring, supply chain optimization, and energy management [144]. Networks for the IIoT usually include a lot of sensors and devices that transmit and receive data wirelessly. Thus, to support IIoT, a robust and reliable network infrastructure is required, which can handle the large volume of data and support real-time communication [143].

To support the IIoT, the traditional networking infrastructure may encounter challenges such as limited coverage, high latency, and poor bandwidth. Performance and characteristics, such as real-time monitoring and control, effective fleet coordination and administration, enhanced security, and real-time video streaming, can be improved by integrating SDUAV networking with IIoT [145]. Besides, SDUAV can help the IIoT in a variety of techniques, including data collection in remote or difficult-to-reach areas, wireless coverage and connectivity in areas that are difficult to reach with conventional infrastructure, and support for real-time monitoring, control, and cloud-based data processing [146]. In this way, the use of UAVs as WBSs can help IIoT devices interact and send data to the cloud by extending wireless coverage and connectivity to locations that are challenging to reach through traditional infrastructure [147]. By offering a flexible and programmable network infrastructure that can adjust to shifting traffic patterns and optimize resource allocation, SDN can play a crucial role in the IIoT in 6G scenarios.

SDUAV-assisted Internet of Vehicles: The integration of vehicles such as UAVs, intra-vehicle, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-controller (V2C), vehicle-to-device (V2D), vehicle-to-UAV (V2U) with the communication networks are referred to as the IoV [148].

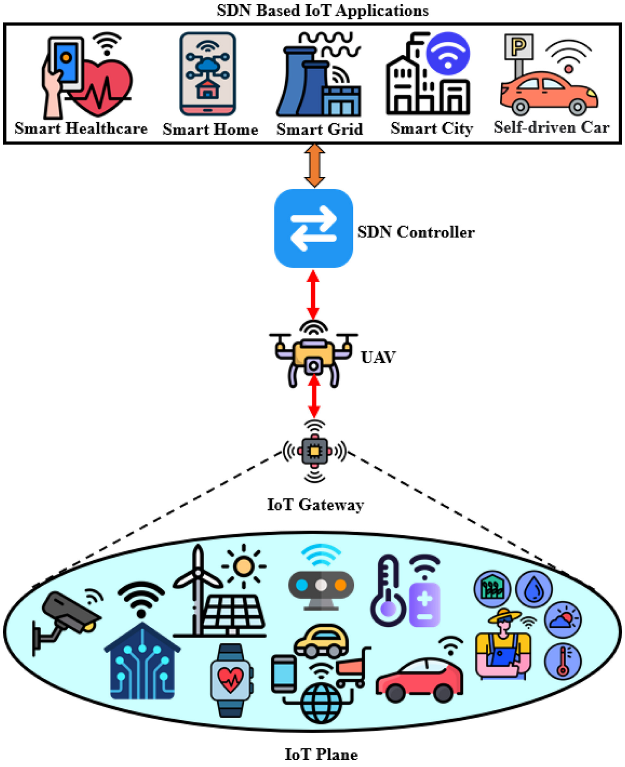

FIGURE 14. SDUAV-enabled IoT applications in 6G.

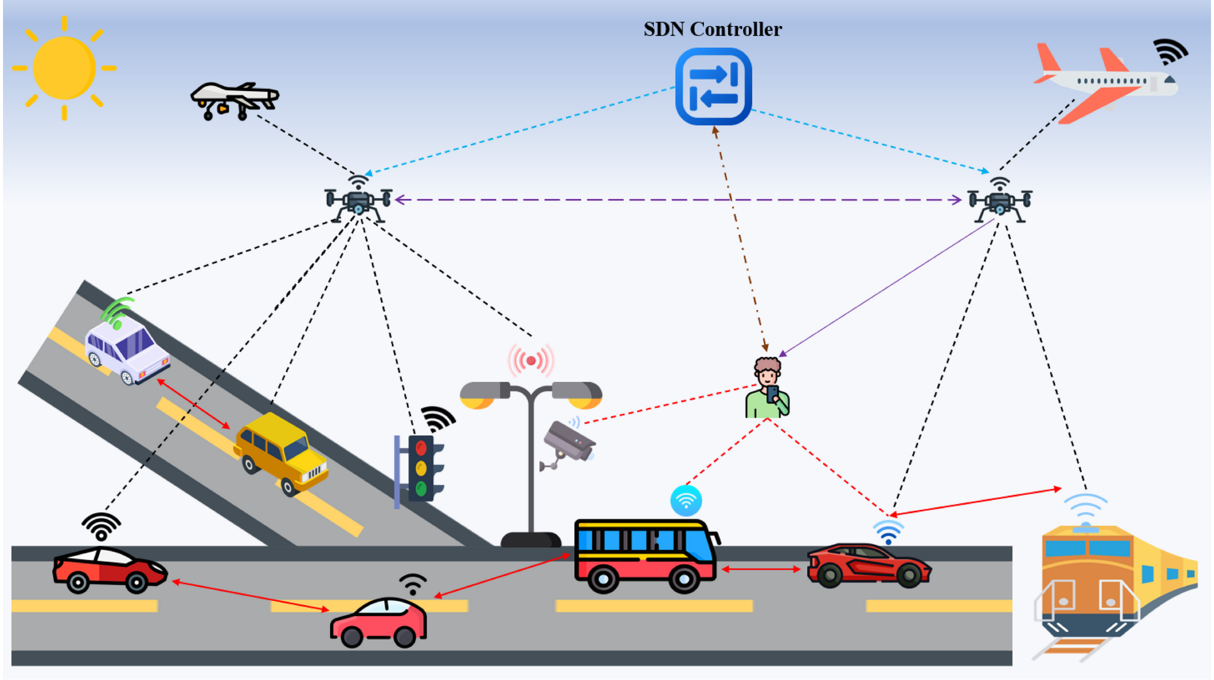

FIGURE 15. SDUAV-based IoV networks.

IoV network aims to create a seamless and intelligent transit system for different vehicles that can boost user experience, efficiency, and safety of the roads. The IoV has a wide range of applications such as traffic management, V2V and V2I communication, intelligent transportation systems, and autonomous driving. However, to support a large number of devices and provide low-latency, high-bandwidth connectivity, IoV networks need a reliable communication infrastructure. Wireless networks, cellular networks, OWC networks, and dedicated short-range communication networks are all can be a part of the IoV systems.

By allowing UAVs to interact with other vehicles and networked devices, as well as by providing real-time data and analytics, SDUAV networking can play a significant role in IoV [91], [149]. UAVs can be deployed to gather and send information about traffic and road conditions to other vehicles, enabling them to modify their routes and speeds in real-time. In addition, UAV networks can be used to spot accidents or unexplained vehicle traffic. Therefore, the integration of SDUAV networking with IoV can result in several performance enhancements. For instance, UAVs can assist in regions with limited ground-based infrastructure and sensors by filling in coverage gaps in the network. Furthermore, SDUAV's capacity to dynamically reconfigure its communication network may contribute to the maintenance of dependable and secure contact in IoV environments. Apart from these, the efficiency and capabilities of SDUAV networking can be enhanced by incorporating SDN principles which can open the door for the incorporation of other cutting-edge technologies, allowing for the development of more advanced and powerful UAV systems. SDN concepts enable UAVs to adapt to shifting network circumstances and improve communication performance, enabling the integration of cutting-edge technologies like edge computing and blockchain [148]. In comparison to conventional networking infrastructure, this can result in better network efficiency and decreased latency, making SDN a perfect networking solution for IoV to support the 6G services. A typical SDUAV-enabled IoV network is demonstrated in Fig. 15.

SDUAV-driven XR: To produce a more immersive and interactive experience, a variety of technologies are referred to as XR. This encompasses technologies for mixed reality (MR), AR, and VR. To enable real-time data transfer, XR applications need networks with high bandwidth, low latency, and dependability. A combination of wired and wireless networks such as WiFi, 5G, and 5G and beyond are needed to support XR applications [150]. The need for high-speed networks, low latency, and high bandwidth, which are not always available in conventional networking system, is one of the challenges and restrictions encountered by XR [151]. Furthermore, not all devices may have the high degree of processing power needed for XR devices.

By providing real-time data and analytics to enhance the functionality and performance of XR applications, SDUAV networking can play a significant part in XR. For remote monitoring and inspection of XR environments, such as building sites or factories, UAVs can be used, for instance, to gather and send data. In XR settings, UAVs also can be deployed for security and monitoring. SDUAV networking and XR integration may enhance efficiency in several ways. For instance, UAVs can assist in regions with limited ground-based infrastructure and sensors by filling in coverage gaps in the network. Furthermore, SDUAV's capacity to dynamically reconfigure its communication network can support the maintenance of dependable and secure contact in XR settings [152].

Integration of SDUAV networking framework with XR applications, therefore, can enhance the performance and capabilities of AR/VR platforms and facilitate the integration of various advanced technologies, allowing for the creation of more sophisticated and capable UAV systems for XR environments [153]. Besides, SDUAV networks can integrate cutting-edge technologies like MEC and AI by using SDN principles to adapt to changing network conditions and maximize their communication performance with a more robust and reliable network for XR applications.

SDUAV-based Internet of Everything: The Internet of Everything (IoE) refers to the integration of people, processes, data, and objects via the Internet. To enable seamless connectivity between different devices, and increase efficiency and productivity in various sectors, IoE can play a significant role [154]. IoE has many different applications like smart homes, smart cities, healthcare, logistics, and transit. However, to support multiple devices in 6G-enabled ultra-dense heterogeneous circumstances, IoE networks require high bandwidth and low latency. Besides, for the wide range of connected gadgets and data, the network infrastructure must be adaptable, scalable, and secure [155]. Hence, the challenges and limitations that IoE encounters with traditional networking infrastructure include network congestion, security concerns, and scalability problems.

IoE, interestingly, can be greatly benefited from the integration of the SDUAVs networks in many ways. Firstly, they can be deployed to gather information from far-off locations and send it back to the network for processing and analysis [156]. Moreover, they can serve as WBSs to extend wireless communication to places that are challenging to access with conventional infrastructure. This facilitates communication between IoE devices and data transmission to the cloud. The efficiency of information gathering, network coverage, real-time monitoring, control, and cloud-based data processing can all be enhanced by combining SDUAV networking with IoE [155]. Besides, the SDN framework can significantly enhance IoE networks' performance by providing dynamic and flexible network design and administration, reducing network complexity, and enhancing network security in 6G systems [157]. As SDN offers a more adaptable, secure, and scalable network architecture that is better suited to meet IoE requirements, it outperforms traditional networking in terms of networking platform and performance. Fig. 16 shows a typical SDUAV-enabled IoE scenario in 6G networks where the SDN controller plays the centralized role to coordinate the IoE elements like people, processes, data, and things and provides a robust networking framework.

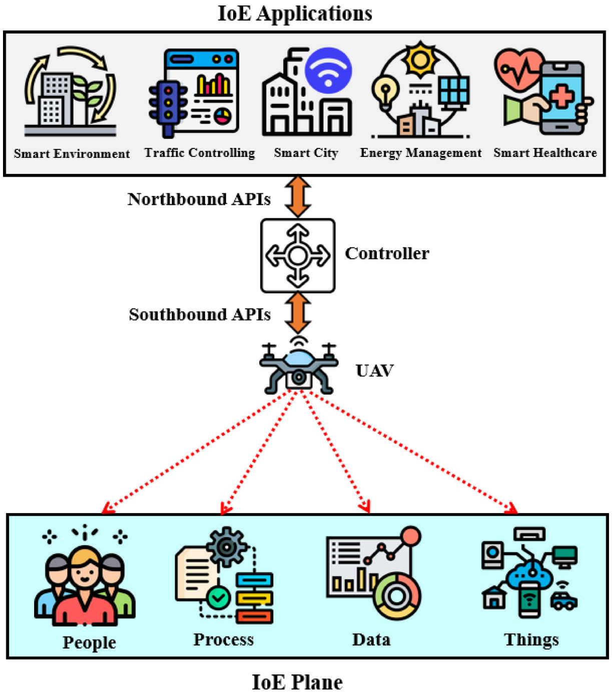

FIGURE 16. SDUAV-integrated IoE scenario.

SDUAV-empowered Industrial Revolution 4.0: The present trend of automation and information exchange in manufacturing and industrial operations is referred to as the fourth industrial revolution (IR 4.0). The IoT, cyber-physical systems, and the Internet of Services (IoS) are integrated with this IR4. Therefore, IR 4.0 seeks to develop "smart factories" that are more productive, adaptable, and customer-focused [158]. Besides, IR 4.0 has significant importance since it has the potential to revolutionize industrial and manufacturing processes, bringing about improvements in productivity, cost-effectiveness, and quality. Additionally, it makes it possible to create new goods and services and can promote commercial expansion. Some of the applications of the IR 4.0 applications are predictive maintenance, digital clones, self-driving robots, AR, and digital twins (DTs) [159]. These innovations depend on sophisticated networking and communication systems, including wireless high-speed networks and low-latency communication protocols. However, cybersecurity threats, data privacy concerns, and the need for a skilled workforce to run and keep the new technologies are among the challenges and limitations of industry 4.0.

SDUAVs can support IR 4.0 by adding features like routing, sensing, and monitoring in challenging locations, like offshore wind fields and oil rigs [160]. In smart factories, they also can be utilized to assist autonomous operations by enabling real-time analysis and control of production processes. By enabling enhanced network coverage, higher transmission rates, and improved network dependability, the

integration of SDUAV networking with IR 4.0 can enhance the performance of the automation processes in IR 4.0 [159], [160]. Moreover, to support the mMTC service in 6G systems, the integration of SDUAV networks with IR 4.0 also can play a vital role [161].

SDUAV-enabled smart healthcare and biomedical systems: The goal of advancements in smart healthcare and biomedical systems utilizing ICT systems is to improve not only the human quality of life but also human safety [162]. To improve patient outcomes, healthcare providers can now collect real-time data, remotely monitor patients, and make wise choices. Therefore, to send and analyze patient data, the networks and communication characteristics of smart healthcare and biomedical communication require high-speed, dependable, and secure connectivity. However, traditional networking infrastructure has several difficulties and constraints, including concerns about security, privacy, and scalability. Hence, to overcome such difficulties, the SDUAV networking framework can play a vital role by enabling real-time data gathering and analysis, reducing the need for physical infrastructure, and improving network flexibility and scalability [163], [164]. Besides, new 6G-enable opportunities and applications like remote medical delivery, search and rescue efforts, and catastrophe monitoring, may be made possible by the utilization of the SDUAV network in smart healthcare and biomedical communication. The effectiveness of smart healthcare and biomedical communication can be enhanced in several ways by incorporating SDUAV networking. For instance, UAVs with sensors and cameras can be used to track patients' vital signs, gather data in real-time, and notify medical personnel of emergencies [163]. As a result, patients may receive better care and experience quicker response times and early health issue detection. Additionally, SDUAV networking enables UAVs in smart healthcare and biomedical communication to better operate by allowing them to adapt to shifting network conditions and avoid network congestion [163], [164].

SDUAV-integrated connected robotics and autonomous systems: In recent times, the advancement of productivity, effectiveness, and safety in a variety of sectors such as manufacturing, healthcare, and transportation, depends on connected robotics and autonomous systems [165]. Hence, autonomous systems and networked robotics have a huge range of applications in 6G systems like assembly, quality assurance, and material handling. They can help with surgeries and give people care in the healthcare industry [166]. Moreover, they can be applied to autonomous cars, drones, and other transportation systems in the field of transportation. However, these autonomous systems may face challenges like latency, dependability, and scalability issues with conventional networking infrastructure.

The productivity of connected robotics and autonomous systems can be enhanced by integrating the SDUAV network which can offer real-time data processing, low latency communication, and dependable communication links [167]. Besides, to support the mMTC in 6G systems, an SDUAV network can handle these massive deployments effectively by offering remote monitoring and control. The low latency and high bandwidth of SDUAV networking also can improve the accuracy and speed of data collection, processing, and analysis [168]. Moreover, the ability to remotely monitor and control autonomous systems via the Internet can also improve the efficiency of these systems, reduce downtime, and lower operational costs [169]. Furthermore, the SDUAV approach can offer virtual network slices that can be customized to meet the specific communication requirements of different connected systems, and can also provide secure and reliable communication channels to protect the systems from cyber-attacks.

SDUAV-driven super smart society: "Super Smart Society" is a concept that aims to create a society that is highly interconnected through advanced technologies, resulting in more efficient and sustainable living [170]. In this regard, the SDUAV networks can play an important role in achieving this goal by providing connectivity and data communication between devices and systems [171]. In rural areas, UAVs equipped with SDN-enabled networks can provide vital communication links to areas that are not easily accessible by traditional means. At the same time, in urban areas, UAVs can provide communication and data transfer to assist in traffic management, infrastructure monitoring, and emergency response [172]. The integration of SDUAV networks can significantly improve the performance of these applications by providing high-speed data transfer, increased reliability, and improved network management. Furthermore, the use of SDN in UAV networks can help to optimize traffic flows, balance network loads, and provide security and quality of service guarantees. Therefore, the role of SDUAV networking is crucial to building a "Super Smart Society" which will be highly interconnected and sustainable [173].

