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Software-Defined Radio Deployments in UAV-Driven Applications: A Comprehensive Review

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ABSTRACT During the last few years, Unmanned Aerial Vehicles (UAVs) have increasingly become primary components of various critical civilian and military applications. As technology rapidly evolves, particularly in the realm of Software-Defined Radio (SDR) and Field-Programmable Gate Arrays (FPGAs), advanced communication protocols and signal processing methods are expected to emerge within UAV-based systems. Crucially, UAVs are expected to capitalize on SDR to enhance communication, sensing, data processing, and defense mechanisms. With this perspective in mind, this paper provides a comprehensive up-to-date review of the integration of SDR technology in UAV-based systems, encompassing the latest techniques, methodologies, and challenges. Specifically, this paper examines case studies and real-world implementations of SDR-assisted UAV-based systems across various domains, including communication, security, detection, classification, and localization, elucidating their efficacy, constraints, and areas for potential improvement. Through this review, valuable insights are offered to researchers, engineers, and practitioners interested in harnessing the synergies between SDR and UAV technologies to address the evolving requirements of contemporary applications and pave the path for future innovations in the field.

INDEX TERMS Communication, detection, localization, security, software-defined radio (SDR), unmanned aerial vehicle (UAV).

I. INTRODUCTION

In recent years, driven by advancements in avionics and electronic systems, Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have emerged with applications spanning numerous domains, including long-range communications, environmental monitoring, surveillance, disaster management, target recognition, military reconnaissance, and beyond [1]. It is worth mentioning that UAVs are among the pivotal technologies that will drive the development of Sixth Generation (6G) networks [2], whereas the global UAV market is forecasted to reach 42.8 billion USD by 2025 [3]. One of the main factors determining the success of UAV operations is the reliable and efficient communication. However, conventional communication systems often struggle to meet the diverse and dynamic requirements of UAV-based applications. Moreover, these systems may operate on different frequency bands, waveforms, and protocols, leading to interoperability issues. To meet mission-critical objectives, such as Quality of Service (QoS), sufficient coverage, cost-effectiveness, and cooperation with existing communication infrastructure, flexible and adaptive communication solutions are indispensable.

Toward this end, Software-Defined Radio (SDR) technology has garnered significant attention as a promising solution to address the aforementioned challenges, facilitating seamless switching between applications through software control [4]. By leveraging SDR technology, communication protocols and signal processing functionalities can be implemented in software, offering unparalleled flexibility, scalability, and programmability, while minimizing the reliance on costly and proprietary hardware solutions. Presently, the majority of modern communication devices utilize SDR technology. Also, the global market value of SDR is projected to rise to USD 32.2 billion by 2028 with a Compound Annual Growth Rate (CAGR) of 7.4% [5]. It is worth noting that the decreased cost and weight of certain SDR equipment make it feasible for UAVs to incorporate SDR technology onboard. Thus, it becomes possible to configure communication parameters based on mission requirements and environmental conditions, dynamically switch between different frequency bands, and even implement advanced Cognitive Radio (CR) techniques to optimize spectrum utilization [6].

Alongside these advancements, the proliferation of UAVs has led to the rise of cybersecurity concerns [7], [8] and created substantial risks to public safety, necessitating the development of effective countermeasures against potential attacks. Given that the communication links of UAV-based systems are typically public, they are vulnerable to a variety of security threats such as eavesdropping, unauthorized access, spoofing and jamming. While security might not seem directly related to radio technology at first glance, SDR can play a pivotal role in safeguarding communication channels [9] through a Physical-Layer security (PLS) standpoint. Through the dynamic adaptation of communication protocols and frequencies, SDR can reduce the risk of interception and preserve the confidentiality of UAV operations. In this context, SDR can promptly identify unauthorized signals and potential intrusions, thereby bolstering the security of UAV operations. In contrast to conventional security methods that operate at higher layers of the communication protocol stack, SDR-assisted security utilizes the Physical Layer (PHY) as its primary source of information. This is because the PHY has a direct connection to the wireless channel, where threats like jamming occur. SDRs, with their adaptive and flexible capabilities, can be also employed as penetration testing tools to examine the attack surface and stress-test the security mechanisms of UAV-based nodes. Consequently, integrating SDR technology into UAV systems not only addresses communication challenges but also significantly improves security, making UAV operations more effective and secure.

From a different viewpoint, the rapid expansion of the UAV industry has outpaced existing regulatory frameworks for safe and lawful drone operations, leading to their association with illegal and potentially harmful activities. Therefore, there exists an urgent need for developing highly accurate detection, classification, and localization systems to ensure security and regulatory compliance [10]. Detection involves the initial identification of a target or signal within the environment, utilizing spectrum sensing techniques to identify the presence of signals of interest amidst noise and interference. SDRs can improve the detection capabilities of UAVs by allowing for flexible and programmable signal analysis, which is essential for tasks like obstacle detection and target identification. Moreover, classification goes a step further by categorizing the detected signals into specific types or classes based on their unique characteristics, such as modulation scheme or frequency pattern. Localization, on the other hand, focuses on determining the spatial coordinates or position of the detected signal sources relative to the UAV or other reference points. SDRs can enhance the precision and reliability of UAV localization by enabling the use of sophisticated signal processing techniques and adaptive algorithms Together, these functionalities enable SDR-assisted UAV-based systems to not only detect and classify signals but also accurately pinpoint their locations, facilitating various applications including spectrum monitoring, communication intelligence, and surveillance.

A. CONTRIBUTION

Inspired by the aforementioned observations, this review paper aims to shed light on a broad set of up-to-date SDR deployments within the UAV-based systems. Recently, a multitude of review and survey papers have been published, each focusing primarily on either UAVs or SDR, with some only partially addressing the amalgamation of UAV and SDR technologies. As far as the authors are aware, there exist no review papers that thoroughly examine and exhaustively cover the intersection of these technologies. This paper seeks to bridge this void by presenting the following contributions:

- An overview of the core principles underlying UAV and SDR technologies is provided, highlighting their distinctive features, functionalities, and operational frameworks. The convergence of UAV and SDR technologies is also clarified.
- Various application domains are covered, including communication, security, detection, classification, and localization, all specifically tailored for SDR-assisted UAV-based systems. For each application domain, the role of SDR is emphasized, and the anticipated outcomes are discussed. The application domains identified in this paper were derived through a systematic literature review conducted across major academic databases pertinent to UAV and SDR research, including Web of Science (WoS), IEEE Xplore, ACM Digital Library, and others. Specifically, we utilized keywords related to the integration of SDR in UAVs and discovered that communication, security, detection, classification, and localization are pivotal areas where SDR technology can provide substantial improvements. We included research articles published in English, primarily in peer-reviewed journals, from 2020 to August 2024, that directly addressed SDR applications in these areas. Articles not focused on SDR technology or those concentrating on unrelated aspects of UAVs were excluded.
- State-of-the-art methodologies and key technologies employed to enhance SDR-assisted UAV-based systems are presented, with an emphasis on recent advancements, hurdles, and potential opportunities in the field.
- Through the analysis of case studies and practical deployments, this study provides insights into the effectiveness, limitations, and potential areas for further exploration.

Fig. 1 depicts the multifaceted benefits of SDR-assisted UAV-based systems, as discussed throughout this paper. These

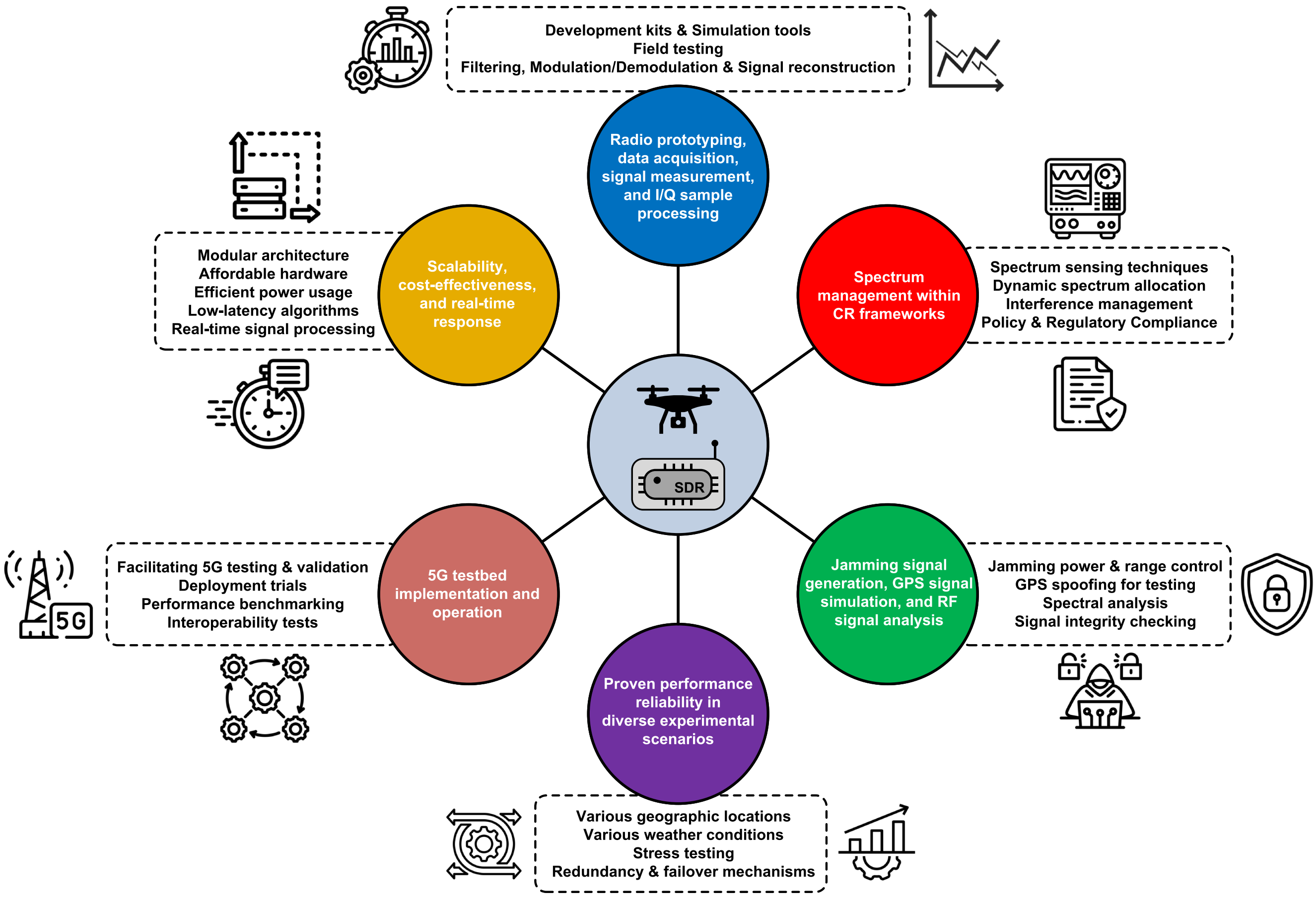

FIGURE 1. Benefits of SDR integration in UAV-based systems.

benefits position SDR-enabled UAVs as powerful tools for modern applications, driving innovation and improving operational efficiency across various sectors. However, it should be noted that the integration of SDRs in UAVs is currently focused on experimenting, prototyping, testing, and advancing new communication technologies. Indeed, integrating SDRs into UAVs faces several challenges, including considerations of size, weight, and power consumption, as existing SDR technology may not always be optimized for these constraints. Additionally, addressing regulatory and safety issues related to SDR-equipped UAVs is essential. Although SDR devices specifically designed for UAVs are not yet widespread, commercially available advanced devices such as the TrellisWare Ghost 880 embedded module [11] and BluSDR Radio Technology Family [12] signify a notable shift towards incorporating commercial SDR solutions into UAV platforms. Additionally, there are instances of SDRs being used in advanced research projects and pilot programs that could lead to future commercial adoption. This trend mirrors the evolution observed in other platforms, such as CubeSats, where commercial SDRs have recently become available [13], [14], [15] indicating a similar potential for UAVs in the near future.

B. STRUCTURE

The remainder of this paper is organized as follows. Section II examines relevant review papers, delineating their objectives and shortcomings. Section III provides an understanding of UAV and SDR technologies, elucidating their convergence. Section IV explores SDR deployments for communication applications, while Section V reviews research endeavors concerning SDR-assisted UAV-based systems in security domains. In Section VI, applications related to detection, classification, and localization are investigated. The lessons learned are discussed in Section VII. Section VIII outlines prospects for future research. Finally, Section IX offers concluding remarks. For readers' convenience, Fig. 2 presents a graphical illustration of the detailed taxonomy of this paper.

II. PREVIOUS REVIEW PAPERS

In the past, several reviews, surveys, and tutorials have been published concerning various aspects of UAVs and/or SDR, as summarized in Table 1. The latest advancements in UAV-based communications technologies and their applications were presented in [16] and several topics were covered, including antennas, network architectures, path

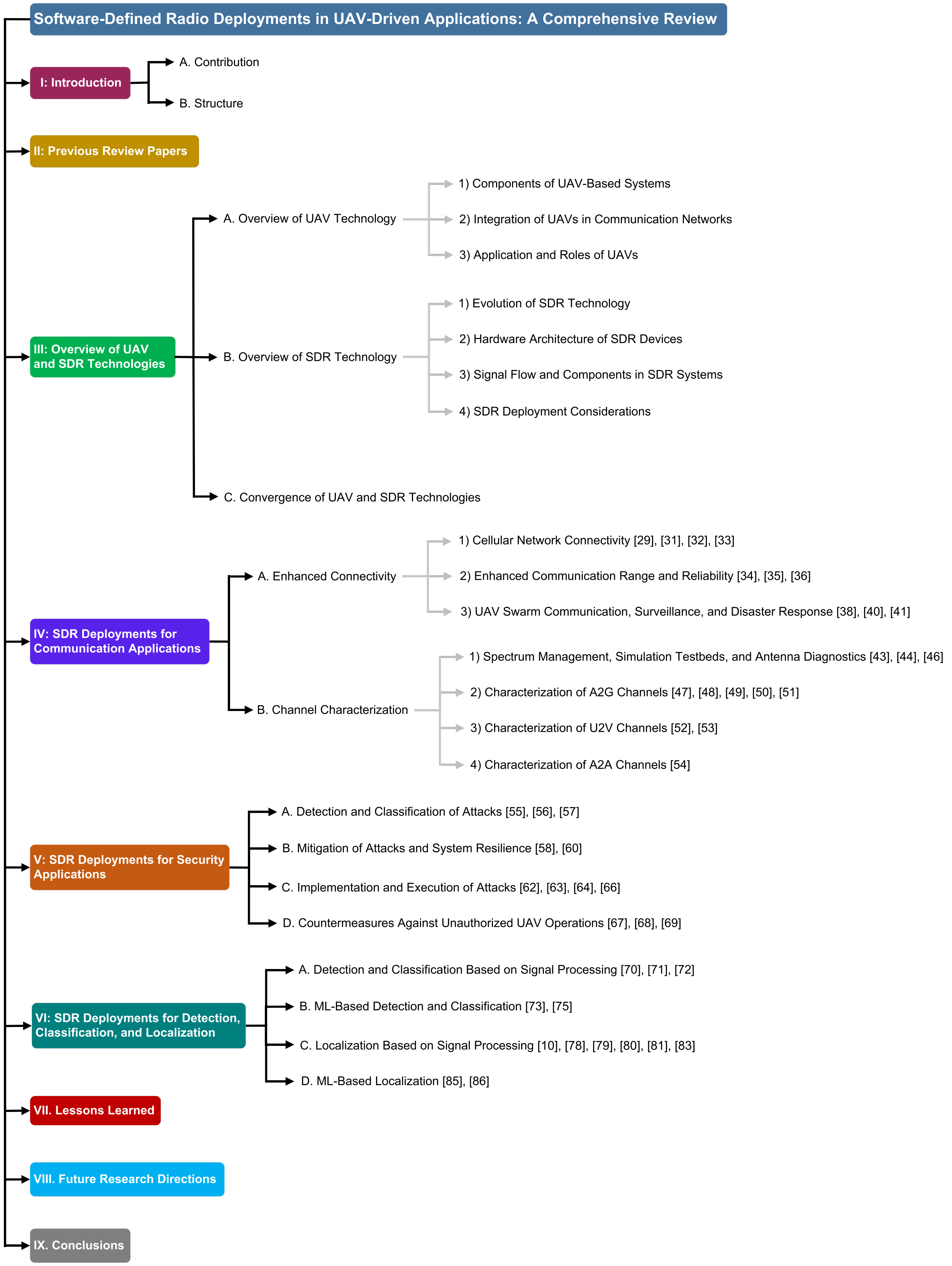

FIGURE 2. Taxonomy of this paper.

