6G NR-U Based Wireless Infrastructure UAV: Standardization, Opportunities, Challenges and Future Scopes

ROJEENA BAJRACHARYA[1], **(Senior Member, IEEE),**
RAKESH SHRESTHA[2], **(Senior Member, IEEE), SHIHO KIM**[2], **(Senior Member, IEEE),**
AND HAEJOON JUNG[1], **(Senior Member, IEEE)**

[1]Department of Electronic Engineering, Kyung Hee University (KHU), Yongin 17104, South Korea
[2]School of Integrated Technology (SIT), Yonsei University, Incheon 21983, South Korea

Corresponding author: Haejoon Jung (haejoonjung@khu.ac.kr)

ABSTRACT Providing ubiquitous connectivity for people and equipment with a wide range of service conditions is regarded as the major design goal of 6G networks. Moreover, the future 6G networks need to be extremely flexible to enable reliable and low-latency access for the dynamic number of mobile user equipment. The current base stations (BSs) and remote relay antennas are mostly, on the other hand, installed at fixed geographic locations based on long-term traffic patterns with little re-deployment flexibility. For most 6G applications, where dynamic data traffic occurs in both spatial and temporal domains, such rigid radio access networks (RANs) are unable to maintain ubiquitous connectivity. On the other hand, the rapid advancement of unmanned aerial vehicle (UAV) technology is creating a unique opportunity for the cellular operator to realize flying wireless infrastructure called wireless infrastructure UAV (WI UAV). WI UAV supports wireless connectivity and can stir itself to improve spectral efficiency, coverage, and quality of service of the end-users. This paper introduces 6G new radio in the unlicensed band (NR-U)-based WI UAV that can be used as a base station, relay, or data collector/disseminator. UAV are categorized based on their characteristics, applications, and operations. Further, this paper discusses various regulatory and standardization initiatives for integrating UAVs into the cellular network. Non-standalone NR-U network architecture is designed and explained for WI UAV. Several opportunities and design challenges of NR-U for the WI UAV are discussed and future scopes of WI UAVs are presented.

INDEX TERMS 6G, cellular network, NR-U, UAV, ubiquitous connectivity, wireless infrastructure.

I. INTRODUCTION

The demand for ubiquitous connectivity for a wide range of user equipment's (UEs) such as remote sensors/actuators, self-driving cars, enhanced mobile broadband (eMBB) equipment, etc. has been a major challenge for 5G network in a variety of applications such as reconnaissance, emergency, or rescue operations, agriculture, surveillance, and inspection [1], [2]. Thus, the future 6G networks will need to support these challenges with extreme flexibility to enable the reliable and low-latency access of large numbers of

The associate editor coordinating the review of this manuscript and approving it for publication was Yafei Hou.

mobile UEs. Most of the base stations (BSs) and remote relay antennas are installed at fixed geographic locations based on long-term traffic patterns with little re-deployment flexibility. Such conventional radio access networks (RANs) will be unable to sustain a ubiquitous connection for most 6G applications because dynamic data flow occurs in both geographical and temporal domains. Thus, to enhance RAN's flexibility for supporting massive dynamic connections, the cellular operators have switched their focus from terrestrial to airborne communications. Promoted by the mature flight control technologies and various commercial unmanned aerial vehicle (UAV) products, the various types of airborne terminals are now being researched and developed all over

the world [3], [4]. Specifically, UAV, commonly known as a drone, has gained large attention as it operates autonomously without a human pilot onboard or partially controlled remotely by a human pilot. The widespread availability of embedded wireless interfaces and softwarization of UAV networks in the communicating entities has allowed the deployment of such a paradigm simpler and easiest way possible into the next generation of mobile network [5], [6]. Furthermore, because of their controlled mobility and customizable heights, UAVs are the best choice for improving performance and overcoming the limitations of terrestrial networks. The industries and academics are developing a wireless infrastructure UAV (WI UAV) that can offer wireless service on the move and dynamically re-position itself to increase spectrum efficiency, availability, coverage, and end-user quality of experience (QoE) [7]. For this, WI UAV can serve as a flying relay node or a base station (BS) or a data collector/disseminator [8]. Some of the potentials of UAVs are the ability to move freely in three-dimensional (3D) space, hover in one location with little restrictions, and have low deployment and maintenance costs [9]. These factors have been highly attributed to the rise and popularity of WI UAV in 6G communication networks [10].

WI UAV can extend the accessibility of a cellular network or boost its capacity in areas where conventional networks are difficult to deploy [7]. It facilitates fast deployment in disasters and crises, such as aiding with evacuation if communications infrastructure is disrupted or delivering capacity for overcrowded events on demand [1], [2]. Multi-hop UAV relaying is one of the potential way for establishing emergency networks to realize information exchange between the disaster areas and outside [11].WI UAV's major application include ubiquitous connection assistance for autonomous vehicles, reconnaissance and armed attacks, remote sensor data dissemination [12]–[14]. Several proof-of-concept or prototypes of WI UAV have already been tested in the real environment by famous tech companies such as Facebook's Aquilla, Google's Loon, Huawei's Digital Sky, Eurecom's Perfume, Nokia's F-cell, and many more [15].

For communication, UAV has no dedicated spectrum. The existing frequency usage by UAVs is facilitated by the unlicensed band as well as the licensed band. WI UAV connectivity services typically deal with military, individual, commercial, and private data, therefore WI UAV must provide trustworthy, resilient, and secured wide-area connections. In this context, licensed band cellular networks seem to be the best option for its features [8], [15], [16]. However, the licensed spectrum is costly and scarce. It will be difficult for cellular carriers to dedicate a new spectrum specifically to the functioning of each WI UAV. Furthermore, any attempt to reuse licensed spectrum might cause serious inter-cell interference with sophisticated terrestrial network systems. Therefore, a free unlicensed band with the potential to increase spectrum consumption through spectrum sharing is a promising approach for the WI UAV communication

service [17]. In this context, the third generation partnership project (3GPP) Release-16 (Rel-16) New Radio in the Unlicensed Band (NR-U) contains the required technologies to introduce WI UAV into the unlicensed spectrum [18], [19]. Some of the significant benefits of adopting NR-U are as follows [17]:

- Abundantly available unlicensed spectrum
- Similar band plans around the globe, which provide advantages for multi-user sharing
- Newly open bands i.e., 3.5 GHz that are less congested
- Larger mid-band spectrum with lower transmit power, which offers optimal deployment possibility of small-cells WI UAV coverage providing strong channel propagation performance

In this article, the overview of UAVs and their categories based on various classifications are discussed at first. Then, the paper introduce a 5G NR-U based WI UAV that may serve as a BS, relay, or data collector are elaborated. The regulatory and standardization initiatives in both academia and industry are examined to incorporate UAVs into the cellular network. Further the operational frequencies and security concerns related to UAV has been discussed in detail. After that, the non-standalone NR-U network architecture for WI UAV is proposed and discussed to increase throughput. The numerous NR-U options for the WI UAV are presented, and design challenges are discussed. Lastly, the future scopes of WI UAV technologies are discussed. The structure of the paper is presented in Fig. 1.

The main contribution of the paper are as follows:

- This paper proposes UAVs as one of the important infrastructures for wireless connectivity in areas, where the conventional terrestrial networks are difficult to reach.
- The exiting WI UAV testbeds, prototypes, and standardization approach are deeply researched and presented in detail.
- Various aspects of WI UAV such as characteristics, applications, operation, types, and services have been deeply investigated and discussed.
- The new integration idea of NR-U technology with WI UAV technology was introduced along with the comprehensive design architecture, opportunities, challenges, and future scopes.
- The simulation results of spectrum sharing based WI UAV with traditional traffic offloading method are presented.

II. UAV

UAVs are flying vehicles that can fly in the designated aerospace remotely controlled by human operators or fly autonomously without human intervention. UAV was first produced for military application and Radioplane OQ-2 was the first mass-produced drone during World War II in US. UAVs have seen a rapid surge in applications due to its great aerial mobility, advanced battery technology, sophisticated rotors, sensors, GPS, gyroscopes, cameras,
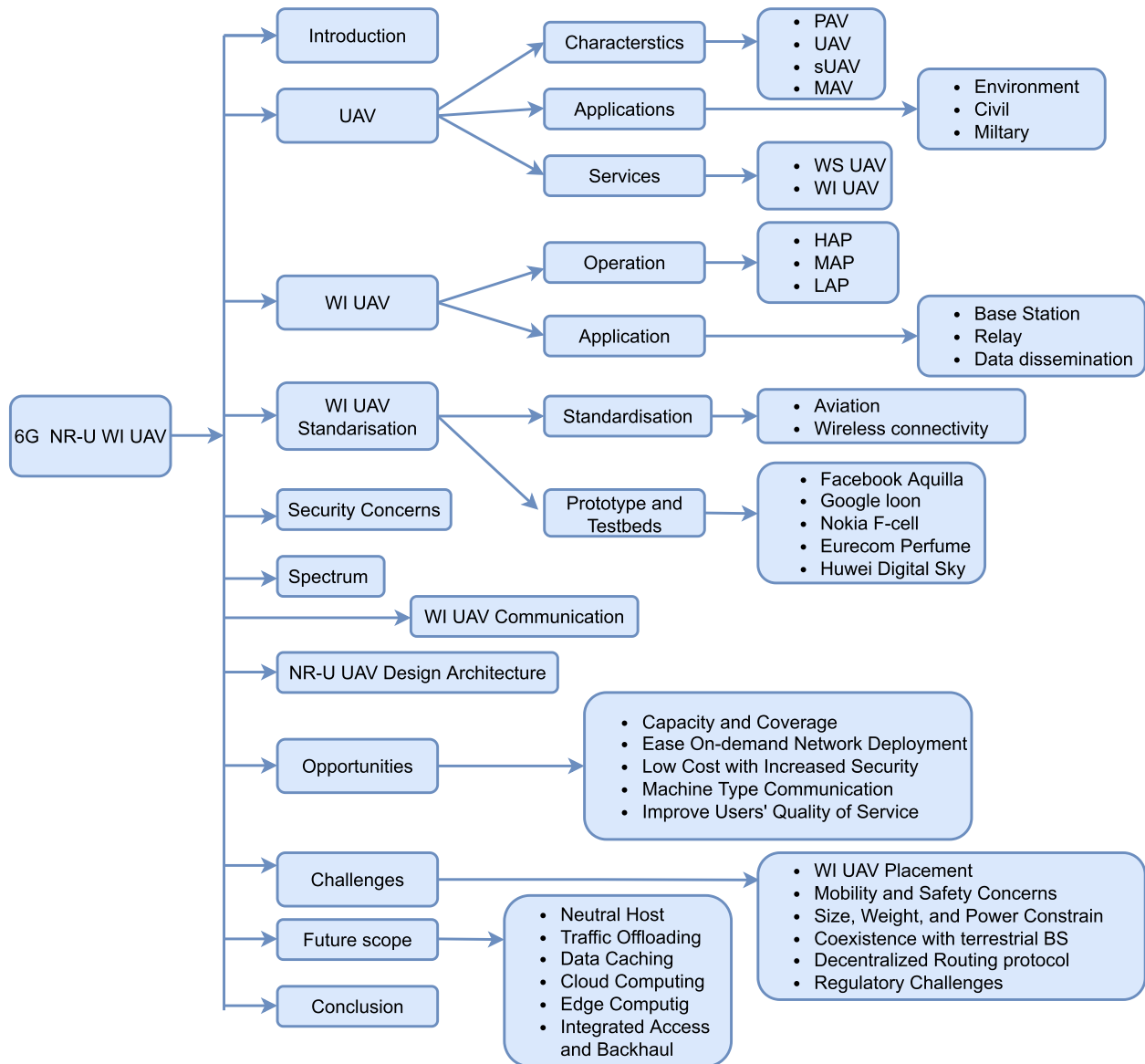
FIGURE 1. Structure of the paper.

cheap manufacturing costs etc. Recently, UAVs and drones have become important robotic equipment for technical applications and recreational consumer equipment.