SDUAV-enabled precision agriculture: Precision agriculture is an innovative form of farming management that uses information and technology to boost crop output and cut waste [174]. In the context of precision agriculture and farming, various applications like crop monitoring, precise spraying, yield estimation, and mapping can be achieved by the integration of SDUAV networks [175]. The UAVs equipped with sensors can collect data about crop health, growth, and water stress, and SDN can enable real-time processing and analysis of this data, enabling farmers to make quick decisions and optimize crop yield. To provide farmers with accurate yield estimates, SDN can automate the analysis of crop density and size data gathered by UAVs which can help the farmers to make better choices regarding the timing of harvests and the distribution of available resources. Using real-time mapping and analysis of high-resolution field maps made possible by SDN, farmers can pinpoint regions in need of particular resources and allocate them more effectively [176]. Hence, a combination of precision agriculture and SDUAV network can increase the effectiveness, accuracy, and efficiency of farming activities. Moreover, farmers can make better decisions and move more quickly with the guidance of SDN, which also enable real-time data processing and analysis, increasing crop yield and decreasing waste. A typical SDUAV-based smart agricultural and farming paradigm is demonstrated in Fig. 17.

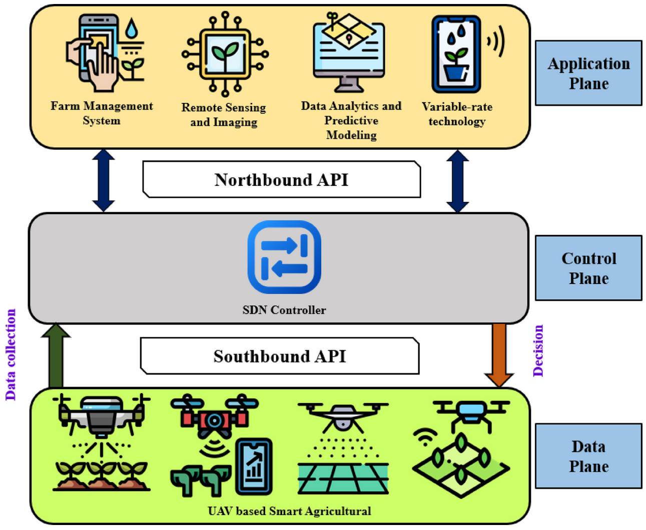

FIGURE 17. SDUAV-enabled smart agricultural.

SDUAV network for infrastructure inspection and maintenance: Regularly inspecting different kinds of infrastructure like bridges, buildings, and pipelines, to identify damage or possible problems and take appropriate action is regarded as infrastructure inspection and maintenance [177]. However, an SDUAV network can make infrastructure inspections safer, secure, and more efficient by employing UAVs equipped with cameras and sensors to collect data on the state of infrastructure. Through the provision of a dependable and adaptable wireless network that enables UAVs to communicate and share data effectively, the integration of SDN technology can enhance the performance of UAVs used for inspections [178]. By applying real-time data analysis techniques such as AI, machine learning algorithms, and big data analytics, SDUAV can enhance the accuracy, scalability, and reliability of this inspection process. By identifying the problems as early as possible, the deployment of SDN-enabled UAVs can ultimately improve the security and dependability of this approach.

SDUAV-based environmental monitoring and conservation: By employing technology to track and evaluate environmental factors and encourage the wise use of natural resources is known as "environmental monitoring and conservation" [179]. It enables more effective management of natural resources and environmental security. Applications of environmental monitoring and conservation include tracking wildlife populations, managing natural resources like forests and fisheries, forecasting and averting natural catastrophes and monitoring air and water quality.

To enable environmental monitoring and conservation, a dependable, low-latency network infrastructure is needed. It may be difficult for the traditional networking infrastructure to send large quantities of data due to issues with bandwidth limitations, poor coverage, and reliability in remote locations. By providing flexible and effective communication between sensors and data processing facilities, an SDUAV network can play a crucial role. UAVs with sensors can be programmed to gather data in off-the-grid locations, send data to a hub, and then return for upkeep or further deployment [180]. By allowing real-time data gathering and analysis, lowering downtime and increasing efficiency, and expanding the range and coverage of environmental monitoring and conservation efforts, the integration of the SDUAV network can enhance performance, scalability, and coverage.

SDUAV network-based military and defense operations: To defend a nation from threats and possible attacks, military and defense operations refer to the utilization of technology and strategic planning. It is substantial since it guarantees a country's and its citizens' safety and security [181]. In this field, combat, communication, logistics, surveillance, and reconnaissance are some examples of uses for military and security activities [181]. In military and defense operations, networks and communication characteristics usually require secure and reliable communication channels capable of handling large amounts of data in real-time. This covers mobile ad hoc networks, wireless mesh networks, and satellite transmission. An extremely secure, resilient, reliable, and environment-adaptive network infrastructure is required for military and defense activities.

However, traditional networking infrastructure in military and defense operations faces challenges and limitations such as signal interference, range limitations, and possible vulnerabilities in network security. By supplying capabilities for situational awareness, intelligence gathering, and reconnaissance in real-time, SDUAVs can be deployed into military and defense activities [182]. Additionally, the SDUAV system can supply chain administration, personnel and equipment transportation, and logistics. Hence, the integration of SDUAV networking with military and defense activities can enhance properties and performances like data processing speed, signal strength, enhanced tracking ability, improved reliability, and network security. By establishing reliable and secure communication between various fields like airborne, army, and navy networks, the UAV, acting as a WBS, can contribute to bettering operations. Fig. 18 illustrates a typical scenario where the SDUAV-based networks are employed in the military and defense operations.

SDUAV-assisted swarm robotics and UAV fleets: A collection of robots or drones that cooperate to complete a task is referred as swarm robotics or UAV fleet [183]. This technology has many significant impacts on the performance of the 6G systems as it can improve flexibility, scalability, efficiency, and safety to support the uMTC, uHDD, uMUB, and uHSLLC services. Swarm robotics and UAV fleets are used for military operations, environmental monitoring, agriculture, surveillance, and search and rescue tasks. In order to communicate with the BS, controller, and other robots and drones in swarm robotics and UAV groups, a strong, dependable, and scalable communication infrastructure is needed. Moreover, real-time data exchange, effective routing, and network resilience should all be supported by this architecture.

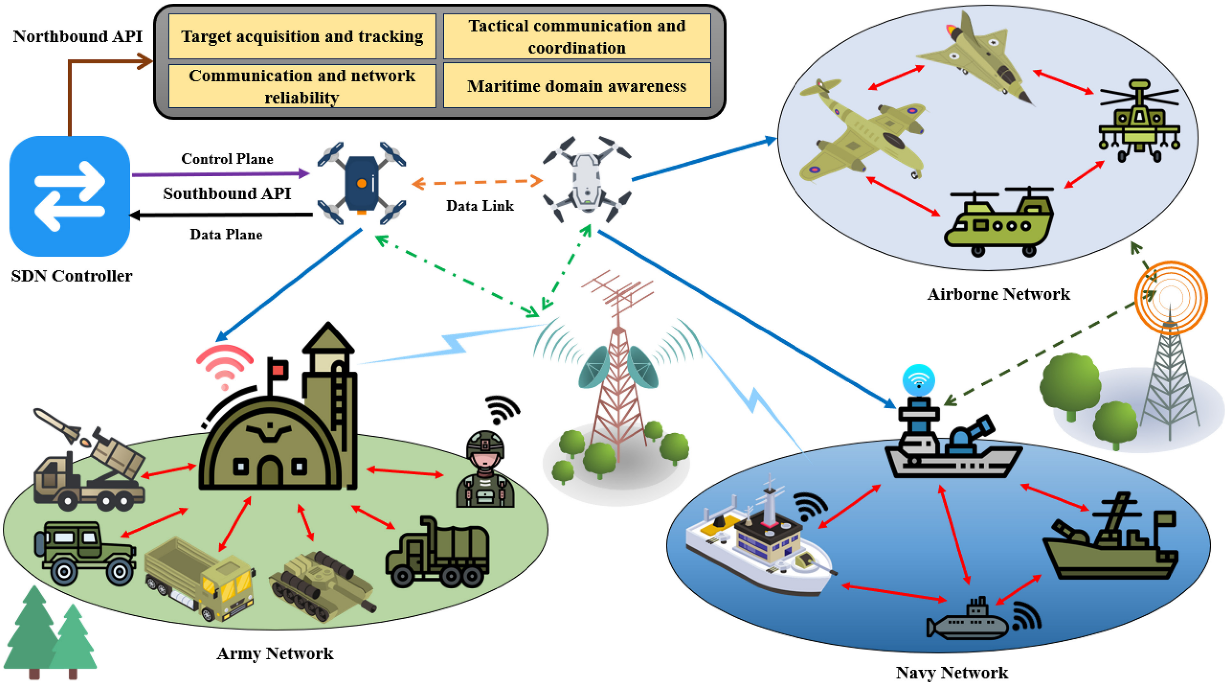

FIGURE 18. SDUAV-based applications in military and defense operations.

By offering a dynamic, adaptable, and programmable communication platform, SDUAV-based network can play a crucial role to enhance the performance of swarm robotics and UAV teams [183]. Besides, the coordination, collaboration, and communication between the robots or UAVs can be improved with the help of SDUAV networks,

This approach also enables adaptive and effective routing. By offering a mobile and adaptable communication infrastructure that can support the robots or UAVs in a variety of places and environments, UAVs acting as WBSs can also improve the performance of swarm robotics and UAV fleets. In swarm robotics and UAV fleets, SDN serves as a centralized and programmable control plane that can manage network resources, improve network performance, and maintain network security. Additionally, SDN can make it easier to integrate diverse networking technologies and allow the deployment of virtualized network services and functions. By providing a more flexible, scalable, and effective networking platform than conventional networking, SDN can play a more effective role to operate the swarm robotics and UAV fleets successfully.

SDUAV network-integrated wearable technology: Electronic devices worn on the body as an accessory or as part of clothing are referred to as wearable technology. Such devices typically gather information about the user's environment, biometrics, and physical activity before sending it to other gadgets or services for analysis [2]. Wearable technology has numerous applications, including health monitoring and exercise tracking as well as industrial and military use cases. Smartwatches, activity monitors, and VR headsets are a few examples of wearable technology that are commonly employed in the 6G scenarios. To send data to other devices or services, wearable technology devices typically utilize wireless communication protocols like Bluetooth, WiFi, or OWC networks. However, a potential problem with conventional networking infrastructure for wearable technology is that it might not be optimized for the low-power specifications of many wearable devices.

By offering low-power, high bandwidth wireless connectivity that is tailored for compact, battery-powered devices, SDUAVs can be of assistance [2]. The combination of SDUAV networking and wearable technology can enhance performance by allowing for faster, more reliable communication between devices, lowering latency, and increasing battery life. UAVs acting as WBSs are additionally helpful in extending network coverage to outlying or difficult-to-reach locations, making wearable technology more useful in broader variety of settings. Hence, to serve the 6G features like uMTC, uHDD, uMUB, and uHSLLC, the combination of SDUAV and wearable technologies can play a vital role.

SDUAV-assisted smart energy harvesting: Utilizing technological advances to gather and preserve energy from renewable resources like solar, geothermal, wave, and wind energy can be referred to as "smart energy harvesting." One of the most common applications of smart energy harvesting is powering various devices and systems such as smart homes, transportation networks, and industrial equipment. Depending on the particular implementation, the networks and communication features of smart energy harvesting systems can change. To transfer and control smart energy harvesting effectively in 6G communication systems, low-power wireless communication capabilities are typically required. The particular application and system size will determine the kind of network infrastructure required for smart energy harvesting. For instance, a small-scale residential energy harvesting system might only need a basic wireless network, whereas a larger-scale commercial energy harvesting system might need a network with more sophisticated communication tools. However, smart energy harvesting faces obstacles and is constrained by factors like high implementation costs, the unpredictability of green energy sources, and the demand for effective energy storage technologies.

To enhance the performance of these smart energy harvesting systems, the SDUAV networking concept can play a vital role. In addition, to monitor and analyze energy generation as well as energy consumption, SDUAV networks can be utilized too. It is possible to raise the effectiveness and efficacy of these systems by combining SDUAV networking with intelligent energy harvesting. Real-time monitoring, adaptive energy management, and increased energy output and storage are among the traits and abilities that can be improved. By offering a steady, high-bandwidth communication network that can support real-time data transmission and analysis, UAVs act as WBSs in 6G systems. As a result, SDUAV networks can enhance the performance of smart energy harvesting systems. To handle renewable energy sources efficiently and respond to shifting energy needs, smart energy harvesting relies on the flexible and scalable networking platform that SDN offers. Hence, by providing minimal network latency and downtime, SDN can outperform conventional networking in terms of efficiency, reliability, and security.

VIII. ENABLING TECHNOLOGIES FOR SDUAV NETWORKS

SDUAV networking is a key enabling technology that allows the integration and coordination between various advanced technologies in 6G networks. These include AI, machine learning, computer vision, and mesh networking. With SDN principles, UAVs can adapt to changing network conditions and optimize their communication performance, making it possible to incorporate these advanced technologies. The resulting SDUAV communication systems are capable of performing complex and sophisticated tasks in various industries, such as agriculture, logistics, surveillance, and more. Tables 7 and 8 address some of the recent works on SDUAV network where different types are advanced technologies are integrated with it. In addition, some of the enabling technologies and their different aspects are briefly discussed below.

AI: A computer system's ability to do functions that typically require cognitive ability such as speech recognition, decision-making, and language translation, has been termed as AI. Intelligence is one of the most essential attributes of 6G autonomous systems [184]. Consequently, AI is one of the most recent significant technologies to be deployed in 6G communication networks. AI-enabled 6G communication systems can unlock the complete potential of radio signals and facilitate the transition from CR to intelligent radio. The adoption of AI in 6G wireless communications will streamline and enhance real-time data transmission for SDUAV networks.

One of the primary aspects is machine learning, which utilizes statistical models and algorithms to provide machines with the ability to learn from data and make predictions or judgments without explicit programming. The development of machine learning opens up intelligent networking and novel opportunities for the 6G environment's SDUAV framework. Additionally, the utilization of machine learning may significantly reduce time-consuming processes like handover, routing, and network selection. In SDUAV networks, machine learning also can be deployed to enhance information processing and decision-making abilities as well as navigation and obstacle avoidance [185].

To increase accuracy and performance, deep learning, a subset of machine learning, involves modeling neural networks on massive volumes of data in 6G systems. In SDUAV networks, this can be employed to improve image and video processing as well as make more complex autonomous decision-making possible [186].

Natural language processing (NLP), a component of AI that allows computers to comprehend and analyze human language, is another crucial aspect of the technology. This is also useful in SDUAV networks for analyzing and comprehending data from various sources including social media and news feeds, as well as to improve communication between SDN controllers and UAVs [187].

Another aspect of AI that can be incorporated into SDUAV networks is predictive analytics. In order to anticipate future events or patterns in 6G environments, this process entails analyzing past data using techniques like data mining, machine learning, and others. Therefore, to enhance mission planning and decision-making, this can be employed in SDUAV networks [188]. Expert systems are an additional kind of AI that also can be implemented into SDUAV networks. These programs can be utilized in tasks like mission planning and risk assessment since they have been developed to replicate the abilities of a human specialist in a specific field to make decisions.

The ability for UAVs to make assessments in real-time based on input data and specified criteria is provided by autonomous decision-making which is another major component of AI [189]. To enable autonomous navigation, obstacle avoidance, and decision-making in challenging settings, AI-based approaches can be implemented in SDUAV networks. Hence, to enhance the capabilities, increase efficiency, and minimize the processing delays of SDUAV networks, AI offers a wide range of unique characteristics and autonomous decision-making features. Such possibilities could enhance SDUAV operations in terms of remote connectivity, signal processing, spectrum mapping, and signal mining.