TABLE 1. Relevant Review and Survey Papers

Ref.	Year	Short Description	UAV	SDR	Communication	Security	Detection	Localization
[4]	2018	A survey of SDR platforms in wireless communication protocols, emphasizing programmability, flexibility, and energy efficiency	✗	✓	✓	Partially	✗	✗
[6]	2021	Overviews of CR technology for enhancing communication in UAVs	✓	✓	Partially	Partially	✓	✗
[7]	2023	Survey of security and privacy issues in UAVs, classified into four levels: hardware, software, communication, and sensor	✓	✗	✗	✓	✓	✗
[10]	2022	Survey of UAV detection and defense systems	✓	✓	✗	✓	✓	✓
[16]	2020	Survey of latest UAV communication technologies, including task modules, antennas, and network architectures	✓	✗	✓	✓	Partially	✗
[17]	2022	Analysis of the fundamental requirements for accurate localization in SUAVs, review of existing localization techniques	✓	✗	✓	✓	✗	✓
[18]	2022	Review of recent trends and challenges in UAV detection and localization methods	✓	✗	✗	Partially	✓	✓
[19]	2022	Review of UAV detection, classification, tracking, security and privacy	✓	✗	✓	✓	✓	✓
[20]	2023	Review of SDN-enabled UAV systems, focusing on enhanced connectivity and scalability while addressing management and security issues	✓	✗	✓	✓	✗	✗
[21]	2022	Overview of GPP-based SDR platforms suitable for various wireless standards	✗	✓	✓	✗	✗	✗
[22]	2018	Survey of measurement methods proposed for UAV channel modeling and characterization	✓	Partially	✓	✗	✗	✗
This paper	2024	Review of SDR implementations in UAV-driven applications across various domains	✓	✓	✓	✓	✓	✓

planning, encryption, and power management techniques. Despite reviewing recent improvements in UAV communication technologies, both hardware and algorithm-based software solutions, this paper did not discuss SDR implementations. In [7], a detailed examination of security and privacy concerns surrounding UAVs was conducted, organized into four distinct levels; sensor-level, hardware-level, software-level, and communication-level. This approach systematically delved into prevalent vulnerabilities, threats, attacks and countermeasures available for each level. Nevertheless, SDR-assisted security solutions were not considered. Furthermore, a Swarm UAVs (SUAVs) architecture and solutions for accurate localization, communication, and coordination were investigated in [17], without specifically highlighting SDR-based techniques. In [18], the trends and challenges of UAV detection methods were reviewed in response to the increasing use of UAVs for illegal and malicious activities. Particularly, various detection techniques were examined (e.g., RF-based, radar, acoustic, electro-optical). However, SDR-based detection techniques were not covered. The advancements, security threats, privacy concerns, and limitations linked with UAVs were explored in [19], such as detection, classification, tracking, and security measures. While SDR technology could potentially be used for security applications, it was not explicitly mentioned in this paper. Also, an in-depth assessment of the integration of Software-Defined Networking (SDN) with UAVs and its implications for next generation communication systems was provided in [20]. Specifically, the architecture, communication mechanisms, and service requirements of SDN-assisted UAV-based networks were described. However, it is important to note that the focus of this paper was on SDN rather than on SDR.

On the other hand, a thorough overview of SDR was offered in [4], encompassing its architecture, hardware platforms, design approaches, development tools, and comparative analysis. While centering on SDR platforms and their applications in wireless communication protocols, this paper did not address UAV-based systems. In [21], a compilation of General-Purpose Processor (GPP)-based SDR platforms meeting the minimum specifications of various wireless technologies was presented. This paper helped enhance comprehension regarding the hardware and software elements of SDR platforms, assisting researchers and developers in choosing the suitable platform for their particular wireless technology applications. Nevertheless, this paper did not elucidate how the findings and recommendations concerning SDR platforms might be relevant to UAV-based systems. Moreover, the main scope of [22] was to survey approaches to characterize UAV channels, emphasizing relevant topics including channel measurement, channel modeling, and challenges in UAV-based communications. Although this paper pointed out the importance of accurate channel characterization for optimizing performance and designing efficient UAV communication systems, the SDR technology was partly discussed. Additionally, the integration of CR technology with UAVs was studied in [6] to enhance communication capabilities through the dynamic selection of transmission channels based on application requirements. In this direction, an overview of CR for UAV communications was presented, ongoing research was presented, and steps to build a simple and cost-effective CR-based UAV testbed were outlined. Although this paper examined how CR technology can be applied alongside UAVs, yet it's important to acknowledge that it did not exhaustively explore the entirety of SDR-assisted UAV-based applications. In [10], a survey of drone detection and defense systems was provided, focusing particularly on methods utilizing RF technologies and solutions implemented through SDR platforms. Toward this end, existing works on this subject were analyzed, highlighting the legal issues surrounding jamming functions for drone annihilation. Nevertheless, this paper did not concentrate on broader communication aspects, such as data transmission and channel characterization. To overcome the limitations of the aforementioned studies and thoroughly explore the landscape of existing SDR-enabled solutions for UAV-based systems, contemporary review papers are necessary.

III. OVERVIEW OF UAV AND SDR TECHNOLOGIES

A. OVERVIEW OF UAV TECHNOLOGY

1) COMPONENTS OF UAV-BASED SYSTEMS

The term UAV encompasses rapidly deployed Low-Altitude Platform (LAP) or airborne vehicle that acts as aerial transceiver, operating at modest altitudes within the troposphere to support various missions and short-term operations [23]. With the evolution of UAV technology, diverse UAV types have emerged, differing in shape, weight, and size – from small recreational drones to large military-grade aircrafts. The configuration of their payloads, including communication equipment, cameras, radars, and sensors, determines the size of UAVs, along with their battery capacity and flight duration. Based on their flight mechanisms, UAVs can be categorized into Remotely Piloted Vehicles (RPVs), multi-rotor drones, fixed-wing drones, hybrid fixed/rotary

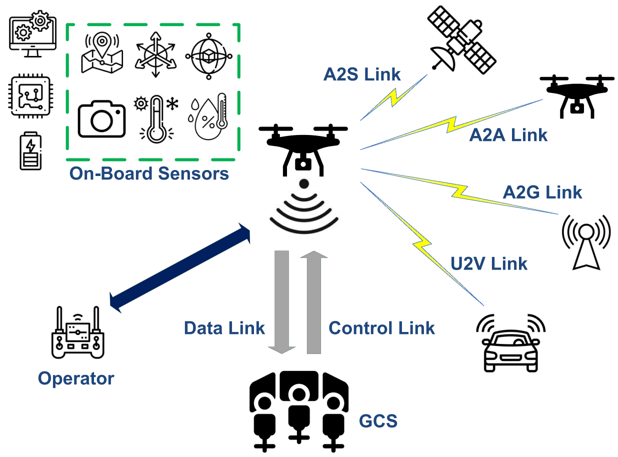

FIGURE 3. High-level architecture of a UAV-based system consisting of the unmanned aircraft, the GCS, and the operator.

wing drones, robot planes, and pilotless aircrafts. Fixed-wing UAVs have stationary wings and require a runway for takeoff and landing, while rotary-wing UAVs (e.g., quadcopters and hexacopters) encompass single or multirotor configurations offering high maneuverability and precise takeoff and control. Based on their ability to fly long distances without human intervention, UAVs can be further classified as fully autonomous UAVs that perform tasks independently, remotely operated UAVs that follow human commands for task execution, and remotely piloted UAVs that are entirely controlled by a human operator [19].

Typically, a UAV system comprises three main components; the unmanned aircraft, the Ground Control Station (GCS), and the Communication Link (CL). As shown in Fig. 3, the unmanned aircraft serves as the central element of the UAV system and is supervised by the operator either through the GCS, which enables remote control and monitoring during flight missions, or via a Remote Controller (RC) [18]. Furthermore, the internal hardware architecture of a UAV encompasses several key elements. Among these elements, the Flight Controller (FC) serves as the UAV's Central Processing Unit (CPU) and acts as an intermediary between the software and onboard devices. Moreover, the wireless communication module facilitates communication with external devices, such as the RC, GCS, and nearby UAVs, incorporating both transmitters and receivers. Also, the rechargeable batteries provide power to the entire UAV system, the actuators generate necessary movements for the UAV during flight, ensuring stability, and the sensors enable environmental sensing by providing measurements. More specifically, UAVs can accommodate a diverse array of sensors, crucial for executing their flight missions, including geospatial sensor technologies capable of collecting substantial data volumes. To ensure stability required for critical applications and mitigate displacements due to environmental factors (e.g., wind and pressure variations), flight control tilt sensors, accelerometers, gyroscopes, and ultrasonic sensors for obstacle avoidance, are typically employed. Additionally, UAVs may also be equipped with electro-optical sensors, radars, and cameras, including Red-Green-Blue (RGB) cameras for surveillance and monitoring applications, Normalized Difference Vegetation Index (NDVI) cameras for precision farming, and Light Imaging, Detection, and Ranging (LIDAR) for efficient mapping and localization [23]. Moreover, sensors such as hyperspectral depth and thermal sensors facilitate aerial thermal imaging for analysis and reporting. These sensors play a vital role in the overall functionality of the UAV system, designed specifically to measure various physical attributes of the surrounding environment, including altitude, speed, and Global Positioning System (GPS) coordinates. The data collected by these sensors is directly forwarded to the FC to determine the appropriate course of action. Regarding software architecture, the UAV operates within a layered system comprising the Firmware, Middleware, and Operating System. These layers collectively form the flight stack, managing tasks, such as guidance, navigation, and communication.

2) INTEGRATION OF UAVS IN COMMUNICATION NETWORKS

With the escalating demand for comprehensive broadband services, global coverage, and ubiquitous access, UAVs emerge as significant supporters of established terrestrial and satellite networks. Future-generation systems, such as 6G systems and Internet of Things (IoT), are anticipated to integrate UAVs as autonomous communicating nodes or aerial relays, facilitating highly reliable connections between sensors and data collection points across diverse terrains [23]. In particular, UAVs can communicate with ground or space-based nodes or directly with each other, independent of any infrastructure, while also maintaining coordination with GCSs. Toward this end, there exist various types of communication, such as Air-to-Ground (A2G), UAV-to-Vehicle (U2V), Air-to-Air (A2A) Air-to-Space/Satellite (A2S), and hybrid communication integrating the functionalities of the aforementioned types [7]. As far as A2G communication is concerned, UAVs hold significant potential to enhance coverage and connectivity by providing Line-of-Sight (LoS) communication with ground nodes, particularly in scenarios where terrestrial systems or satellite networks encounter connectivity restrictions.

Aside from their individual utilization, UAVs have also the capability to form interconnected networks within the framework of Flying Ad hoc Networks (FANETs), facilitating real-time data communication from sensors or actuators [24]. In deployments of the Internet of Drones (IoD) paradigm [25], network architectures commonly revolve around combinations of aerial and ground infrastructures, or they consist solely of aerial nodes in ad hoc configurations. The former entails groups of UAVs, users, and a GCS equipped with robust computational resources and ample energy supply. In this scenario, the GCS oversees and directs the UAVs remotely throughout their missions. On the other hand, the latter involves aerial nodes functioning in a decentralized manner, relying on communication links between UAVs for operation. This architecture offers enhanced scalability, reliability, survivability, and efficient task distribution.

3) APPLICATIONS AND ROLES OF UAVS

UAVs aim to facilitate diverse civilian, commercial, and governmental missions, including IoT applications, spanning from military and security operations to entertainment and telecommunications. Moreover, UAVs serve various purposes within constrained timeframes, enabling swift deployment of multi-hop communication backbones in challenging scenarios, without human intervention. Such applications encompass public safety operations, search and rescue missions, surveillance activities, emergency communications during post-disaster scenarios, photographic reconnaissance, urban traffic monitoring, precision agriculture, and media traffic surveillance. Depending on the specific application scenario, UAVs can fulfill various roles as follows [8]:

- *Aerial Base Stations (BSs):* UAVs can act as mobile platforms for providing communication services to areas where conventional communication infrastructure is limited or unavailable.
- *Aerial Relays:* UAVs can bridge connectivity gaps and facilitate the retransmission of data packets between a ground transmitter and a terrestrial BS, thereby amplifying signal strength at relatively low transmission power levels and enhancing cellular coverage in challenging radio environments.
- *Aerial RF Sensing and Spectrum Sharing:* UAVs may need to share spectrum with terrestrial users, necessitating advanced spectrum sensing and access mechanisms to exploit the increasing availability of unlicensed and shared spectrum.
- *Aerial Scouts:* UAVs can sense various environmental parameters and monitor wireless communication links, offering valuable insights to enhance handover procedures, resource allocation, interference management, and network load balancing.
- *Aerial Attackers:* UAVs can be utilized as malicious entities within wireless networks, functioning as eavesdroppers or jammers.
- *Aerial Supporting Nodes:* UAVs can be utilized as friendly jammers emitting artificial noise directed towards potential malicious nodes.

B. OVERVIEW OF SDR TECHNOLOGY

1) EVOLUTION OF SDR TECHNOLOGY

In the 1990s, Joseph Mitola coined the term SDR to describe radios that could be reprogrammed and reconfigured via software rather than hardware [26]. Although SDR has been a technological concept for years, it's only in recent times that affordable SDR solutions, facilitated by user-friendly hardware platforms, such as Universal Software Radio Peripherals (USRPs) [27], have become accessible. The rising popularity of SDR technology is attributed to advancements in computing and the availability of free open-source software libraries over recent decades. This trend has led to the development of various SDR devices with different form factors, performance specifications, and interfaces. Currently, SDRs play a pivotal role in the development of wireless standards owing to their adaptability and programmability features [4]. These features are important, since the majority of signal processing and waveform design, including channel selection, modulation, and demodulation, occurs in the digital domain. Such operations are typically executed within software running on GPPs, Digital Signal Processors (DSPs) and Graphics Processing Units (GPUs) [28], but they can also be implemented on programmable hardware, such as Field-Programmable Gate Arrays (FPGAs) [4]. It is worth noting that FPGAs have significantly transformed the SDR landscape by providing a flexible and powerful platform for real-time signal processing. Their reconfigurability allows SDR systems to efficiently adapt to various communication standards and signal processing algorithms on-the-fly, which is crucial for the dynamic nature of SDR applications and multi-mission capabilities. Moreover, FPGA-integrated SDRs are essential for handling high-throughput data streams and supporting high-bandwidth applications (e.g., High-Definition (HD) video streaming or large-scale data collection). Their ability to perform parallel processing is also critical for demanding tasks, such as real-time modulation/demodulation, channel coding, filtering, and error correction. Additionally, FPGAs are energy-efficient, making them ideal for portable and embedded SDR platforms with limited computational resources. Conversely, SDRs have gained popularity in Proof-of-Concept projects due to the programming ease and flexibility offered by GPPs.