A. TYPES OF UAVs BASED ON CHARACTERISTICS

The UAVs or aerial vehicles can be classified into different categories based on various characteristics and parameters such as flight capabilities, body length, rotor size, altitude, velocity, weight, air time, etc., according to [20]. Basically, the aerial vehicles can be categorized into micro aerial vehicles (MAV), small UAV (sUAV), UAV and personalized aerial vehicles (PAV). MAVs weight ranges from 50g to 2kg with a flight range of less than 10km. They might have fixed wings, flapping wings, vertical take-off and landing

plane (VTOL), and rotary wings with varying wings size from 15 cm to 1m. The sUAVs are very light weight UAVs whose weight ranges from 2kg to 5kg with a wingspan of 1m to 2m. They are capable of flying with a flight range of 10km to 15km with one time battery charge. The UAV category consists of wide array of unmanned vehicles from mid-range to advance architecture based on their models, configuration, take-off and landing properties. These UAVs consisting of diverse weight (5∼150 kg), wingsize (2∼7 m), and flying range (10∼250km). The PAV category consists of huge aerial vehicles used for human transportation as well as cargo deliveries from one point to another. It has higher weight (140∼1500 kg), greater wing size (>7 m) and long distance endurance with a flight range greater than 250km.
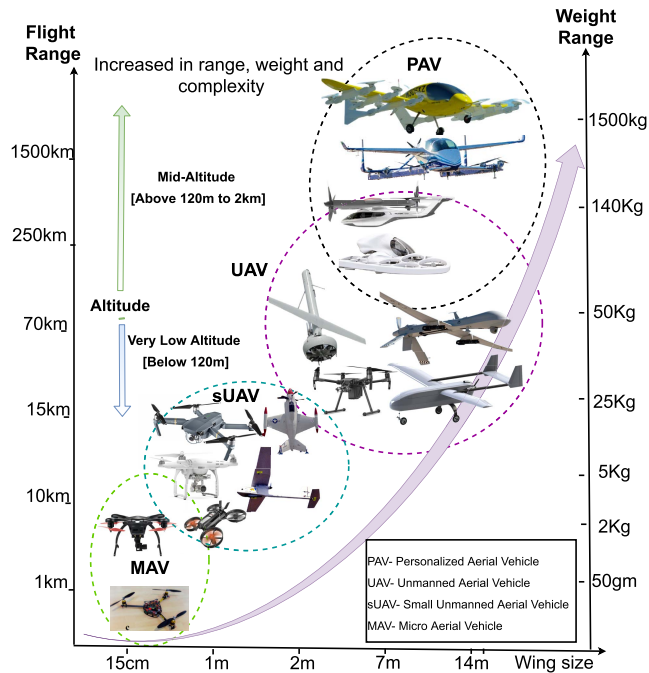
FIGURE 2. Comparison of various kinds of WI UAVs depending on several criteria.

Currently, these types of aerial vehicles are used by military for defense, however, commercial and private PAVs will be deployed soon along with the progress of urban air mobility. Fig. 2 shows various categories of aerial vehicles along with their properties.

B. TYPES OF UAVs BASED ON APPLICATIONS

The UAVs provide advantages in terms of affordable access, easy data collection, low energy consumption, less risk to humans, logistics etc. The UAVs can be categorized into civil, environment and military based on their potential applications as shown in Fig. 3. UAVs have a wide range of application in civil sector such as UAVs are helpful in performing search and rescue operations of missing people, aerial photography, recreation, construction, manufacturing, transportation, inspection of electric power lines, logistic deliveries, surveillance, crowd monitoring, mining, archaeology, etc. One of the important application of UAVs is delivering medical facilities and medicines in critical situations. UAVs are equally useful in environmental sectors such as wildlife conservation surveillance, pollution monitoring, crop monitoring, mountain inspection, land and water monitoring [21]. UAVs are also used for scientific research such as oceanic, atmospheric and hurricane monitoring at inaccessible areas for humans. UAVs were first launched to carry out military operations such as intelligence, spying, reconnaissance, monitoring, target identification, etc., and subsequently they were used for civilian and environmental purposes. In military sectors, UAVs are used in warzones, spying, combat aircraft, attack and missile launching, border surveillance, etc.

C. TYPES OF UAVs BASED ON SERVICES

From a communications perspective, the UAV can be classified into a wireless service UAV (WS UAV) and a wireless infrastructure UAV (WI UAV). UAVs under the first category are user equipment of the wireless networks, which might include private UAV networks. These types of UAVs are utilized in a wide range of applications, including transport and logistics, surveillance and monitoring, and inspections and surveys. WS UAVs are mostly supported from the ground station hence establishing two types of communication with a ground control station. First, the command-and-control link is utilized for remote piloting, navigation, identification, telemetry data, and other purposes. The second kind of link created with a ground control station is the application link, which transmits data like sensor data, audio, video, and graphics. Different from WS UAV, WI UAV serves as aerial nodes with all or some of the functionalities of access point or BS to increase network capacity and coverage in order to improve network capabilities. WI UAV is mainly used in increasing capacity on-demand, expanding service area, improving reliability and efficiency as an aerial station to ground or air. This can be categorized based on their functions and requirements. such as UAV as a BS, UAV as a relay, and UAV as a data collector/disseminator. WI UAV is a fairly new approach and a detailed explanation can be found in the following subsections.

III. WIRELESS INFRASTRUCTURE UAV

WI UAV is a system for wireless communication that uses UAVs as infrastructure to provide a wireless aerial connection for devices that do not have easy access to terrestrial connectivity [22]. The UAV's flexible design of movement and significant ease of deployment are very helpful for fulfilling a variety of the next-generation wireless network requirements, such as providing coverage in hotspots or regions with limited infrastructure. Moreover, due to UAV's high altitude operation, there is always a better chance of establishing a line-of-sight (LOS) contact with ground users, resulting in more reliable communication links and larger coverage regions. Hence, the WI UAV might be used for a variety of purposes, including 1) offloading BSs in densely populated regions and 2) providing coverage for remote regions, which generally have poor cellular coverage due to a lack of incentives for operators.

Typically, based on the altitude and functions of the UAVs, there are three types of WI UAV platforms. Specific WI UAV platforms can operate at a specific height, allowing them to resist both flying and operational conditions such as weather, wind, and temperature. They also provide services ranging from monitoring, broadband connectivity, and backhaul connectivity as shown in Fig. 4. The three types of platforms based on altitude are as follows:

A. TYPES OF WI UAV BASED ON ALTITUDE OPERATION
1) HAPS

HAPS are high-level aerial platforms located a stratospheric layer at an altitude of 15km to 25km from the ground
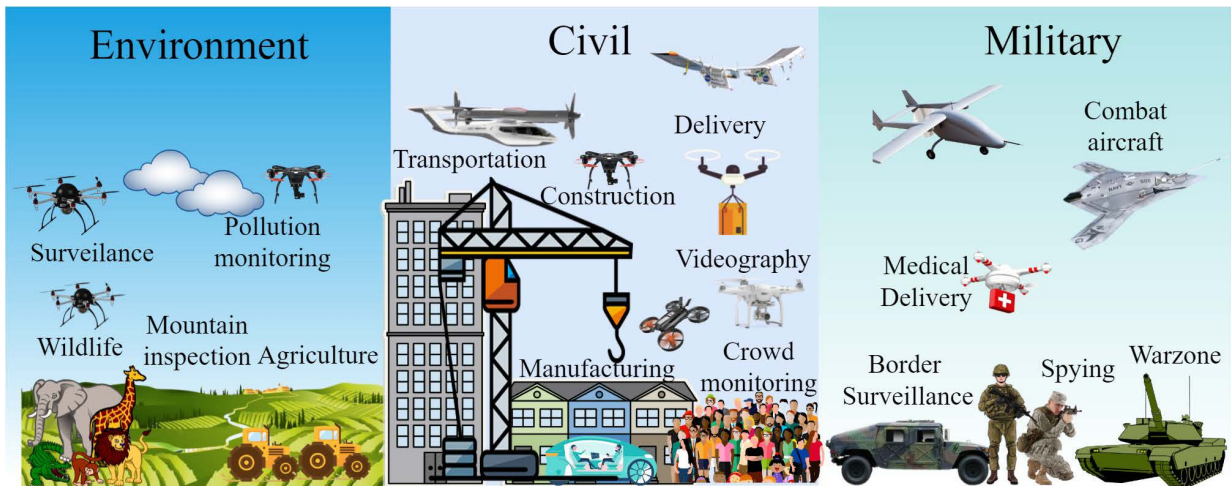
FIGURE 3. Comparison of different types of WI UAV based on applications.

level [23]. HAPS can deliver a very wide range of communications up to radius of 30km geographical range. Some of the communication services include broadband communication, cellular communication, and emergency services. These platforms can be manned, unmanned aircraft, or airships that can carry weights ranging from a few kilos to several tons and stay in the air for several hours to several years based on their nature, size, power limitations, and energy capacity. HAPS provides ubiquitous and extended coverage for multiple aerial platforms at lower levels via backhaul and fleet coordination functions that are based on free-space optics (FSO).

2) MAPS
MAPS are mid-level aerial platforms located below HAPS at an altitude of 5km to 15km from the ground level. MAPS can be used as a relay between HAPS and LAPS. The MAP can be used with extended endurance capabilities as well as manned aerial vehicles, depending on the operating environment. UAVs in these platforms can stay in the air for several hours with heavier payloads to act as relays and are typically used for military tasks. The MAP coverage area is anticipated to have a radius of up to 5km.

3) LAPS
LAPS are low-level aerial platforms located below MAPS at an altitude up to 5km from the ground level. LAPS can be used as a flying BS, where a BS is mounted on the LAP nodes, to provide extended connectivity to locations where terrestrial networks are not available. In addition, LAPs can offer service to access points by placing backhaul or fronthaul hub on LAP to form an aerial backhaul or fronthaul center that can send and receive traffic information between terrestrial BSs and ground gateways. If there is an issue then the traffic can be routed to a higher level such as MAPS, HAP or a satellite [24]. LAPS are characterized by small size, limited payload, strength, and can be rapidly deployed as fleets. LAPS can

be deployed as traffic offloading from an overcrowded BS during a sports event or disaster environment.

B. TYPES OF WI UAV BASED ON APPLICATION
Furthermore, there are several applications of WI UAVs due to their low cost, high flexibility, capacity to hover in the air, and fast-easy deployment capacity. It can be used in all types of scenarios such as wide surveillance, calamity monitoring, delivery, emergency-situation aid, etc. In terms of wireless communication, the use of a radio access node or BS onboard a drone to improve coverage in various circumstances has already caught the attention of the community. From the application perspective, the WI UAV can be categorized into three types and they are as follows:

1) WI UAV AS BASE STATION
The drone provides the communication infrastructure for the ground nodes to communicate and connect with the 5G/6G core networks via the BS module attached to the drone. [25]. The WI UAV as BS can be easily implemented if BS on the drones has the capability to connect with the 5G/6G core networks. The fleet of drones can self-organize to form a network of drones and can provide seamless coverage within the serving locations. Even if the terrestrial BS malfunctions due to various reasons such as power cuts or natural disasters, the WI UAV can act as BS and provide fast service recovery after infrastructure failure. It can even be used for offloading data from the terrestrial BS. Some of the common applications in this category are emergency support, temporary coverage for terrestrial users, hot-spots applications, etc.

2) WI UAV AS RELAY
This type of application uses a WI UAV equipped with a radio access node which connects with the terrestrial BS, subsequently it connects with the 5G/6G core network [26].

That means the WI UAV acts as a relay UAV for providing communication infrastructure, where it provides connectivity to more than one neighbor UAV/drones to extend its relay connectivity. This type of application is most common in military operations where secure wireless communication is required for data transfers between the front line and the headquarter or data centers. Some of the examples are the WI UAV as relay can be used in a situation where there are no terrestrial networks available such as mountainous terrain where two WI UAV relays can be used to transmit signals to the other side of the mountain.

3) WI UAV AS DATA COLLECTOR/DISSEMINATOR

Data collection and dissemination by autonomous sensors is one of the crucial tasks in remote locations where human presence is not available or at least very difficult to reach. In such scenarios, Air-to-ground and ground-to-air data transfers are supported by UAVs with radio access nodes, allowing sensor networks to gather and disseminate data [27]. The WI UAV as data collection and dissemination are capable of working as a delay-tolerant sensory data exchange medium for wireless sensors that provide cheap, easily implementable backhauling solution [28]. Some of the applications scenarios in this category are periodic sensing and information multi-casting for ground sensors and vehicles. It can also be deployed for data collection operations in hostile situations and difficult terrains.

IV. WI UAV STANDARDISATION

WI UAV constitutes flight on the top of connectivity, therefore there are mainly two areas that establish the criterion for WI UAV standards: (a) aerospace technology for UAV flight control standard and (b) wireless communications technology for communication standard.

A. AVIATION STANDARDISATION

In the United States, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) are in charge of UAV flight operations, while in Europe, the European Aviation Safety Agency (EASA) has been in operation. Similarly, in Asia, the International Civil Aviation Organization (ICAO) is responsible for formulating WI UAV operation regulations. All of these organizations have the same goal: to govern WI UAV operation while taking into account a range of factors such as WI UAV category and identification, WI UAV's height, speed, and weight of operation [20], [29].