Blockchain: Blockchain is a type of digital ledger that enables secure, open, and shared records of activities among the user in a network [190]. It is a decentralized system

TABLE 7. **Recent studies on advanced technologies that can enable SDUAV networks.**

Reference	Authors	Year	Contributions and research direction	Integrated technologies
[201]	Y. Gao *et al.*	2021	A blockchain-based data sharing framework is proposed for the IIoT that leverages SDN for pervasive edge computing.	SDN, IIoT, and edge computing
[202]	T. Alharbi	2020	A survey is presented on the deployment of blockchain technology in SDNs, discussing its benefits and challenges, as well as potential use cases.	SDN and blockchain
[203]	I. H. Abdulqadder *et al.*	2022	A secure network slicing method using blockchain in an edge-assisted SDN/NFV-6G environment is proposed that offers context-aware authentication handover.	SDN, NFV, 6G, and network slicing
[204]	J. Gao *et al.*	2019	A blockchain-SDN-enabled environment for the IoV is proposed which leverages fog computing and 5G networks for enhanced security and efficiency.	IoV, blockchain, SDN, and 5G
[31]	H. Cheng *et al.*	2021	A virtualized emulation environment is proposed which can utilize deep reinforcement learning (DRL) algorithms to generate and collect on battery-powered UAV networks.	UAV, 6G, DRL, and AI
[205]	P. K. Sharma *et al.*	2019	A fog-based blockchain cloud architecture for the IoT is developed that can utilize SDN to improve resource utilization and scalability.	SDN, IoT, fog computing, cloud architecture
[206]	J. Pie *et al.*	2020	A deep reinforcement learning-based approach for optimal VNF placement is proposed in SDN/NFV-enabled networks.	SDN, NFV, and VNF
[38]	A. Hermosilla *et al.*	2020	Security orchestration and enforcement issues are addressed in UAV deployments using NFV/SDN technology.	SDN, NFV, and UAV
[207]	Z. Lv *et al.*	2020	The interaction between edge and cloud computing based on SDN and NFV to support the next generation of IoT applications is proposed.	SDN, NFV, next generation IoT, and edge computing
[208]	Y. Cao *et al.*	2020	An AI agent-based approach for network service prediction and wireless resource scheduling optimization in SDNs is introduced.	SDN and AI
[209]	M. H. H. Khair *et al.*	2021	A machine learning-based approach for detecting and classifying conflict flows in SDN is proposed.	SDN and machine learning
[210]	Y. Zhao *et al.*	2019	A survey is conducted on the role of machine learning in SDN concepts and architecture.	SDN and machine learning
[211]	J. Diaz *et al.*	2020	A flexible SDN-based architecture is developed for identifying and mitigating low-rate DDoS attacks using machine learning techniques.	SDN and machine learning
[212]	D. Kaur *et al.*	2018	A tensor-based big data management scheme for dimensionality reduction in smart grid systems from an SDN perspective is presented.	SDN and big data
[201]	P. Qin *et al.*	2015	The trends of using bandwidth-aware scheduling with SDN in Hadoop for big data processing are addressed.	SDN and big data
[213]	Y. Cui *et al.*	2017	An SDN-based approach for big data caching in ISP networks is proposed.	SDN, big data, and ISP
[214]	A. A. Z. Ibrahim *et al.*	2020	A heuristic algorithm for placing controllers in multi-control 5G networks using the SDN/NFV architecture is presented.	SDN/NFV and 5G
[215]	A Betzler *et al.*	2019	An SDN wireless backhaul solution for 4G/5G small cell networks is proposed that can improve network performance and simplify network management.	SDN and 4G/5G

that uses a network of computers to keep the ledger's integrity through consensus methods. In blockchain technology, blocks of data must be created and connected using cryptographic methods. Each block has a set of operations in it that the network of users must approve before adding the block to the line of preceding blocks. As a result, a permanent and unchangeable record of every network activity is produced [191].

To manage massive quantities of data and information in 6G's incredibly dense heterogeneous networks, blockchain technology is crucial. To achieve the goal of uHDD, mMTC, and uHSLLC services, blockchain technology can offer features like cross-device interoperability, traceability of massive data, autonomous interconnections between different connected devices, as well as dependability for massive connectivity of 6G networks. By providing better

TABLE 8. Recent studies on advanced technologies that can enable SDUAV networks (continue).

Reference	Authors	Year	Contributions and research direction	Integrated technologies
[216]	E. Coronado *et al.*	2019	An SDN platform for 5G radio access networks (RANs) named 5G-EmPOWER is proposed that enables efficient and flexible network management and resource allocation.	SDN, 5G, and RANs
[217]	C. Vagionas *et al.*	2023	An SDN-controllable mmWave fiber-wireless 5G X-haul network for real-time service provisioning is developed.	SDN, 5G X-haul network, and mmWave
[218]	H. Cao *et al.*	2021	A resource allocation approach is proposed for 6G networks which can utilize softwarization and virtualization to tailor network slices to meet specific performance and resource requirements.	Network slicing, SDN, and 6G
[219]	F. Chiti *et al.*	2022	A distributed quantum computing architecture, as well as entanglement-based quantum key distribution services, are proposed for the SDN-enabled UAVs.	Quantum computing, SDN, and UAV
[220]	A. Aguado *et al.*	2017	A time-shared approach is designed as a cost-effective solution for practical deployment.	Quantum technology, SDN, NFV, and optical network
[221]	H. Abulkasim *et al.*	2022	A quantum-based scheme to prevent unauthorized drones from accessing a specific flight zone is proposed.	Quantum technology and the Internet of Drones
[222]	L. Ge *et al.*	2020	The IRS-aided UAV communication system is presented with a cooperative optimization of the UAV's trajectory and passive phase shifts of reflection elements.	IRS, UAV, and DRL
[223]	Q. Qiu *et al.*	2020	A technique of channel selection is provided for the SDUAV swarm network.	Swarm intelligence, SDN, and UAV
[183]	F. Alsolami *et al*	2021	A synchronization precision method is proposed that can predict the UAV location estimation.	Swarm intelligence, SDN, and drone network
[49]	L. Zhu et al.	2023	A traffic flow optimization technique for UAVs in multi-layer information-centric SD-FANET is presented.	SD-FANET, cloud computing, queueing model, and UAV
[224]	C. Lin *et al.*	2021	An SDN-based UAV network is provided which can serve as MEC nodes.	MEC, SDN, and UAV
[195]	F. Luo *et al.*	2019	A big data-integrated cloud-based UAV network is designed.	Big data, cloud computing, and UAV
[196]	R. Zhang *et al.*	2021	A UAV-based data transmission protocol is presented for V2X networks integrated with proactive caching.	Proactive caching, UAV, and V2X
[197]	X. Xu *et al.*	2018	The endurance challenges associated with UAV-enabled communications with proactive caching are addressed.	Proactive caching and UAVs
[225]	M. Channegowda *et al.*	2013	The possible optical transport technologies are addressed by integrating the SDN and OWC.	OWC and SDN
[226]	W. Bouachir *et al.*	2019	A supervised detection-based counting technique for determining the number of planting microsites on a mechanically prepared block is outlined for UAVs.	Computer vision and UAV
This paper			The vision, design goals, architecture, and networking approaches for the SDUAV communications network are discussed to support the 6G requirements. In addition, the expected utilization of different networking and communication technologies, as well as the method of interaction and its requirements, are addressed in 6G scenarios.	SDN, UAV, SDUAV, and 6G

security, confidence, autonomy, traceability, coordination, and decision-making, blockchain, on the other hand, also can help the SDUAV systems [190], [191]. By using blockchain, it is possible to secure the information exchanged between UAVs and SDN controllers while avoiding unwanted access to 6G networks from attackers. In addition, smart contracts which are self-executing contracts with the conditions of the agreement between the parties written in code, can be made possible by blockchain. This technology also can be helpful in network administration and control by automating tasks like task delegation to UAVs, resource management for the network, and network security, [192]. Furthermore, Blockchain's distributed nature not only eliminates the single point of failure issue in SDUAV networks but also strengthens the decentralized tamper-resistance and confidentiality, revealing possibilities to make it compatible with many different kinds of 6G system applications [192].

By enabling more effective and secure communication between UAVs and SDN controllers, lowering network complexity, enhancing 6G networks scalability, and improving overall UAV network performance, the integration of blockchain and SDN has the potential to improve SDUAV networking performance. Hence, more effective and secure UAV-based autonomous applications and services for 6G networks can be deployed in a variety of fields including agriculture, monitoring, and emergency wireless network coverage.

Big data analytics: Big data refers to extremely large datasets that are too complex and voluminous to be processed by traditional data processing applications. The information can be organized, unstructured, or semi-structured and originates from a variety of places such as sensors, social media, videos, and images [193]. The fundamental idea behind big data is to collect, store, analyze, and present data in a meaningful manner to generate insights and influence decision-making. Consequently, this technology can be extensively applied in 6G systems for handling an extensive amount of data. E2E delay reduction in 6G wireless systems is one of the prominent applications of big data analytics.

To increase network performance by enhancing data processing skills, big data can be integrated with SDN-enabled UAV networks. By using big data technologies to process the massive volumes of data collected by UAVs, useful insights can be obtained in real-time that can be utilized to enhance network management and control, increase security, and optimize performance. For instance, big data analytics can be used to analyze the information gathered by UAV sensors to spot trends, spot anomalies, and extract helpful data that can be used to improve network performance. Besides, big data can be utilized to maximize network resources, avoid congestion, and enhance service quality by forecasting network traffic and demand [193]. By examining network traffic patterns and spotting suspicious activity in SDUAV networks, big data also can detect security threats and vulnerabilities in 6G communication systems. Additionally, it can be employed to spot possible network issues or failures and take preventative action before they materialize. Thus, big data integration with SDUAV networks has the potential to improve the 6G network's efficiency, security, and dependability while also helping to optimize overall network performance [194].

Cloud computing: Cloud computing is a model of computing where computing resources such as servers, storage, applications, and services are delivered over the Internet on a pay-per-use basis. In other words, cloud computing provides on-demand access to a pool of shared resources that can be rapidly provisioned and released with minimal management effort [46]. The working principle of cloud computing is based on the concept of virtualization where physical resources are abstracted and presented as logical resources to users. Hence, cloud computing providers typically use virtualization technology to create a pool of resources that can be shared across multiple users or tenants in 6G environments. These resources can be managed by the cloud provider who ensures that the resources are available and secure for 6G services like mMTC, uMUB, uHSLLC, and uHDD.

By utilizing cloud-based services to provide computing resources for SDUAV operations, cloud computing can be linked with SDUAV networks [195]. At first, cloud-based services can be employed to provide storage, computing power, and real-time data analytics for SDUAVs. Without the requirement for local infrastructure, SDUAV networks can access resources on-demand by utilizing cloud computing. At the same time, the SDUAV network's operation can be supported by additional computing resources due to the scalability of cloud computing [195]. Besides, cloud computing's cost-effectiveness could help in minimizing the overall cost of maintaining the SDUAV-assisted 6G networks. On the other hand, cloud computing's dependability and accessibility can guarantee that the SDUAV network has access to the resources it needs to function properly. Furthermore, the adaptability of cloud computing can enable SDUAV network operators to keep an eye on and control the network from a distance. Consequently, cloud computing can significantly enhance SDUAV-based 6G networks by enhancing their efficiency and performance [46], [195].

Proactive caching: Proactive caching is a technique that seeks to improve content delivery performance by pre-storing commonly accessed data in caches before it is requested [196]. In other words, proactive caching prepares content for the cache in advance of user demand so that it can be rapidly retrieved and provided to the user. Surprisingly, this recent innovation can work by anticipating the future demand for material and proactively storing it in caches. This forecast is supported by statistical models and past access trends. When a user asks for material that is cached, it can be quickly delivered without having to be retrieved from the source.

One of the major challenges for 6G is the massive deployment of small cell networks, which will considerably improve network capacity, coverage, and mobility management. Due to this, the BSs will experience massive downlink traffic congestion in 6G environments. To improve user quality of experience and reduce access delay and traffic offloading to achieve uMUB, uHSLLC, and uHDD services for 6G, proactive caching has become an imperative solution. Therefore, from a communication and networking standpoint, proactive caching is crucial because it can lower the latency and bandwidth for content distribution. Pre-storing content in caches allows for fewer data to be transmitted over the network, which speeds up content distribution and eases network congestion. Integrating proactive caching with an SDN-enabled autonomous UAV network can provide several advantages. For instance, proactive caching can lower the latency and bandwidth needs for content distribution, which is especially beneficial for real-time applications like video streaming and remote sensing [197]. By reducing dependence on the content's initial source, proactive caching can also increase the network's robustness. Furthermore, proactive caching can make it easier for UAVs to access commonly used content swiftly and effectively, enhancing their operational efficiency. As a result, proactive caching can be integrated into an SDUAV network to enhance the 6G network's performance by lowering latency and bandwidth needs, enhancing network resilience, and enhancing operational effectiveness [196], [197]. This could result in the more effective and efficient use of UAVs in various applications and services in 6G systems like aerial surveillance, crisis response, military services, and precision agriculture.

MEC: The near-real-time synthesis of massive volumes of information generated by edge devices and applications located closest to where it originates is known as MEC. As the 6G system is anticipated to offer a simultaneous wireless connection that will be 1000 times faster than 5G, MEC minimizes latency in 6G networks by integrating compute capabilities into the network, which is closer to the end users [198]. To enable the MEC functions, computing tools like servers and storage must be placed at the network's edge usually at BSs or APs. A central controller in charge of managing these resources is also responsible for managing the edge device applications. Thus, MEC is significant from a networking and communication point of view as it has the potential to enhance the performance of data-intensive applications by minimizing the latency and bandwidth requirements.

MEC can offer several advantages to the SDUAV networks. By integrating MEC with the SDUAV framework, an SDUAV network can adapt to shifting computational and storage demands in ultra-dense heterogeneous networks in 6G environments [199]. To minimize the processing time, and provide real-time response for SDUAV networks, MEC can enable features like big data analytics and image processing at the edge of the 6G networks. Besides, MEC also can allow UAV operators to view their UAVs and information from any location with a connection link, which can enhance the operational flexibility and effectiveness of the UAVs. As a result, UAVs can be deployed more effectively and efficiently in ultra-dense heterogeneous networks to support the uMUB, uHSLLC, mMTC, and uHDD services in 6G. Therefore, integrating the MEC with an SDN-enabled UAV network can enhance network performance by offering scalable and flexible resources, facilitating the creation and implementation of UAV applications, and enhancing operational effectiveness. A typical MEC-enabled SDUAV network is illustrated in Fig. 19.

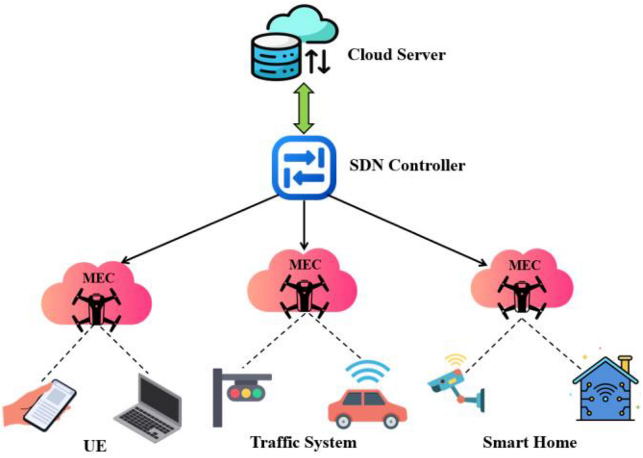

FIGURE 19. MEC technology for SDUAV networks.

Massive MIMO: Massive MIMO is a wireless communication technique that makes use of a significant number of BS antennas to boost the capacity and dependability of wireless networks [85]. The foundation of massive MIMO is spatial multiplexing which enables numerous users to send and receive the data concurrently while utilizing the same frequency bands. In massive MIMO, each of the multiple beams created by these antennas can be pointed at a different user or collection of users. The BS can separate the signals from each user and broadcast them concurrently over the same frequency band by using sophisticated signal processing algorithms [85]. Therefore, massive MIMO is essential in communication and networking because it can greatly increase wireless network capacity and coverage while reducing interference and improving energy efficiency. To enable uHSLLC, mMTC, uHDD, and uMUB functions in the 6G system, this massive MIMO technology will be crucial. Utilizing massive MIMO technology is a key strategy for improving spectral efficiency [200].

Due to demands for higher frequencies, enhanced spectral and energy efficiency, as well as increased transmission speeds, massive MIMO can be included in 6G systems. Besides, these features are also crucial for UAV networks where robust communication links and high bandwidth are necessary for secure and effective operations. By using SDR technology to regulate the antennas and beams at the BS, massive MIMO can be combined with an SDN-enabled UAV network. As a result, it will be possible to design a wireless network that is fluid and adaptable and can change along with the network and the traffic. An SDUAV network can increase network efficiency and reliability by utilizing massive MIMO to create high-bandwidth, low-latency communication links between the UAVs and SDN controllers [201]. With real-time data processing and high-speed data transfer, this can allow new and creative applications like remote sensing, environmental monitoring, and super-smart city. Thus, the combination of massive MIMO with the SDUAV network can certainly improve network performance and efficiency while opening up new and creative applications that can raise the security and efficiency of UAV operations.

NFV: NFV is a technology that enables network functions to be delivered as software applications on virtualized infrastructure as opposed to depending on specialized hardware devices [204]. Without the need for pricey hardware upgrades, it offers a flexible and agile approach to networking that enables service providers to quickly roll out new services and make modifications to their networks [206]. The unique capabilities offered by NFV can be employed to enhance the performance of SDUAV networking in a wide range of manners like virtualization, resource optimization, service chaining, scalability and reliability, flexibility and agility, and cost savings [214].