2) HARDWARE ARCHITECTURE OF SDR DEVICES

The hardware architecture of an SDR device encompasses several key components designed to facilitate both transmission and reception of radio signals with high flexibility and sufficient performance. At a high level, an SDR transceiver is a generic radio transceiver with a streamlined but flexible analog/RF component. The ideal SDR architecture features an analog part diminished at an amplifier and a front-end filter, though current technology does not yet fully support such an architecture. Typically, an SDR architecture includes an RF module, a digital front-end module, and baseband processing. The digital front-end module generally handles rate conversion, rate adaptation, and filtering, and serves as a digital Intermediate Frequency (IF) block. Depending on the SDR type, an analog IF part may also exist. The RF/IF and digital front-end modules are built from diverse hardware solutions offered by various manufacturers, each tailored for specific functionalities. High-performance RF components support wideband and frequency-agile operations, crucial for modern communication systems, while flexible data conversion stages ensure effective data acquisition and waveform generation across various frequency bands. Therefore, the RF component should provide extended bandwidth support and reconfigurable, agile features for center frequency selection and gain control. The baseband processing module, which may constitute a blend of hardware and software, manages signal filtering modulation, demodulation, encoding, decoding, generally all waveform synthesis and analysis parts, as well as, post-processing tasks. Baseband processing may be performed on the host, i.e., a computing unit connected to the SDR hardware via an interface (e.g., network, USB, PCIe, etc.), through embedded GPP units, or utilizing specialized hardware (e.g., DSPs or FPGAs). The former is also known as the digitizer-host model, where, for example, in receiver operations, the generic SDR equipment is only used to provide the In-phase and Quadrature (I/Q) samples at a selected frequency and bandwidth, while all other processing is performed on the host. This model has significantly contributed to the popularity of SDRs (especially USRPs) in research organizations, as it enables Over-the-Air (OTA) measurement and evaluation using conventional programming techniques and languages. Despite its ease of use, employing GPPs in conventional computers and operating systems has significant limitations for real-time processing. As a result, while this model was functional for up to 40 MHz bandwidth (depending on the tasks and setup), the advent of Fifth Generation (5G) with increased bandwidths requirements necessitated a shift from this modus operandi. More specifically, the digital front-end of the SDR hardware, typically implemented using an FPGA, is also employed for uploading waveform synthesis and analysis functions, in addition to the standard channelization/conversion operations. Moreover, hybrid schemes have been introduced that involve programming at the digital front-end and other processing units embedded within the SDR (e.g., System-on-Chip (SoC) solutions that typically employ an FPGA and an ARM processor), as well as the system host. Furthermore, the host may incorporate more complicated processing features (e.g., GPUs or DSPs). High-capacity processors and efficient high-speed interfacing enable seamless data transfer, essential for implementing broadband wireless protocols.

3) SIGNAL FLOW AND COMPONENTS IN SDR SYSTEMS

Fig. 4 clarifies the signal flow within a Multiple-Input Multiple-Output (MIMO)-enabled SDR system and illustrates the essential components involved in transmitting and receiving data. Modules available for custom waveform design and analysis code deployment are highlighted in blue color, though not all options are always available. For example, in conventional digitizer-host pairs (e.g., Ettus USRP B210), baseband processing is performed only at the host; in more elaborate solutions, FPGA offloading is available (e.g., Ettus USRP X310), while in SoC-based (e.g., Ettus USRP X410) or embedded (e.g., Ettus USRP E320) solutions, processing in integrated processors is possible. On the transmitter side, digital data is initially generated and modulated, up-converted to the desired IF through a Digital Up-Converter (DUC), processed by the digital front-end, converted to analog by a Digital-to-Analog Converter (DAC),

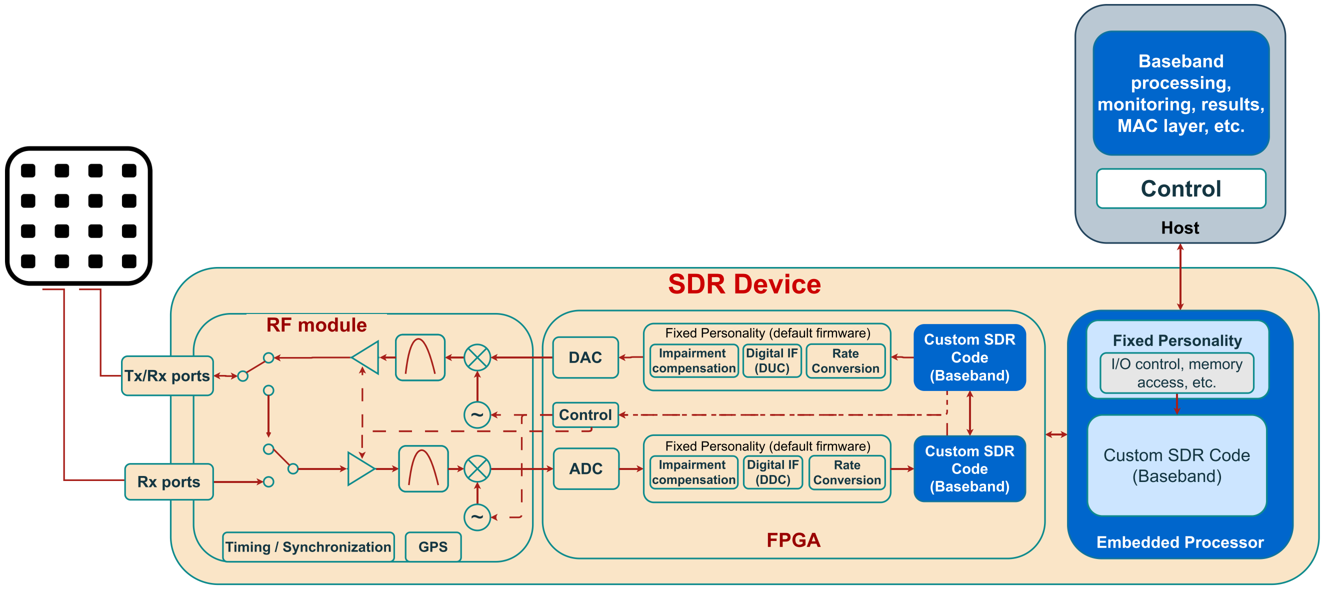

FIGURE 4. **Block diagram of an FPGA-integrated SDR device with MIMO capabilities.**

further up-converted to the desired RF frequency, amplified to a suitable level for transmission by a Power Amplifier (PA), and transmitted through the antenna. Conversely, on the reception side, the weak incoming RF signal is captured by the antenna, amplified by a Low Noise Amplifier (LNA), down-converted to an IF signal, converted into digital samples by an Analog-to-Digital Converter (ADC), processed by a Digital Down-Converter (DDC) to extract the desired baseband signal, further processed by specialized hardware, and finally outputted to the data sink for use or analysis.

4) SDR DEPLOYMENT CONSIDERATIONS

Table 2 provides a comparative assessment of the features of various SDR devices. It can be seen that each SDR device has its own unique specifications and capabilities, catering to different use cases, with most of these SDR devices integrating FPGA technology. These devices operate across a broad frequency spectrum, enabling them to interface with various communication standards. They also provide extensive bandwidth support, essential for capturing and processing complex signals with high data rates. Typically, SDR devices can handle a wide range of mega samples per second (MSPS) rates to meet different signal bandwidths and application requirements. In particular, high MSPS rates are crucial for capturing wideband signals and ensuring high-resolution digital representation of the analog input. Moreover, SDR devices feature a variety of interfaces to ensure flexible and robust connectivity for diverse applications. The primary interface is often Universal Serial Bus (USB), which provides a straightforward and high-speed connection to a host computer for data transfer and device control. Additionally, many SDR devices include Ethernet interfaces, enabling network connectivity that facilitates remote operation, networked applications, and integration into larger systems. Some advanced SDRs may also support Peripheral Component Interconnect Express (PCIe) interfaces for high-throughput applications, offering direct integration with computer systems for low-latency data processing.

It is important to recognize that SDR devices used on resource-constrained and battery-operated systems, such as UAVs, need to be lightweight, compact, and energy-efficient to improve payload capacity and extend flight endurance. Numerous SDRs compatible with USB connectivity meet these criteria and are suitable for UAV deployment. USB compatibility also allows for easy integration with small-sized Personal Computers (PCs), which feature compact dimensions and low power requirements. On the other hand, the SDRs deployed at ground nodes usually need to support high-speed connectivity with multiple other SDRs over the air, possess MIMO capabilities for higher sample rates rather than conventional Single-Input Single-Output (SISO) ones, and include powerful processing units to handle computation-intensive tasks.

C. CONVERGENCE OF UAV AND SDR TECHNOLOGIES

As the applications of UAVs continue to expand, driven by technological advancements and the increasing demands of users for more powerful and effective solutions, SDR technology represents a paradigm shift in the way communication, sensing, and data processing tasks are handled. The integration of UAVs in communication networks provides substantial benefits, especially when paired with SDR, thanks to their capability to operate in LoS-dominant environments. Unlike terrestrial radio communications, which often suffer from multipath effects and Non-Line-of-Sight (NLoS) propagation between the transmitter and receiver, UAVs can maintain unobstructed LoS channels. This characteristic mitigates the signal deterioration typically encountered in ground-based

TABLE 2. Main Technical Specifications of Various SDR Devices (Price Ranges: Low: <200$, Moderate: 200$–1000$, High: 1000$–5000$, Very High: >5000$)

SDR Device	FPGA	Frequency Range	Sample Rate	RF Bandwidth	Other Features	Interface	Weight	Cost
ADALM PLUTO	Xilinx Zynq Z-7010	325 MHz to 3.8 GHz	Up to 61.44 MSPS	Up to 20 MHz	Full duplex, SISO	USB 2.0	About 114g	Low
AntSDR E200	AMD/Xilinx ZYNQ7020	70 MHz - 6 GHz (AD9361)	Up to 61.44 MSPS	Up to 56 MHz (AD9361)	Full duplex, MIMO	Gigabit Ethernet	About 500g	Moderate
BladeRF 2.0 micro xA4/xA9	Altera Cyclone V	47 MHz to 6 GHz	Up to 61.44 MSPS	Up to 56 MHz	Full duplex, MIMO	USB 3.0	About 360g	Moderate
BladeRF x40	Altera Cyclone IV	300 MHz to 3.8 GHz	Up to 40 MSPS	Up to 28 MHz	Full duplex, SISO	USB 3.0	About 270g	Moderate
Ettus USRP B20xmini	Xilinx Spartan-6	70 MHz to 6 GHz	Up to 56 MSPS	Up to 56 MHz	Full duplex, SISO	USB 3.0	About 24g	High
Ettus USRP B210	Xilinx Spartan-6	70 MHz to 6 GHz	Up to 61.44 MSPS	Up to 56 MHz	Full duplex, MIMO	USB 3.0	About 350g	High
Ettus USRP E312	Xilinx Zynq 7020 (Dual-core ARM Cortex and 7 Series FPGA)	70 MHz to 6 GHz	Up to 61.44 MSPS	Up to 56 MHz	Half duplex, MIMO	Gigabit Ethernet and 2 host USB 2.0 ports	About 450g	High
Ettus USRP E320	Xilinx Zynq-7045 SoC (Dual-core ARM Cortex and 7 Series FPGA)	70 MHz to 6 GHz	Up to 61.44 MSPS	Up to 56 MHz	Full/half duplex, MIMO	SFP+ port (1/10 Gigabit Ethernet, Aurora), RJ45 port (1 Gigabit Ethernet), Type A USB 2.0, Micro-USB	About 900g	Very high
Ettus USRP N210	Xilinx Spartan 3A-DSP 3400	10 MHz to 6 GHz	Up to 100 MSPS	Up to 20 MHz	Full/half duplex, MIMO	Gigabit Ethernet	About 1.2kg	High
Ettus USRP X3xx	Xilinx Kintex-7	Direct current (DC) to 6 GHz	Up to 200 MSPS	Up to 160 MHz	Full duplex, MIMO	Gigabit Ethernet, PCIe	About 1.7kg	Very high
HackRF One	-	1 MHz to 6 GHz	Up to 20 MSPS	Up to 20 MHz	Half Duplex, SISO	USB 2.0	About 200g	Moderate
LimeSDR	Altera Cyclone IV	100 kHz to 3.8 GHz	Up to 61.44 MSPS	Up to 30.72 MHz	Full duplex, MIMO	USB 3.0	About 50g	Moderate
NI 5791R	Xilinx Kintex7-410T	200 MHz to 4.4 GHz	Up to 130 MSPS	Up to 100 MHz	Full duplex, SISO	PXIe	About 400g	Very high
NI USRP 2930	Xilinx Kintex7-410T	50 MHz to 2.2 GHz	Up to 200 MSPS	Up to 120 MHz	Full duplex, SISO	Gigabit Ethernet	About 1.2kg	High
NI USRP 2942R	Xilinx Kintex7-410T	400 MHz to 4.4 GHz	Up to 200 MSPS	Up to 120 MHz	Full duplex, MIMO	PCIe	About 1.6kg	Very high
NI USRP 2943 (2943R)	Xilinx Kintex7-410T	1.2 GHz to 6 GHz	Up to 200 MSPS	Up to 120 MHz	Full duplex, MIMO	Gigabit Ethernet	About 1.6kg	Very high
NI USRP 2950R	Xilinx Kintex7-410T	50 MHz to 2.2 GHz	Up to 200 MSPS	Up to 120 MHz	Full duplex, SISO	Gigabit Ethernet	About 1.6kg	Very high
NI USRP 2954R	Xilinx Kintex7-410T	10 MHz to 6 GHz	Up to 200 MSPS	Up to 160 MHz	Full duplex, MIMO	Gigabit Ethernet	About 1.6kg	Very high
RTL-SDR	-	24 MHz to 1766 MHz	Up to 3.2 MSPS	Up to 3.2 MHz	Half Duplex, SISO	USB 2.0	About 30g	Low

communications, where stronger transmit powers and more sensitive antennas, such as those using MIMO technologies, are necessary to compensate for the adverse effects of multipath propagation. Consequently, UAVs are particularly well-suited for SDR equipment, which usually features weaker transmit powers and simpler antenna hardware. The clear LoS channels accessible to UAVs enhance the performance of SDR-based communication systems, making UAVs ideal platforms for deploying such technologies.

In the past few years, the concept of SDR has begun to appear in UAV-based applications, either through custom-made SDRs or commercially available ones. By adopting SDR, UAVs can overcome the limitations of conventional communication systems and unlock new opportunities for innovation in various domains, ranging from civilian and commercial applications to defense and public safety. SDR technology offers unparalleled adaptability and programmability, rendering it a prime cost-effective choice for both characterizing channels and enhancing the communication capabilities of UAVs. Channel characterization entails analyzing and modeling wireless communication channels to grasp propagation characteristics, signal strength fluctuations, multipath effects, and interference patterns, crucial for crafting efficient communication systems capable of mitigating channel impairments and adapting to evolving environmental dynamics and mission requirements. Also, SDR empowers UAV-based systems with flexibility by implementing communication protocols and signal processing algorithms (e.g., adaptive beamforming, noise cancellation, and signal enhancement algorithms) in software, enabling real-time adjustment of transmission parameters, modulation schemes, and error correction techniques based on channel characterization feedback, in stark contrast to the rigidity of traditional hardware-dependent radio systems. This integration offers robust and reliable communication in challenging scenarios (e.g., urban environments or congested airspace), interference mitigation, spectrum efficiency, and rapid prototyping and deployment of new communication protocols and algorithms, facilitating quick adaptation to evolving operational demands and emerging technologies. Another advantage of SDR is its role as a universal platform accommodating various communication standards and protocols, thus fostering interoperability among diverse UAV platforms and facilitating collaborative missions involving multiple UAVs.