B. WIRELESS CONNECTIVITY STANDARDIZATION

The Federal Communications Commission (FCC) and Electronic Communications Committee (ECC) in the US and Europe respectively, are the regulating authorities for drafting wireless regulations [30] for UAVs. The communication standardizing for WI UAV was first initiated by 3GPP in 2017, followed by the International Telecommunication Union (ITU) in the same year, and subsequently, the Institute of Electrical and Electronics Engineers (IEEE) joined a year later. As shown in Table 1, these three standard bodies have actively contributed several technical reports and sections via intensive theoretical and practical investigations that help in the development of WI UAV [4]. The four basic objectives of the 3GPP wireless communication standard for WI UAVs are as follows:

- Understanding WI UAV traffic specifications;
- Creating a channel model to describe the properties of air-to-ground propagation;
- Determining if current LTE infrastructure can be leveraged to provide cellular service to aerial UEs;
- Defining the changes needed to support WI UAVs efficiently based on LTE Rel-14 functionality.

Later, in Rel-15, the studies were improved with LTE support for aerial vehicles, resulting in the TR 36.777 and TS 36.331 technical reports and specifications, respectively [31]. Rel-16 contained early research on remote detection of unmanned aerial systems (TS 22.125). Rel-17 investigated enhanced UAVs Stage 1 (TR 22.829, TS 22.125, New TR 23.755, TR 23.754), which included application layer support for UAS connection, identification, and tracking. In addition, Rel-17 included UxNB, an on-board radio access node for UAVs [32]. UxNB is a UAV-borne radio access node that connects UEs to the Internet as well as a UAV traffic management system. The following are the primary study topics in UxNB:

- The 5G system should support UxNBs to provide improved and more flexible radio coverage.
- The 3GPP system should provide adequate controls for the functioning of the UxNBs (e.g. to start operation, stop operation, replace UxNB, etc.).
- The 3GPP system should provide mechanisms for reducing the UxNBs' power usage. (e.g. optimized operation parameters, optimized traffic delivery, etc).
- The 3GPP system should minimize interference caused by UxNBs shifting locations.

The 3GPP RAN standardization team began discussing the scope of Rel-18 June 2021 as a beginning of 6G or 5G advanced. This release mainly consider to include more intelligence into wireless networks by including suitable machine-learning-based techniques in different levels of the UAV communication network [33]–[36]. Apart from only increasing communication speed and capacity of WI UAV [37], some of other interesting WI UAV-related enhancements goals in Rel-18 also known as "6G and beyond drones" are RAN enhancements for the remote control of drones, rogue drone detection to improve the situational awareness of first responders, Internet of drones or a connected sky with drones [38], marine communication drone [39] etc. Moreover, with a recent inspiring example, the NASA's perseverance rover carrying a drone helicopter landed on Mars on February 18, 2021, interplanetary drone communications and networking will be considered on the path to 6G and beyond [38], [40].
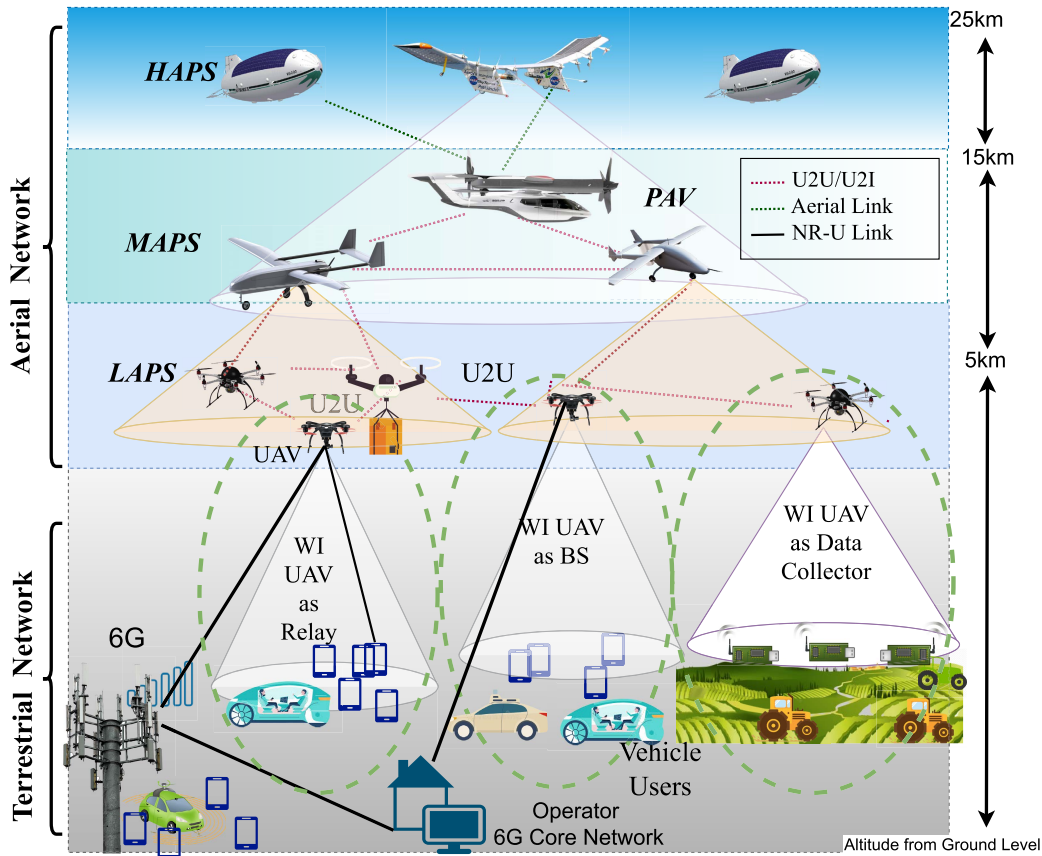
FIGURE 4. WI UAV deployment scenario.

C. PROTOTYPES AND TEST-BEDS

Several WI UAV test-beds and UAV prototypes have been built and demonstrated during exhibitions and commercial events in tandem with the standardization and parameter definition process for WI UAV aviation and communication. The main objective of these test-beds is to improve user experience by dynamically installing WI UAVs as required to increase coverage where terrestrial wireless infrastructure is not available. Table 2 lists the most notable prototypes or test-beds along with their features. Some of them had been carried out where the UAVs were used as BSs at high altitudes. In 2016, Facebook launched Aquila project that used high-altitude autonomous UAVs as BSs to provide Internet access in remote locations [41], [42]. The UAVs are positioned at an altitude between 18 to 20km providing coverage at a range of 100km. Aquila utilizes free space optic (FSO) connections to ground access points, which then serve terrestrial users through Wi-Fi or LTE technologies. However, this project was closed due to a failure in landing operation in 2018. In 2011, Google started Loon project that launched balloons at a high altitude of 18 to 25km in the stratosphere [43]. It operates on radio frequency 2.4GHz and 5.8GHz ISM bands providing a data rate of 1 Mbps from ground stations to the user devices via the balloons. The

Nokia F-cell project is a self-configured and auto-connected drone used as a BS for low altitude applications in 2016 [44]. It is a solar-powered BS prototype consisting of 64 antennas for backhaul communication. The F-Cell architecture is redesigned to provide completely ''wireless'' networking by eliminating the power and backhaul connections required in conventional small cell. This feature was obtained by utilizing massive multiple-input-multiple-output (MIMO) spatial multiplexing below 6GHz to realize high-capacity wireless networks under non-LOS circumstances. European Research Council started the Eurecom PERformance FUture Mobile nEtworking (PERFUME) in 2015 and the project was funded for five years until 2020 [45], [46]. This project investigated and introduced ''autonomous aerial cellular relay robots,'' in which UAVs serve as relay BSs to improve connectivity and throughput for commercial endpoints. Its main goal is to create machine learning algorithms that can locate and regularly update the appropriate 3D position of airborne wireless relays utilizing fine-grained data about their LOS circumstances as well as other wireless data. In 2017, Huawei initiated digital Sky to enhance low airspace network coverage in its Wireless X Lab [47]. It was located at an altitude of 200m from the ground level with two authorized fly zones having a 3km radius. It used cellular networks to

TABLE 1. Efforts for standardizing WI UAV communications.

Efforts	Organisation	Year	Standard	Status
UAV and UAV controller functional architecture based on IMT-2020 networks	ITU	2017	ITU-T Y.UAV.arch	Finalization in 2021
Civilian UAV communication service requirements	ITU	2019	ITU-T F.749.10	Finalization in 2020
Framework standard for drone applications	IEEE	2018	IEEE P1936.1	Finalization in 2022
Standard framework of low-altitude airspace structuring for UAV operations.	IEEE	2019	IEEE P1939.1	Finalization in 2021
Standard for airborne communication and networking	IEEE	2020	IEEE P1920.1	Finalization in 2021
SID has been revised to include improved support for UAVs	3GPP	2017	3GPP Rel-15 (RP-171050)	Finalized
Improved LTE connection for aerial vehicles	3GPP	2018	3GPP Rel-15 (TR 36.777)	99% Finalized
Support for UAV systems (UAS) in the 3GPP	3GPP	2018	3GPP Rel-17 (TS 22.125)	Finalized
Enhancement of 5G for UAVs	3GPP	2018	3GPP Rel-17 (TR 22.829)	Finalized
Support for aerial vehicles, system communication, identification, and tracking are investigated	3GPP	2020	3GPP Rel-17 (TR 23.754)	50% Finalized
Investigation on application layer functionalities for UAS	3GPP	2020	3GPP Rel-17 (TR 23.755)	45% Finalized
Study on enhanced architecture for UAS Applications	3GPP	2021	3GPP Rel-18 (TR 23.700)	10% Finalized
NR support for UAV (Uncrewed Aerial Vehicles)	3GPP	2021	3GPP Rel-18 (TR 21.900)	0% Finalized
Study on Phase 2 of UAS, UAV and UAM	3GPP	2021	3GPP Rel-18 (TR 23.256)	0% Finalized

ensure Command and Control communication (C2) between drones and ground controller stations.

V. SECURITY CONCERNS IN WI UAVs

An attacker cannot carry out an attack without first developing an attack vector, which is the technique an attacker employs a vulnerable route to spread malicious code or obtain illegal access. So, verifiable UAV end-to-end pathways for safety and operational situations should be included in the design stage before implementation, and all functional and nonfunctional paths must be evaluated afterward. WI UAV are in the early stages so they are more vulnerable to electrical/electronic, cyber, and physical attacks [20], [48]. We will briefly discuss some of the physical, electrical and electronics attacks, and cyber attack.

In a physical attack, the WI UAVs are attacked physically through various means to take down the UAVs. The attackers perform UAV napping to detain the air vehicles in order to gather critical data by using numerous susceptible interfaces such as Bluetooth, USB, WiFi, etc. Some of the physical attacks are:

- Force takedown: The attackers use physical means to take down the UAV by using stones, net or any other

means. They might potentially tamper with and destroy UAVs by employing external equipment or physical effort to aggravate the attack.
- Intentional collision: The enemy may use their attack drones to intentionally collide with the drones and crash on the ground with the intention to take the data or memory.
- Enemy attack: Similarly, the enemy tries to fire the UAVs in a tactical environment by using fire, guns, etc. They attempt to physically damage the drones so that the drones do not take crucial information to their base.
- Birds/animal attack: Sometimes, various birds and animals may attack the drones while flying. The animals might crash or destroy the drone if it comes into their captivity.