To make optimum utilization of hardware resources in 6G systems, virtualization enables the establishment of virtual network functions (VNFs) and virtual machines (VMs). In addition, NFV technology enables billions of devices to be connected on a single physical platform. To assure flexibility, reconfigurability, and programmability, the virilization feature is an essential aspect of the design process for 6G networks. When it comes to SDUAV networking, virtualization, on the other hand, can create virtualized network functionalities that can be installed on various UAVs based on the mission and task that are needed [35].

Another NFV aspect, resource optimization, employs dynamic resource allocation and de-allocation based on the load and demand of the network to benefit SDUAV networking to enable the services like uHSLLC, mMTC, uHDD, and uMUB for 6G. By accomplishing this, it is possible to guarantee effective resource utilization and enhanced network performance. At the same time, service chaining is an NFV feature that enables the deployment of numerous VNFs in succession to carry out a certain operation. As data travels from the UAVs to the GCS, service chaining in the context of SDUAV networking can facilitate the development of a series of VNFs that carry out certain tasks including data processing, encryption, and authentication [35]. Another crucial aspect of NFV that can enhance the efficiency of SDUAV networking is scalability [203]. By permitting the dynamic allocation and de-allocation of resources, NFV ensures that the network can accommodate a variable number of UAVs and can be scaled up or down as needed. This can ensure that the network is always accessible and can deliver trustworthy. An additional factor of NFV that can help SDUAV networking is flexibility and agility. By providing the on-demand deployment of new VNFs, NFV allows the network to adapt to changing mission requirements and accommodate new applications and services. Another significant advantage of NFV for SDUAV networking is cost reduction. The entire cost of network deployment and operation for 6G can be decreased by utilizing hardware resources efficiently, dynamically allocating resources, and deploying VNFs on demand [208].

Quantum technologies: To develop novel and effective information processing and transmission technologies, the study and application of quantum mechanics phenomena and principles are known as quantum technologies [220]. In the context of communication and networking, quantum technologies can be employed to create network architectures and secure routes for communication that can fend off cyberattacks and different kinds of security risks. Interestingly, the convergence of quantum computing, quantum communications, quantum machine learning, and communication systems are regarded as key enablers of 6G. To provide strong security against various kinds of cyber-attacks in 6G systems, these quantum technologies can be deployed. Due to the superposition characteristics of qubits, quantum technologies may enhance the throughput of 6G networks.

The fundamental ideas of quantum physics, such as superposition, entanglement, and measurement, serve as the foundation for quantum technologies' operation. Qubits, which can simultaneously represent information in numerous states, are made using these principles. Unlike classical bits, which can only have a value of either 0 or 1, qubits can exist in a superposition of both values simultaneously. Quantum communication utilizes these qubits to communicate information in a method that is immune to interception or eavesdropping as any attempt to intercept or view the qubits will cause them to change their state and render the information meaningless [220].

Similarly, by offering a safe and effective method of data transmission between the UAVs and SDN controllers, quantum technologies can be combined with SDN-enabled UAV networks to support the 6G features. The unique functions offered by quantum technologies such as quantum key distribution (QKD), quantum cryptography, quantum teleportation, quantum computing, and quantum sensors can be utilized to improve the security, dependability, and effectiveness of SDUAV networks in several domains including secure communication, routing optimization, and environmental sensing [219]. Firstly, QKD is one of the most promising quantum technologies. With the use of QKD, two parties can construct a shared secret key without worrying about being intercepted or eavesdropped [221]. When it comes to SDUAV networks, where secure and reliable communication is fundamental, this capability can be especially helpful. Similarly, SDUAV networks can use quantum cryptography which is another potential quantum technology. To guarantee the secrecy and integrity of transmitted data, this technology makes advantage of quantum mechanical concepts. It guarantees an exceptionally high degree of privacy that cannot be easily breached by conventional hacking techniques by utilizing quantum keys and protocols [220]. Moreover, quantum teleportation is a form of quantum technology that supports the transfer of quantum states between two faraway sites without the information being physically transferred. For the transmission of entangled qubits and other quantum states for use in quantum computing and communication in SDUAV networks, this capability can be advantageous [221].

At the same time, it is possible to solve complicated computational problems in 6G which are challenging for classical computers using quantum computing, a fast-developing field of quantum technology. Apart from this, quantum sensors are such technologies that utilize quantum technologies to precisely and sensitively detect and quantify physical quantities like temperature, magnetic fields, and pressure. To detect and keep track of environmental factors including air pressure, temperature, and humidity, these sensors can be utilized in SDUAV networks to enhance the overall performance of the 6G networks.

Intelligent reflecting surfaces: IRS is an advanced innovation that seeks to enhance 6G wireless communication by reflecting signals in the desired directions [222]. An IRS is simply a planar collection of passive reflecting components that can modify the amplitude and phase of incoming electromagnetic waves. With the help of a control, an IRS can amplify and reflect the signal in a particular way to increase the signal-to-noise ratio. The idea of positive interference serves as the foundation for how an IRS operates. When an electromagnetic wave reacts with an IRS, the reflected electromagnetic wave will combine with the incident wave to intensify the signal in that direction. The phase shift and amplitude of each reflecting element which defines the direction and power of the reflected wave, are adjusted to control the IRS.

There are several advantages to integrating the IRS with an SDN-capable autonomous UAV network in 6G environments. As SDUAV networks require an adaptable and efficient technique of managing network resources, the IRS can assist them by providing adaption capabilities for changing 6G wireless circumstances [227]. Moreover, IRS can enhance coverage in locations where the signal is feeble or obstructed by objects. By reflecting the signal away from the interfering devices, an IRS also can lessen disturbance from other wireless devices in 6G [222]. Even, the IRS can increase network bandwidth by focusing the signal on specific areas with high demand. Besides, adding the IRS-based SDUAV framework can enhance the overall 6G network's efficiency by expanding coverage, minimizing interference, and raising capacity. Therefore, the IRS-assisted approach not only can improve the U2U and U2C communication but also can provide more practical and efficient utilization of UAVs across a wide range of prospects in 6G communication scenarios.

Fog computing: To move computing power closer to the edge of the 6G networks where data is being created and processed, fog computing can be employed which is considered an advanced form of cloud computing [228]. Fog computing operates on the premise that computing resources such as servers and storage should be placed at the network's edge, near the gadgets and sensors that are producing the data. As a result, data handling can be done more swiftly and effectively with lower latency and better security. The ability for devices to handle data locally rather than having to send it back and forth to the cloud makes fog computing crucial from a communication and networking standpoint. The amount of data that needs to be transmitted over the 6G networks can be decreased as a result, and applications that require real-time processing also can experience faster response times.

By placing fog nodes at the edge of the 6G network and near the UAVs, fog computing can be integrated with SDN-assisted UAV networks [228]. The efficiency and capabilities of the UAVs can be enhanced due to the faster and more effective processing of data like video streams and sensor data. Moreover, fog computing also allows a more distributed and localized data processing approach which can lighten the load on the central SDN controller and help to optimize network efficiency in SDUAV-enabled 6G networks. As a result, UAVs can be able to operate more quickly and effectively by reducing latency and increasing network scalability [228]. Therefore, the integration of fog computing with SDN-enabled UAV architecture can help to enhance the capabilities and performance of the 6G networks by enabling the UAVs to operate more effectively and efficiently in ultra-dense heterogeneous environments.

Computer vision: Computer vision is an area of AI and computer science that aims to give computers the ability to interpret and comprehend visual information from their surroundings [226]. It involves developing algorithms and systems that can decode, interpret, and evaluate pictures, videos, and other visual data. In order to analyze and understand visual data in 6G networks, computer vision utilizes mathematical models and machine learning algorithms. To accomplish this, images or video frames must first be processed to detect patterns, objects, and characteristics before any pertinent information can be extracted.

By utilizing the wide range of capabilities that are provided by computer vision, SDUAV networks' performance can be optimized to support the 6G systems [228]. One of the most promising features of computer vision is object detection and recognition which makes use of computer vision algorithms to instantly find and identify items. This function allows SDUAVs to navigate through obstacles, avoid collisions, and detect targets. Similarly, facial recognition is another crucial component of computer vision that can be applied to identification and tracking, making it particularly helpful in surveillance and security applications in 6G scenarios. Additionally, computer vision can offer the feature of gesture recognition which enables the control of UAVs without the need for direct control. To give the SDUAV operators more information, computer vision additionally has the potential to develop AR experiences [226]. In remote control and inspection applications, this functionality can be quite useful. In addition, computer vision algorithms can be utilized to conduct visual inspections of buildings, machinery, and IIoT. This is particularly helpful in maintenance and inspection applications where the SDUAV can be used to investigate difficult-to-reach regions. Computer vision, therefore, offers SDUAV networks more situational awareness, better navigation and control, and improved inspection and maintenance capabilities to support the 6G requirements [228].

OWC technology: OWC is a communication technology that utilizes light to transmit data wirelessly through the air [2], [229]. It involves the transmission of signals over a distance, usually, several kilometers using laser or LED sources between two or more points. The technique can be applied to building-to-building links, aircraft-to-ground communications, and inter-satellite links among other things in ultra-dense heterogeneous 6G networks [229]. With a direct LOS between the transmitter and receiver, OWC networks are usually point-to-point or point-to-multipoint systems. The communication features of OWC include secure connectivity, high bandwidth, minimal latency, low interference, and transmission rates [2].

The effectiveness, reliability, and productivity of SDUAV networks can be significantly enhanced by utilizing the advantages of OWC techniques [225]. For 6G communication systems, OWC technologies can offer several features for SDUAV networks. OWC can enable high data rates, minimal jitter and latency, immunity to electromagnetic interference, increased bandwidth accessibility, enhanced safety, and infrastructure flexibility [229]. These positive aspects will ensure real-time responses, dependable connectivity in challenging locations, support for applications that require massive amounts of data, improved security and privacy, and adaptable network configurations which are required for SDUAV systems. As a result, in the era of 6G communication systems, this combination of SDN, UAV technology, and OWC produces an effective ecosystem that can be driven for more sophisticated 6G services and features like seamless connectivity, and superior user experiences. Therefore, by offering an adaptable and flexible network architecture, OWC technologies can improve the performance of SDUAV networks, and the incorporation of SDN can offer a more effective, reliable, and scalable networking platform for 6G systems to support the uMUB, uHSLLC, mMTC, and uHDD services.

Swarm intelligence: Swarm intelligence is a branch of AI that models the collective behavior of decentralized, self-organizing systems such as insect colonies or bird flocks to solve complex problems [223]. The principle behind swarm intelligence is that the collective behavior of a group of individuals can result in emergent intelligence that is greater than the sum of its parts. Swarm intelligence algorithms are based on simple rules that govern the behavior of individual agents, such as ants or bees, and the interaction between them. These rules are used to create a distributed network of agents that can work together to solve a problem or achieve a goal. From a communication and networking perspective, swarm intelligence can be employed to optimize the 6G network performance by creating a self-organizing network of devices that can adapt to changing conditions and traffic patterns in ultra-dense heterogeneous networks. This can improve network efficiency, reliability, and scalability while reducing the need for centralized control [183], [223].

Swarm intelligence can be integrated with an SDUAV network by using distributed algorithms to manage the resources and traffic flow in the 6G networks. This can enable the creation of a self-organizing network of UAVs that can work together to achieve a common goal like search and rescue or package delivery. Swarm intelligence algorithms also can be utilized to optimize UAV flight paths and resource allocation based on real-time data and feedback from the network. This can improve network performance and efficiency while reducing the risk of collisions or other safety hazards [183]. Hence, integrating swarm intelligence with an SDN-enabled UAV network can boost network performance, efficiency, and reliability while enabling new and innovative applications in the 6G environment such as autonomous swarm operations and collaborative search and rescue missions.

Fig. 20 depicts the enabling technologies which can improve the overall performance of the SDUAV communication system. In addition, Table 9 contains an overview of all the possible emerging technologies under various SDUAV functions.

IX. EMERGING COMMUNICATION AND NETWORKING TECHNOLOGIES FOR SDUAV NETWORKS

To provide a dependable and effective networking infrastructure in the 6G systems, especially in ultra-dense heterogeneous networking contexts where SDUAVs can be deployed alongside different aircraft, smooth and seamless connectivity with different networks is very crucial. The interaction of the SDUAV networks with different types of communication and networking approaches not only enables an uninterrupted handover mechanism but also provides a chance to utilize the advantages of the other networks. Some of the most important interactions between the SDUAV networks and various types of communication and networking are briefly discussed below.

A. EMERGING NETWORKING TECHNOLOGIES FOR SDUAV NETWORKS

Interoperability with diverse networking technologies is an essential requirement for SDUAV networks to operate effectively and reliably in complex and dynamic circumstances. SDUAVs can communicate with various networking systems and gain from each system's advantages, such as cellular networks' high data rates or satellite networks' long-range communication abilities. Additionally, by providing redundancy and backup communication pathways in case of network failures or disturbances, interfacing with various emerging networking systems also can contribute to the stability and resilience of the SDUAV networks. The linkages of SDUAV networks with some of the most contemporary networking architectures are discussed below.

Long-Range Low-Power Networking: A long-range low-power (LoRa) is a wireless communication technology that requires relatively small energy to transmit data across long distances [230]. The LoRa network is made up of gateways, end devices, and a network server. LoRa can provide long-distance data transmission that can travel up to three miles or five kilometers in urban areas and up to 10 miles or 15 kilometers and more in rural regions while using relatively small power. However, For the long-range

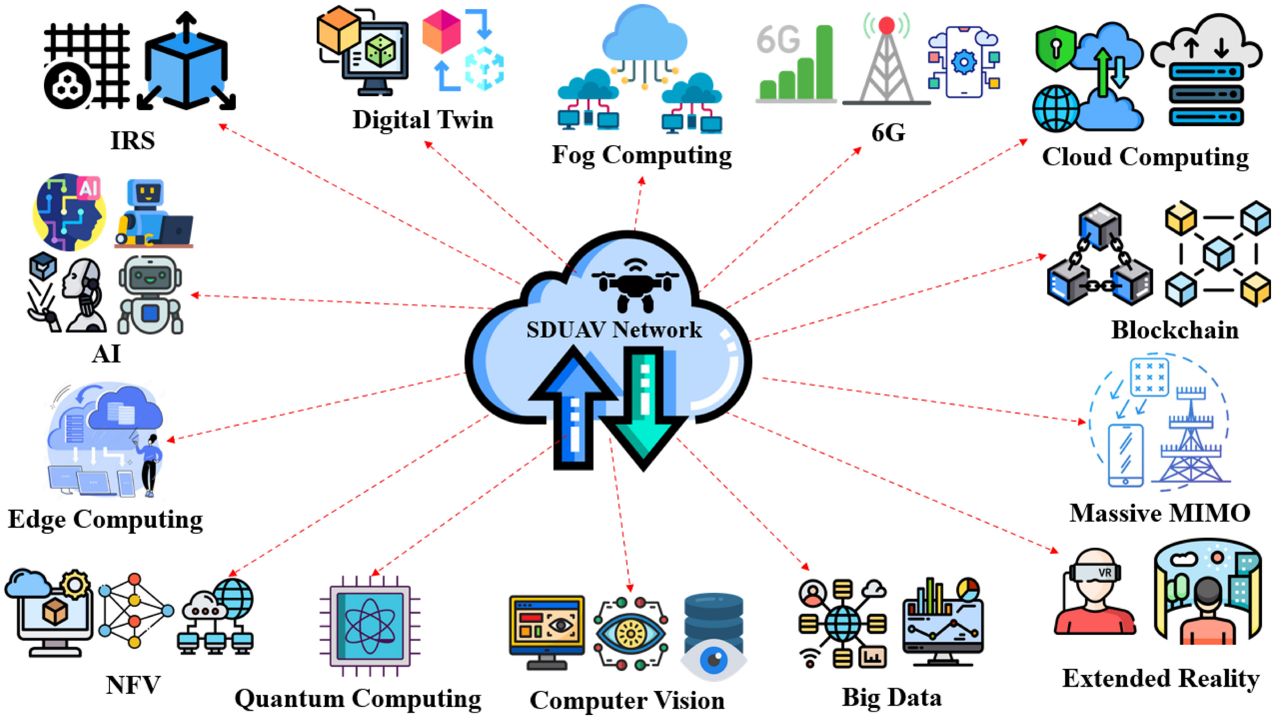

FIGURE 20. Enabling technologies for SDUAV networks.

modulation wide area network (LoRaWAN), a low-power wide-area network (LPWAN) transmission can require reasonably significant amount of current, preferably less than 17 milliamperes [230]. Therefore, it primarily targets the M2M, M2D, D2D, IoV, IoT, and IoE networks which require low bandwidth, affordable pricing, and minimal power consumption. Due to the spread-spectrum technique's adoption of chirp spread spectrum modulation in LoRa, signals can traverse far distances while using minimal energy.