Apart from fulfilling communication-based requirements, SDR technology can substantially bolster the security of UAV-based systems and enable the adoption of sophisticated signal processing methods for tasks, such as detection, classification, and localization. In security applications, the flexibility of SDR enables UAVs to adapt their communication protocols and encryption methods in response to changing threats or operational requirements, ensuring covert, secure, and reliable communication channels. Moreover, SDR-equipped UAVs can perform spectrum sensing to detect and identify signals across a wide frequency range, such as unauthorized or malicious transmissions, jamming signals or communication from potential threats. Real-time detection and analysis of these signals offer early warning and improve situational awareness for security personnel. Also, SDR platforms have the capability to capture signals from diverse sensors, (e.g., radar, LIDAR, and cameras) and fuse this information to further improve detection and localization accuracy. Besides, SDR technology enables UAVs to implement advanced localization techniques, such as Angle-of-Arrival (AoA) estimation, to accurately determine the location of RF emitters. Fig. 5 depicts the application domains of SDR-assisted UAV-based systems, which are thoroughly examined in the subsequent sections of this paper.

Although SDR technology can provide substantial benefits, certain issues should be carefully considered when integrating it into UAV platforms, particularly for critical applications. SDR systems typically consume more power due to their reliance on general-purpose processors or FPGAs for signal processing, which can significantly reduce battery life in UAVs, especially smaller ones. Moreover, the components required for SDR, such as powerful processors and cooling systems, can add size and weight, negatively impacting flight time, agility, and payload capacity. Additionally, the complexity of SDR systems increases both cost and the need for specialized expertise for maintenance and updates. Regulatory challenges also arise due to SDRs' ability to operate across various frequencies, risking non-compliance with legal standards. Furthermore, the flexibility of SDRs can make them more susceptible to security threats, such as hacking or software modifications, which could compromise UAV control or communication. Lastly, the reliance on software in SDRs can affect reliability and robustness in extreme conditions, introducing vulnerabilities if software malfunctions or contains bugs.

IV. SDR DEPLOYMENTS FOR COMMUNICATION APPLICATIONS

This section investigates recent research works that address communication challenges by implementing SDR schemes. SDRs offer flexible and adaptive communication capabilities, which are essential for maintaining reliable and efficient UAV operations in various environments. In coordination with the SDR deployments, an array of technologies was also adopted in these works to tackle communication hurdles, thereby fostering advancements in communication reliability, coverage, and efficiency within intricate and ever-changing environments. These technologies are delineated in Fig. 6.

A. ENHANCED CONNECTIVITY

Communication stands as a cornerstone in the efficacy of UAV-based systems, spanning applications from surveillance and monitoring to disaster response and delivery services. Below, several research works are reviewed focusing on SDR deployments aimed at enhancing connectivity. The summary of these works is presented in Table 3.

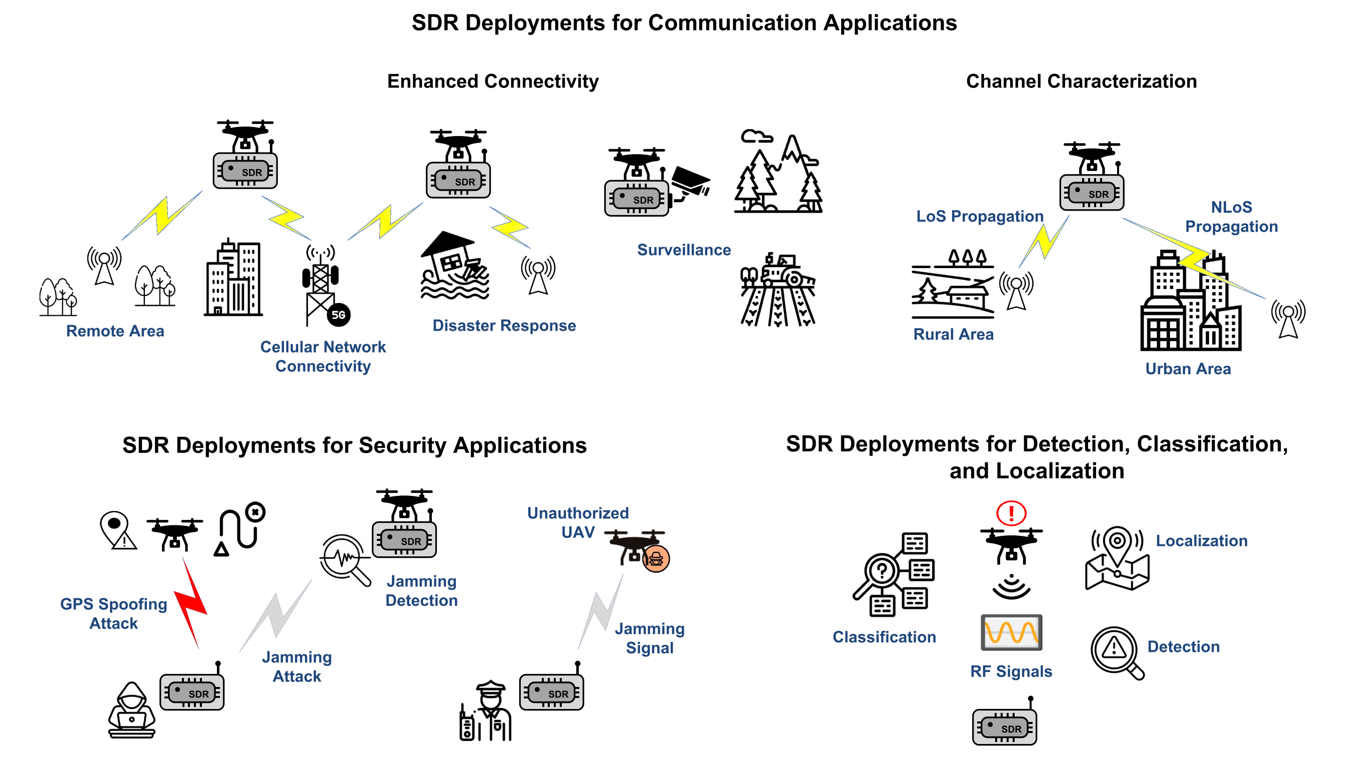

FIGURE 5. Application domains and architectural frameworks of SDR-assisted UAV-based systems, encompassing communication, security, detection, classification, and localization.

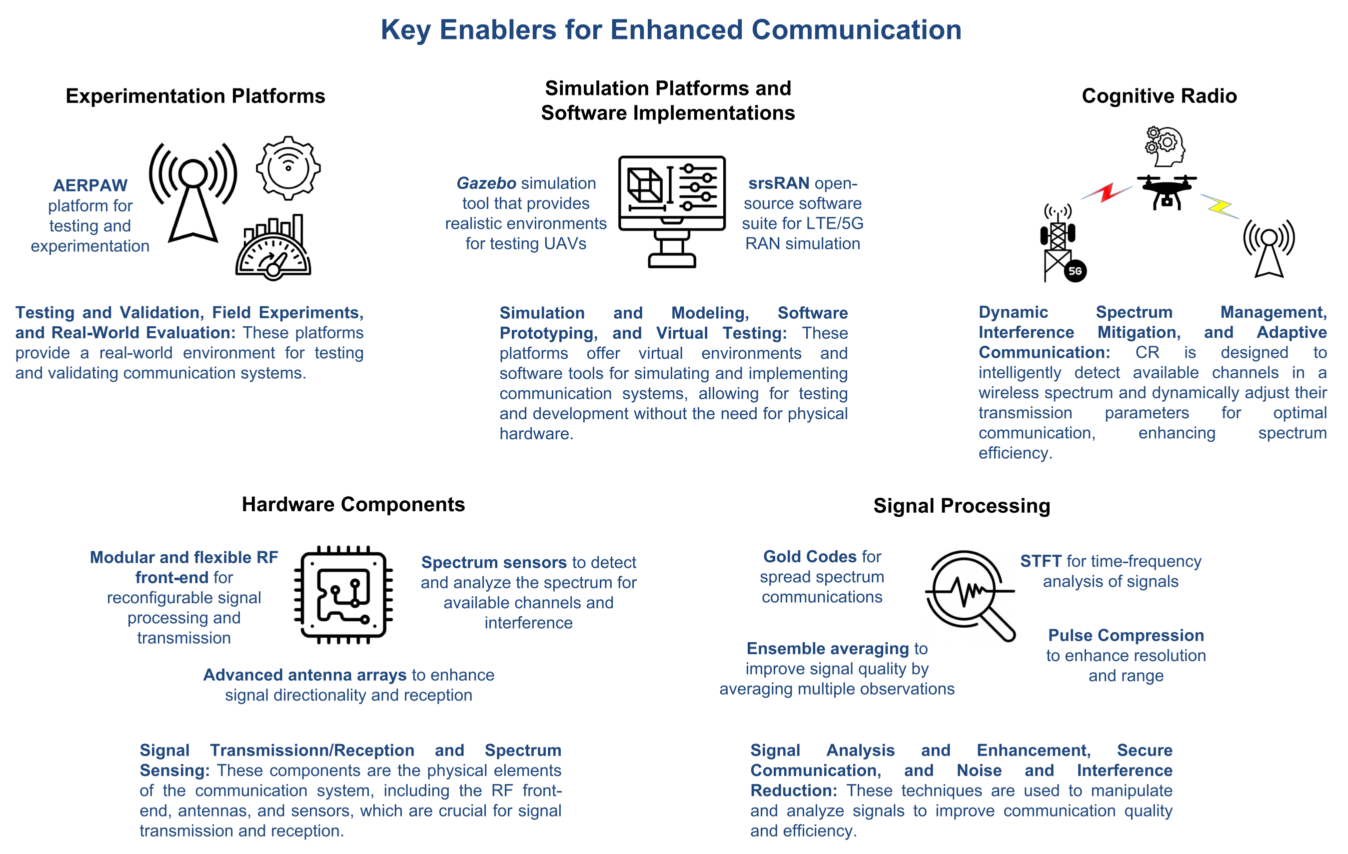

FIGURE 6. Key technologies that enable advanced functionalities in SDR-assisted UAV-based operations, addressing communication challenges in diverse environments.

TABLE 3. Synopsis of Recent Research Works on SDR Deployments for Enhanced Connectivity

Ref.	Year	Type of UAVs	Type of SDR	Role of SDR	Key Technologies	Outcome
[29]	2022	DJI Matrice 600	Ettus USRP B205mini-i	Radio prototyping, data acquisition and generation, signal measurement	3GPP standard-compliant system, modular and flexible RF front-end, srsRAN, Open5GS, AERPAW	Implementation of a communications testbed for research on cellular network-connected UAVs
[31]	2023	Customized hexacopter UAV	Ettus USRP B205mini	Collection and analysis of LTE signals transmitted by a BS	AERPAW Experimentation Platform, GPS, srsRAN software, LTE signal processing algorithms, 3-D antenna pattern modeling	Reliable and seamless connectivity for cellular-connected UAVs operating in rural environments, particularly enabling BVLoS communications
[32]	2023	Programmable UAV	Ettus USRP B205mini	Collection, processing, and integration of raw I/Q samples	AERPAW Experimentation Platform, GPS, srsRAN software, MATLAB LTE Toolbox	A2G cellular network coverage analysis for UAV-based communications at different altitudes
[33]	2024	Quadcopter UAV	LimeSDR	RF front-end for the LTE system	NVIDIA Jetson TX2 (CPU and GPU computing unit), FDD	Enhanced aerial connectivity by establishing an LTE BS for both indoor and outdoor environments
[34]	2023	DJI Matrice 200	RTL-SDR	Signal measurement and data collection	Digital VHF handsets and GPS	Long-range VHF UAV-based communication, particularly aimed at emergency communication scenarios
[35]	2024	DJI Matrice 100	Ettus USRP B210	Generation transmission, reception, and collection of signal data	R-DTBF, Gold codes for simultaneous synchronization and calibration, statistical channel models, GNU Radio toolkit	Swift and reliable communication in scenarios requiring rapid UAV deployment without infrastructure support
[36]	2024	Lightweight drones and tethered Helikite	USRP-X300 (Helikite), Ettus USRP B205mini (drone)	Implementation and operation of the 5G network testbed	O-RAN, RIC, VNFs, and ML	Rapidly deployable mobile networks to support connectivity in underserved and remote areas
[38]	2021	Emulated UAVs	Emulated SDR	Monitoring, allocating, and dynamically managing spectrum usage within the CR framework	CR and TDMA	Coordinated operations of multiple UAVs (i.e., surveillance and monitoring missions), under the management of a GCS
[40]	2022	Emulated UAVs	Emulated SDR	Provision of adaptive multiband waveforms, support of HCM	CR and HCM	Robust communication for surveillance purposes using UAV swarms over diverse terrains
[41]	2024	Emulated UAVs	Emulated SDR	Interoperability, support of HCM	HCM	Autonomous multi-hop communication for disaster response utilizing a MAC-centric cross-layer protocol

1) CELLULAR NETWORK CONNECTIVITY

This subsection explores cellular network connectivity for UAVs in complex environments and details experiments utilizing SDRs to assess Long-Term Evolution (LTE) performance, with a focus on evaluating antenna radiation patterns and signal strength at different altitudes.

In [29], the performance of cellular network-connected UAVs was assessed and a series of experiments was conducted using a comprehensive testbed designed with SDRs and Commercial Off-The-Shelf (COTS) hardware. The experiments took place in a rural environment, characterized by minimal interference, providing a clear LoS between UAV and BS. Specifically, an LTE configuration was evaluated using Frequency-Division Duplexing (FDD) mode in 3GPP Band 22 (C-Band). The experimental setup included a fixed ground BS mounted 2.5 meters above ground level, equipped with an Ettus USRP B205mini-i serving as the eNodeB (eNB), and a DJI Matrice 600 UAV equipped with another USRP acting as the Aerial User Equipment (AUE). This UAV operated at low altitudes, maintaining a flight duration of approximately 30 minutes. The SDR platform specifications included support for Third Generation Partnership Project (3GPP) standard-compliant cellular communications, instantaneous bandwidths of at least 20 MHz, and frequency agility necessary for 5G operations. This platform served as the foundation for the initial SDR experiments carried out through the Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) of National Science Foundation (NSF) [30]. The RF front-end featured a high linearity PA with a gain of 30–45 dB to ensure reliable communications over distances up to 1km, and LNAs to enhance the reception of weak signals. It should be noted that the use of open-source software (srsRAN for eNB and AUE as well as Open5GS for Evolved Packet Core (EPC) framework of the LTE) facilitated rapid prototyping and adjustments, showcasing the benefits of an open-source approach for research. Aerial coverage measurements indicated that the UAV, acting as an AUE, could maintain high uplink and downlink throughputs, achieving up to 50 Mbps and 60 Mbps respectively, at distances over 400 meters from the BS. The performance, although it degraded with increasing distance due to Path Loss (PL), remained above 10 Mbps beyond 1 km.

The primary objective of [31] was to overcome the challenge of establishing reliable and seamless connectivity for cellular-connected UAVs to enable Beyond Visual LoS (BVLoS) communications. Specifically, the importance of accurate modeling of three-dimensional (3-D) A2G propagation was emphasized, considering the critical role of UAV antenna radiation patterns, particularly in elevation angles. To achieve this, a measurement campaign was carried out at the AERPAW testbed site [30] utilizing UAVs equipped with SDR receivers and GPS receivers. The UAVs were deployed across rural regions to collect data for modeling A2G PL, whereas the SDR receiver captured LTE signals transmitted by a BS tower equipped with srsRAN open-source software. Specifically, the experiments utilized Ettus USRP B205mini SDRs, capturing 20 ms segments of LTE signals every 100 ms. During the experiments, the UAVs navigated predetermined flight paths, executing precise zig-zag maneuvers across the experimental terrain while maintaining consistent altitudes ranging from 30 meters to 110 meters. To obtain Reference Signal Received Power (RSRP) at different UAV locations, LTE I/Q samples were collected and post-processed. Then, the impact of three different 3-D antenna patterns (measured, dipole, isotropic) on PL modeling accuracy was evaluated, with results indicating that incorporating measured antenna patterns significantly enhanced modeling accuracy, especially in capturing deep fades and peaks in RSRP. Furthermore, an RSRP-based ground signal source localization algorithm was proposed and evaluated both offline and online, demonstrating improved localization accuracy when utilizing accurate 3-D antenna patterns. Additionally, this work presented an approach to estimate 3-D antenna patterns from RSRP measurements and compared them with measured antenna patterns, showing overall similarity in directivity.