The electrical and electronic attacks are a severe threat to WI UAV, and if well developed by an attacker using the necessary tools and technologies, they may have severe negative consequences for the unmanned aircraft. Some of the electronic attacks are as follows:

- GPS/communication jamming: Attackers will send out jamming signals using jamming devices such as commercial off-the-shelf (COTS) jammers on the same

TABLE 2. WI UAV prototypes and test-beds.

| Prototypes	Year of operation	Features
Facebook Aquilla [41], [42]	(2016-2018)	• Stations providing remote areas with Internet access (HAP) • A range of 18-20km with a coverage of 100km • Suspended due to structural failure that occurred during landing operations.
Google Loon [43]	(2011-2021)	• The use of a stratospheric balloon for relaying data from the ground to users (HAP) • A range of 18-20km with 1 Mbps data rate • Operates on ISM bands of 2.4 and 5.8 GHz
Nokia F-cell [44]	(2016)	• A self-configuring and auto-connecting drone • Provides support for non-LOS • Utilize the 6GHz band
Eurecom Perfume [45], [46]	(2015-2020)	• Base stations for relay services • The best 3D position of flying wireless relays is continuously discovered and updated through machine-learning techniques.
Huawei Digital Sky [47]	(2017)	• Improved coverage of low-altitude networks. • Flying zones approved for 6km diameter, 200m altitude maximum with wireless charging zones scattered on the ground • Use cellular network for Command and Control communication (C2) between drones and ground controllers.
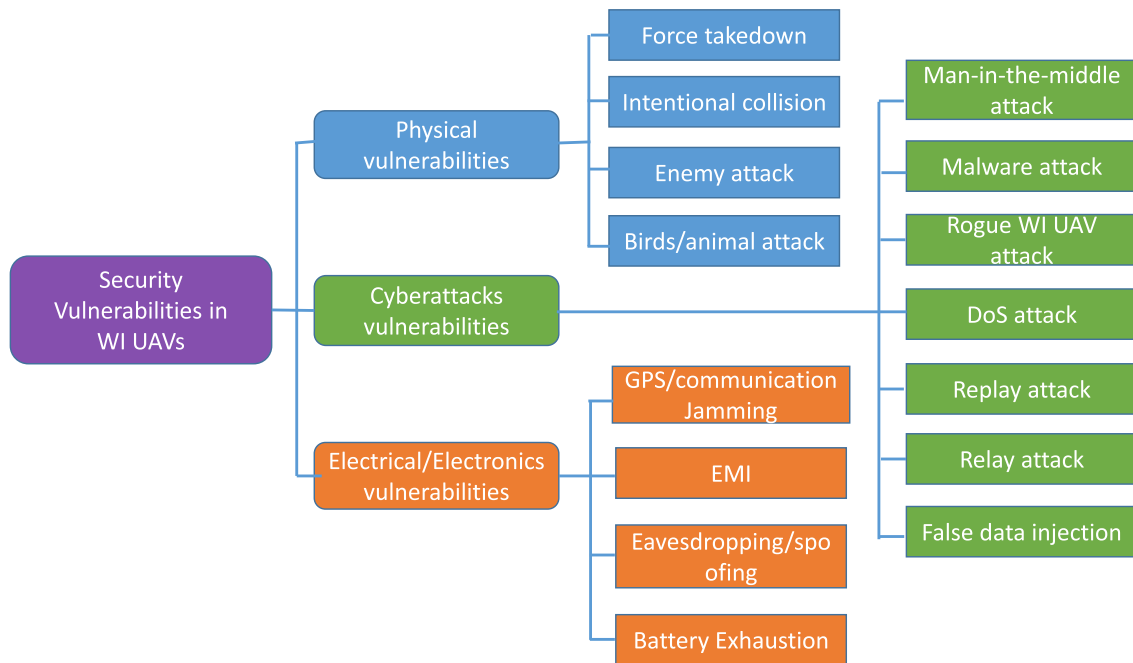
FIGURE 5. Security vulnerabilities in WI UAVs.

radio frequency as the WI UAV in order to disrupt communication between the operators and the WI UAVs, or even between the UAVs leading to accidents.
• Electromagnetic interference (EMI): It may be carried out in a similar manner as jamming, but with less power and resources. EMI generally focuses on the network connection, degrading it to the point where all communication with/from the WI UAV is lost.

• Eavesdropping and spoofing: Eavesdropping and spoofing is another popular type of attack, in which attackers obtain sensitive information by eavesdropping on communications between transmitter and receiver WI UAVs via spoofing address resolution protocol (ARP) packets.
• Battery Exhaustion attack: Battery operated systems like drones and power-unit systems in big WI UAV are vulnerable to sleep exhaustion attacks, in which

adversaries drain their power source by requesting actions from them until the battery or power unit runs out of power, causing the entire system to shut down and ultimately crash on the ground.

Cyberattacks, unlike electronic and physical attacks, are more difficult to identify and typically do not appear until the systems have been attacked. Attackers in cyberspace rely primarily on the target network architecture's existing vulnerabilities. Some common cyberattacks on WI UAVs are as follows:

- Man-in-the-middle attack: This type of attack occurs in the communication link between the WI UAVs and their communication base tower. In this type of attack, the attacker taps into the communication frequency through radio transmission and the attacker commands the WI UAV with spoofed messages posing as a base tower, which might lead to a crash.
- Malware attack: In this type of attack, the attacker exploits vulnerabilities in systems and infects programs on cyber-physical systems, gaining unauthorized access to data, the network, and even manipulating the WI UAV once the attack is effective. The goal of all malware is to carry out an attacker's malicious intent by using viruses, worms, Trojan horses, etc.
- Rouge UAV attack: An attacker can introduce a rogue WI UAV into the network, which poses as a legitimate node, reading all the network traffic and having the potential to transfer messages and malicious data to other nodes in the network.
- Denial of Service (DoS) attack: In a DoS attack, attackers use tools such as Telnet to flood the WI UAV communication system with messages, causing network congestion and exhaustion of the UAV's bandwidth and energy.
- Replay attack: In a replay attack, the attacker intercepts the WI UAV control and sensor information and then replays that information after some time to deceive the system and gain access control.
- Relay attack: Similarly, in the case of a relay attack, an attacker can intercept a command and rebroadcast it at a later time for harmful intentions such as confusing a system or gaining unauthorized access. Both the relay and replay attacks' ultimate goal is to cause confusion to the WI UAV system and gain unauthorized access.
- False data injection: The main objective of the attacker is to insert false data in the WI UAV database by manipulating the database record and even can corrupt the whole database. It might have a serious impact as the attacker can completely compromise the database.

VI. SPECTRUM FOR UAVs

For many generations increasing transmission rate has been one of the important achievements of all the generations. Likewise, 6G visions to transmit up to 1 Tbps per user [49], [50] by efficiently using low, mid, and high bands. Spectrum is a critical parameter of the UAV industry too for providing positioning; detect and avoid capabilities; vehicle control; payload support, and traffic management. At this moment, there is no spectrum available dedicated to UAV only. Thus, UAV applications can be carried out in both licensed and unlicensed spectrum bands. The European Union adopted a flexible use spectrum policy framework in 2015 that does not mandate specific uses, but rather ensures that the finite resources of the spectrum are put to the best possible use by allowing service providers to exploit the spectrum relying on technical standards to prevent harmful interference. In addition to flexible usage, the industries have been looking at spectrum sharing prospects. As the demand for the spectrum grows and the unoccupied spectrum becomes increasingly limited, policymakers throughout the world are looking for methods to fulfill it. The shared use of spectrum enables multiple users to access certain spectrum frequencies efficiently, which in effect makes additional spectrum resources available. At the same time, the risks of spectrum sharing must also be addressed. To the moments, the various frequency bands have been considered for UAV applications [51], Table 3 gives a brief description of the used spectrum, corresponding technology, and the purpose to this date.

Apart from the above frequencies, the new spectrum's 27 MHz, 35 MHz, 2.4 GHz, and UHF 433MHz are under consideration for the UAV data traffic purpose [52]. The frequency bands 27 MHz and 35 MHz offer the benefit of long-range which can be as long as 1 mile with conventional first-person view (FPV) gear. Similarly, 2.4 GHz is a handy choice of the band that offers a decent range and does not create any interference to other drones as it uses frequency hopping spectrum spread (FHSS) technology. The 433MHz UHF band can be used for long-range flight, i.e., a range as large as 25km. The drawback associated with all these radio frequencies is that any other WI/WS UAVs or other incumbent technologies may hop onto the same channel which will cause interference. Thus, it is prudent to keep track of channels assignment in the surroundings and co-exist harmoniously in the shared spectrum. Moreover, there are power limits associated with some of these frequency bands which could be inappropriate for WI UAV applications due to the small service area.

The unlicensed spectrum offers a variety of WI UAV design alternatives that may be integrated with the existing network. Traffic offloading and resource sharing are two distinct practices of delivering data traffic over unlicensed bands [53]–[55]. Traffic offloading is the most common and old method, which offloads the data/traffic to other existing unlicensed band technology such as Wi-Fi. The distributed coordination function (DCF) protocol is used by WI UAV to support the number of cellular users in the unlicensed band. Moreover, to ensure the QoS of cellular traffic, careful selection of offloading traffic is required in this strategy to avoid saturation and excessive packet collisions. In contrast, resource sharing is a revolutionary approach that shares the time resources of the unlicensed band technology. WI UAV

TABLE 3. Used spectrum's in UAV communication.

Frequency	Technology	Organisation/Forum	Purpose
5030 – 5091 MHz	General	WRC-12,15,19, and 23	Control link for satellite and terrestrial UAV
800 - 900 MHz	4G LTE	ITU	Control of UASs and would have a range of up to one mile
5.9 GHz	802.11p	ITS	Control of UASs Collision Avoidance and Vehicle to Vehicle Communications
1090 MHz	ADS-B	ITU	Surveillance
All (except WRC- 12 & 15 control links)	802.11p, Cellular	ITU	Payload
4200 – 4400 MHz	WAICA	WRC-15	In-flight diagnostics.
24 GHz	Radar	ITU	Collision Avoidance and Vehicle to Vehicle Communications
1030 MHz, 1090 MHz	SSR, TCAS	-	Collision detection system

operates in the unlicensed band using the NR-U method to support its cellular users. Here, the time resource is shared between the NR-U WI UAV and incumbent users. It has high spectrum efficiency and has better QoS than the traffic offloading method however it needs effective resource sharing strategies for cellular and incumbent traffic. As both technologies were designed with the same goal in mind: to improve the network performance of cellular users without affecting incumbent users in the common unlicensed band. Here, we compare the average per-user throughput of the user in both cases. In traffic offloading, the utility function is to maximize the number of users that can be offloaded from cellular to WI UAV. Assuming that cellular users will offload N_T users to WI UAV, the average per-user throughput of cellular users while guaranteeing the incumbent performance can be formulated as

$$\max_{N_T} \frac{C_L}{N_L - N_T}$$
$$s.t \quad \frac{R(N_U + N_T)}{N_U + N_T} \geq R_{min}$$
$$N_T \leq N_{max}, \qquad (1)$$

where C_L is average capacity of license channel, N_L is number of user in licensed band, N_U is number of Wi-Fi user in unlicensed band, N_{max} is largest number that satisfies equation $R(.)$ and R_{min} is the minimum per-user throughput of Wi-Fi user. $R(.)$ is the saturation throughput of WiFi network calculated using Bianchi model [56]. Solving the above equation, we get the maximum per-user throughput of the cellular system as

$$\frac{C_L}{N_L - N_T *}. \qquad (2)$$

In resource sharing, the utility function is to maximize the occupancy of time slots of the unlicensed band, i.e., α. The average per-user cellular throughput while guaranteeing the

incumbent performance can be formulated as

$$\max_{\alpha} \frac{C_L + \alpha C_U}{N_L}$$
$$s.t \quad \frac{(1 - \alpha)R(N_U)}{N_U} \geq R_{min}. \qquad (3)$$

Solving the equation 2, we get the maximum per-user throughput of the cellular system as

$$\frac{C_L + \alpha * C_U}{N_L}. \qquad (4)$$

with the occupancy of time slots of the unlicensed band $\alpha* = 1 - \frac{R_T N_U}{R(N_U)}$.

Fig. 6 plots the relationship between the average per-user throughput of the cellular user N_L and the number of Wi-Fi users, N_U with N_L set to 35. Similarly, Fig. 7 plots the relationship between the average per-user throughput N_L and the number of cellular users, N_U, where $N_U = 4$. For both cases, Wi-Fi required throughput threshold of R_{min} is set to 10Mbps and throughput capacity of license and unlicensed band are set to 204Mbps and 62Mbps, respectively. From the both figure, when R_{min} is large ($R_{min} = 10$ Mbps), the maximum number of users that Wi-Fi can support, i.e., N_T, is small. Therefore, resource sharing always performs better than traffic offloading. Whereas for smaller RT ($R_{min} = 5$ Mbps, traffic offloading performs better than resource sharing only if the number of existing users in Wi-Fi is small enough. When the Wi-Fi user number grows large NR-U based WI UAV performs better. This is because, as N_U is large, offloading new users will significantly increase the collision, leading to the degradation of Wi-Fi throughput. Therefore, in this case, it is better to use the unlicensed bands by directly occupying several time slots. Hence, NR-U-based WI UAV is much better than conventional traffic offloading method for increasing the average throughput of cellular users while maintaining required QoS with incumbent users.
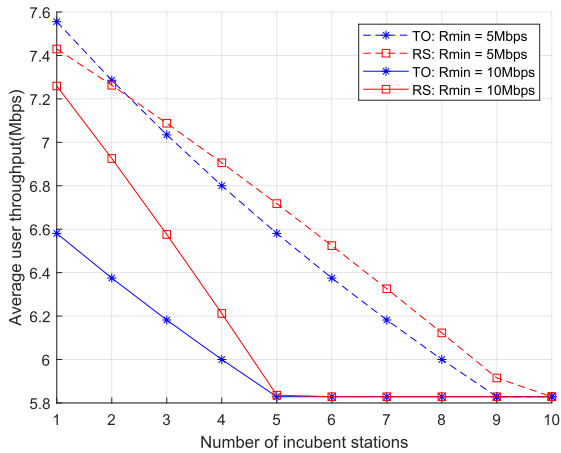
FIGURE 6. Average per-user throughput of the cellular uses vs variable wifi users.
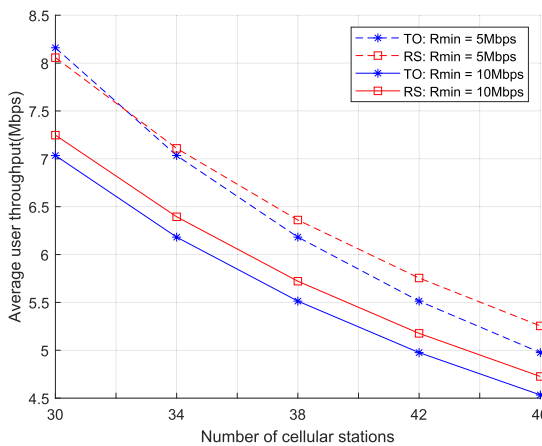

FIGURE 7. Average per-user throughput of the cellular uses vs variable cellular users.