To enable long-distance communication between the UAV and SDN controllers in the 6G environment, this LoRa technology can be utilized with the SDUAV networks. To gather sensor data and receive commands from the SDN controller, LoRa technology can be implemented for UAV telemetry and control. At the same time, LoRa technology also can be utilized in various SDUAV-based 6G applications like environmental sensing, remote monitoring, and tracking. In addition, longer flight lengths and more effective mission planning can be achieved by deploying LoRa technology. Apart from these, the LoRa technique can offer a low-cost and low-power solution for SDUAV architecture. Furthermore, the application of LoRa technology also can minimize the complexity of network infrastructure, making it easier to implement and maintain the SDUAV networks. Hence, by integrating the LoRa technology into the SDUAV framework, it is possible to enhance the communication range of the UAV networks and improve the reliability of the 6G networks at the same time [230].

Tactile Internet: The working principle of the tactile Internet (TI) is based on the combination of technologies like high-speed and low-latency networks, edge computing, as well as advanced control and communication protocols [231]. The TI concept has been constructed on the idea of allowing haptic or touch-based communication and network administration in addition to audiovisual communication. It is anticipated that the TI would reach latencies as low as 1 millisecond with extremely high reliability and security. Besides, TI can offer extremely low latency and extremely high dependability for real-time communication and control applications. Apart from this, TI can enable a wide range of applications for 6G systems, including remote surgery, driverless vehicles, virtual and AR, and industrial automation [231]. Consequently, to support the uMUB, uHDD, mMTC, and uHSLLC services in 6G, TI can play an essential role.

For UAVs' operation in dynamic and unpredictable environments in 6G networks, the TI can be incorporated into SDUAV architecture to provide real-time control and feedback. As an illustration, a UAV conducting a task in an ultra-dense heterogeneous environment could need real-time input from sensors and cameras to adjust to the changing environment and avoid hazards. For such circumstances, the TI can offer the low latency and high dependability necessary, enabling more successful UAV operations. Additionally, by offering real-time feedback and control and facilitating more precise and accurate decision-making, the TI can enhance the overall throughput of SDUAV networks [231]. Hence, integration of the TI with SDN-enabled UAV networks can potentially enable new applications and use cases for the 6G scenario.

TABLE 9. Characterization of several evolving technologies under diverse SDUAV services [29], [35], [46], [85], [145], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193], [194], [194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204], [205], [206], [207], [208], [209], [210], [211], [212], [213], [214], [215], [216], [217], [218], [219], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229], [230], [231], [232], [233], [234], [235], [236], [237], [238], [239], [240], [241], [242], [243], [244], [245], [246], [247], [248], [249], [250].

Technologies	Centralized controllability	Programmability features	Network Automation	Network Intelligence	High-speed with Low-latency	Security and Privacy	Network Orchestration	Monitoring and Management	Seamless connectivity	Scalability and Reliability
AI	✓	✓	✓	✓		✓	✓	✓		✓
Blockchain						✓	✓	✓	✓	✓
NFV	✓	✓	✓		✓		✓	✓		✓
OWC					✓	✓			✓	✓
Quantum technology		✓	✓	✓		✓	✓	✓		✓
Massive MIMO					✓			✓	✓	✓
Cloud computing	✓		✓			✓	✓	✓		✓
Big data analytics		✓	✓			✓	✓			
Proactive caching					✓			✓	✓	✓
MEC			✓		✓		✓	✓	✓	✓
Computer vision	✓	✓	✓	✓		✓	✓	✓		
IRS									✓	✓
Swarm intelligence	✓			✓			✓	✓	✓	✓
DT	✓	✓	✓	✓		✓	✓	✓		✓
THz communication					✓				✓	✓
Dynamic network slicing			✓			✓				
3D networking					✓			✓		✓
XR	✓		✓	✓			✓	✓		
Backscatter communication					✓				✓	✓

Electromagnetic nano-networking: Electromagnetic nano-networking (ENN) is an entirely novel approach to wireless communication networks which applies electromagnetic waves to link nanoscale devices collectively [232]. By utilizing the characteristics of electromagnetic waves in the THz frequency spectrum, it seeks to establish a network of nanoscale devices, such as nanomachines, nano sensors, and nanorobots, that can communicate with each other. The transmission of electromagnetic waves between nanoscale devices is essential to the operation of ENN and can be accomplished in several ways, including THz radiation, near-field communication, and molecule communication. To convey information in the form of bits that can be decoded at the receiving end, the signals between these devices are modulated. In terms of the communication aspect, ENN is crucial because it makes it possible to create a network of nanoscale devices that may be applied to a variety of tasks, including biological sensing, environmental monitoring, and industrial automation [232].

To enhance the performance and scalability of the UAVs, ENN can be linked with SDN-based UAV networks. By utilizing SDN approaches to regulate the connection between the UAVs and the nanoscale devices, ENN can be connected with the SDUAV networks. Based on the network conditions, The SDN controller can dynamically allocate resources for communication between the UAVs and the nanoscale devices in 6G networks. Furthermore, by bringing the SDUAV networks real-time information about the environment and empowering the UAVs to make well-informed choices, the integration of ENN with SDN-enabled UAV networks is capable of improving the performance of the SDUAV networking. Besides, the ENN framework not only can enhance the security of the 6G networks by establishing a secure communication channel between UAVs and nanoscale devices but also can enable the uMTC, uHSLLC, and uMUB services in 6G systems.

Digital twin networking: A digital twin networking (DTN) is a virtual representation of a physical object or system, such as a machine, a structure, or even a whole municipality [233]. The physical systems and the DT are linked by sensors and gateways which enables the DT to continuously update and provide real-time information about the functionality and status of the real-world systems. The fundamental concept behind DTN is to gather information from multiple sources, process it, and then input it into the DT models. Advanced big data analytics and machine learning algorithms are subsequently employed by the DT model to examine the data and generate insights into the functionality of the physical systems. Therefore, DTN has the potential to support uMUB, uHDD, mMTC, and uHSLLC services in 6G systems.

Due to its ability to track, forecast, and enhance the performance of real-world systems, DTN plays an important role in terms of 6G communication and networking. Hence, different sectors might utilize it to increase operational effectiveness, minimize downtime, and discover possible issues before they become apparent. By generating a DT model of the UAV network and utilizing it for monitoring and enhancing network performance, DTN can be integrated with SDN-enabled UAV networks. The DTN paradigm, for instance, also can be applied to anticipate network congestion, optimize network routing, and uncover potential security risks for SDUAV networks. By offering a method to continuously monitor and optimize network performance, DTN can assist SDN-integrated UAV networks. Hence, this can result in increased reliability, decreased interruptions, and improved security [233].

Internet-based networking: Internet-based networking (IBN) is a new networking architecture that aims to automate network operations and simplify network management by utilizing advanced technologies AI, machine learning, and big data analytics [234]. IBN operates on the concept of gathering information from various devices, applications, and consumers, evaluates that information, and then utilizes these results to enhance network security and overall performance. By automating tedious configuration management tasks, IBN seeks to simplify the process of developing, managing, and enforcing network regulations. Besides, IBN turns the hardware-based traditional network into a controller-led network that recognizes company intent and converts it into regulations that can be processed and enforced consistently across the entire network.

By employing SDN for network infrastructure management and service orchestration, IBN can be combined with SDN-enabled UAV networks. To help the SDUAV systems, IBN can offer real-time network information and insights on network performance and security [234]. Therefore, IBN automates network operations and improves security in SDN-integrated UAV networks. Taking malware and unauthorized access attempts as an example, it automatically detects and reduces network security concerns. Additionally, it recognizes network bottlenecks to improve network performance and dynamically reconfigures the network. Consequently, by automating network administration, maximizing network performance, and boosting network security, IBN boosts the performance of SDUAV systems.

Graph neural networks: To represent and analyze graph-structured data, such as connections between people and transportation systems, graph neural networks (GNNs) can be deployed. GNNs are neural networks that work on graph data structures [235]. The model can learn a representation for each node based on its connections to other nodes in the network by using a message-passing mechanism to transport information between nearby nodes in the graph. Besides, GNNs can forecast network traffic patterns, identify vulnerabilities, and construct and optimize communication networks such as wireless sensor networks (WSNs) or ad hoc networks in 6G scenarios.

By modeling and analyzing the topology and traffic patterns of SDN-enabled UAV networks, GNNs can be integrated with these systems [235]. Such information can be utilized to optimize routing and traffic management in real-time, boosting network performance and minimizing latency. To avoid disruptions, traffic can be proactively rerouted using GNNs to predict network failures in SDUAV networking architecture [236]. Therefore, GNNs can be incorporated with the SDUAV networks to improve network performance and reliability in 6G systems.

Mesh networking: Mesh networking is a type of network topology where every node relays information to the rest of the network. A mesh network's nodes are frequently linked to one another via different routes which increases the network's resilience and node failure resistance [237]. Mesh networks are frequently utilized in scenarios where reliable connectivity is required to enable 6G services like URLLC. Hence, mash networking can be deployed in IoT networks, emergency communications, and locations with inadequate or unreliable traditional network infrastructure. In addition, mesh networks are also scalable, self-configuring, and capable of self-healing, which makes them perfect for dynamic contexts where nodes often enter and exit the network.

By enabling UAVs to function as nodes in the mesh network to transmit and relay data to other nodes in the network, mesh networking can be linked with SDN-enabled UAV networks [237]. In places with possibly limited access to conventional communication infrastructure, this might improve network coverage and dependability. Mesh networking can be very helpful for facilitating communication between UAVs and ground-based equipment in SDN-integrated UAV networks. To transfer instructions and telemetry information between an SDN controller and a swarm of UAVs, a mesh network could be adopted. Depending on the individual implementation, mesh networking can have a positive or negative effect on SDUAV networking performance. However, it can improve the coverage and reliability of 6G networks which also can be vital to support the mMTC and uMUB services.

Time-sensitive networking: A time-sensitive networking (TSN) is the IEEE 802.1Q specified standard technology which can enable deterministic communications on regular ethernet [238]. For certain real-time applications in 6G systems that demand determinism, TSN technology can utilize schedule to offer delivery assurances and minimize jitter. As a result, TSN aims to provide a solution to the problem of variable transmission delay or jitter in standard ethernet networks by defining a set of protocols that ensure precise and predictable timing for critical data [238]. For providing time-critical applications with the requisite amount of determinism and latency, the TSN's operating concept entails the adoption of numerous protocols such as time synchronization protocols, traffic scheduling protocols, and QoS-based protocols. TSN provides this by prioritizing vital data over other types of data on the network and by employing advanced buffering and queuing mechanisms to reduce jitter.

By integrating critical real-time control and communication systems with conventional ethernet networks, TSN can play an essential role in communication and networking. Besides, it can be utilized in different sectors like industrial automation, automotive, and aviation. In terms of cost savings, less complexity, and improved interoperability, this integration can offer substantial advantages for the SDUAV framework. Using TSN-enabled ethernet switches and gateways, TSN can be integrated with SDN-enabled UAV networks. TSN enables deterministic and low-latency communication between UAVs and SDN controllers as well as between various UAVs in a swarm which can help to enhance the performance of SDN-enabled UAV networks. As a result, UAVs may be controlled and coordinated more precisely, and information transfer can be more dependable and effective [238]. By permitting more precise and predictable timing for crucial control and communication data, TSN can significantly increase SDUAV networking performance to support the uHSLLC and URLLC services in 6G. Hence, this can increase the overall performance and dependability of SDUAV networks, minimize the probability of collisions, and improve the precision of location and velocity measurements.

Cognitive swarm networking: Cognitive swarm networking (CSNs) are networks that implement swarm intelligence principles with cognitive networking techniques [239]. The nodes of the network in CSN are structured in a swarm-like fashion, with each node operating as an autonomous agent that works with other nodes to achieve a shared objective. The nodes have cognitive powers as well, enabling them to adjust to environmental changes, make choices, and draw knowledge from their experiences [239]. Swarm intelligence algorithms can be deployed in the CSN's operating system which can promote cooperation and coordination among the network's nodes. Hence, these algorithms can be employed to improve network performance, boost network efficiency, and enhance network resilience to support the 6G requirements such as uHDD and uMUB.

From the perspective of communication and networking, CSN is essential due to how it permits the development of massive, self-organizing networks that are capable of adjusting to environmental changes and responding to dynamic conditions. To maximize the bandwidth and throughput of the network, improve scalability, and increase security, CSN can be connected with SDUAV networks. By enabling the development of a self-organizing and adaptable network that is capable of reacting to changes in the environment such as weather conditions, traffic volume, or interference, CSN can certainly enhance the reliability of the SDUAV communication system. Moreover, CSN can also increase network privacy and security by providing the capacity to identify and respond to security threats instantaneously to each data node in the 6G systems. As a result, CSN not only can substantially boost SDUAV networking throughput to support the 6G services by enabling the development of a highly scalable, self-organizing, and adaptive network but also can improve network reliability and privacy.

Cognitive radio networking: Cognitive radio networking (CRN) is a kind of wireless communication technology which can increase the effectiveness and dependability of communication devices in 6G networks. In a CRN framework, each device of the network is capable of detecting the available RF and can intelligently utilize them [122]. The underlying idea of CRN is spectrum sensing which utilizes cognitive approaches to find unutilized frequency bands in a specific area. To increase spectrum efficiency and minimize interference, CRN devices can dynamically allocate frequencies for communication. Additionally, CRN can increase the dependability and security of 6G communication networks by making utilization of unoccupied frequency channels.

In terms of integration with the SDUAV networks, CRN can bring improvements such as enhanced spectrum efficiency and less interference, which can eventually improve network performance. Additionally, to establish a secure communication channel between the SDN controller and UAVs, the CRN approach can optimize the available spectrum resources. Therefore, by offering a more effective and dependable method of communication between UAVs and ground-based controllers, CRN has the potential to dramatically enhance and improve the performance of SDUAV networking. Besides, by dynamically adapting to changing network conditions and requirements in ultra-dense heterogeneous circumstances, CRN can ensure the SDUAV network's operations at maximum efficiency and deliver the highest possible level of performance to support the 6G requirements like the mMTC and uMUB [122].

Delay tolerant networks: Delay tolerant networks (DTNs) are a specific type of networking architecture that allows communication in circumstances when conventional networks are unreliable due to extensive and unpredictable delays, inconsistent connectivity, or limited bandwidth. However, with the utilization of DTN over the conventional networking infrastructure, these obstacles can be eliminated [240]. The DTN operating principle relies on the concept of store-carry-and-forward networking. Instead of sending messages instantly to the destination, DTN nodes buffer messages and carry them until they get to a node that is nearer the destination or has a better chance of delivering the message. To determine the optimum route to the destination, DTN nodes also employ sophisticated routing algorithms, taking into account elements including network structure, node mobility, and message.

DTN is crucial for communication and networking as it allows connectivity in areas where typical networks are not feasible or reliable. Consequently, by utilizing sophisticated routing algorithms that take into consideration UAV mobility and network architecture, DTN could be linked with SDUAV networks [240]. To increase the functionality of SDN-integrated UAV networks, DTN can also be applied in conjunction with other networking technologies such as LoRa, mesh networking, and CR networking. By enabling a different path for message delivery, lowering message loss, and enhancing network resilience in SDN-enabled UAV networks, DTN can aid in enhancing network performance. It can also help reduce the network load by preventing unnecessary signal broadcasts.

Wireless body area network: To enable remote monitoring of physiological parameters as well as health-related information, a wireless body area network (WBAN) connects numerous sensors and medical devices which can be implanted inside or worn on the body [241]. WBAN operates based on low-power, short-range wireless communication technologies such as Bluetooth, Zigbee, or RF identification (RFID) and offers a reliable and secure connection between devices and the receiving station. In terms of communication and networking, WBAN plays an important role because it makes it possible to track health problems in real-time, which can help with early detection and disease prevention. As patients may be monitored remotely from their homes, it is also helpful in lowering the need for hospitalization and the accompanying expenditures.

By deploying UAVs as WBSs to gather data from the sensors on the human body and transfer it to the cloud-based data analysis and processing center, WBAN can be linked with SDN-enabled UAV networks [241]. For remote and inaccessible places, this integration can provide real-time health monitoring, which might be extremely important in emergency scenarios. To ensure the shortest possible latency and greatest possible throughput, the data gathered from the sensors can be forwarded through the most efficient network path. As it enables effective data collecting, transmission, and processing, WBAN can be integrated with SDN-enabled UAV networks to increase communication and networking effectiveness for SDUAV.