The A2G cellular network coverage was examined in [32] using raw LTE I/Q sample data. Due to the limited availability of datasets that analyze cellular technology coverage for UAV flights at various altitudes, the AERPAW [30] was utilized. The UAV employed in this experiment was equipped with both a GPS receiver and an Ettus USRP B250mini SDR, assigned with the responsibility of gathering LTE I/Q samples during flight maneuvers along a zigzag path at altitudes spanning from 30 m to 110 m. Moreover, the UAV-mounted SDR operated at a center frequency of 3.51 GHz with a bandwidth of 1.4 MHz and functioned as a receiver to collect I/Q samples transmitted by an LTE BS configured as an eNB. In particular, the SDR captured 20 ms segments of data with a 2 MHz sampling rate every 100 ms, ensuring comprehensive data collection while mitigating the risk of data loss due to continuous computation demands. The setup included additional hardware components such as a lowpass filter, a High-Power Amplifier (HPA), and a Band-Pass Filter (BPF). Moreover, the receiver setup incorporated a low noise amplifier to enhance signal reception quality. The experiments provided detailed Received Signal Strength Indicator (RSSI) measurements at various altitudes, demonstrating how signal strength varies with altitude and distance from the BS. Furthermore, the data collection was performed using srsRAN open-source SDR software to configure the LTE eNB and the SDR. The collected data allowed for fitting the measured RSRP to PL models, such as the free space and two-ray PL models, which incorporated antenna radiation patterns and ground reflection paths, yielding better characterization of the RSRP measured at different UAV altitudes. Based on channel estimation, the signal quality varied significantly with altitude and distance from the BS. High RSRP regions exhibited flat fading, while low RSRP regions experienced selective fading in both time and frequency domains. Post-processing analysis of the collected data was also carried out using MATLAB LTE Toolbox to extract radio metrics and Key Performance Indicators (KPIs). This dataset and the associated post-processing methodology enables the training, testing, and refinement of Machine Learning (ML) models and optimization techniques.

In [33], an advanced UAV-based airborne computing platform was developed, incorporating SDR technology to establish an LTE BS and significantly improve aerial connectivity. The platform utilized a quadcopter UAV equipped with NVIDIA's Jetson TX2, a high-performance computing unit combining CPU and GPU capabilities. In addition, the SDR hardware, a LimeSDR board, was configured with a single antenna setup. FDD was implemented with an uplink frequency of 1787.4 MHz, a downlink frequency of 1878.4 MHz, and a 3 MHz bandwidth to reduce interference with local

LTE services. Performance evaluation of the LTE BS was conducted in both indoor and outdoor settings. In the indoor environment, the Jetson TX2 was placed at one end of a 5-meter-long room, with User Equipment (UE) devices positioned at varying distances to assess latency and throughput. For outdoor testing, the UAV was flown at various distances from the UE to evaluate performance in dynamic conditions. Key performance indicators, including latency, throughput, Signal-to-Noise Ratio (SNR), and resource consumption, were measured. Results indicated that while the UAV-based LTE system had higher latency and lower throughput compared to a traditional laptop-based system, it exhibited a greater variation in SNR. This suggests that with software optimization, the UAV-based platform can provide enhanced performance and is a promising solution for applications requiring robust and adaptable connectivity.

2) ENHANCED COMMUNICATION RANGE AND RELIABILITY

This subsection investigates cutting-edge approaches to extend the communication capabilities of UAVs in challenging environments. Moreover, this subsection highlights how leveraging Very High Frequency (VHF) bands and UAV-based relay systems can significantly improve communication range and reliability, which is vital for emergency and military operations. Furthermore, this subsection discusses advancements in beamforming techniques and the integration of terrestrial and non-terrestrial networks (NTNs), which further enhance the effectiveness of UAVs in delivering reliable and scalable communication solutions.

The research discussed in [34] focused on leveraging the VHF band to enhance long-range communication capabilities for UAVs, particularly vital for emergency response, disaster relief, and military communications across vast and challenging environments prone to infrastructure failures and damages. In this work, a UAV-based relay system was proposed to significantly extend VHF communications beyond what ground systems alone can achieve. The UAVs acted as platforms for carrying lightweight SDR receivers, which are crucial components for signal reception and processing. This framework capitalized on maintaining LoS by deploying UAVs at high altitudes to minimize signal blockage and mitigate system performance degradation. To validate the proposed framework, an experimental campaign was conducted. The type of UAV utilized was the DJI Matrice 200 (operated at heights around 500 meters) capable of carrying the SDR equipment at a height of 500 meters above the ground. Moreover, the SDR receivers used in the experiments were based on RTL-SDR dongles connected to Raspberry Pi 3, powered by USB power banks. These receivers were equipped with telescopic whip antennas and tuned to a center frequency of 160.4MHz, suitable for capturing VHF-band signals. The experiments involved measuring VHF signal strength at ground level and at an altitude of 500 meters above the ground, mimicking typical convoy scenarios encountered by the Irish Defence Forces during humanitarian missions. Specifically, the experiments utilized Motorola DP4801e digital VHF handsets as transmitters, operating at a transmit power of 5 W with a digital wideband waveform. To estimate the Path Loss Exponent (PLE) values and evaluate the performance of the communication link, the measured signal powers were compared against the Free-Space Path Loss (FSPL) model. Results demonstrated significant improvements in communication distance achieved through aerial relays, with successful signal reception at distances exceeding 50 kilometers. Despite some signal degradation observed due to physical obstacles encountered by the aerial relays, the results demonstrated a notable increase in range compared to ground station coverage. These findings confirmed that UAVs can serve as valuable communication assets, providing significant range extension support for military and emergency operations in remote or challenging environments.

The work in [35] dealt with the extension of the downlink range through the implementation of Retrodirective Distributed Transmit Beamforming (R-DTBF) and intra-network communication protocols using Gold codes for synchronization and calibration, all facilitated by a group of collaborating UAVs. This approach aimed to enhance communication SNR without requiring receiver Channel State Information (CSI) feedback. This is particularly beneficial in scenarios where UAVs need to be rapidly deployed, possibly in ad hoc configurations, without infrastructure support that would facilitate feedback loops. The proposed R-DTBF method leveraged channel reciprocity to align the phases of transmitted signals from multiple UAVs, maximizing reception without necessitating receiver feedback. This can reduce overhead and simplify the communication process. Nevertheless, achieving frequency and time synchronization among UAVs is crucial for effectively coordinating transmissions to enable efficient beamforming. At the core of this approach lay the intricate orchestration of these UAVs, comprising a leader and followers, each equipped with single antennas and coordinated through a sophisticated intra-network communication protocol. This protocol, facilitated by SDRs, provided seamless synchronization and calibration among the UAVs without necessitating precise feedback from the target receiver. The type of SDR device used was the Ettus USRP B210, which offers a versatile platform for implementing various wireless communication protocols and signal processing tasks. To carry out the transmitter and receiver processing, the GNU Radio software development toolkit was utilized. Moreover, integral to the proposed system's robustness was the incorporation of statistical channel models derived from experimental measurements. These measurements, conducted across various frequencies including 915 MHz, 2550 MHz, and 5900 MHz, encompassed the characterization of UAV hovering behaviors and short-term oscillator stability. Such detailed empirical insights not only informed the system model but also enabled precise evaluation of beamforming performance under real-world conditions. The experimental validation, conducted with two DJI Matrice 100 UAVs, underscored the system's efficacy, demonstrating swift convergence within a mere 200 milliseconds. Furthermore, the achieved beamforming gains, exceeding 90% of theoretical maxima, and results aligning closely with modeling predictions affirmed the system's reliability and accuracy. This validation marked a pivotal milestone, representing the first-ever demonstrations of R-DTBF in a mobile environment without requiring feedback from the target receiver. Ultimately, this work set the stage for the deployment of scalable and dependable wireless communication systems leveraging UAV technology, with potential applications spanning emergency response, surveillance, and beyond.

In [36], terrestrial and NTNs were integrated using an Open Radio Access Network (O-RAN) framework, optimizing network performance through the RAN Intelligent Controller (RIC). The O-RAN was explored in conjunction with UAVs to address challenges in reliability and coverage faced by traditional terrestrial networks in remote or underserved regions, especially during temporary emergency events. In this direction, lightweight drones and tethered balloons (i.e., Helikite [37]) were employed, each serving distinct roles in the network. Drones, positioned in the low airborne layer, provided mobile and temporary network coverage, enabling rapid deployment and support for various IoT applications. Helikites, on the other hand, offered more permanent solutions with their ability to sustain long flight times and carry heavier payloads, thus extending the network coverage over several kilometers. Moreover, SDRs were used to create a flexible and rapidly deployable 5G network testbed, ideal for scenarios where existing infrastructure is unavailable. In this work, the USRP-X300 and USRP B205mini SDRs were used. The USRP-X300, configured as a 5G Radio Unit (RU), operated below 6 GHz and could handle FDD and Time-Division Duplexing (TDD) with appropriate external components. Besides, the USRP B205-mini, used as a 5G UE or small cell, was lightweight and adaptable, supporting both 5G and Wireless Fidelity (Wi-Fi) connectivity. The typical configuration included a 10 MHz reference clock, external amplifiers, and a cavity duplexer, with omnidirectional antennas ensuring a maximum gain of 2 dBi. In the proposed network, Virtual Network Functions (VNFs) were deployed to enhance flexibility, scalability, and efficiency. These VNFs interfaced with the SDRs, allowing dynamic and efficient network operations. Extensive field experiments were conducted to evaluate the performance of the UAV-based network. The Helikite was equipped with a low-power 5G RU payload, providing coverage at altitudes up to 60 meters. Tests included evaluating preparation and maintenance times, as well as network throughput and coverage, using mobile handsets to log the RSRP and throughput under various conditions. The Helikite demonstrated superior LoS coverage, with RSRP ranging from -70 dBm to -125 dBm depending on distance. Additionally, the 5G network provided robust throughput, with notable performance in clear LoS conditions. Integration of ML through the RIC also enabled optimized control over the aerial network, adjusting various performance parameters like energy efficiency, throughput, and flight trajectories.

3) UAV SWARM COMMUNICATION, SURVEILLANCE, AND DISASTER RESPONSE

This subsection reviews progress in UAV swarm communication and its applications in surveillance and disaster response. Moreover, this subsection focus on innovative communication architectures, which leverage SDR technology for dynamic channel allocation and robust, adaptable communications.

In [38], a sophisticated communication architecture, named UAVs Swarm Communications leveraging CR and Dynamic TDMA (USC2RDT) was considered, designed for coordinated operations of multiple UAVs under the management of a GCS. The SDR's role in this context was critical, enabling dynamic channel allocation and monitoring to avoid interference, particularly from Primary Users (PUs). Specifically, the SDR facilitated real-time spectrum analysis and channel switching, crucial for maintaining reliable communication in dynamic environments. Moreover, the CR solution integrated a dynamic Time-Division Multiple Access (TDMA) technique, where the GCS dynamically assigned time slots to UAVs, aiming to reduce collision and interference probabilities and promote fairness among UAVs. Different classes of messages were prioritized based on urgency (normal, critical state, important results), enabling QoS optimization. Experiments conducted in a surveillance context evaluated the performance of the proposed architecture in terms of total data transfer time, packet count, and achieved throughput. To conduct the performance evaluation, videos sourced from the MDVD (Mini-Drone Video Dataset) [39] were utilized. The MDVD consists of 38 unique videos recorded in Full HD (FHD) resolution using the Phantom 2 Vision+ mini-drone in a car parking environment. These recorded videos are categorized into three distinct groups: normal, suspicious, and abnormal, based on the observed actions of individuals depicted in the footage. Simulation outcomes demonstrated the robustness of the proposed USC2RDT strategies, showing consistent performance superiority over Wi-Fi in varied PU arrival scenarios, particularly in scenarios where primary frequencies remain available. Although the performance evaluation demonstrated promising results, this research work lacks real-world experiments with SDR-equipped UAVs.

The work in [40] highlighted the integration of 5G technology with UAV swarms, supported by SDRs, to create resilient, flexible, and economical communication networks for surveillance applications over diverse terrains. The UAVs were deployed in swarms, utilizing off-the-shelf navigation and control systems for quick deployment and operation. To achieve efficiency, reliability, and redundancy in communication, these UAVs operated in a coordinated manner. Depending on operational needs, their type varied, ranging from small to medium-sized drones capable of carrying necessary payloads for surveillance and communication equipment. The primary objective of this work was to enable infrastructure-less, adaptive, and efficient communication among UAVs and with a GCS across diverse terrains. In this direction, a Hybrid Connectivity Module (HCM) was proposed that combined conventional 5G infrastructure, satellite communications, and adaptive multi-band SDR waveforms. This configuration facilitated cooperative and reliable communications among swarm UAVs and GCS. The SDR technology utilized was multiband, enabling cooperative communication and adaptability to different frequency bands and waveforms. This allowed the UAV swarm to operate in environments where traditional wireless infrastructure may be limited or absent. Furthermore, a cognitive communication architecture was employed to dynamically select between 5G, satellite communication, or multi-band SDR waveforms based on environmental conditions, ensuring availability and performance. In the performance evaluation, several scenarios were considered, such as locust monitoring in remote desert areas lacking 5G infrastructure. The simulations using MATLAB indicated how the HCM selects the most suitable communication mode based on channel conditions and required throughput, ensuring reliable communication within the UAV swarm. Specifically, the results depicted the effectiveness of the proposed architecture in meeting communication requirements under varying conditions. The system's ability to adapt to different terrains and operational scenarios was also highlighted, paving the way for applications such as surveillance, security, agriculture monitoring, and disaster management.

In [41], the focus shifted to disaster scenarios where existing communication networks often fail, impeding emergency response and rescue operations. This work proposed a solution using UAVs equipped with SDRs (e.g., Ettus USRP mini-series) capable of adaptive frequency and protocol adaptation to establish rapidly deployable adhoc networks. Similar to [40], this architecture incorporated a HCM to enable bidirectional A2G and A2A aerial links, fostering cooperative and effective UAV operation in challenging communication environments. The system's versatility was enhanced through multi-interface communications enabled by SDR reconfiguration capabilities, ensuring high reliability and availability. Moreover, the SDR-enabled UAV networking architecture supported multi-hop communication using a Medium Access Control (MAC)-centric cross-layer protocol, optimizing resource allocation and ensuring efficient data routing and QoS in dynamic network environments. Experimental evaluations using OMNET++ and MATLAB simulations exhibited significant improvements over traditional ad hoc routing protocols, such as OLSR (Optimized Link State Routing) and AODV (Ad hoc On-Demand Distance Vector) in terms of data latency and network throughput. For instance, the proposed protocol achieved up to 2600kb/s throughput with ten sub-nets, surpassing existing approaches and enhancing emergency response operations. The architecture's low latency and high throughput performance, along with its capability to operate in infrastructure-free environments, renders it highly effective across a range of disaster response scales and emergency situations.

B. CHANNEL CHARACTERIZATION

A pivotal challenge in UAV-based communications lies in comprehending and characterizing the wireless channels facilitating data transmission. To address this, it is crucial to design portable channel sounding hardware that can be mounted on small UAV platforms. Current channel sounding hardware includes commercial measurement instruments, off-the-shelf communication devices, and SDR modules [42]. Below, several research works that explore SDR deployments designed to characterize UAV-based channels are reviewed. The summary of these works can be found in Table 4.

1) SPECTRUM MANAGEMENT, SIMULATION TESTBEDS, AND ANTENNA DIAGNOSTICS

This subsection examines how SDR-assisted UAV-based systems can improve spectrum management through real-time frequency analysis, support simulation testbeds for UAV communication modeling, and offer precise antenna diagnostics, addressing traditional measurement limitations.