VII. WI UAV COMMUNICATION

For future 6G communication systems, WI UAV communication is supposed to deliver broad wireless connectivity and high data-rate transmission. Notably, various communication scenarios are engaged in UAV communications, such as intercommunications between UAVs and communications with the various terrestrial stations such as UEs, BSs, vehicles, IoT devices, and ground terminals as shown in Fig. 4. Hence, a typical UAV communication scenario mainly consists of three categories: UAV-to-UAV, UAV-to-BS, and UAV-to-GS/UE. In UAV-to-UAV communication, the inter-communications between UAVs are mainly performed to guarantee reliable beyond-line-of-sight communication links in long-distance flights in a form of aerial relay and flying ad hoc networks. Whereas the backhaul communication is mostly related to the UAV-to-BS communication. And, the BS can be in any form either a ground BS station or a low orbit satellite station. Lastly, UAV-to-GS/UE communication refers to the link between UAV and GS, serving ground UEs as an aerial base station. UAV-to-GS/UE mostly operates in unlicensed bands such as 2.4 and 5 GHz.

The WI UAV communication links UAV-to-UAV, UAV-to-BS, and UAV-to-GS/UE can be further categorized into air-to-air (A2A) and air-to-ground (A2G) channels propagations. The recent progress of A2A and A2G channel modeling includes large and small-scale statistics for system design and performance. Path loss and shadow fading (SF) are two main large-scale channel statistics that vary based on the UAV attitude of operation and the operating frequencies. It is found that as the altitude of the UAV rises, the path loss exponent (PLE) becomes smaller. And, for low-frequency operations, PLE increases due to the rich scattering, reflections, and diffraction properties for both A2A and A2G channels. Similarly, the shadowing is highly related to the selected environment and it is measured in a Gaussian random process with zero mean and standard deviation of σ. According to [57], the average SF values for A2A channels vary from 1.9 to 5.5 dB, which is slightly lower than for A2G channels due to the presence of few scatters effect in the neighborhood of both UAVs. Specifically for A2G, the suburban environment has a significant SF value compared to the open field environment. Table 4 summarized the important settings and corresponding channel statistics for A2A and A2G channels. Similarly, in small-scale channel properties, UAV channel design performance is mostly characterized by multipath propagation and evaluated in the root-mean-square delay spread (RMS-DS) and Rician K-factor (KF). According to [60], [62], [63], RMS-DS and Rician KF are comparatively low for over-the-sea environments whereas for urban areas both factors have a higher impact due to the strong impact of terrestrial scatters and reflections on the Non LOS power.

VIII. NR-U WI UAV DESIGN ARCHITECTURE

Because of the regulatory restrictions such as maximum transmission power and coverage limitation of 150 meters, unlicensed band operation for WI UAV's is considered as unattractive until Rel-15 TS 37.213 [64]. However, this restriction is only applicable to terrestrial wireless BS. WI UAV can freely travel in space for the aerial applications to alter the projected range and altitude of the UAV for better coverage. Moreover, NR-U enhancements (TR 38.889) such as flexible sub-carrier spacing, mini-slots, frame structure, carrier aggregation, and integration choices of low, mid, and high band operations have increased the opportunity for UAV applications in the unlicensed spectrum [65]–[68]. Furthermore, by using narrow beams and interference suppression, NR-U's beamforming and mmWave techniques can be employed to improve the received signal to interference and noise ratio (SINR) [69]–[71]. As a result, NR-U offers a variety of WI UAV design alternatives that may be integrated with the existing core while taking advantage of the abundant and free unlicensed spectrum.

Fig. 8 depicts WI UAV architecture based on NR-U for integration in the 5G protocol layer. The purpose of an NR-U WI architecture is to covers the integration of drones from various protocol stack architecture where simplified

TABLE 4. UAV channel measurement statics.

Ref	Link	Height	Frequency	Terminal	Environment	Channel Statics
[57]	A2A	0-50m	NB, 2.4 GHz	UAV	Suburban	n = 2.3-2.7, σ = 9-5.5 dB
[58]	A2A	6-15m	WB, 60 GHz	UAV	Urban	n =2.2-2.3, σ = 0.8-8.0 dB
[59]	A2G	15-120m	NB, 800 MHz	Cellular	Suburban	n =2.0-3.7, σ = 3.4-7.7 dB
[60]	A2G	15-100 m	WB, 2.585 GHz	Cellular	Suburban	n = 1.3-3.7, σ = 2.7/3.0 dB, PDP, KF, RMS-DS
[61]	A2G	4-16 m	WB, 3.1-5.3 GHz	GS	Open-field, Suburban	n = 2.5-3.0, σ = 2.8-5.3 dB, PDP, CFR
[62]	A2G	580, 800 m	WB, 968, 5060 MHz	GS	Over-water	n = 1.5-2.2, σ = 2.6-4.2 dB, PDP, SD, KF, RMS-DS
[63]	A2G	504-924m	WB, 968, 5060 MHz	GS	Suburban, Near-urban	n = 1.5-2.0, σ = 2.6-3.2 dB, PDP, KF, RMS-DS, SIC

WB: Wideband, NB: Narrowband, SD: Stationarity distance, SIC: Spatial and inter-frequency correlation, CFR: Channel frequency response

reference point model for unlicensed WI UAV integration option has been shown. Here, WI UAV acting as SgNB uses NR/NR-U radio for connectivity option. Here, a non-standalone NR-U architecture is considered, in which the serving WI UAV maintains proximity to the UEs. Non-standalone NR-U means that control plane connections are based on the licensed band, and data plane connections are based on the unlicensed band. As shown in Fig. 8, NR-U-based WI UAV can be placed within the large coverage area of a macro-eNB or macro-gNB or MAB/HAP WI UAV. This design model can offer two possible modes of WI UAV operations: switch bearer and split bearer [72]. The packets of the switch bearer are always routed via the NR-U network, whereas the packets of the split bearer can be scheduled over either NR-U or NR or even both. If a split bearer between the MgNB and the WI UAV is used, the Xx-C/U interface can link the NR/LTE PDCP layer to the NR-U RLC layer of the WI UAV. Similarly, the EPC/S1-U NGC's link can transfer user plane data directly over the WI UAV's NR PDCP layer for the switch bearer. Comparing both the bearers types for WI UAV application, split bearers are more suitable than switch bearers for enhancing end-user performance by increasing the total of peak data throughput over both channels, but switch bearers are favored for lowering the device complexity for integration.

IX. OPPORTUNITIES OF NR-U WI UAV

Here, the various opportunities provided by WI UAV based on NR-U technology are discussed.

A. CAPACITY AND COVERAGE

NR-U is well-known for utilizing a large amount of unlicensed spectrum. Recently, 600 MHz of spectrum in the 5 GHz range became available for global unlicensed use. Many low, mid, and high band spectrum's are also in the process of becoming free. These unlicensed bands
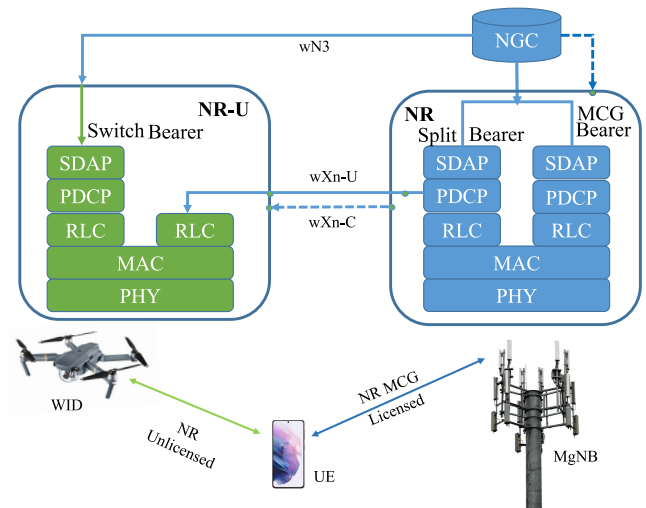

FIGURE 8. Non standalone NR-U architecture for WI UAV.

can be divided into multiple channels, each with different bandwidth. As a result, using carrier aggregation or unlicensed spectrum integration, NR-U WI UAV may be able to serve a higher volume of users in highly dense scenarios with high data rate. Furthermore, the WI UAV may hover over a height of 100-120 meters, which is higher than the normal height of a terrestrial BSs (10-20 meters). Therefore, LOS communication may be constructed easily. Hence, the WI UAV can provide wider coverage compared to standard terrestrial infrastructure, while reducing interference from other terminals.

B. EASE ON-DEMAND NETWORK DEPLOYMENT

The ability to set up a wireless network on demand is one of the key benefits of WI UAV. However, to set up the cellular WI UAV, the operator must go through a lengthy, expensive, and time-consuming spectrum licensing process. The use
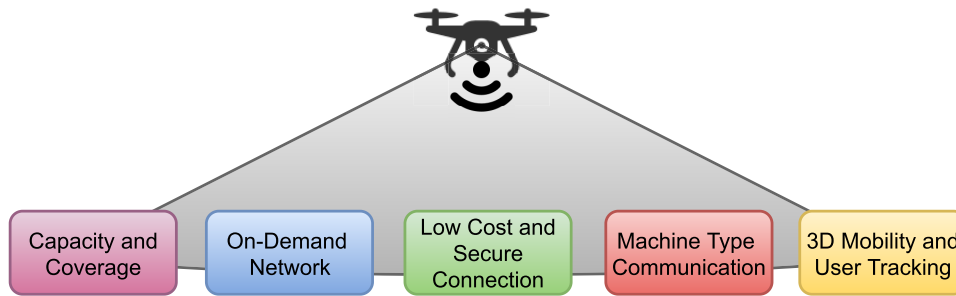
FIGURE 9. Opportunities of NR-U base WI UAV.

of an unlicensed band in WI UAV via NR-U technology helps speed up the deployment process, because NR-U does not require any licensing. In addition, 5G technologies such as core-network in box virtualization functions will aid in remote network parameter setting and management. These elements can be exploited not just in WI UAV's deployment speed but also in its dynamic capability.

C. LOW COST WITH INCREASED SECURITY
NR-U WI UAV permits wireless technologies to be implemented at a lower cost and with better security compared to existing unlicensed/licensed technologies (e.g., WiFi technology). NR-U uses existing cellular access technologies to provide private networks in newly available and open unlicensed broadband spectrum (3.5/5/6/60GHz). This ensures network isolation, data security, and device/user authentication, resulting in more cost-effective, dependable, and secure communication.

D. MACHINE-TYPE COMMUNICATION
Instead of communicating via the centralized BS, device-to-device (D2D) communications allow direct connectivity between nodes in close proximity. Most WI UAVs backhaul their data in a single hop to centralized macro/micro core stations, which are either in-ground or satellite-based. WI UAV D2D communication is feasible via the "listen before talk" protocol of NR-U, which allows for easy establishment of multi-hop D2D services between WI UAVs. Such multi-hop backhauling technique can considerably minimize latency and enable high-speed communication in a densely populated area.

E. IMPROVE USER's QUALITY OF EXPERIENCE
Due to unlicensed bands' power regulation, NR-U is limited to a small coverage area. This is a major disadvantage for terrestrial NR-U, as most signals suffer from path loss, attenuation, and fading. Nevertheless, WI UAVs are mobile and their signal strength can be changed by retaining a reasonable distance from the end-users, so transmit power limitations are not a major concern for WI UAVs. Furthermore, WI UAVs can sustain 3D mobility dynamically, while maintaining continuous LOS links to users, which corresponds to fewer

hand-overs and better services for end-users. With WI UAV transceivers, moving users (pedestrians, vehicles, and IoT devices) can be also be well supported through the reliable LOS connections.

Thus, using NR-U for WI UAVs has the potential to revolutionize future UAV technologies by providing superior radio performance in terms of coverage/link budget, capacity, spectral efficiency, mobility, configurable QoS, interoperability, deployment ease, spectrum options, security, and a road map to 6G and beyond. However, in order to be feasible for operation in the unlicensed band, NR-U-based WI UAVs must meet the following key requirements: First and foremost, they must comply with all applicable regulatory criteria for unlicensed band operation, such as transmit power, spectral density, and channel occupancy constraints. Second, it must coexist fairly with other terminals of the same or different technology, such as Wi-Fi, Radar, Bluetooth, and so on. From a technical perspective, the implementation of the NR-U WI UAV poses a number of regulatory and coexisting issues on the top of UAV integral challenges which has been discussed in the next section.