B. EMERGING COMMUNICATION TECHNOLOGIES FOR SDUAV NETWORKS

When UAVs communicate with different devices or networks, they also interact with various wireless signals in the same frequency band and spectrum. However, this can cause interference, which can degrade the quality of the UAV's communication link and impact its ability to transmit or receive data. Additionally, interactions with various communications can also cause network congestion, which can further impact performance. Thus, to mitigate these issues, SDUAV networking systems needed to use advanced algorithms, protocols, and different techniques to manage interactions with different communications. Besides, the ability of a UAV to effectively interact with different communications is also essential for ensuring reliable and efficient operation. Therefore, by managing interactions with various wireless signals and networks, SDN-enabled UAV networking systems can optimize performance and ensure that critical data is transmitted and received with minimal delay or interference. Some of the examples of interactions with different communication systems are addressed below.

Terahertz communication: THz communication is a wireless communication technology that operates in the frequency range between 100 GHz to 10 THz [2]. It has the potential to provide very high data rates, low power consumption, and high reliability in communication networks. Real-time control and monitoring of the UAV also can be accomplished through more efficient and swift communication [242]. Additionally, by allowing communication in a frequency range that is less susceptible to interference, signal deterioration, and dropped connections, it can enhance both the safety and the dependability of wireless communication between the UAV and the SDN controller.

With the integration of THz communication instruments and protocols into the SDUAV networks, a swift and secure communication link between the UAV and SDN controller can be established. In this regard, the SDN controller manages the THz communication systems integrated with the SDUAV network, making sure they are properly set functioning and optimized for the SDUAV environment, managing network traffic, and setting THz communication data priorities. As a result, SDUAV networks can operate safely and effectively in 6G scenarios [242]. Therefore, THz communication can increase the performance and reliability of SDUAV networks to support the 6G networks [4].

Acoustic underwater communication: Underwater acoustic communication is a method of transmitting and receiving signals under the surface of the water. There are many ways to use this type of communication, but hydrophones are by far the most popular. To enable the 6G services like the uMUB, uMTC, uHSLLC, and uHDD, acoustic communication can play a crucial role.

Acoustic communication can be utilized as an alternative to RF communication in the scenario of wireless networks for SDUAVs [243]. In areas where RF communication is constrained, such as underwater or underground environments, acoustic communication can assist SDUAV networks to perform better by offering a more dependable communication link. Furthermore, SDUAVs can interact more efficiently with one another and with the SDN controller seamlessly with the help of an acoustic communication approach. By serving as a backup communication connection in case of RF communication failure or as a redundant communication link in specific areas of the SDUAV network, acoustic communication can be employed to enhance the performance of the UAV. In situations where RF communication may be constrained by interference from other UAVs or other wireless equipment, acoustic communication might be utilized, for instance, to transmit data between UAVs in swarm operations. By allowing for the deployment of large swarms of UAVs, the use of acoustic communication can also increase the SDUAV network's capacity for growth. Therefore, by providing a more reliable communication link

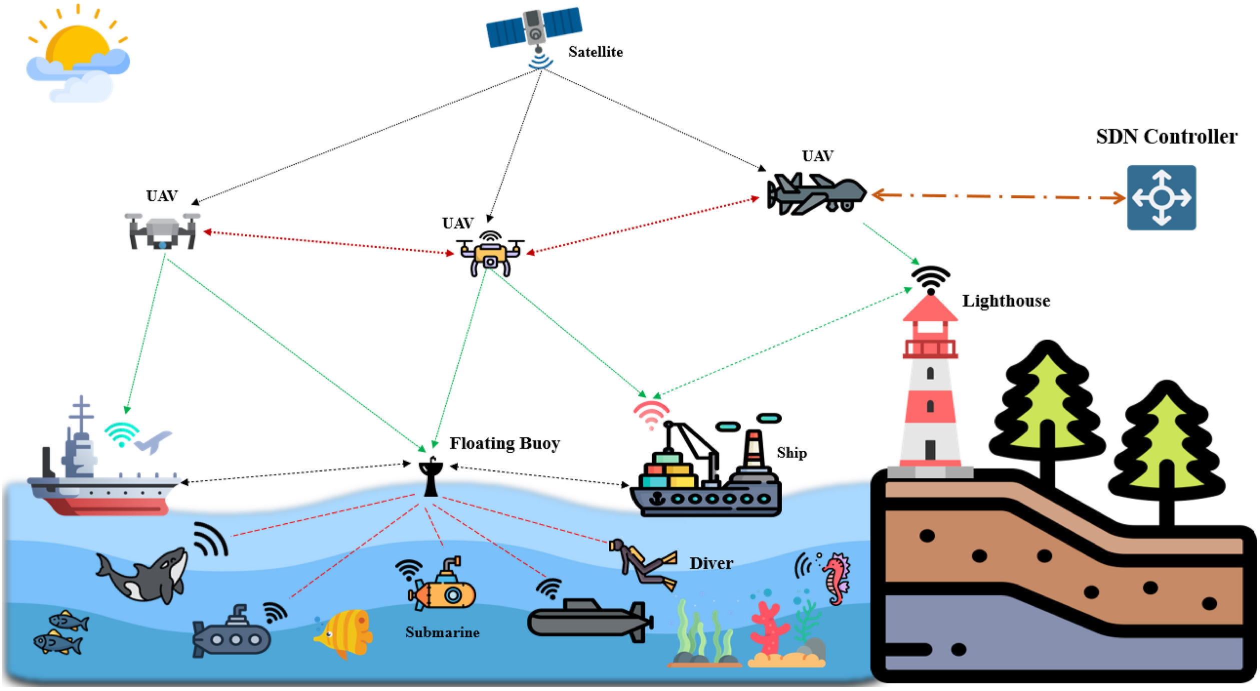

FIGURE 21. SDVAU-integrated acoustic underwater communication.

and permitting communication in 6G circumstances where RF communication may be limited, acoustic communication can help to increase the number of UAVs that can operate in a given region [243]. Fig. 21 depicts a typical SDVAU interconnected acoustic underwater wireless communication in a 6G framework.

Cell-free communication: Cell-free communication is a kind of wireless communication that does not rely on the infrastructure of the conventional cellular network but rather depends on distributed antenna systems [2]. In cell-free communication, signals are transmitted and received by several scattered antennas, each of which is simultaneously connected to many UEs. As a result, the cell-communication framework not only can handle the spectrum management mechanism but also can improve the efficiency of the 6G networks [4].

A reliable and high-bandwidth communication link between the UAVs and controller also can be made possible by cell-free communication, which is capable of enhancing the efficiency and adaptability of the SDUAV network. During UAV operations, it can be utilized for command and control, real-time video streaming, and essential communications [244]. By using the SDN approaches, it is possible to increase network capacity, enable seamless transitions between different antennas or networks, and manage and distribute resources dynamically. As a result, the adoption of cell-free communication in SDUAV networks can considerably improve network performance, stability, and scalability in 6G scenarios.

Molecular communication: Molecular communication is a sort of communication where molecules can be utilized to transfer information [245]. In molecular communication, information is encoded in the concentration, timing, and other properties of the molecules, which are subsequently released into the environment to be picked up by a receiver. By offering an additional communication connection for SDUAVs, molecular communication can be applied to improve the performance of the wireless network. Molecular communication, for instance, can offer a dependable and effective communication link if an SDUAV is intended to operate in a scenario where traditional wireless communication is not feasible, such as in a crowded metropolitan place or a location with significant interference.

Depending on the purpose of the application and the surroundings that the UAV is working in, molecular communication could prove advantageous in a particular area of the SDUAV. In a search and rescue initiative, for example, molecular communication can be implemented to permit communication between the UAV and a person trapped in a collapsed building, when conventional wireless communication may be restricted by signal blockage [245].

Due to the significant differences in how molecular communication functions compared to various wireless communication technologies, handover and smooth communication between molecular communication and other wireless communication technologies can be a challenge [245]. Nevertheless, SDN solutions can be applied to control the changeover between various communication channels and guarantee fluid communication. By adding communication links that can function in contexts where traditional wireless communication is either impossible or untrustworthy, the usage of molecular communication can increase the scalability and dependability of the SDUAV network.

Nanoscale communication and networking system: Nanoscale communication and networking refers to the design, analysis, and implementation of communication and networking protocols at the nanoscale level [246]. To enable quicker and more precise communication between UAVs and their controlling systems, this method can be deployed to increase the efficiency and reliability of the SDUAV-based 6G services. Additionally, nanoscale communication enables more accurate coordination and control between multiple UAVs, which can improve their overall performance. In particular, flawless communication and handover capabilities of the SDUAV can be enhanced through nanoscale networking and communication.

With nanoscale communication, switching between multiple channels could be accomplished more smoothly, ensuring seamless connectivity and control of the UAVs even when switching between various communication networks. Furthermore, by enabling the deployment of multiple UAVs in ultra-dense heterogeneous networking environments, nanoscale communication, and networking also can increase the scalability of SDUAV networks to provide better backhaul and fronthaul networking infrastructures for 6G applications. Hence, the utilization of nanoscale devices and materials allows more efficient resource consumption, more adaptability, and flexibility communication platform for 6G-enabled systems.

Biomedical communication: In the field of biomedical communications, medical data, and information are transmitted between healthcare providers, patients, and medical devices via networking, wireless communication, and telecommunications technologies [247]. The ability to quickly and effectively convey vital health information makes biomedical communications extremely important in the domain of 6G networks.

Biomedical communications can play an essential role in SDUAV-enabled 6G systems as they can enable real-time transmission of health data from the UAV to medical personnel on the ground. To offer quick medical attention in an emergency, this could be helpful for injured people. Additionally, wearable technology aboard UAVs can be utilized to convey medical data to healthcare providers via biomedical communications that can provide ongoing patient monitoring. Therefore, by enabling the swift transmission of vital medical data, biomedical communication-assisted SDUAV networking systems can considerably improve the overall services and prospects of the 6G networks [247].

Haptic communication: The use of touch and tactile feedback in communication is known as haptic communication [248]. By providing more nimble and responsive control of the UAV, haptic communication can improve the operational efficiency of SDUAV networks. This is especially important in scenarios like poor light or loud surroundings when visual or aural feedback may be scarce or unreliable. Haptic communication in particular can enhance SDUAV control and operation in several ways. Through the utilization of tactile sensors and actuators, which send the operator feedback through touch or vibration, SDUAVs can engage through haptic communication. To give the operator haptic feedback in this situation, a joystick or other control device could be fitted with tactile sensors and actuators. As a result, haptic communication integration into SDUAV networks can considerably enhance UAV control and operation in 6G scenarios.

Energy efficiency communication: Energy-efficient communication refers to communication technologies that require less energy while maintaining reliable and high-quality communication connectivity [2]. To decrease power consumption and maximize communication performance in 6G systems to enable green communication, the energy efficiency communication approach can play a vital role by providing optimize communication protocols, signal processing techniques, and new hardware design [67]. For battery-powered systems like WSNs, IoT devices, and UAVs, energy-efficient communication can play a crucial role since it provides them the capability to function for prolonged periods without needing regular battery replacements or recharging.

In the case of the SDUAV network, energy-efficient communication is critical for improving the network's performance and scalability. Since UAVs often rely on batteries, their energy consumption is an important factor that affects both their flying length and overall performance. Thus, increasing the energy economy can contribute to extending the UAVs' battery life, which could result in longer flight periods and improved mission capabilities. Additionally, the SDUAV network can employ energy-efficient communication protocols for data transfer, routing, and handling of 6G networks. The power needed to transport information can be minimized while maintaining a given degree of data throughput and dependability by using energy-efficient modulation and coding algorithms. Besides, it is possible to lower the energy consumption of network nodes whereas data is being forwarded by using energy-efficient routing protocols [67]. Furthermore, the overall energy consumption of the network can be decreased by using energy-efficient network management strategies like sleep scheduling and power control. Therefore, the introduction of energy-efficient communication protocols in the SDUAV network could improve overall network performance and scalability by extending the flying duration and mission capabilities of the UAVs to support the mMTC and uMUB features of 6G.

Ultra-wideband communication: An ultra-wideband (UWB) communication system is a wireless communication technology that utilizes a wide bandwidth of several GHz to transmit data over short distances [249]. UWB is capable of identifying the precise position of a device at a range of less than 200 meters. However, it performs ideally with a LOS between locations or sensors and executes most efficiently at short ranges, often between 1 and 50 meters. UWB enables a more extensive range of bandwidths (5-500 MHz), greater data rates (up to 480 Mbps), and different frequency bands compare to Bluetooth connectivity [249]. Additionally, UWB technology facilitates applications like video streaming, file sharing, and gaming due to its high data transfer rates of up to 10 Gbps. Moreover, UWB technology is perfect for battery-operated products like smartphones and wearables since it consumes very small electricity. Interestingly, UWB signals are characterized by their low power and short range, high data rates, and resistance to interference. Hence, for battery-operated devices in 6G networks like smartphones and wearables, UWB technology is perfect as it consumes extremely little power.

For the SDUAVs network, UWB can be deployed to improve the communication performance and reliability of UAVs in 6G scenarios. UWB can be employed in several specific parts of the SDUAV network such as communication between UAVs, communication between UAVs and GCSs, and communication between sensors and UAVs to achieve high-speed data transfer and low-latency communication. Moreover, UWB can be used for the ranging and localization of UAVs, enabling precise positioning of the UAVs in real-time to support the uHDD and mMTC services in 6G. Handover and seamless communication also can be achieved by leveraging the multi-band nature of UWB communication which allows it to operate in different frequency bands and use different modulation techniques [249]. At the same time, the low power consumption of UWB also makes it suitable for deployment in battery-powered UAVs. Besides, UWB can improve the UAV's performance and scalability by enabling reliable and high-bandwidth communication, even in harsh and noisy environments to provide uHSLLC features in 6G.

Free-space optical communication: FSO communication is a wireless communication approach that employs modulated light to transport data between two sites, often across the atmosphere. It is a LOS communication method that transmits data via lasers or LEDs [250]. In the case of SDUAV networking, FSO can provide a high-speed, low-latency communication link between two UAVs or between a UAV and a BS. When RF communication is not safe or reliable such as in crowded urban areas or for military purposes, this can be particularly beneficial.

FSO communication mechanism, however, can be integrated with SDUAVs through the use of FSO-RF communication. As a result, the UAV can alternate between FSO and RF transmission depending on the availability and strength of the signal to enable the uHSLLC service for 6G networks. In this respect, the centralized controller of the SDN can dynamically route the data through the most effective and dependable communication channel by deploying machine learning or big data analytics approaches. One of the most significant benefits of FSO is its high bandwidth and low latency which can considerably increase the performance and scalability of the SDUAV network in 6G scenarios [250]. To ensure dependable and seamless communication for SDUAV-enabled 6G applications and services, the FSO communication technique can certainly play a vital role.

X. RESEARCH ACTIVITIES ON SDUAV NETWORKS

Several research works already have introduced the concept of SDN-enabled UCSs for various purposes. Recently, different telecom and networking industries also have come forward in this regard. Moreover, to support the 6G services different countries like the USA, China, Canada, Japan, and South Korea have recently launched numerous projects on SDN-assisted UAV technology. However, basis standardizations and proper guidelines are needed to establish a successful SDN-assisted UAV platform for future 6G communication systems. Some of the key activities on standardization and research issues as well as research projects by different industrial sectors and countries are addressed below.

A. RESEARCH PROJECTS BY DIFFERENT SECTORS, INSTITUTIONS, AND FORUMS

In recent times, various projects and experimentation in SDUAV networking have been conducted in both academic and business contexts [48]. The target of an SDUAV networking research project across numerous industries and nations is to create and deploy a flexible, scalable, and adaptive SDUAV network that can meet the particular needs and problems of UAVs operating in various industries and nations. To support the 6G systems, several organizations, and nations have started their preliminary research activities on SDUAV networks [251]. Some of the major initiatives are briefly discussed below.

IEEE standards association: For the integration of UAVs with various kinds of wireless networks, the IEEE standards association has created standards. The IEEE 802.11ba standard, which incorporates modifications to facilitate UAV communication with WiFi networks, was accepted by the IEEE standards association in 2020 [252]. To improve the efficiency of UAV communication with WiFi networks, the standard provides novel features for WiFi networks, such as increased positioning precision along with quicker affiliation and disassociation times [253].

Similarly, IEEE has various committees, such as the IEEE 802.11 Task Group S (TGs) and IEEE 802.16 Task Group T (TGT), that are focused on SDN-based networking for UAVs [254]. For wireless networking protocols that can enable UAV applications, including SDN-based networks, these working groups are in charge of creating guidelines and specifications. To create a standard for SDN-based UAV networks, IEEE has established a working group named IEEE P1920.1. The group is focusing on creating mechanisms and protocols for the effective management of network resources as well as tackling privacy and security concerns in UAV systems in 6G networks.