The work in [43] concentrated on the role of UAVs in spectrum management within dense networks and the challenge of developing and maintaining accurate 3-D Radio Environment Maps (REMs) for aerial networks, essential for enabling dynamic access to radio resources. Specifically, a novel experimental setup was introduced utilizing a constellation of three sensed UAVs to establish a testbed for measuring communication signals and spectrum occupancy, employing an SDR-enabled UAV-based spectrum sensor. The sensor UAV was a Freefly ALTA X quadcopter equipped with a BladeRF 2.0 micro SDR. To encompass the control frequencies of the UAVs (2.4GHz), the SDR was utilized through GNU Radio alongside a typical omnidirectional Industrial, Scientific, and Medical (ISM)-band antenna. The sensor UAV flew across a trajectory designed to cover a two-dimensional (2-D) plane at varying altitudes (i.e., 80, 90, 100, and 110 meters), capturing the communication signals from the sensed UAVs. On the other hand, the sensed UAVs, including various DJI models (i.e., Matrice 600 Pro, Inspire 2, and Mavic 2 Enterprise Dual), operated as active spectrum users, transmitting signals which were recorded by the sensor UAV. The experiments were conducted in a real-world outdoor environment and the sensor UAV followed the predetermined trajectory covering 40 points, with data collection at each point for 5 seconds. This process was repeated at four different altitudes to construct the 3-D REM. The sensed UAVs' transmissions were recorded within a 20 MHz band centered at 2.427GHz, whereas the collected RF data were analyzed across temporal, spatial, and frequency domains. Key metrics included received mean power level, average difference of the mean power, and percentage of meaningful correlations. Temporal analysis revealed that signal power variations diminished with increasing altitude, attributed to better propagation conditions

TABLE 4. Synopsis of Recent Research Works on SDR Deployments for Channel Characterization

Ref.	Year	Type of UAVs	Type of SDR	Role of SDR	Key Technologies	Outcome
[43]	2022	Freefly ALTA X, DJI Matrice 600 Pro, DJI Inspire 2, DJI Mavic 2 Enterprise Dual	BladeRF 2.0	Signal measurement and data collection	Spectrum sensors, wideband signal processing, GNU Radio toolkit	Measurement of communication signals and spectrum occupancy, highlighting signal power variations across different altitudes
[44]	2023	Multirotor UAV, VTOL hybrid UAV	Ettus USRP X310	HITL channel emulator	PX4 flight controller, Gazebo physical world simulation, FPGA-based HITL channel emulator	Modeling of real-world UAV-based channels and assessment of communication system resilience in dynamic environments
[46]	2022	Custom multi-rotor UAV	LimeSDR	Dual-channel receiver and signal source	Dual-polarized probe antenna, RFoF, laser-based VR tracking system, and IESS	Accurate near-field measurements and conversion of these measurements into far-field patterns
[47]	2023	Customized hexacopter UAV	Customized SDR (aerial transmitter) and NI PXIe digitizer with PXIe-1085 chassis, 8135 controller, 7976 FPGA module, and 5791 RF adapter (ground receiver)	Channel sounding and channel characterization	GPS-based time synchronization, adaptive antenna pattern analysis, and real-time hardware algorithms for CIR extraction, system response elimination, power loss recovery, and adaptive MPC recognition	Characterization of nonstationary A2G communication channels, including PL, K-factor, and path angle analysis during different UAV flight phases
[48]	2023	DJI Inspire 2	Ettus USRP 320 (UAV), 32 NI USRP 2942R (BS)	Collection of I/Q samples and CSI measurements	MaMIMO, URA, MRC, OFDM, GPSDO clocks	Characterization and analysis of the A2G communication channel for MaMIMO-supported UAV-based communications
[49]	2024	DJI Inspire 2	Ettus USRP 320 (UAV), 32 NI USRP 2942R (BS)	Collection of I/Q samples and CSI measurements	MaMIMO, URA, OFDM, GPSDO clocks	Measurement and analysis of non-stationary channels in MaMIMO-supported UAV-based communications
[50]	2024	DJI Inspire 2	Ettus USRP 320 (UAV), 32 NI USRP 2942R (BS).	Collection of I/Q samples and PL measurements	URA, OFDM, GPSDO clocks	Large scale fading analysis of the A2G SIMO channel in a suburban environment
[51]	2024	Fixed-wing UAV	Ettus USRP X310	Transmission of OFDM signals and real-time signal processing and analysis	Rubidium clock, IMU, OFDM	Aerial-based channel sounding for A2G channel characterization in a rural environment
[52]	2024	DJI M600 Pro	Ettus USRP E312 (transmitter) and Ettus USRP X310 (receiver)	Channel sounding and channel characterization	RTK receivers and GNSS receivers	Analysis of large-scale and small-scale fading characteristics of U2V channels in ITS environments
[53]	2024	DJI M600 Pro	Ettus USRP E312 (transmitter) and Ettus USRP X310 (receiver)	Channel sounding and channel characterization	RTK receivers and GNSS receivers	Multi-link channel modeling of U2V communications in ITS environments
[54]	2022	DJI Matrice 600 Pro	BladeRF 2.0 micro xA9	Channel sounding and channel characterization	Sweeping chirp signals, ensemble averaging and STFT for signal processing	Empirical modeling of A2A channels

and reduced multipath effects. Furthermore, spatial analysis showed significant power level variations at lower altitudes, with higher altitudes exhibiting more stable and stronger signals. Additionally, frequency domain analysis segmented the bandwidth into sub-bands, finding that higher altitudes had more consistent correlations, particularly in the first sub-band.

The work in [44] introduced a Simulated UAV Network (SUN) testbed for accurately modeling real-world UAV-based channels while enabling rapid prototyping and testing. The UAVs used in this testbed were equipped with the PX4 flight controller and were simulated within the Gazebo environment [45], which provides a comprehensive physical world simulation including flight dynamics, obstacles, and sensors. These UAVs played a critical role in performing missions, such as data gathering from IoT sensors and disaster response, relying on robust and flexible communication networks. Moreover, the Ettus Research X310 SDR was utilized as a Hardware-In-The-Loop (HITL) channel emulator. This SDR is capable of wideband, bidirectional communication and is instrumental in experimenting with next-generation wireless links for UAV control in challenging environments. In particular, the X310 features a FPGA that implements a 41-tap complex FIR filter to model the channel's impulse response, enabling realistic emulation of wireless communication scenarios. This setup allowed for real-time adaptation of channel parameters based on UAV positions simulated in Gazebo. Experiments conducted with SUN included evaluations of the SDR integration for UAV control and a data-ferrying mission using both a multirotor and a Vertical Takeoff and Landing (VTOL) hybrid UAV. The results showed a filter implementation verification with an average difference of 0.6% between FPGA and CPU implementations, and a channel delay measurement of 3.5 μ s, translating to an equivalent OTA distance of approximately 1km. In addition, the results from the data-ferrying mission indicated a 100% message delivery rate despite deviations in the UAV's actual flight paths, highlighting the resilience of the communication system.

In [46], a custom-designed multi-rotor UAV equipped with an SDR and a dual-polarized probe antenna was used for on-site antenna diagnostics. This approach offers a practical alternative to traditional methods that involve placing the Device-Under-Test (DUT) in an anechoic chamber. Such chambers are often impractical due to large antenna sizes, environmental influence (e.g., in mobile or broadcasting settings), and cost constraints. The UAV, built with an aluminum frame, positioned the probe antenna at the front to minimize interference from the UAV's frame and propellers, ensuring more accurate near-field measurements. By adopting this UAV design, adjustable payload positions were achieved, maintaining balance and mechanical decoupling, thereby minimizing vibration effects on sensitive equipment. In the proposed system, a LimeSDR was utilized, serving both as a dual-channel receiver for the probe antenna and a transmitter for the DUT. The LimeSDR was chosen for its capability to use the same local oscillator for both transmit and receive stages, essential for phase-coherent measurements. This SDR generated a continuous wave signal transmitted via an RF over Fiber (RFoF) link to the DUT, ensuring phase stability and minimizing the effects of coaxial cable weight and loss. A cylindrical scan around a horn antenna was performed, with the UAV maintaining a precise flight path while taking near-field measurements of irregularly distributed samples. This process was monitored using an affordable laser-based virtual reality (VR) tracking system. Such measurements are essential for large antennas, made feasible by near-field to far-field transformation algorithms. The system achieved a positional accuracy within a few centimeters despite UAV tethering and chamber air turbulence. Near-field samples were processed using an Inverse Equivalent Sources Solver (IESS) for antenna diagnostics and far-field calculations, demonstrating the system's ability to measure frequencies up to several GHz effectively. The results showed good agreement with standard Spherical Near-Field (SNF) scans, with minimal deviation in the measured near-field and calculated far-field patterns. These results also underlined that the UAV-based measurements exhibited slight truncation errors due to the limited vertical scan range, which were accounted for in the IESS processing.

2) CHARACTERIZATION OF A2G CHANNELS

This subsection discusses previous research on the characterization of A2G channels and the intricate communication dynamics between UAVs and ground stations. Specifically, this subsection underlines the necessity for accurate measurements in dynamic environments and the critical role of SDR in achieving precise synchronization and capturing channel dynamics across different altitudes.

The work in [47] tackled the challenges of measuring and characterizing non-stationary A2G communication channels involving UAVs, with a specific focus on dynamic, non-stationary scenarios. This is crucial for applications, such as disaster response, relief efforts, and forest fire monitoring, which require precise and synchronized data collection. Previous efforts in A2G channel sounding fell short in adequately characterizing the highly dynamic propagation links and did not consider the impact of UAVs on signal behavior. Thus, this work proposed a UAV-assisted channel sounder system equipped with real-time processing capabilities. In particular, a customized hexacopter UAV served as the transmitter, equipped with a GPS module for time synchronization, a customized SDR module with four RF channels, an HPA, and an omnidirectional dipole antenna. On the other hand, the ground receiver comprised a reconfigurable L-type antenna array, LNAs, a National Instruments (NI) PCI eXtensions for Instrumentation Express (PXIe) digitizer as an SDR module, and a high-rate disk array for data storage. The SDR modules employed Xilinx Kintex7-410T FPGA chips for real-time hardware processing, including Channel Impulse Response (CIR) extraction, System Response Elimination (SRE), Power Loss Recovery (PLR), and Adaptive Multipath Component (MPC) recognition. The primary innovation of the proposed system was its capability to minimize the effects of the UAV airframe on antenna patterns, clock drift on correlation, and high sampling speeds, ensuring robust performance in dynamic A2G environments. To validate the system's performance, controlled experiments were carried out at 3.5 GHz in a campus scenario involved measuring PL, K-factor, and path angle during different UAV flight phases. The results demonstrated consistency with existing measurements and theoretical expectations. Notably, the system's real-time data processing capabilities significantly reduced processing time compared to traditional methods, facilitating efficient non-stationary channel measurements. Verification and calibration using a commercial channel emulator confirmed the accuracy of measured path delay and amplitude. Moreover, the developed system revealed insights into A2G channel characteristics, including the dominance of LoS paths and the impact of ground reflections. Additionally, this system accurately estimated arrival angles of LoS paths, validating its reliability in angle estimation.

The use of CSI for Massive MIMO (MaMIMO) UAV-based systems was investigated in [48]. This study mainly centered on characterizing the A2G link by analyzing spectral efficiency using Maximum Ratio Combining (MRC) and testing various UAV trajectories and altitudes. In this respect, a measurement campaign was conducted with a MaMIMO testbed, exploring different heights and flight patterns. The aerial station was mounted on a DJI Inspire 2 UAV equipped with an Ettus USRP E320 mobile station, while the MaMIMO ground BS featured 32 USRPs in an 8x8 Uniform Rectangular Array (URA) configuration. Measurements were synchronized using GPS Disciplined Oscillators (GPSDOs) at both the UAV and the BS. This setup enabled the collection of an extensive dataset that detailed the complex interactions between UAVs and ground stations in real-world conditions. Initial results from the CSI dataset revealed insights into channel effects influenced by UAV movements and positions. The data included measurements of delay spread, stationarity distance, and antenna correlation. Based on the results, the Root Mean Square (RMS) delay spreads averaged around 500ns across different trajectories, indicating significant multipath effects in such environments. Spectral efficiency was notably impacted by the presence of LoS, NLoS, or Obstructed-LoS (OLoS) conditions highlighting the necessity of maintaining LoS for optimal UAV-based communication efficiency. This study also examined temporal stationarity and spatial antenna correlation, finding that stationarity distances are generally longer in LoS conditions, providing a more stable communication channel. Moreover, spatial correlation results showed high correlations between adjacent antenna elements, emphasizing the importance of strategic antenna placement and alignment in UAV communication systems. Furthermore, the effects of UAV mobility on the A2G communication channel were analyzed, revealing that the pitch and roll dynamics of the UAV, which vary with the flight path, significantly influence channel characteristics. Overall, this research work confirmed that MaMIMO can greatly enhance UAV communication channels, but also underlined the challenges posed by UAV dynamics and environmental factors on signal stability and quality. These findings are crucial for designing robust and efficient UAV communication systems for 6G networks.

In [49], a rotary-wing UAV, specifically a DJI Inspire 2, equipped with SDR was employed to investigate the 3-D non-stationary characteristics of A2G channels in MaMIMO communications. This UAV, serving as a mobile transmitter, flew at altitudes of 8m, 11m, and 24m along a straight path parallel to the BS antenna array, facilitating precise A2G communication measurements. The custom payload on the UAV included a USRP E320, a LNA, and a PA, enabling comprehensive A2G channel analysis. It is noted that the SDR played a crucial role in real-time acquisition of CSI and was essential for achieving precise OTA synchronization between the UAV and the MaMIMO BS, which was equipped with a 64-element antenna array. In the experimental setup, a MaMIMO testbed comprised of 32 USRPs, each with two transceiver channels, was used to measure uplink CSI and assess spatial, temporal, and frequency stationarity. The USRPs were synchronized using a GPSDO and connected to a 64-element URA array. Measurements, taken at varying distances between the UAV and the BS, were analyzed using power delay profiles (PDPs), spatial correlations, coherence bandwidth, and RMS delay spread. The results indicated that the A2G channels were predominantly influenced by LoS components, leading to greater temporal stationarity with fewer multipath reflections compared to ground-to-ground (G2G) communications. Specifically, spatial correlation varied significantly across the MaMIMO antenna elements, while coherence bandwidth and RMS delay spread offered insights into frequency stationarity. Additionally, the experiments revealed that multipath effects were more pronounced at 11m altitude, causing greater variations in received power and stationarity metrics compared to the other altitudes.

A comprehensive experimental study on PL modeling for Single-Input Multiple-Output (SIMO) UAV-based communications in a suburban setting was presented in [50]. This work investigated the effects of various altitudes and LoS conditions using a UAV-mounted platform and a ground-based station setup. Similar to [48] and [49], the aerial node was a DJI Inspire 2 UAV equipped with an Ettus E320 USRP transmitting Orthogonal Frequency Division Multiplexing (OFDM) pilot symbols through a downward-facing patch antenna. On the other hand, the BS featured 64 patch antennas arranged in an 8x8 URA. Operating at a center frequency of 2.61 GHz with an 18 MHz bandwidth, the BS was positioned in a parking lot, with trajectories measured in proximity to a 25-meter-tall building and tree line. In addition, the UAV flew along six predetermined trajectories at different heights (ranging from 12.1 m to 49.4 m) and under various conditions (i.e., LoS, OLoS, NLoS). The collected path loss data aimed to examine the impact of altitude and obstructions, such as buildings and trees, on signal propagation. As revealed by the log-distance PL model, the PLE values increased with altitude, ranging from 6.3 to 8.4 as the UAV's altitude increased from 12.1 m to 49.2 m. Additionally, the presence of vegetation significantly increased the PLE to 15.0 and 13.2 at different heights, illustrating substantial signal attenuation due to foliage. The sin-log-elevation model, which incorporated an elevation angle-dependent PL component, slightly improved the model fit in only two scenarios. This model was not significantly more effective than the log-distance model, pointing out the challenges of accurately modeling UAV-based communication over varying elevations and obstructions.