X. CHALLENGES OF NR-U WI UAV
A. WI UAV PLACEMENT AND COVERAGE
NR-U WI UAV can freely move without any borders, thus the optimal placement i.e., appropriate number, locations, and altitudes of WI UAV and its trajectory design is more challenging in 3D space compared to the terrestrial BSs. As WI UAV may be positioned at a range of various altitudes in the sky, the service coverage and the UL and DL channels change with the transceiver height. Moreover, the optimal position of the WI UAV is highly affected by the aerial vehicle's energy limitation, the positions of the other drones, the distance to the users/backhaul transceiver, interference from other aerial vehicles/ terrestrial BSs in the same service region. On top of these basic UAV placement challenges, the use of NR-U technology in WI UAV complicates this process. Due to the maximum transmit power regulations, the range and altitude of the drone application may not extend beyond 150m [3]. Moreover, the use of larger sub-carrier spacing and/or mini-slot-based transmissions as suggested in Rel-15 increases throughput but renders less energy per symbol

for the same transmit power, and hence reduced coverage. Consequently, it is more difficult to support the access links of WI UAV applications. The extensive research in academia and industries has resulted diverse solution towards these problems by using mathematical programming techniques and a machine learning [73], [74]. And, these techniques that are used to solve UAV placement and trajectory design optimization mainly involves two objectives: (1) increasing network revenue (coverage, reachable rate, etc.) under certain constraints like transmission power, fight duration, number of UAVs, etc. (2) reduce the cost of deployment (transmission power, fight duration, number of UAVs) to achieve desired quality of service.

B. AERIAL VEHICLE MOBILITY, SAFETY, AND SECURITY CONCERNS

Mobility is a built-in capability and function of WI UAV, which empowers WI UAV to dynamically support end-user experience through optimal placement in response to the ground user movements. For this, cruising WI UAV necessitates autonomous mobility control algorithms that improve the end-user performance by directing WI UAV in the optimal direction without colliding with users or any other WI UAVs, aerial vehicles, buildings, and obstacles. Specifically, for NR-U WI UAV, it becomes more challenging as proximity is only the way to increase the received signal strength in the unlicensed band for the serving micro/picocells as 5G NR-U adheres to the maximum equivalent isotropic radiated power (EIRP). Moreover, under these circumstances, WI UAV is also required to maintain a continuous backhaul connection to the terrestrial/non-terrestrial BS and keep a certain distance from drone recharging stations. The non-standalone NR-U radio access technology will be one of possible approach to solve the proximity problem of WI UAV as it allows licensed band to support user/control plane connections within the large coverage area of macro gNB [72]. In addition to mobility and safety concerns, WI UAV also have to deal with security concerns which has been discussed above in section V. Several security issues can be tackled by using authentication, identification, and encryption to prevent network attacks. However, more robust and reliable communication channel needs to be designed to meet the security requirements.

C. SIZE, WEIGHT, AND POWER CONSTRAINT

In general, flying vehicles are energy-constrained systems due to their limited battery size and capacity [75]. Even after many years of development and steady improvements, the battery industry is only delivering around 25 minutes of flight time for regular multi-copters. This limits their hovering and flying time, and various trade-offs may occur between the quality of services given to users (i.e. transmitted power) and energy constraints. Thus, the major issue of WI UAV is a short flying lifespan caused by battery depletion. To increase the battery's life, it is necessary to operate in a power-efficient manner in both

FIGURE 10. Challenges of NR-U-based WI UAV.

communications (electronics) and mobility (mechanics). The mechanical energy consumption in drones are determined by weights and motor/propeller characteristics, which directly affect the flying time of the drone. In addition, limiting transmit power poses difficulties in providing coverage that might affect the customers' data-rate requirements. Hence, the design of communications (electronics) and mobility (mechanics) of WI UAV should strictly consider these in-tangled relationship of WI UAV size, weight, and power constraint in UAV. There has been many research to optimised these relation using mathematical programming techniques and a machine learning techniques such as [20], [76]–[78].

D. COEXISTENCE WITH TERRESTRIAL BASE STATIONS

The presence of both WI UAV and terrestrial BS can result in a WI UAV-dominant network area. At greater altitudes, multiple UEs and BSs in various terrestrial cells will have dominating LOS connectivity with the aerial WI UAV. Consequently, a single NR-U WI UAV broadcast might influence on uplink/downlink capacity of terrestrial BS/UE residing in multiple cells. As a result, a single NR-U WI UAV broadcast can create interference on many ground UE under various BSs as they follow the "listen before talk" procedure to access the shared channel. In contrast to the centralised scheduling approach of the cellular technology, "listen before talk" procedure is a technique whereby a radio transmitters first sense its radio environment before it starts a transmission. It provide appropriate mitigation levels to avoid harmful interference to other users in the band. Therefore, a fair coexistence mechanism is required to coordinate resource scheduling with various terrestrial network such as coordinated transmission, beamforming, and interference mitigation between aerial and ground BS/UEs.

Furthermore, the fair coexistence method is not confined to its own NR-U technology environment, but also includes WiFi, Radar, Bluetooth, etc. Thus, the indefinite channel access latency and spectrum efficiency due to contention mechanism between different technology for shared channel are the main concern in NR-U WI UAV communication. The number of optimisation approaches such as duty cycling [66], most vacant channel selection [67], limited user admission approach [53], contention window adaption [79], [80] etc., has been proposed to reduce the delay and increased the spectrum efficiency in NR-U technology.

E. DECENTRALIZED ROUTING PROTOCOL

WI UAVs should be scalable networks in which the number of WI UAVs engaged should be dynamically adjusted depending on the use cases. In an urban location, a large number of WI UAV constellations might be required for efficient coverage, while very few WI UAVs are required in remote locations. For this, NR-U WI UAVs should be characterized by a decentralized routing protocol for data information transmission in the sparse and intermittent network, and a wireless backhaul in a highly dynamic environment. Most of the UAV routing protocols are still in their developmental stage. The highly dynamic network routing techniques are still an open research issue as most of the routing protocols proposed for UAV yet are based on vehicular routing protocol such as MANETs and VANETs [81]. However, these are not inherently suitable for UAVs as routing protocols owing to the unique characteristics of UAVs and have therefore been unable to yield good performance in UAV networks. The main routing challenges for UAV networks are frequent link failures, packet losses, limited bandwidth, high routing overhead, triggered routing table updates, and low convergence rate in networks. The previously proposed UAV routing protocols are mainly based on Network architecture and data forwarding based routing protocols. The network architecture based routing protocol generally considers topology, position and hierarchic of UAV for routing path selection. On other hand, data forwarding based routing protocol uses deterministic, stochastic, social-network based routing technology for routing path selection.

F. REGULATORY CHALLENGES

There is an absence of unique legal global regulation for the UAV communication. The regulatory requirements can be divided into two groups, one for UAV aviation technology and the other for wireless communications. Each of these groups has its own unique regulatory challenges. Current UAV aviation regulations are usually restricted to low-altitude operations (below 120m or 400ft) and within the visual line of sight of a human pilot who is in permanent control of the drone. Nevertheless, many WI UAV applications are only viable when the UAV is either be flown beyond the visual line of sight or when it flies autonomously, which usually means that the platform is out of sight and without direct control of the pilot. In UAV wireless communication the regulatory framework to use unlicensed spectrum policies differ among countries and zones around the world. For example, NR-U regulatory frameworks for the use of unlicensed spectrum in the United States, China, and Korea generally set policies to safeguard the co-band and adjacent-band primary users, with fewer strict spectrum-sharing obligations for unlicensed UEs. Contrary, the regulatory structures in India, Japan, and Europe, on the other hand, are not the same, and particular coexistence protocols are required in unlicensed spectra, that is "listen before talk". Furthermore, UAVs and their uses have a lot of potential in the future. The challenges of the near future in the WI UAV ecosystem is regulation of the UAV traffic itself and its integration with the current manned aviation. Currently, there are already a large numbers of UAVs in the airspace and the expectation is that this number is only going to rise. Hence, it is important to find a structured solution that regulates all the traffic in the airspace, unmanned and manned via initiation of different programs to define the rules of UAV operation conjointly by aviation and communication authorities around the world.

XI. FUTURE SCOPES

UAV technology has evolved from its basic beginnings to what we know today, and as new applications emerge, it will become increasingly interwoven into society. As of now, UAV technology has a wide range of applications and is employed in a variety of sectors as mentioned above. The future of WI UAV technology and its applications are expansive. In this section, we'll be discussing innovations that will further propel the future of WI UAV technology. Fig. 9 shows the future scopes of NR-U WI UAV.

A. NEUTRAL HOST

5G envisions a new self-contained network architecture called neutral host network (NHN). In the NHN mode, users gain access to services from different types of vendors, such as traditional mobile network operators and non-traditional service providers, without the need for a SIM card. In other words, it is a network infrastructure owned and maintained by a third neutral party that rents or leases its infrastructure to any network operators, so that they can scale up their network capacities [18]. NR-U-based WI UAV provides perfect platform to realize NHN network. With NR-U WI UAV architecture, the features of both cellular networks (i.e., carrier grade quality) and Wi-Fi networks (i.e., easy deployments) can be combined. However, the multiple stakeholders wishing to manage shared resources MNO, Neutral Host, Enterprise Customer, requires dedicated management and orchestration interfaces.

B. TRAFFIC OFFLOADING

The WI UAV can be used for data offloading in places where the terrestrial cellular BS downlink is under high traffic load. If the terrestrial BS is overloaded with traffic data, then the BS requests the nearby WI UAVs to offload the data service to terrestrial mobile users. For this, the BS manages mobile users in multiple disjoint sets to offload the data [82].
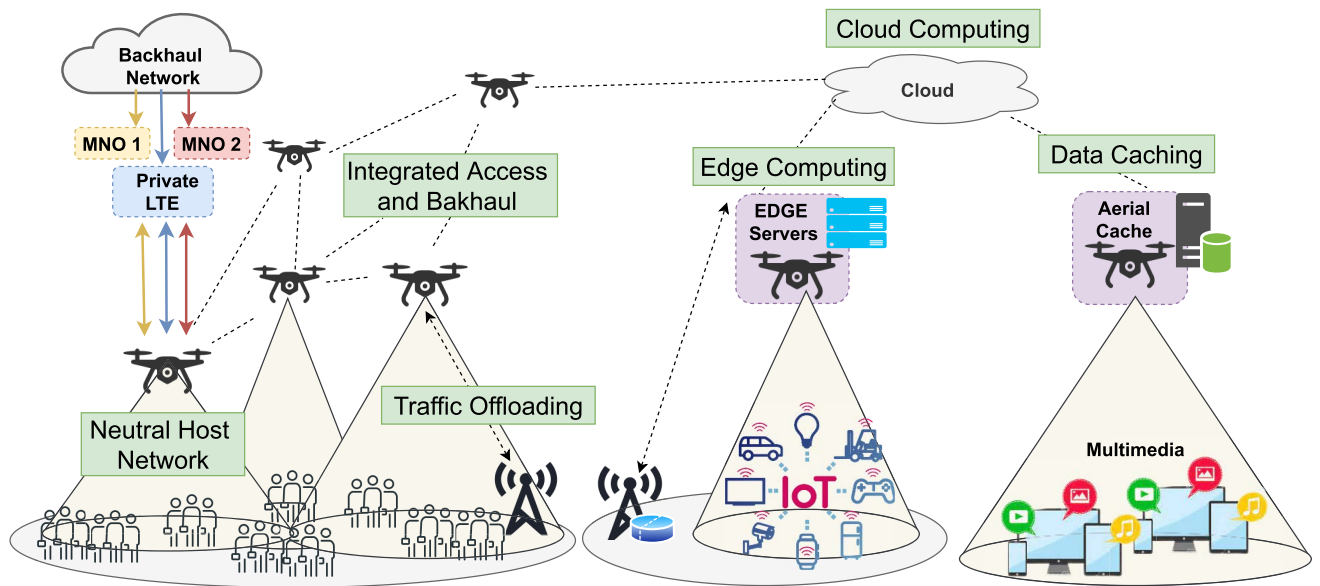
There will be negligible interference between various UAV networks, as WI UAVs may be equipped with antenna arrays for beamforming. Further, the performance of beamforming can be enhanced through intelligent reflecting surface (IRS) on UAV which reconfigure the propagation environment when WI UAV communications suffers from blockage and eavesdropping due to the complex environment [83]. One of the issue in the UAV-based offloading will be energy consumption due to high computation offloading and multichip routing. Also, it is required to discriminate the delay-sensitive user traffic from delay-insensitive user traffic.