3rd generation partnership project: The 3GPP is a telecommunications standardization organization that is responsible for defining standards for wireless networks such as 5G and 6G. However, recently, they had a working group researching an SDN-based framework for UAV applications. The 3GPP RAN Working Body 1 (WG1) is the body in charge of developing standards and recommendations for using cellular networks to support UAVs [255]. At the same time, for integrating UAVs with cellular networks, the 3GPP is also creating standards. These standards specify interfaces and protocols for linking UAVs to cellular network infrastructure, providing UAVs to communicate and connect through cellular networks. Additionally, the 3GPP has established a brand-new class of hardware known as UAVs with enhanced capabilities (UAV-eC), which is intended to satisfy the particular needs of UAV communication with other 6G-empowered cellular networks.

European telecommunications standards institute: In Europe, there is a standardized organization for telecommunications called European telecommunications standards institute (ETSI). Additionally, they have a working group for the standardization of SDN-based networking architecture and various UAV communication technologies. This working group is known as the ETSI industry specification group for unmanned aerial systems (UAS), and it is responsible for developing standards and guidelines for SDUAV communication systems that can enable 6G applications. Similarly, to integrate UAVs with satellite communication systems, the ETSI is establishing standards. The standards specify interfaces and protocols for connecting UAVs to the satellite communication infrastructure, allowing UAVs to communicate and connect via satellite communication systems.

Open networking foundation: The SD-RAN project is an open-source SDN-based wireless networking infrastructure being developed by the open networking foundation (ONF) [256]. The SD-RAN project can offer a customizable wireless networking technology that can be adjusted to meet the specific requirements of many different scenarios in 6G, including UAV communication. Besides, the platform incorporates various novel features, such as a centralized control plane, dynamic spectrum allocation, and compatibility with multiple wireless protocols.

Internet engineering task force: The Internet engineering task force (IETF) is an organization that establishes standards for the Internet as well as Internet protocols like transmission control protocol/Internet protocol (TCP/IP). However, the IETF network working group is one of the working groups they have set up to create SDN-based networking protocols for UAVs. To facilitate SDN-enabled networks for UAV applications, this working group is tasked with developing standards and recommendations.

International telecommunication union: The international telecommunication union (ITU) is a telecommunications organization that develops guidelines for telecommunications networks and technologies across the globe. To standardize UAV communication technologies, including SDN-based UAV networks, they established a collaborative committee. This working group is known as the ITU Focus Group on UAVs, and it is in charge of producing standards and guidelines for communication systems that can enable UAV applications. To provide protocols for the remote control and management of UAVs utilizing SDN, the IETF has created a working group called the remote operations for UAV group [253]. In addition to developing standardized interfaces and protocols for the management and control of UAVs, the group is also focusing on UAV network issues related to privacy and security.

Telecommunications industry association: The TIA-6906 standard, which is being developed by the telecommunications industry association (TIA), will allow UAVs to communicate with cellular networks. In addition to providing instructions for the development and implementation of UAV communication platforms, the standard additionally offers interfaces and protocols for attaching UAVs to cellular networks.

European aviation safety agency: In order to allow UAVs to operate in civil airspace, the European aviation safety agency (EASA) is working and trying to create regulations for UAV systems. The regulations include requirements for UAV communication and control, as well as the standards and protocols that must be used for UAV communication.

Federal aviation administration: Regulation of the airspace and safety of UAV activities are the responsibilities of the federal aviation administration (FAA). It is working on regulations and guidelines for UAV communication and networking, including the implementation of SDN. Global unmanned traffic management association is an international non-profit organization dedicated to the development of unmanned traffic management technologies. To enable the effective and reliable governance of UAV traffic, it is investigating the usage of SDN in UAV task management systems.

Radio technical commission for aeronautics: For the integration of UAVs into the national airspace system (NAS), the radio technical commission for aeronautics (RTCA) has established standards. The standards include requirements for UAV communication and navigation, as well as performance specifications that UAVs must achieve to enable safe and dependable operation in the NAS.

Universities and research institutions: Research on the implementation of SDN in UAV networks is being done by numerous universities and research organizations to support various applications. Among the organizations researching this subject are the Universities of Oxford, Michigan, Singapore's National University, California's University of Los Angeles, the National Institute of Standards and Technology, California's University of San Diego, the Georgia Institute of Technology, and the Massachusetts Institute of Technology. To support wildlife conservation, emergency response operations, urban planning, and management, environmental monitoring and management, disaster response and recovery operations, precision agriculture, and search and rescue operations, their research aims to create SDN-based UAV networks. The overall objective of the project is to create a framework for deploying SDN and NFV in UAV networks, which can allow for the effective control of network resources and the provision of dependable and secure communication.

The initiatives from various organizations and groups are aimed at standardizing SDN-based UAV networking. By creating open-source SDN integrated networking platforms, defining new device categories for UAV communication, developing standard interfaces and protocols for integrating UAVs with wireless networks, and establishing expert task forces on UAVs, they are significantly advancing the field. These contributions will probably speed up the deployment of SDN-based UAV wireless networking and encourage the creation of revolutionary applications for UAVs [253].

B. RESEARCH ACTIVITIES BY DIFFERENT COUNTRIES AND NATIONS

Adoption of the SDUAV technology, as well as research and deployment (R&D) in this industry, is critical for various nations and territories for different kinds of reasons. SDUAV technology and its advancements can provide improved productivity, reduce expenses, and better outcomes in a variety of sectors, including transportation, forestry, agriculture, and emergencies. Besides, the invention and implementation of SDUAV technologies can potentially offer new job opportunities, stimulate economic growth, and boost global competitiveness. Therefore, international cooperation and the ties between nations can be strengthened through collaboration and investment in SDUAV research and development.

Recently, several countries have made significant investments in the development of SDUAV systems. As a pioneer in UAV technology, the United States of America is making huge investments in the advancement of SDUAV networking. Solutions for SDN-based UAV networking are also being funded by organizations like Northrop Grumman, Lockheed Martin, and Boeing. UAV technology has advanced significantly in China as well, with SDN-based UAV networking solutions being developed by organizations like Da-Jiang Innovations (DJI), EHang, Huawei, and Tencent. Similarly, South Korea is actively developing SDUAV systems and has generated unique solutions through organizations such as the Electronics and telecommunications research institute (ETRI), Samsung, and LG. On the other hand, the U.K. government and public sectors are investing in UAV technology and SDN-integrated networking solutions through businesses like British Aerospace (BAE) systems, QinetiQ, and Cobham. Israel has also made significant contributions to SDN-based UAV networking solutions through industries like Elbit systems and Israel aerospace industries (IAI). The adoption of SDUAV networking is also being actively explored by Japan, Canada, Australia, and the European Union, with companies and organizations like Nippon Electric Company Limited, Mitsubishi Electric, Honeywell Aerospace, Canadian aviation electronics, Boeing, Airbus, Thales, and the European space agency (ESA) driving innovation.

The advancement of SDUAV networking, therefore, is a global effort, with multiple organizations and governments actively contributing to its development. The advancements and initiatives of these collaborating nations and organizations will have a direct effect on this technology's future. As SDUAV networking advances, more organizations and governments are likely to become part of the effort to accelerate its progress and growth.

XI. FUTURE TRENDS AND RESEARCH DIRECTIONS FOR SDUAV NETWORKS

To effectively install the SDUAV communication systems, several technical concerns need to be resolved. A few possible concerns are briefly covered below.

Multi-domain SDN: Multi-domain SDN is a type of network architecture that enables centralized administration and control over numerous network domains in 6G domain. By integrating the multi-domain SDN with an SDUAV network, several advantages including enhanced network efficiency, better resource management, and more dependable communication can be achieved [257]. Through this integration, different network domains such as RF, NTN, and OWC networks can be seamlessly integrated and also can be managed and controlled dynamically. In addition, the dynamic network reconfiguration and failover strategies across every domain ensure link continuity and minimize the effect of interference and signal degradation on network performance. Hence, deployment of multi-domain SDN in the SDUAV network can enhance the overall reliability of the SDUAV networks.

Intent-based communication and networking: By using advanced technologies like machine learning, AI, and computer vision, intent-based networking (IBN) transforms high-level business and operational objectives into network policies and configurations [258]. Hence, the effectiveness of the network, resource management, and transmission reliability can be improved by integrating IBN with the SDUAV communication system. Furthermore, UAV networks can enhance communication performance, adjust to changing network circumstances, and adapt to shifting communication requirements by dynamically regulating network resources in 6G environments. Likewise, to guarantee the effective and efficient use of UAV network resources, advanced network management techniques like policy-based routing, dynamic path selection, and network segmentation can be used. To avoid communication failure, guarantee link continuity, and lessen the effect of interference and signal degradation on the overall network, dynamic policy enforcement and security measures also can be implemented on UAV network communication links.

Software-defined radio access network: To manage and optimize radio access network (RAN) resources automatically, a networking architecture called software-defined RAN (SD-RAN) can be utilized [259]. Deploying SD-RAN in conjunction with the SDUAV network can boost network efficiency, improve resource allocation, and increase transmission reliability. With the help of this technology, RAN resources like frequencies, BSs, and antennas can be managed and controlled dynamically, improving overall QoS while also maximizing transmission efficiency [259]. Additionally, by allowing dynamic interference management and signal processing techniques, SD-RAN can enable more sophisticated RAN management strategies like network slicing and edge computing, as well as help to increase communication reliability in 6G systems. At the same time, the combination of SD-RAN and SDUAV networking can provide a more adaptable, efficient, and dependable networking environment for networks. Hence, the efficiency, adaptability, effectivity, and reliability of the UAV networks can be enhanced in different 6G applications and environments by the integration of SD-RAN with an SDUAV network.

Software-defined wide area network: A software-defined wide area network (SD-WAN) utilizes the principles of SDN to WANs [260]. Incorporating SD-WAN with the SDUAV network might have many advantages such as better data rate, improved resource management, and more dependable communication. Hence, the ability to dynamically control and manage WAN resources allows UAV networks to improve communication performance, adjust to shifting network conditions, and meet new communication demands in the 6G era. Furthermore, SD-WAN enables more advanced WAN management techniques for UAV network resources like traffic prioritization, application-aware routing, and policy-based security, enhancing overall network performance and communication dependability. Apart from these, SD-WAN offers multiple network connections, such as broadband, LTE, and multiprotocol label switching, to create a more flexible, resilient, and cost-effective network infrastructure for 6G services [260].

The programmable data plane of the SDN: In SDN, the programmable data plane enables real-time software programming and management of packet forwarding behavior. When it is combined with an SDUAV network, throughputs of the SDUAV network can be improved and latency as well as delays can be minimized which can support the uHSLLC and mMTC services of the 6G systems [261]. Besides, the resource management abilities and communication reliabilities of the SDUAVs also can be enhanced. Hence, this dynamic control can enhance service quality, increase communication efficiency, and adjust to shifting circumstances. Again, the programmable data plane enables the UAV network to apply advanced management techniques to data plane resources, reducing the effect on network performance, such as packet steering, traffic shaping, and load balancing. Furthermore, it allows the application of dynamic traffic engineering and path optimization strategies to communication links, minimizing the impact of interference and signal degradation on the overall performance of the SDUAV networks.

Software-defined storage: The software-defined storage (SDS) is an architecture that divides storage control and management from the core hardware. As a result, the storage resources can be controlled and provisioned dynamically and flexibly with the help of SDS controllers [262]. At the same time, integration of SDS with an SDUAV network can enhance data management, resource utilization, and reliability. In addition, SDS enables dynamic storage resource allocation and management, more sophisticated storage management strategies, and data reliability and availability. By utilizing SDS, UAV networks also can improve the throughput at which information is stored and retrieved, adjust to shifting storage requirements, and lower storage-related latency, enabling UAV networks to function constantly and dependably in a range of prospects and applications in 6G aspects.

Software-defined cloud computing: Software-defined cloud computing (SD-cloud computing) has the potential to play a critical role in the development and implementation of SDUAV systems for 6G communication networks [263]. The combination of SDN and cloud computing provides the design and implementation of a dynamic and adaptable network framework that can meet the different requirements of SDUAV operation in various scenarios. SD-cloud computing also can provide multiple advantages to SDUAV networks for 6G. By offering a scalable and dynamic infrastructure for computing, storage, and network resources, it can support the rapid implementation of UAVs as well as associated services [263]. As a result, resources can be managed effectively, and it's possible to react instantly to the changing requirements of applications as they adapt. On the other hand, SD-cloud computing not only can integrate multiple SDUAV networks into a single coherent system but also can increase the coordination and collaboration between UAVs and 6G-enabled devices. Hence, these features are particularly essential for the mission-critical SDUAV functions that can offer greater situational awareness, enhanced agility, and increased efficiency for the 6G networks.

Software-defined IoT: The software-defined IoT (SD-IoT) is a novel networking technique that employs SDN concepts in IoT networks and devices so that it can improve the scalability, flexibility, and efficiency of the IoT to support the 6G features [138]. By combining SD-IoT with SDUAV networks, bandwidth utilization, resource management, and security can be improved. The performance, latency, and QoS of the UAV network also can be improved by enabling the dynamic control and administration of IoT networks. SD-IoT, on the other hand, can maximize the security of the IoT by implementing dynamic security policies and access control rules for IoT devices and nodes, preventing unauthorized access, and responding to possible threats [138]. As a result, more sophisticated network management techniques such as traffic shaping and load balancing can be applied to IoT networks and devices which can enhance the performance of the UAV networks in 6G. Hence, it is possible to create a more adaptable, effective, and secure networking environment for the SDUAV networks to support the 6G services like mMTC.

Software-defined antenna: Software-defined antenna (SDA) is a recent invention that utilizes programmable hardware and software to dynamically regulate antenna parameters like frequency, radiation pattern, polarization, and beamforming. To meet the increasing demand for high bandwidth in 6G systems and provide advanced communication technologies like dynamic beamforming, frequency agility, polarization agility, and adaptive tuning for the SDUAV systems, SDA can play a crucial role [264]. Therefore, integrating SDA with the SDUAV framework can enhance the optimal signal reception and transmission, resource management, and communication reliability to avoid interferences. Moreover, advanced antenna management techniques such as beam steering and nulling, can be applied to the antennas of the UAV networks to guarantee the effective and efficient utilization of antenna resources. Besides, dynamic antenna switching and diversity techniques also can be deployed in SDUAV systems to minimize signal degradation and communication loss and enhance the overall network performance in 6G communication systems.

Hybrid cloud networking: A network that runs on a hybrid model to exchange information and enables applications between on-premises information technology-related resources, private clouds, and public clouds can be referred to as hybrid cloud networking [265]. In a hybrid cloud, applications are executed not only in a hybrid computing environment that combines computing, storage, and services from both private and public clouds but also in on-premises data centers and edge locations. Therefore, with the help of telecommunication technologies, cloud services, and SDN, hybrid cloud computing offer more secure, reliable, scalable, and cost-effective features to support various 6G communication systems.

To fulfill the requirements of SDUAV prospects to support 6G, hybrid cloud networking can offer scalability, flexibility, offloading computing, and better resilience. One of the prominent advantages of hybrid cloud networking is the utilization of the public-private cloud infrastructure for the SDUAV networks. By employing this approach, private clouds can provide enhanced security and management over the confidential information and applications of SDUAV, while public clouds can provide scalable resources for data storage, processing, and analytics simultaneously [265]. At the same time, hybrid cloud networking also can provide a robust and resilient framework for SDUAV networks. By distributing resources across multiple cloud providers and destinations, hybrid cloud networking can provide redundancy and failover capabilities to ensure that the network remains operational even in the face of failures or disturbances. As a result, SDUAV networks can function more effectively and efficiently in 6G environments.

XII. CHALLENGES FOR SDUAV NETWORKS

Several types of technological challenges and obstacles can affect the implementation of SDN-enabled UAV network infrastructures. Hence, before the SDUAV systems are properly implemented, several technological issues must be rectified. Some of the significant issues that the SDUAV network might have to deal with are addressed below.

Network orchestration and management: To tackle the ultra-dense heterogeneous networks in the 6G system, network management will become one of the major challenges in SDUAV networks [63]. The centralized control system may create congestion in the SDUAV networks which not only can decrease the capabilities of the UAV networks but also can minimize the performance of the 6G systems as well. As a result, this will create difficulties for the UAVs to interact effectively with each other in the UCSs and also will decrease the network's dependability and stability [266]. Thus, to guarantee efficient and effective network operation in a dynamic and challenging environment, it is important to consider the design and management strategies of the SDUAV networks [49].

Heterogeneous hardware constraints: Due to different hardware configurations among different UAVs, the heterogeneous hardware constraints issue in SDUAV networking may emerge [251]. As a result, the throughput of the network might decrease and the latency might increase which will minimize the overall performance of the SDUAV networks. Moreover, it is crucial to control network traffic, guarantee network security, and enhance network functionality while taking into consideration the various hardware restrictions of the UAVs. Therefore, to meet this challenge, careful consideration of the network design and management strategies, as well as the hardware configurations of the UAVs, is necessary to guarantee efficient and effective network operation in the ultra-dense heterogeneous networks in the 6G system [251].