In [51], a measurement campaign was carried out to investigate A2G channel characteristics using a fixed-wing UAV, chosen for its extended flight endurance and high operational altitude. This UAV, capable of reaching up to 700 meters, served as an aerial BS to enhance communication coverage in a rural area. It was equipped with a high-performance SDR system, specifically an Ettus USRP X310, complemented by a rubidium clock and an Inertial Measurement Unit (IMU) for precise signal transmission and measurement. Specifically, this SDR device transmitted an OFDM signal at 2.7 GHz with a 25 MHz bandwidth and 36 dBm power. During the experiments, the UAV followed a circular flight path at altitudes between 300 and 700 meters in a sparsely built, vegetation-heavy rural environment. On the ground, the receiver, an NI vector signal transceiver PXIe-5841, captured the CIR snapshots. This work focused on analyzing key A2G channel aspects, including path loss, shadow fading, and small-scale fading. Results indicated a significant altitude dependence for both shadow fading and small-scale fading. In particular, the observed small-scale fading was less severe than in terrestrial scenarios, attributed to a strong LoS path at higher altitudes. Moreover, the Rician distribution effectively modeled LoS propagation for UAVs above 300 meters, with the Rician K-factor showing notable dependency on both direct distance and UAV altitude, leading to the proposal of a full-dimension empirical K-factor prediction model. For shadow fading modeling, the robust Gamma distribution was recommended, while a combined exponential and sinusoidal function model fitted the autocorrelation characteristics better. Deviations from traditional path loss models, such as Log-distance and two-ray, were also noted due to the complex rural environment, highlighting the need for accurate terrestrial surface maps and ray-tracing methods for precise power prediction. Furthermore, this work revealed that models incorporating both exponential and sinusoidal functions, such as the Double Exponential Decay Sinusoidal Model (DEDSM), provide a superior fit compared to simpler models.

3) CHARACTERIZATION OF U2V CHANNELS

This subsection reviews research works that investigated large- and small-scale fading characteristics of U2V communication channels in Intelligent Transportation Systems (ITS) scenarios through the use of SDR technology and measurement campaigns.

In [52], a U2V channel measurement campaign was conducted to analyze the communication link characteristics within ITS environments. This work utilized SDR technology and focused on S-band and C-band frequencies. Toward this end, a DJI M600 Pro drone was employed, known for its reliability and payload capacity, equipped with a Real-Time Kinematic (RTK) receiver and a USRP E312 for transmitting signals. Moreover, two vehicles carried receiving setups comprising USRP X310 devices and Global Navigation Satellite System (GNSS) receivers. These SDRs allowed for real-time reception and processing of narrowband Continuous Wave (CW) signals transmitted from the UAV. The primary focus of this work was on measuring and analyzing large-scale fading (i.e., PL, shadow fading) and small-scale fading (i.e., amplitude distribution) characteristics for different U2V communication scenarios. Specifically, measurements were conducted at 2.4 GHz (Wi-Fi band) and 5.9 GHz (vehicular communications band) with extracted channel parameters specific to these bands. The SDR platform played a critical role in this measurement campaign by facilitating real-time signal processing and flexibility in adapting to different frequency bands. In addition, the UAV served as a mobile transmitter, while vehicles acted as dynamic receivers capturing the high dynamics and complexity of the ITS environment. Furthermore, the use of specific SDR devices (i.e., USRP E312 and X310) ensured accurate reception and analysis of the transmitted signals. Experiments involved statistical analysis of PL models (e.g., log-distance) and amplitude distribution models (e.g., log-normal) to characterize large-scale fading. Also, autocorrelation modeling was performed to understand shadow fading behavior, crucial for reliable U2V communication design. Results indicated that the log-distance model outperformed other PL models, while the log-normal distribution accurately represented shadow fading. The findings emphasized the importance of frequency-dependent characteristics, with higher frequencies exhibiting increased PL due to signal attenuation.

In [53], the authors of [52] continued the exploration of A2G links between UAVs and vehicles for ITS applications, emphasizing multiple links in dynamic environments. Their motivation stemmed from observing that prior research predominantly concentrated on single-link systems, overlooking cross-correlation properties in multi-link scenarios. In this work, an SDR-based measurement system was employed to conduct U2V narrowband channel sounding at 2.4 GHz and 5.9GHz. The SDR-based channel sounding system utilized USRP E312 as the transmitter and USRP X310 as the receiver, emitting continuous waves with specified powers at respective frequencies. To minimize interference, antennas are strategically positioned; the transmitting antenna mounted underneath the UAV and receiving antennas fixed atop vehicles. This work also leveraged GNSS receivers for precise positioning. Essential channel parameters were systematically analyzed, including large-scale fading (i.e., PL and shadow fading) and small-scale fading characteristics (i.e., fading depth, magnitude distribution and Rician K-factor). Moreover, cross-correlation characteristics were examined among different channel parameters along with the impact of the number of receiving antennas in the two frequency bands. The results revealed nuanced dependencies influenced by antenna spacing, frequency bands, and measurement environments. Notably, high correlation was observed among dual-antenna setups, while shadow fading and Rician K-factor exhibit low cross-correlation. This underscored the necessity for detailed analysis in scenarios involving multi-link channel propagation. Additionally, these findings can facilitate the optimization of antenna design, enhance communication system reliability, and guide future UAV-based ITS developments.

4) CHARACTERIZATION OF A2A CHANNELS

This subsection presents prior research on the characterization of A2A communication channels by examining large-scale channel propagation statistics, specifically focusing on LoS conditions utilizing a SDR-based channel sounder and commercially available UAVs.

The work outlined in [54] identified the need for characterizing A2A communication channels involving moving nodes and investigated the large-scale channel propagation statistics for LoS A2A communications to estimate the PLE. Utilizing a custom-developed, low-cost, lightweight SDR-based channel sounder, measurements were conducted at 5.8 GHz using commercially available drones that employed sweeping chirp signals as sounding waveforms. In this regard, the BladeRF 2.0 micro xA9 was used, paired with a Lucix S020180L3205 RF PA, a Raspberry Pi 4B mini-computer, and a circularly polarized antenna. The data collected from the measurement campaigns served as a valuable empirical baseline for developing a measurement-based statistical model of A2A channels, offering a realistic representation of these channels. To ensure reliability in a controlled FSPL environment before proceeding with real-world measurements, the system's accuracy was initially validated in an anechoic chamber. Experiments involved two DJI Matrice 600 Pro hexacopters, equipped as transmitter and receiver, performing measurements in a rural area with separation distances between transmitter and receiver ranging from 25 to 425 meters at a constant altitude of 50 meters. As wireless impairments could alter the signal's statistical characteristics, ensemble averaging was used to preserve them. This was achieved by extracting bursts from the spectrum and estimating sweep signal parameters via Short Time Fourier Transform (STFT). The STFT, applied with a time-dependent window and Discrete Fourier Transform (DFT), provided temporal parameters and center frequency information. Based on the results, the PLE can be estimated with reasonable accuracy, with the models yielding slightly varied results due to focusing on different portions of the time-frequency data. These results also showed PLE values of 1.995, 2.046, and 1.932 for the time-based, time-frequency based, and frequency-based methods respectively, with RMSE values demonstrating the robustness of the measurements.

V. SDR DEPLOYMENTS FOR SECURITY APPLICATIONS

This section provides a nuanced perspective on how SDR technology can either enhance or challenge the security landscape of UAV-based systems. Specifically, this section outlines significant SDR-based security strategies proposed in previous works, which are summarized in Table 5, with a focus on the development of robust countermeasures and methodologies for executing attacks. In conjunction with SDR, previous works employed a wide range of technologies to confront security challenges and counter threats in intricate and dynamic environments, as shown in Fig. 7.

A. DETECTION AND CLASSIFICATION OF ATTACKS

This subsection focuses on techniques and methodologies for identifying and classifying various jamming attacks, including the use of ML and Deep Learning (DL) approaches.

In [55], a comprehensive approach was introduced that utilized ML techniques to effectively detect and classify jamming attacks targeted at OFDM receivers, particularly in the context of UAVs. This approach examined the intricacies of four distinct jamming attack types, i.e., barrage, protocol-aware, single-tone, and successive-pulse, deployed through SDR technology, which enabled the collection of radiometric features before and after jamming attacks. In this work, each jamming type qualitatively evaluated, considering factors such as severity, launch complexity, and effective jamming range. For instance, barrage jamming, characterized by noise from a normal distribution, is relatively straightforward to initiate but exhibits reduced efficacy with wider transmission bandwidths. Conversely, protocol-aware jamming involves transmitting low-interference shot-noise pulses to mimic targeted protocols, necessitating a high level of launch complexity but maintaining low detection probability. To systematically test these jamming scenarios, this work established a robust experimental setup involving a Holy Stone HS720E quadcopter UAV, an Ettus USRP B210, and the GNU Radio software development toolkit. The flexibility and versatility afforded by SDR device ensured accurate data acquisition, essential for training and validating ML algorithms aimed at detecting and classifying jamming attacks. Attacks were conducted within a 40 MHz bandwidth to accommodate all subcarriers, ensuring a realistic environment for training datasets. The research proceeded to extract radiometric features before and after jamming attacks, employing SDR devices in proximity to the UAV to capture essential data points such as SNR, energy threshold, and key OFDM parameters. This dataset was then utilized to develop two classification models; a feature-based model utilizing conventional ML algorithms and a spectrogram-based model employing state-of-the-art DL techniques, specifically Convolutional Neural Networks (CNNs). The performance of these models was

TABLE 5. Synopsis of Recent Research Works on SDR Deployments for Security Applications

Ref.	Year	Type of UAVs	Type of SDR	Role of SDR	Key Technologies	Outcome
[55]	2022	Holy Stone HS720E	Ettus USRP B210	Accurate data acquisition for training and validating ML algorithms	ML, OFDM, radiometric features, CNNs	Detection and classification of jamming attacks
[56]	2023	It is not specified	Ettus USRP X310	Collection and analysis of I/Q samples, generation and transmission of jamming signals	CNN, GNU Radio toolkit	Jamming detection
[57]	2024	Emulated UAVs	Ettus USRP X310, LimeSDR Mini	Collection and analysis of I/Q samples	Sparse autoencoders, GNU Radio toolkit	Jamming detection
[58]	2022	Hexacopter Tarot	HackRF One (UAV) and Ettus USRP B210 (Ground System)	Measurement of power data and facilitation of secure data exchange	Blockchain technology, asymmetric key cryptography, ring signature, and maximum likelihood estimation method for signal parameter estimation	Signal source identification
[60]	2021	It is not specified	LimeSDR (receiver) and Ettus USRP X310 (jammer)	Detection of jamming signals and measurement of RSS (LimeSDR), generation and transmission of jamming signals (Ettus URSP X310)	GNU Radio toolkit, GPS, Pratt's algorithm, PID controllers	Jammer localization, dead reckoning navigation in jammed areas, detection of GPS jamming
[62]	2023	Small UAVs	BladeRF 2.0 and HackRF One	Generation of forged GPS signals	GPS, LSTM networks, and knowledge distillation techniques	Detection and prevention of GPS spoofing attacks
[63]	2024	3DR IRIS+, Tarot 650 v2.2, DJI Inspire, and Sky Hunter	HackRF One	Generation and transmission of artificial signals	GNSS, TCXO, synthetic signal generation, GPS receiver analysis	Assessing the impact of spoofing and jamming threats
[64]	2022	Holybro S500	HackRF One	Generation and transmission of forged GPS signals and jamming signals	PCA, one-class classifiers, ML, GPS-SDR-SIM software, GNU Radio Companion	Development of an IDS to detect and mitigate GPS spoofing and jamming attacks
[66]	2022	It is not specified	HackRF One	Generation of GPS spoofing signals	GPS, GPS-SDR-SIM software, TCXO, crowd-sourced information integration	Detection and mitigation of GPS spoofing attacks in various environments
[67]	2020	Hornet mini-UAV	BladeRF x40	Transmission of forged GPS signals	GPS, LIDAR, accelerometers, magnetometers, NMEA messages	Implementation of a mobile spoofing system to induce location errors in targeted GPS receivers
[68]	2020	DJI Spark and Parrot Bebop 2 FPV	BladeRF x40	Implementation of jamming techniques	Spectral interference techniques, GNU Radio toolkit	Countering unauthorized UAV operations by implementing jamming techniques to disrupt GPS navigation systems crucial for UAV autonomy
[69]	2022	DJI Phantom 3 Standard	BladeRF x40	Versatile signal processing for adaptive jamming and spoofing techniques	Biometric authentication, GPS signal disruption, GNU Radio toolkit, GPS-SDR-SIM software	Jamming and spoofing GPS signals, safeguarding critical infrastructure against unauthorized UAV intrusions

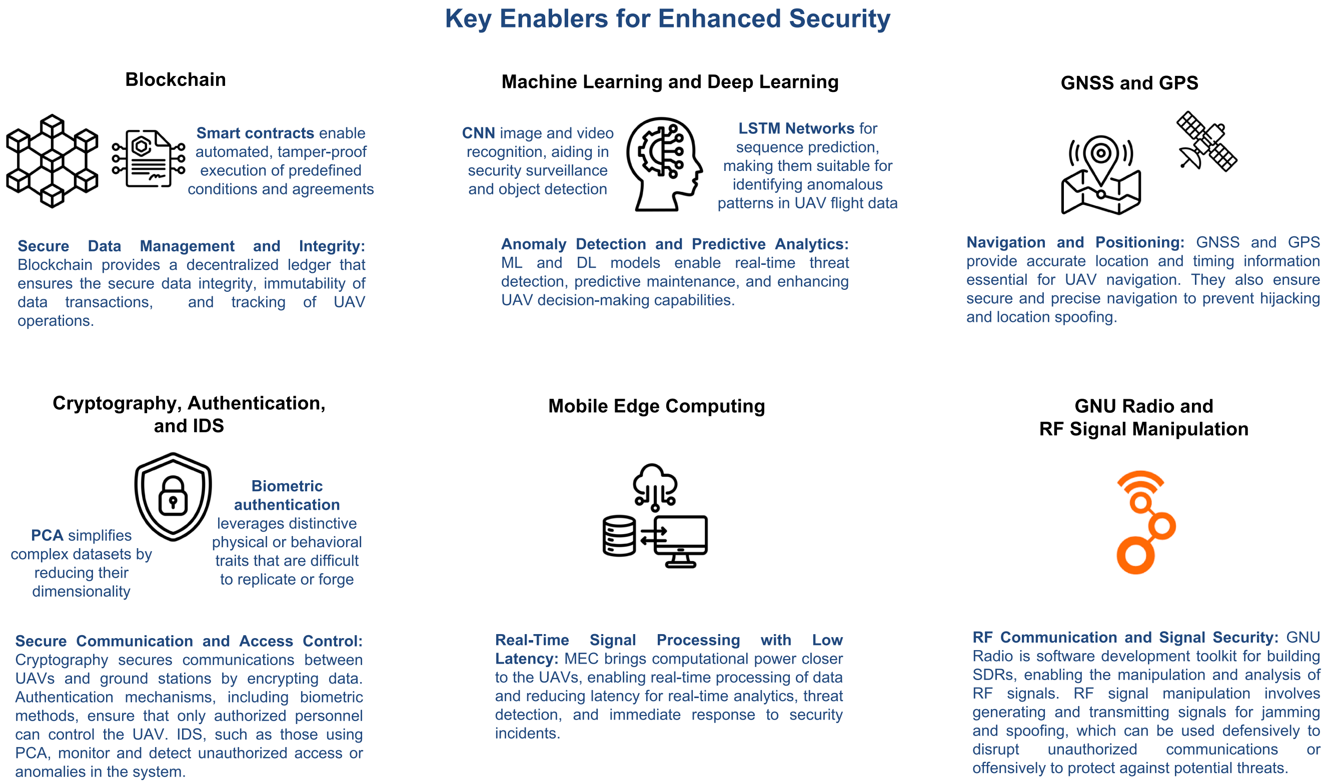

FIGURE 7. Key technologies that enable advanced functionalities in SDR-assisted UAV-based operations, addressing security challenges in diverse environments.

rigorously evaluated, with the spectrogram-based approach showcasing remarkable improvement over its feature-based counterpart. Achieving an accuracy of 99.79% and a false alarm rate of 0.03%, the spectrogram-based model proved highly effective in detecting and classifying jamming attacks. This work not only provided valuable insights into the effectiveness of different ML algorithms but also contributed additional datasets and proposed innovative methodologies not explored in previous research. Furthermore, it analyzed the impact of SNR levels on classification accuracy, shedding light on the robustness of the developed models under various conditions. Moreover, the deployment of DL models was explored, including AlexNet, VGG-16, ResNet-50, and EfficientNet-B0, for spectrogram-based classification. These models leveraged spectrogram images obtained from SDR devices. and QT GUI Waterfall Sink blocks, demonstrating significant improvements in detection rates and classification accuracy. EfficientNet-B0, in particular, emerged as the top performer, achieving a detection rate of 100% for two-class models and 99.79% for five-class models. This work also examined the computational aspects, showcasing the training and testing times of the CNN models and highlighting the potential for real-time jamming detection and classification.