C. DATA CACHING

Data caching is one of significant importance for the IoT devices with limited capabilities. There will be a huge surge of cellular IoT devices in coming years [84], which results in an increasing demand for images and video contents. Many users often request common and prominent contents most of the time. Thus, the aerial data caching can alleviate excessive data access demand and provide high multimedia data throughput for IoT devices by pre-caching such prominent content in local memory of WI UAVs [85]. In the case of data caching of content in local storage of WI UAVs, there are some issues due to the limited storage capacity of the UAV flying in aerospace. There might be higher caching cost and time required while storage and retrieval of the multimedia contents in the UAVs. Thus, the file caching technique should be carefully designed such as providing the caching service to a limited local area to reduce the caching cost by the UAVs.

D. CLOUD COMPUTING

The WI UAV might be used for cloud/fog computing as they can contain computing devices with significant

processing power. The aerial clouds can be able to execute complicated algorithms that require a large amount of processing power. Such type of cloud computing is generally used for delay-tolerant tasks that require huge computation efforts such as multimedia processing, meteorological condition analysis, etc. Furthermore, they can be used for fog computing, which provides computation closer to the end-devices. As a result, the latency can be reduced, while consuming less network bandwidth. This type of aerial fog computing could be used for delay-intolerant applications such as path planning optimization, traffic simulation, etc. However, the WI UAVs has limited endurance to fly on the aerospace for a long time due to limited battery power. The WI UAV as cloud may need to consider the air time before providing cloud computing for a long duration to reduce delay and offload the computation tasks. Computing operations should be offloaded promptly, and computational outputs must be provided back to mobile users in real-time, therefore efforts should focus on how to predict mobile user movement and follow their trajectory. All these limits the cloud services to the local area such as stadiums, concerts, festival areas where there is a huge crowd that requires these services.

E. EDGE COMPUTING

In cellular networks, multi-access edge computing (MEC) is a new paradigm, where the BSs deliver cloud-like services such as communications and computing in close proximity to UEs and IoT devices [86]. This strategy provides significant reduction in latency for several time-critical and computational-intensive tasks such as speech recognition, augmented reality, virtual reality, etc. If the WI UAVs are used as MEC at the edge of the network, then there is no

need to off-load computation tasks to the centralized cloud that add delay to the network. In the future, the processing capabilities of MEC can be further improved by AI and hardware accelerators. Despite the significant advantages provided by the design of UAV-enabled MECs in providing low latency and high-reliability services to IoT devices, there are still various obstacles. Intra-UAV communication, UAV security, air data security, data storage, energy efficiency and joint trajectory design and management are some of these challenges.

F. INTEGRATED ACCESS AND BACKHAUL (IAB)

With the objective to cope with the increasing demand for wireless backhaul of future technology. 3GPP Rel-16 proposed an integrated access and backhaul (IAB) approach which allows rapid and cost-effective millimeter wave (mmWave) multi hop deployments through self-backhauling in the same wireless spectrum [87]. The use of wireless channel for backhaul communication to other stations results in improved performance, more efficient spectrum utilization, and reduced equipment costs, as well as less dependency on wired backhaul availability at each access node site. In addition, IAB is designed for a variety of deployment situations, including outdoor and interior dense small cell deployments, as well as coverage expansion. IAB is an attractive complement to fiber, with the ability to provide backhaul hence the integration of IAB with NR-U based WI UAV technology can play significant role in enhancing the performance of the network. However, the performance of aerial IAB networks can be affected by some individual characteristics of non-terrestrial networks, such as long propagation distance and movement of aerial BSs. As a result, the network deployment design will be an important issue in the NR-based WI UAV IAB networks. In a multi-hop IAB network, the first backhaul hop must carry the backhaul bandwidth not only for the first IAB node but also for all other IAB nodes further down in the hop chain. Deploying multi-hop networks will therefore eventually lead to backhaul-limited nodes due to congestion in the first hop. Moreover, increasing the number of hops will also increase the end-to-end latency and raise the complexity for scheduling and routing to satisfy QoS.

XII. CONCLUSION

For a variety of applications, WI UAV offers a plethora of design opportunities for wireless connectivity i.e., relays, BSs, and data collectors by utilizing UAVs as infrastructures. In this regard, the WI UAV is being standardized by both academia and industry. This paper introduce WI UAV based on NR-U technology for providing connectivity service to the end users. The paper has opened the door to a variety of opportunities to extend connections to mobile UEs in areas, where the conventional terrestrial networks are difficult to reach, with NR-U-based WI UAVs. Nevertheless, there are still few concerns and technical challenges such as the

positioning of WI UAVs, their safety and mobility; power, weight, and size constraints, coexistence with terrestrial BSs, administrative issues, etc., which must be resolved prior to the commercialization of NR-U-based WI UAV. Lastly, the paper has been concluded with possible future scopes of NR-U UAVs.

REFERENCES

[1] M. Chen, F. Zeng, X. Xiong, X. Zhang, and Z. Chen, "A maritime emergency search and rescue system based on unmanned aerial vehicle and its landing platform," in *Proc. IEEE Int. Conf. Electr. Eng. Mechatronics Technol. (ICEEMT)*, Jul. 2021, pp. 758–761.

[2] M. A. Ma'sum, M. K. Arrofi, G. Jati, F. Arifin, M. N. Kurniawan, P. Mursanto, and W. Jatmiko, "Simulation of intelligent unmanned aerial vehicle (UAV) for military surveillance," in *Proc. Int. Conf. Adv. Comput. Sci. Inf. Syst. (ICACSIS)*, Sep. 2013, pp. 161–166.

[3] I. Bor-Yaliniz, M. Salem, G. Senerath, and H. Yanikomeroglu, "Is 5G ready for drones: A look into contemporary and prospective wireless networks from a standardization perspective," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 18–27, Feb. 2019.

[4] A. S. Abdalla and V. Marojevic, "Communications standards for unmanned aircraft systems: The 3GPP perspective and research drivers," *IEEE Commun. Standards Mag.*, vol. 5, no. 1, pp. 70–77, Mar. 2021.

[5] B. Alzahrani, O. S. Oubbati, A. Barnawi, M. Atiquzzaman, and D. Alghazzawi, "UAV assistance paradigm: State-of-the-art in applications and challenges," *J. Netw. Comput. Appl.*, vol. 166, Sep. 2020, Art. no. 102706.

[6] O. S. Oubbati, M. Atiquzzaman, T. A. Ahanger, and A. Ibrahim, "Softwarization of UAV networks: A survey of applications and future trends," *IEEE Access*, vol. 8, pp. 98073–98125, 2020.

[7] E. Chaalal, L. Reynaud, and S. M. Senouci, "Mobility prediction for aerial base stations for a coverage extension in 5G networks," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, 2021, pp. 2163–2168.

[8] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.

[9] T. Kimura and M. Ogura, "Distributed 3D deployment of aerial base stations for on-demand communication," *IEEE Trans. Wireless Commun.*, vol. 20, no. 12, pp. 7728–7742, Dec. 2021.

[10] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021.

[11] N. Zhao, W. Lu, M. Sheng, Y. Chen, J. Tang, F. R. Yu, and K.-K. Wong, "UAV-assisted emergency networks in disasters," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 45–51, Feb. 2019.

[12] R. Shrestha, S. Y. Nam, R. Bajracharya, and S. Kim, "Evolution of V2X communication and integration of blockchain for security enhancements," *Electronics*, vol. 9, no. 9, p. 1338, Aug. 2020.

[13] S. Kim and R. Shrestha, *Automotive Cyber Security*. Singapore: Springer, 2020.

[14] T. Li, J. Ye, J. Dai, H. Lei, W. Yang, G. Pan, and Y. Chen, "Secure UAV-to-vehicle communications," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5381–5393, Aug. 2021.

[15] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, and L. G. Giordano, "Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3417–3442, 4th Quart., 2019.

[16] N. Sharma, A. Kumar, H. Pervaiz, M. Magarini, L. Musavian, M. Alam, A. Jindal, and M. A. Imran, "Aerial base station assisted cellular communication: Performance and trade-off," *IEEE Trans. Netw. Sci. Eng.*, vol. 8, no. 4, pp. 2765–2779, Dec. 2021.

[17] R. Bajracharya, R. Shrestha, Y. B. Zikria, and S. W. Kim, "LTE in the unlicensed spectrum: A survey," *IETE Tech. Rev.*, vol. 35, no. 1, pp. 78–90, Jan. 2018.

[18] R. Bajracharya, R. Shrestha, and H. Jung, "Future is unlicensed: Private 5G unlicensed network for connecting industries of future," *Sensors*, vol. 20, no. 10, p. 2774, May 2020.

[19] Y. Jiang, Z. Fei, J. Guo, and Q. Cui, "Coverage performance of the terrestrial-UAV HetNet utilizing licensed and unlicensed spectrum bands," *IEEE Access*, vol. 9, pp. 124100–124114, 2021.

[20] R. Shrestha, R. Bajracharya, and S. Kim, "6G enabled unmanned aerial vehicle traffic management: A perspective," *IEEE Access*, vol. 8, pp. 91119–91136, 2021.

[21] X. Li and A. V. Savkin, "Networked unmanned aerial vehicles for surveillance and monitoring: A survey," *Future Internet*, vol. 13, no. 7, p. 174, Jul. 2021.

[22] R. Bajracharya, R. Shrestha, and H. Jung, "Wireless infrastructure drone based on NR-U: A perspective," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2021, pp. 834–838.

[23] Y. Xing, F. Hsieh, A. Ghosh, and T. S. Rappaport, "High altitude platform stations (HAPS): Architecture and system performance," in *Proc. IEEE 93rd Veh. Technol. Conf. (VTC-Spring)*, Apr. 2021, pp. 1–6.

[24] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, and H. Yanikomeroglu, "Airborne communication networks: A survey," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 10, pp. 1907–1926, Sep. 2018.

[25] P. Q. Viet and D. Romero, "Aerial base station placement: A tutorial introduction," 2021, *arXiv:2110.01399*.

[26] D. Zhai, H. Li, R. Zhang, and H. Cao, "3D position optimization for the UAV-assisted relay networks enhancing by NOMA and MRC," in *Proc. IEEE 22nd Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2021, pp. 329–334.

[27] R. Zhang, F. Zeng, X. Cheng, and L. Yang, "UAV-aided data dissemination protocol with dynamic trajectory scheduling in VANETs," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.

[28] X. Ma, T. Liu, S. Liu, R. Kacimi, and R. Dhaou, "Priority-based data collection for UAV-aided mobile sensor network," *Sensors*, vol. 20, no. 11, p. 3034, May 2020.

[29] *5G!Drones: Unmanned Aerial Vehicle Vertical Applications' Trials Leveraging Advanced 5G Facilities*, Oulun Yliopisto, Finland, 2019.

[30] R. Shrestha, I. Oh, and S. Kim, "A survey on operation concept, advancements, and challenging issues of urban air traffic management," *Frontier Future Transp.*, vol. 4, pp. 1–27, Feb. 2021.

[31] *Unmanned Aerial Systems Over 5G*, 3GPP, France, 2019.

[32] *Unmanned Aerial System (UAS) support in 3GPP*, document TS 22.125, 3GPP, 2015.

[33] Ericsson. (2021). *An overview of 3GPP Releases 17 and 18*. [Online]. Available: https://www.ericsson.com/4a92c5/assets/local/reports-papers/ericsson-technology-review/docs/2021/an-overview-of-3gpp-releases-17-and-18.pdf

[34] N.-N. Dao, Q.-V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho, "Survey on aerial radio access networks: Toward a comprehensive 6G access infrastructure," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1193–1225, 2nd Quart., 2021.

[35] M. Giordani and M. Zorzi, "Non-terrestrial networks in the 6G era: Challenges and opportunities," *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, Mar./Apr. 2021.

[36] M. Mahdi Azari, S. Solanki, S. Chatzinotas, O. Kodheli, H. Sallouha, A. Colpaert, J. Fabian Mendoza Montoya, S. Pollin, A. Haqiqatnejad, A. Mostaani, E. Lagunas, and B. Ottersten, "Evolution of non-terrestrial networks from 5G to 6G: A survey," 2021, *arXiv:2107.06881*.

[37] R. Kunst, E. Pignaton, T. Zhou, and H. Hu, "Application of future 6G technology to support heavy data traffic in highly mobile networks," in *Proc. 1st Int. Conf. Smart Syst. Emerg. Technol. (SMARTTECH)*, Nov. 2020, pp. 144–148.

[38] Ericsson. (2021). *The Sky is Not the Limit: The Past, Present, and Future of the Internet of Drones*. [Online]. Available: https://www.ericsson.com/en/blog/2021/6/internet-of-drones-sky-is-not-the-limit

[39] Y. Liu, C.-X. Wang, H. Chang, Y. He, and J. Bian, "A novel non-stationary 6G UAV channel model for maritime communications," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 10, pp. 2992–3005, Oct. 2021.