Spectrum and interference management: Spectrum and interference management can ensure effective and efficient communication between UAVs and also can minimize interference with other wireless devices in the 6G systems [251]. However, spectrum and interference management will be challenging issues for the future SDUAV networks. The inability to handle spectrum and interference can result in decreased network and UAV performance, communication breakdowns, and system failures in 6G networks [267]. Besides, this difficulty will restrict the UAVs' capacity for efficient data processing, coordinated operation, and the network's capacity for performance optimization. Consequently, to address these challenges, comprehensive considerations must be given to spectrum resources, interference management, and network design and administration strategies [267].

The complexity of resource management: The efficiency of the SDUAV network can be greatly impacted by the complex management of the resources in 3D networking. The signal strength and quality of wireless communication links between UAVs can differ, which can lead to connectivity problems and an increase in resource usage [90]. At the same time, managing spectrum and bandwidth also can create difficulties in 6G environments. To tackle these issues, advanced techniques such as power control, beamforming, and scheduling can enhance network efficiency [251]. Moreover, to keep the quality of communication, the network must quickly adapt to changes in the 3D environment. Therefore, for dependable and effective communication in 3D networking, advanced algorithms, and techniques are required for the SDUAV networks to support the 6G services [49].

Physical layer security: An SDUAV network may face major difficulties with physical layer security, which will impact its functionality and performance. To keep the network's confidentiality, integrity, and availability, wireless communication links between UAVs must be secured from hacking and jamming attempts [48], [266]. However, to avoid the depletion of resources, the network's limited resources must also be protected from unauthorized access or abuse. Therefore, to address these issues, UAV networks can utilize encryption and authentication methods, access control and intrusion detection mechanisms, and distributed algorithms and protocols for dynamic network configuration and optimization. Likewise, due to their mobility in 6G networks, UAVs also require rapid and effective radio environment adaptation to keep communication quality. In this regard, utilizing quantum technologies and machine learning algorithms can be an effective solution to ensure reliable and secure communication [266].

Planning economic perspective: Economic planning of an SDUAV network entails weighing the advantages and disadvantages of the various choices. It is necessary to take into account the long-term costs of technology, software, upkeep, and operations. A network's potential for generating income should be assessed, and future maintenance costs should be factored into the budget. In addition to complying with legal and regulatory requirements, possible effects on the environment and nearby communities should also be taken into account. Also, the selection process should go through an evaluation process to make sure the chosen framework can offer the best performance and cost-effectiveness balance while also guaranteeing compliance with all applicable legal and regulatory requirements. To design an SDUAV network economically, it is crucial to carefully consider the advantages and disadvantages of multiple possibilities [90].

Limited bandwidth: For information exchange and contact between the UAVs and the GCS, an SDUAV network requires huge bandwidth. Moreover, the available bandwidth may become constrained, particularly in areas with bad connectivity, which could lead to slower data transmission and communication rates in 6G networks [267]. Furthermore, limited bandwidth can impair the UAVs' ability to make real-time decisions, resulting in delayed or inaccurate answers [49]. However, this problem can be solved by using adaptive modulation and coding methods in the design of SDUAVs, which can maximize the utilization of the available bandwidth. Additionally, bandwidth for sensitive information can be prioritized and allocated using intelligent machine learning-based routing algorithms.

Latency and delay: In SDUAVs, data transmission, and processing may take longer, resulting in greater latency and delay. Since UAVs must navigate and avoid obstacles, this has an impact on the network's real-time decision-making capacity. However, SDUAVs can be built with low-latency communication protocols, such as the IEEE 802.11p standard for vehicle-to-vehicle transmission, to solve this issue [251]. Furthermore, edge computing and fog computing can be deployed to process data closer to the source, reducing the delay created by transmitting data to a centralized location for processing [267].

Security and privacy: SDUAVs are vulnerable to security risks like information leaks, cyberattacks, and jamming. The UAVs and the information they gather may become out of control if there is a network security attack [266]. When UAVs are deployed for crucial tasks like military activities or disaster relief, this can be especially worrying. To handle this issue, SDUAVs can be outfitted with robust security protocols such as encryption and authentication mechanisms. Furthermore, intrusion detection and protection systems can be added to UAVs to help them recognize and address security threats [49].

Scalability: As the number of UAVs grows, the SDUAV network might get crowded and function worse [251]. With numerous layers of UAVs communicating with each other and the BS, SDUAVs can be built with a hierarchical architecture to overcome this problem [49]. Depending on the quantity of UAVs and their communication needs, dynamic resource allocation algorithms can also be utilized to improve network efficiency [267].

Energy consumption: Batteries, which power UAVs, have a finite lifetime. In SDUAVs, the UAVs must share data with the GCS and communicate with it, which can use up a lot of energy. This could reduce the flight duration of UAVs and decrease their performance [49]. By incorporating energy-saving communication protocols like duty cycling and sleep modes, SDUAVs can be created to solve this issue. Additionally, energy harvesting systems, such as solar panels, can be fitted to UAVs. These systems can turn solar energy into electrical energy that can be utilized to power the UAVs. Other energy harvesting devices include wind turbines, piezoelectric generators, and thermoelectric generators. These systems can help extend the flight duration of UAVs and decrease the need for frequent battery replacements [268]. For additional savings lower the total energy consumption, UAVs can be built with energy-saving parts like low-power sensors and processors. By taking these steps, the total energy efficiency of an SDUAV can be increased which can also allow them to run more effectively and for longer periods.

Reliability: To guarantee the security and efficiency of UAV activities, the SDN-enabled UAV network needs to be dependable and resilient [64]. The efficacy of the SDN and the UAVs can both be impacted by network failures or outages, which could have negative operational and safety effects [48].

Interoperability: UAVs and SDN solutions may originate from different vendors or be developed independently, which could contribute to interoperability issues [48]. To fully utilize the SDUAV network, it is essential to make sure that UAVs and SDN systems can communicate with one another [90].

Economical perspectives: For an SDUAV network, costing is one of the biggest issues that can affect the system's efficiency [48]. The issue comes from the high cost of creating and deploying the necessary hardware and advanced networking infrastructure to support SDUAV networking. The affordability and scalability of UAV networks may be constrained by the expensive cost of hardware, software, and maintenance, especially in small-scale or low-cost applications [49]. To meet this challenge, hardware and software solutions that are affordable, scalable, and broadly accessible must be created. These solutions must support the efficient and effective operation of UAV networks. To create a networking infrastructure that is both affordable and effective and can support the expansion and adoption of UAV networks in various 6G applications and services, a collaboration between the hardware and software makers, network operators, and UAV operators is a must.

Specialized SDN-enabled networking hardware: To increase network efficiency and speed, an SDUAV network requires specialized SDN-enabled networking hardware [48]. The scalability and affordability of UAV networks, however, may be constrained by the price and accessibility of specialized hardware, which also will have an impact on the system's efficiency. This problem requires the development of innovative networking hardware that can accommodate the special needs of UAV networks and is scalable, affordable, and broadly accessible [49]. To overcome this issue and support the efficient and effective operation of SDUAV networks, specialized networking hardware must be developed [64].

Management and configuration complexity: In SDUAV networking, it is challenging to configure and administer SDN-enabled UAV networks. By increasing latency, decreasing network throughput, and degrading UAV performance, the complexity of the task has the potential to have a substantial effect on safety-critical applications. To overcome these challenges, it is essential to consider network architecture, policy development, and management strategies that ensure an efficient and effective network operation in a dynamic, challenging environment in 6G scenarios [49].

Regulatory environment: The performance of an SDUAV network is sensitive to the regulatory environment, which is an essential issue [48], [49]. The regulatory environment in SDUAV networking can limit the utilization of specific frequency bands, restrict UAV operation in specific airspace, and impose extra safety and security requirements. As a result, the network's performance may also be constrained by a decrease in the spectrum that is accessible and the addition of new security requirements that may harm network effectiveness [48]. To guarantee the secure and productive functioning of SDUAV networks in ultra-dense heterogeneous environments in 6G networks, cooperation is required between UAV operators, network operators, and regulatory authorities.

Dynamic network conditions: The operation of UAVs may be required in dynamic environments where network conditions can frequently change. For instance, the UAV might have to travel through obstacles, at different altitudes, or experience wireless device interference. To maintain stable wireless connectivity in 6G networks, the SDUAV framework must be able to adapt to these shifting network conditions [48].

Standardization: The development of a common set of protocols and interfaces for SDUAV networking is difficult due to the UAV business's lacks industry standards. This may restrict the network's ability to scale and create interoperability problems [90].

Regulatory compliance: UAVs are regulated by local laws, which can differ between nations and areas and include restrictions on power and frequency of use. To guarantee that the network can function legally in the deployment location, it must be designed to comply with these laws.

Limited connectivity: In certain deployment scenarios, the UAV may have restricted or temporary network connectivity, making real-time communication and data transfer challenging [267]. Using offline data caching and processing, for example, the network can be configured to handle these situations of limited connectivity [48]. Therefore, the network must be built to adhere to these strict specifications while keeping a high level of availability and reliability to support the 6G services [266].

Although the challenges impacting SDUAV networks are substantial yet are not impossible to overcome. To address these challenges, industries, governments, and universities are required to work together to define standards and protocols, support research and development, and develop efficient laws and norms. Despite all of such challenges, SDUAV networks have so many potential advantages to offer, and the technology can fundamentally revolutionize a wide range of services and applications in 6G systems.

XIII. CONCLUSION

As a candidate for future networking approaches to support the 6G systems, SDUAV networks have already emerged as a potential area of research in recent years. An SDVAV network can enable features like centralized controllability, programmability, and network automation which can support the services like uHDD, uMUB, uHSLLC, and mMTC in 6G systems. Therefore, the prominent advantages of SDN-based UAVs are massive, including advanced security, enhanced adaptability, and scalability, and can lead to more efficient and effective utilization of UAV-based communication systems. At the same time, recent technological advances like computer vision, AI, and machine learning can increase the programmability and intellectual decision-making probability, whereas techniques like blockchain and quantum computing can improve reliability and ensure security. However, there are also several difficulties with the adoption of SDN for UAV networking, including the requirement for innovative software and hardware, the development of novel algorithms and protocols, and the requirement for regulations and guidelines to ensure privacy and security. Despite these challenges, SDUAV networks have a wide range of potential prospects and opportunities in the 6G domains such as IoT, IoV, IIoT, IoE, military and defense operations, precision agricultural, construction, VR, AR, and XR related services, and super smart society. As technology advances, we can expect to witness many advancements in enabling technologies such as proactive caching, holographic beamforming, edge computing, fog computing, and big data analytics that will further increase the potential of SDN for UAV networking. In addition, advanced technologies and techniques for networking like OWC, 3D networking, DSS, DNS, backscatter communication, IRS, THz communication, and massive MIMO will undoubtedly improve the SDUAV systems' capability to function in collaboration with different networking and communication systems. Overall, the SDUAV network is a fascinating and swiftly expanding area of study that will continue to impact performance of the UAV-enabled communication systems and prospects as well as the services of the 6G systems. Motivated from these, this article comprehensively outlined prospective applications as well as the technological advances required for the implementation of SDUAV platforms. Additionally, the probable challenges and future research areas are also discussed that are essential for SDUAV networks to accomplish 6G goals. Hence, it is anticipated that this comparison study will be an invaluable resource for understanding research contributions in the rapidly developing field of SDUAV wireless technologies. Furthermore, this in-depth survey will motivate further endeavors to effectively incorporate SDUAV systems as an integral complement to traditional fixed BS-based cellular systems within the framework of future 6G as well as subsequent heterogeneous wireless networks.

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MD. ABU BAKER SIDDIKI ABIR (Member, IEEE) received the B.Sc. degree in electrical and electronic engineering (EEE) from the Khulna University of Engineering and Technology (KUET), Bangladesh, in 2018, and the M.Sc. Eng. degree in information and communication technology (ICT) from the Institute of Information and Communication Technology, KUET, in 2023. He has been working as an Assistant Network Engineer with the ICT Cell, KUET, since February 2020. He also served as a Lecturer with the Department of EEE, Imperial College of Engineering affiliated with the University of Rajshahi for one and a half years. He has published a few research papers in international conferences and journals. His research interests include software-defined networking, software-defined systems, UAV-based cellular networks, nonterritorial network, campus area network, optical wireless communication, Internet of Everything, digital-twin technology, mobile-edge computing, smart energy management, machine learning, and B5G/6G mobile communications. He also served as a Reviewer for IEEE ACCESS which is a well-recognized international journal.

MOSTAFA ZAMAN CHOWDHURY (Senior Member, IEEE) received the B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology (KUET), Bangladesh, in 2002, and the M.Sc. and Ph.D. degrees in electronics engineering from Kookmin University, South Korea, in 2008 and 2012, respectively. In 2003, he joined the Electrical and Electronic Engineering Department, KUET, as a Lecturer, where he is currently working as a Professor. He has been working as the Head of the Department of Biomedical Engineering, KUET, since April 2022. He was a Postdoctoral Researcher with Kookmin University from 2017 to 2019 supported by the National Research Foundation, South Korea. He has published research articles in top-quality journals, such as IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, IEEE TRANSACTIONS ON SERVICES COMPUTING, IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, IEEE SYSTEMS JOURNAL, *IEEE Communications Magazine*, IEEE COMMUNICATIONS LETTERS, *IEEE Consumer Electronics Magazine*, IEEE ACCESS, and *Nature Scientific Reports*. He was involved in many Korean government projects. His research interests include convergence networks, QoS provisioning, small-cell networks, Internet of Things, eHealth, 5G and beyond communications, and optical wireless communication. In 2008, he received the Excellent Student Award from Kookmin University. His three papers received the Best Paper Award at several international conferences around the world. He received the Best Reviewer Award 2018 by *ICT Express*. Moreover, he received the Education and Research Award 2018 given by the Bangladesh Community in South Korea. He was a TPC Chair of the International Workshop on 5G/6G Mobile Communications in 2017 and 2018. He has been serving as the Publicity Chair of the International Conference on Artificial Intelligence in Information and Communication from 2019 to 2023 and the International Conference on Ubiquitous and Future Networks in 2022 and 2023. He served as a Reviewer for many international journals, including IEEE, Elsevier, Springer, ScienceDirect, MDPI, and Hindawi published journals and IEEE conferences. He has been working as an Editor of *ICT Express*, an Associate Editor of IEEE ACCESS and *Frontiers in Communications and Networks*, a Lead Guest Editor of *Wireless Communications and Mobile Computing*, and a Guest Editor of *Applied Sciences*. He has served as a TPC member for many IEEE conferences.

YEONG MIN JANG (Member, IEEE) received the B.E. and M.E. degrees in electronics engineering from Kyungpook National University, South Korea, in 1985 and 1987, respectively, and the Doctoral degree in computer science from the University of Massachusetts, USA, in 1999. He was with the Electronics and Telecommunications Research Institute from 1987 to 2000. Since 2002, he has been with the School of Electrical Engineering, Kookmin University, Seoul, South Korea, where he was the Director of the Ubiquitous IT Convergence Center from 2005 to 2010, and has been the Director of the LED Convergence Research Center since 2010, the Internet of Energy Research Center since 2018, and the AI Mobility Research Institute from 2021 to 2023. He has also been granted more than 120 patents. His research interests include 5G/6G mobile communications, Internet of Energy, ESG, IoT platform, AI platform, eHealth, smart factory, optical wireless communications, optical camera communication, AI mobility, and Internet of Things. He was the recipient of the Young Scientist Award from the Korean Government from 2003 to 2006 and the KICS Dr. Irwin Jacobs Award in 2018. He has organized several conferences and workshops, such as the International Conference on Ubiquitous and Future Networks from 2009 to 2017, the International Conference on ICT Convergence from 2010 to 2016, the International Conference on Artificial Intelligence in Information and Communication since 2019, the International Conference on Information Networking in 2015, and the International Workshop on Optical Wireless LED Communication Networks from 2013 to 2016. He served as the Founding Chair of the Korean Institute of Communications and Information Sciences (KICS) Technical Committee on Communication Networks in 2007 and 2008. He had served as the Executive Director of KICS from 2006 to 2014, the Vice President of KICS from 2014 to 2016, and an Executive Vice President of KICS in 2018. He was the President of KICS in 2019. He was the Organizing Chair of the Multi-Screen Service Forum from 2011 to 2017 and the Society Safety System Forum from 2015 to 2021. He has been the Organizing Chair of ICT Convergence Korea Forum since 2017 and the ESG Convergence Forum since 2022. He served as the Chairman of the IEEE 802.15 Optical Camera Communications Study Group in 2014 and the IEEE 802.15.7m Optical Wireless Communications TG from 2015 to 2019. So, he successfully published IEEE 802.15.7-2018 and ISO 22738:2020 standards. He has been the Chairman of IEEE 802.15.7a Higher Rate and Longer-Range OCC TG since 2020. He is the Editor-in-Chief of *ICT Express* (indexed by SCIE).