[40] M. Mozaffari, X. Lin, and S. Hayes, "Towards 6G with connected sky: UAVs and beyond," 2021, *arXiv:2103.01143*.

[41] Facebook. *Building Communications Networks in the Stratosphere*. Accessed: Jul. 30, 2016. [Online]. Available: https://engineering.fb.com/2015/07/30/connectivity/building-communications-networks-in-the-stratosphere/

[42] T. S. Perry. *Facebook Aims to Remake Telecom With Millimeter Waves and Tether-Tennas*. Accessed: Apr. 19, 2017. [Online]. [Online]. Available: https://spectrum.ieee.org/facebook-aims-to-remake-the-telecom-infrastructure-with-millimeter-waves-and-tethertennas

[43] *Balloon-Powered Internet for Everyone*. Accessed: Nov. 30, 2021. [Online]. Available: https://x.company/projects/loon/

[44] Nokia. (Oct. 2016). *F-Cell Technology From Nokia Bell Labs Revolutionizes Small Cell Deployment by Cutting Wires, Costs and Time*. [Online]. Available: https://www.nokia.com/news/releases/2016/10/03/f-cell-technologyfrom-nokia-bell-labs-revolutionizes-small-cell-deployment-by-cuttingwires-costs-and-time

[45] (2019). *Smart Device Communication: A Paradigm for High Performance Future Mobile Networking*. [Online]. Available: https://cordis.europa.eu/project/id/670896

[46] Eurecom. *ERC Perfume Project*. [Online]. Available: http://www.ercperfume.org/about/

[47] Huawei. *Connected Aerial Vehicle Live*. Accessed: Dec. 10, 2021. [Online]. Available: https://www.huawei.com/en/technology-insights/industry-insights/outlook/mobile-broadband/xlabs/use-cases/mbbf2017-connected-aerial-vehicle-live

[48] R. M. Fouda, "Security vulnerabilities of cyberphysical unmanned aircraft systems," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 33, no. 9, pp. 4–17, Sep. 2018.

[49] M. Latva-aho, K. Leppänen, F. Clazzer, and A. Munari, "Key drivers and research challenges for 6G ubiquitous wireless intelligence," 6G Res. Vis. 1, 6G Flagship, Univ. Oulu, Finland, Tech. Rep., 2020.

[50] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 18–27, Sep. 2019.

[51] *Drones, UTM and Spectrum—A Review*. Accessed: Dec. 12, 2021. [Online]. Available: https://dronealliance.eu/wp-content/uploads/2016/06/Spectrum-Allocation-White-Paper-Drone-Alliance-Europe-fin.pdf

[52] (2021). *Radio Frequencies*. [Online]. Available: https://top-10-drones.com/radio-frequencies/

[53] R. Bajracharya, R. Shrestha, and S. Kim, "An admission control mechanism for 5G LWA," *Sustainability*, vol. 10, no. 6, p. 1999, Jun. 2018.

[54] Q. Chen, G. Yu, H. Shan, A. Maaref, G. Y. Li, and A. Huang, "An opportunistic unlicensed spectrum utilization method for LTE and WiFi coexistence system," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6.

[55] Q. Chen, G. Yu, H. Shan, A. Maaref, G. Y. Li, and A. Huang, "Cellular meets WiFi: Traffic offloading or resource sharing?" *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3354–3367, May 2016.

[56] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[57] T. Liu, Z. Zhang, H. Jiang, Y. Qian, K. Liu, J. Dang, and L. Wu, "Measurement-based characterization and modeling for low-altitude UAV air-to-air channels," *IEEE Access*, vol. 7, pp. 98832–98840, 2019.

[58] M. Polese, L. Bertizzolo, L. Bonati, A. Gosain, and T. Melodia, "An experimental mmWave channel model for UAV-to-UAV communications," in *Proc. 4th ACM Workshop Millimeter-Wave Netw. Sens. Syst.*, Sep. 2020, pp. 1–6.

[59] R. Amorim, H. Nguyen, P. Mogensen, I. Z. Kovács, J. Wigard, and T. B. Sørensen, "Radio channel modeling for UAV communication over cellular networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 514–517, Aug. 2017.

[60] X. Cai, J. Rodríguez-Piñeiro, X. Yin, N. Wang, B. Ai, G. F. Pedersen, and A. P. Yuste, "An empirical air-to-ground channel model based on passive measurements in LTE," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1140–1154, Feb. 2019.

[61] W. Khawaja, I. Guvenc, and D. Matolak, "UWB channel sounding and modeling for UAV Air-to-Ground propagation channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–7.

[62] D. W. Matolak and R. Sun, "Air–ground channel characterization for unmanned aircraft systems—Part I: Methods, measurements, and models for over-water settings," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 26–44, Jan. 2017.

[63] D. W. Matolak and R. Sun, "Air–Ground channel characterization for unmanned aircraft Systems—Part III: The suburban and near-urban environments," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6607–6618, Aug. 2017.

[64] (2021). *Physical Layer Procedures for Shared Spectrum Channel Access*. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3435

[65] *Study on NR-Based Access to Unlicensed Spectrum*, document TR 380889, 2018. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3235

[66] R. Bajracharya, R. Shrestha, S. A. Hassan, K. Konstantin, and H. Jung, "Dynamic pricing for intelligent transportation system in the 6G unlicensed band," *IEEE Trans. Intell. Transp. Syst.*, early access, Oct. 21, 2021, doi: 10.1109/TITS.2021.3120015.

[67] R. Bajracharya and H. Jung, "Contextual bandits approach for selecting the best channel in industry 4.0 network," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2021, pp. 13–16.

[68] R. Bajracharya, R. Shrestha, S. A. Hassan, H. Jung, R. I. Ansari, and M. Guizani, "Unlocking unlicensed band potential to enable URLLC in cloud robotics for ubiquitous IoT," *IEEE Netw.*, vol. 35, no. 5, pp. 107–113, Sep. 2021.

[69] S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojovic, A. Demir, and M. Beluri, "New radio beam-based access to unlicensed spectrum: Design challenges and solutions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 8–37, 1st Quart., 2020.

[70] Q. Chen, K. Yang, H. Jiang, and M. Qiu, "Joint beamforming coordination and user selection for CoMP enabled NR-U networks," *IEEE Internet Things J.*, early access, Mar. 4, 2021, doi: 10.1109/JIOT.2021.3063733.

[71] K. Kosek-Szott, A. L. Valvo, S. Szott, P. Gallo, and I. Tinnirello, "Downlink channel access performance of NR-U: Impact of numerology and mini-slots on coexistence with Wi-Fi in the 5 GHz band," *Comput. Netw.*, vol. 195, Aug. 2021, Art. no. 108188.

[72] R. Bajracharya, R. Shrestha, R. Ali, A. Musaddiq, and S. W. Kim, "LWA in 5G: State-of-the-art architecture, opportunities, and research challenges," *IEEE Commun. Mag.*, vol. 56, no. 10, pp. 134–141, Oct. 2018.

[73] A. Mazaherifar and S. Mostafavi, "UAV placement and trajectory design optimization: A survey," *Wireless Pers. Commun.*, vol. 2021, pp. 1–21, Dec. 2021.

[74] C.-C. Lai, L.-C. Wang, and Z. Han, "Data-driven 3D placement of UAV base stations for arbitrarily distributed crowds," in *Proc. IEEE Global Commun. Conf.*, Dec. 2019, pp. 1–6.

[75] M. K. Shehzad, S. A. Hassan, M. Luque-Nieto, J. Poncela, and H. Jung, "Energy efficient placement of UAVs in wireless backhaul networks," in *Proc. 2nd ACM MobiCom Workshop Drone Assist. Wireless Commun. 5G Beyond*, 2020, pp. 1–6.

[76] M. A. Jan, S. A. Hassan, and H. Jung, "UAVs: Communication aspects and cellular service provisioning," in *Drones Smart-Cities*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 79–91.

[77] H. Jung and I.-H. Lee, "Performance analysis of millimeter-wave UAV swarm networks under blockage effects," *Sensors*, vol. 20, no. 16, p. 4593, Aug. 2020.

[78] N. Waqar, S. A. Hassan, A. Mahmood, M. Gidlund, and H. Jung, "Joint power and beamforming optimization of UAV-assisted NOMA networks for B5G-enabled smart cities," in *Proc. 1st Workshop Artif. Intell. Blockchain Technol. Smart Cities 6G*, Oct. 2021, pp. 25–30.

[79] C. K. Kim, C. S. Yang, and C. G. Kang, "Adaptive Listen-Before-Talk (LBT) scheme for LTE and Wi-Fi systems coexisting in unlicensed band," in *Proc. 13th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2016, pp. 589–594.

[80] R. Ali, N. Shahin, R. Bajracharya, B.-S. Kim, and S. Kim, "A self-scrutinized backoff mechanism for IEEE 802.11ax in 5G unlicensed networks," *Sustainability*, vol. 10, no. 4, p. 1201, Apr. 2018.

[81] M. Y. Arafat and S. Moh, "Routing protocols for unmanned aerial vehicle networks: A survey," *IEEE Access*, vol. 7, pp. 99694–99720, 2019.

[82] Q. Zhang, W. Saad, M. Bennis, X. Lu, M. Debbah, and W. Zuo, "Predictive deployment of UAV base stations in wireless networks: Machine learning meets contract theory," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 637–652, Jan. 2021.

[83] X. Pang, M. Sheng, N. Zhao, J. Tang, D. Niyato, and K.-K. Wong, "When UAV meets IRS: Expanding air-ground networks via passive reflection," *IEEE Wireless Commun.*, vol. 28, no. 5, pp. 164–170, Oct. 2021.

[84] S. Mandal. (Feb. 2021). *Counterpoint's Global Cellular IoT Module and Chipset Forecast*. [Online]. Available: https://www.counterpointresearch.com/global-cellular-iot-module-shipments-2024

[85] B. Jiang, J. Yang, H. Xu, H. Song, and G. Zheng, "Multimedia data throughput maximization in Internet-of-Things system based on optimization of cache-enabled UAV," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3525–3532, Apr. 2019.

[86] R. Shrestha, R. Bajracharya, and S. Y. Nam, "Challenges of future VANET and cloud-based approaches," *Wireless Commun. Mobile Comput.*, vol. 2018, May 2018, Art. no. 5603518.

[87] Y. Zhang, M. A. Kishk, and M.-S. Alouini, "A survey on integrated access and backhaul networks," 2021, *arXiv:2101.01286*.

ROJEENA BAJRACHARYA (Senior Member, IEEE) received the M.S. degree in information and communication engineering from the Daegu Gyeongbuk Institute of Science and Technology (DGIST), South Korea, in 2014, and the Ph.D. degree in information and communication engineering from Yeungnam University (YU), in 2019. She is currently a Research Associate with the Department of Electronic Engineering, Kyung Hee University, Yongin, South Korea. From November 2019 to August 2021, she worked as a Postdoctoral Researcher with the Department of Information and Telecommunication Engineering, Incheon National University (INU), South Korea. From 2010 to 2012, she works as an ICT Consultant at UNICEF Regional Office for South Asia, Nepal. Her research interests include 5G wireless communications and networks, 6G unlicensed, new radio in unlicensed, 6G, and heterogeneous networks.

RAKESH SHRESTHA (Senior Member, IEEE) received the M.E. degree in information and communication engineering from Chosun University, South Korea, in 2010, and the Ph.D. degree from Yeungnam University, South Korea, in 2018. He is currently working as a Postdoctoral Researcher with the School of Integrated Technology, Yonsei University. From 2010 to 2012, he worked as a Core Network Engineer at Huawei Technologies Company Ltd. He has worked as a reviewer in several renowned journals and conferences. His research interests include UAV, UTM, wireless communications, vehicular *ad hoc* networks, blockchain, the IoT, deep learning, AI, 5G, and wireless security.

SHIHO KIM (Senior Member, IEEE) founded the PAV Research and Development Center supported by Incheon Metropolitan City and Soomvi Inc., in 2020. He has been directing the Seamless Transportation Laboratory, since 2011. He is currently a Professor with the School of Integrated Technology, Yonsei University, Seoul, South Korea. His research interests include the development of software and hardware technologies for autonomous vehicles and reinforcement learning for intelligent transportation systems.

HAEJOON JUNG (Senior Member, IEEE) received the B.S. degree (Hons.) from Yonsei University, South Korea, in 2008, and the M.S. and Ph.D. degrees from the Georgia Institute of Technology (Georgia Tech), Atlanta, GA, USA, in 2010 and 2014, respectively, all in electrical engineering. From 2014 to 2016, he was a Wireless Systems Engineer at Apple, Cupertino, CA, USA. From 2016 to 2021, he was with Incheon National University, Incheon, South Korea. Since September 2021, he has been with Kyung Hee University, as an Associate Professor in electronic engineering. His research interests include communication theory, wireless communications, wireless power transfer, and statistical signal processing.