The work described in [56] introduced BloodHound, a DL-based solution designed to detect and identify jamming in mobile environments by analyzing the PHY of communication links. In this context, a mobile entity, such as a drone or a connected car, was considered while performing specific tasks. This entity encountered escalating jamming effects as it approached a statically positioned jammer, intended to disrupt communications within a defined area. For experimental assessments, Ettus X310 SDR units equipped with UBX160 daughterboards were utilized to operate as transmitters, jammers, or receivers within a NLoS office environment. These SDRs captured I/Q samples at a high rate of 1 million samples per second, processed them to identify jamming signals, and leveraged their high dynamic range, low noise figure, and FPGA-based real-time signal processing capabilities. In addition, VERT2450 omnidirectional antennas facilitated signal transmission and reception, and the GNU-Radio toolkit provided software control. Unlike conventional methods that rely on post-disruption indicators such as packet loss and signal strength, BloodHound analyzed shifting patterns in raw I/Q samples to preemptively detect jamming, thereby enhancing situational awareness and communication robustness. Various jamming scenarios including no jamming, tone jamming, and Gaussian jamming were simulated across different power levels to assess system performance. Results indicated a detection accuracy exceeding 99% and a bit error rate below 0.01. The use of CNNs for analyzing I/Q samples demonstrated robust identification of jamming scenarios across diverse distances, jamming intensities, and hardware setups. Overall, BloodHound represents a significant advancement over traditional methods by enabling early detection and precise classification of jamming types, thereby ensuring enhanced reliability in wireless communications.

The work in [57] proposed BloodHound+, an innovative system designed to detect jamming attacks in low-BER scenarios using UAVs and SDRs. BloodHound+ transformed raw I/Q samples from the wireless channel into grayscale images for anomaly analysis indicative of jamming and utilized sparse autoencoders for detecting image anomalies. The experimental setup involved training the autoencoder on unjammed I/Q samples and testing on both unjammed and jammed samples to compute metrics such as the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve. This method ensured robust performance across varying levels of Received Jamming Power (RJP), demonstrating BloodHound+'s effectiveness in low-BER scenarios. Two types of SDR devices were employed to emulate UAVs and provide the radio hardware interface for capturing and processing I/Q samples directly from the wireless channel. The USRP X310 was used for baseline and high-accuracy testing, suitable for controlled and precise experimental conditions. Conversely, the LimeSDR Mini was used to test BloodHound+'s robustness under less ideal conditions, such as with cheaper hardware and different sampling rates, demonstrating its effectiveness in real-world scenarios with potential hardware imperfections. Extensive indoor measurements with varying hardware setups, jamming strategies (including deceptive jamming), and communication parameters validated the proposed system. Results showed BloodHound+'s superior performance compared to benchmark CNN-based approaches (e.g., ResNet-18) [56] in detecting jamming across different RJP values and distances from the jammer. For instance, at RJP = 0.5 and a receiver distance of 10 meters, BloodHound+ consistently achieved 99.7% classification accuracy, outperforming CNN-based solutions that struggle in lower RJP scenarios. While the Ettus Research USRP X310 provided more accurate and reliable measurements, the LimeSDR Mini introduced some variability due to its lower cost and associated imperfections. Despite these challenges, BloodHound+ proved to be robust and reliable across different SDRs and oversampling ratios, illustrating strong performance in detecting jamming under various conditions and hardware setups.

B. MITIGATION OF ATTACKS AND SYSTEM RESILIENCE

This subsection emphasizes strategies and technologies used to mitigate the impact of attacks and enhance the resilience of communication systems, including hardware setups and Blockchain integration.

A signal source identification system was proposed in [58], offering a promising solution for addressing the challenges posed by complex and dynamic environments. By combining data from binocular cameras and received signal strength, the underlying methodology represented a significant leap forward in the accurate discernment of signaling objects amidst cluttered environments. The core of this system was Blockchain technology [59], serving as the backbone for organizing and coordinating UAV tasks through the implementation of smart contracts. This not only streamlined task allocation but also addressed inherent challenges, such as the lack of knowledge regarding transmit power and channel parameters, ensuring efficient task execution. Security and privacy were paramount considerations in the system's design, with various secure schemes integrated into the Blockchain-based architecture. These measures, including asymmetric key cryptography, ring signature, and consensus mechanisms, ensured that all operations were conducted in a privacy-preserving manner, bolstering the overall security of the system. To tackle uncertainties in signal parameters, a robust maximum likelihood estimation method was introduced, designed to accurately estimate parameters within the PL log-normal shadowing model. Leveraging mean squared error as a metric for distinguishing signaling objects, the proposed system demonstrated commendable efficacy in simulated environments, setting the stage for practical implementation. The experimental evaluations were conducted on a comprehensive testbed configuration and validated the efficacy and reliability of the proposed system. The hardware setup comprised Hexacopter Tarot UAVs equipped with Raspberry Pi 4, a Metoak binocular camera, and a HackRF One SDR module, interconnected with a ground system consisting of a laptop with a discrete GPU and a Wi-Fi access point (AP). Also, the Mobile Edge Computing (MEC)-enabled ground system employed a USRP Ettus B210 device to gather power data from various locations. The experiments demonstrated the system's ability to accurately identify the target object even in complex and dynamic environments, underscoring its robustness and scalability. Key findings from the experiments highlighted the pivotal role played by SDR technology in facilitating secure data exchange and communication between participants. Through the establishment of secure channels and the provision of encryption keys by the miner, SDR enabled participants to securely transmit and receive data related to task parameters and results. This ensured that sensitive information remained protected throughout the entire process, from task initiation to completion. Moreover, SDR's real-time capabilities enhanced the efficiency and reliability of data exchange, contributing to the seamless execution of identification tasks in the target area. Moreover, the integration of Blockchain technology enhanced transparency and reliability, while smart contracts governed transactions, further bolstering security.

In [60], a realistic communication channel model under jamming conditions was developed, diverging from traditional theoretical models such as Friis and Rician. The scenario investigated involved a mobile receiving device, such as a UAV equipped with a LimeSDR, and a static jammer emitting high-power signals to block communication across multiple frequencies (500 MHz, 1,575.42 MHz, and 2,437 MHz). In this setup, the jammer was emulated using an Ettus USRP X310 SDR with a UBX160 daughterboard, emitting Additive White Gaussian Noise (AWGN) signals at 20 dBm peak power. The mobile device aimed to detect jamming through GPS signal loss or elevated Received Signal Strength (RSS) on the GPS channel, exceeding a threshold of −97.8 dBm. To this end, the LimeSDR captured the RSS samples at various distances (0.5 m to 20 m) from the jammer over 10 minutes per frequency, necessary for modeling the communication channel under jamming. To identify the location of the jammer, Pratt's algorithm was utilized [61]. Moreover, the jammer localization system was modeled using a closed-loop control system, wherein the mobile entity employed a Proportional-Integral-Derivative (PID) controller to compensate for errors in power estimation. Apart from jammer localization, another notable application of the underlying system is dead reckoning navigation within a jammed area. This involves estimating the current position of a mobile device by utilizing previously-determined locations and supplementary cyber-physical information (e.g., speed, wind, and other reference data not explicitly intended for navigation purposes). Measurements were taken using different antennas suited to the specific frequencies under test. Based on the experimental results, it was revealed that the RSS samples followed a *t-locationScale* distribution, regardless of frequency or distance. Additionally, the power of received jamming signals decayed following a power-law distribution, characterized by coefficients dependent on the operating frequency. Besides, jamming source localization achieved errors as small as 29 cm.

C. IMPLEMENTATION AND EXECUTION OF ATTACKS

The utilization of GPS technology within the context of small UAVs constitutes a critical aspect of their operational framework, particularly as they play an increasingly significant role in the expansive landscape of the IoT and Cyber-Physical Systems (CPS). However, the reliance on GPS navigation exposes UAVs to a range of vulnerabilities, chief among them being the looming threat of spoofing attacks. SDR technology represents a pivotal component in the execution of GPS spoofing attacks, introducing a level of sophistication and flexibility to the malicious activities targeting small UAVs. Among the prominent SDR devices commonly employed by attackers are BladeRF 2.0 and HackRF One, renowned for their compact form factor, versatility, and programmability. These SDR platforms enable attackers to manipulate radio signals with high precision, facilitating the generation of counterfeit GPS signals that can deceive UAVs into calculating erroneous positions. Spoofing attacks operate by exploiting weaknesses inherent in GPS signals, wherein attackers utilize SDR devices to capture and analyze satellite signals broadcasted by GPS satellites. This process enables attackers to acquire crucial information about the structure and content of authentic GPS signals, essential for crafting convincing spoofed signals. Subsequently, using specialized GPS simulator tools, attackers generate forged GPS signals that closely mimic authentic transmissions, including satellite identification codes, signal strength, and timing information. This subsection explores the use of SDRs in executing GPS spoofing attacks against small UAVs and manipulating GPS signals with high precision. Additionally, this subsection discusses the development and evaluation of detection and mitigation systems, aimed at enhancing UAV security against these sophisticated threats.

The work in [62] introduced a novel and innovative lightweight detection model specifically tailored for UAV systems. Central to this approach was the utilization of Long-Short Term Memory (LSTM) networks, renowned for their proficiency in handling time-sequential data, thereby enabling effective identification of GPS spoofing attacks even from considerable distances. Moreover, through the application of knowledge distillation techniques, the detection model was intelligently condensed into a compact form, optimized for seamless integration within the control systems of UAVs. This strategic optimization ensured optimal utilization of onboard computational resources while maintaining high detection efficacy. The efficacy of the proposed lightweight detection algorithm was rigorously validated through comprehensive experimentation and evaluation. Leveraging open-source datasets and sophisticated simulation tools, this work compared the performance of the LSTM-based detection model against traditional methods such as Recurrent Neural Networks (RNNs) and Gated Recurrent Units (GRUs). The results unequivocally demonstrated the superior stability, accuracy, and timeliness of the LSTM-based approach in predicting GPS localization and effectively thwarting spoofing attacks perpetrated via SDR devices. Through this innovative approach, the security and reliability of UAV operations can be fortified amidst the evolving landscape of cybersecurity challenges.

The work in [63] investigated the ramifications of integrating the HackRF One 1.0, an affordable and widely used SDR device, into the operational framework of UAVs, particularly in light of the persistent threats posed by spoofing and jamming of the GNSS signal. It scrutinized the system's architecture and methodology, with a keen focus on how the HackRF One, equipped with an external Temperature Compensated Crystal Oscillator (TCXO), could induce artificial interference within the GNSS signal. This interference, carefully crafted and transmitted, aimed to assess its impact on the operational capabilities and safety of UAVs, particularly in scenarios where GNSS signals were vital for navigation and positioning. The experiments were methodically designed to cover various stages, starting from configuring the HackRF One with the external TCXO to generating synthetic signals mimicking GNSS data, transmitting them, and finally analyzing their reception using specialized equipment. Moreover, the evaluation process measured the influence of spoofed signals on the performance of GNSS receivers installed on UAVs (i.e, 3DR IRIS+, Tarot 650 v2.2, DJI Inspire, and Sky Hunter), documenting significant instances of receiver failures and notable degradation in accuracy metrics during the transmission of synthetic signals. This process involved configuring the HackRF One device to generate artificial GPS signals, transmitting them, and analyzing their effects on a GPS receiver systematically. The inherent flexibility and adaptability of SDR devices, exemplified by the HackRF One, enabled rapid parameter adjustments and the simulation of diverse scenarios, facilitating comprehensive assessments of UAV safety and resilience in the face of evolving security threats. This work demonstrated that transmitting artificial spoof GPS signals resulted in the failure of the GPS receiver to capture any visible satellites, posing a substantial risk in real-world operational scenarios. Deviations in course and accuracy measures were evident during interference, with significant changes observed in course values and accuracy measures with respect to the position determination, such as RMS2D (root mean square error in two dimensions). Specifically, the reference RMS2D value was recorded at 2.4, indicating a high level of accuracy, with a precision probability of more than 97%. However, when the generated spoof signal was transmitted, the RMS2D value decreased substantially. Additionally, in a second measurement without an active GLONASS receiver, significant deviations in course values and a notably higher RMS2D value compared to the reference measurement were observed, emphasizing the critical importance of considering different scenarios and configurations when assessing interference effects on GNSS receivers. In particular, the RMS2D value soared to 249.0, representing an approximately 57-fold increase compared to the reference measurement. This drastic increase in RMS2D indicates a substantial decrease in accuracy and precision in determining the position, primarily due to the complete loss of the GPS L1C signal without reference to another satellite navigation system. These empirical findings underscored the vulnerability of UAVs to artificial interference, highlighting the urgent need for robust countermeasures to safeguard UAV operations, particularly in airspace environments susceptible to malicious attacks targeting GNSS signals.

One promising approach to secure UAVs involves developing an intelligent Intrusion Detection System (IDS). However, a key obstacle in IDS research and development is the scarcity of accessible datasets. To tackle this problem, live experiments were conducted in [64], and a methodology was proposed that utilizes Principal Component Analysis (PCA) and one-class classifiers to detect and mitigate attacks. This method leverages flight logs as training data, providing a versatile and widely applicable solution. Integrating this detection method into a comprehensive IDS, named MAVIDS, can enhance the UAV's defensive capabilities. MAVIDS operated within a resource-constrained agent device onboard the UAV, enabling the detection and potential mitigation of attacks. GPS spoofing and jamming were selected for experimentation due to their prevalence and feasibility using cost-effective SDR technology. Specifically, a HackRF One SDR was utilized for these attacks as it can broadcast within GPS frequency bands. In a controlled Faraday cage environment, a Holybro S500 quadcopter UAV was deliberately deprived of regular GPS signals. To establish a baseline for the experiments, the Keysight EXG N5172B signal generator was employed to broadcast GPS signals. Following activation, the UAV successfully detected up to thirteen 'satellites' and established a GPS lock. All experimental flights were conducted in position mode, relying on a stable GPS signal, with GPS-related fail-safes deactivated to prevent manual mode reversion. Before initiating attacks, the UAV underwent a benign flight, serving as training data for subsequent ML training. After the training flight's completion, attack experiments began. The GPS-SDR-SIM software [65] generated GPS baseband signal data streams using a daily GPS broadcast ephemeris file for signal generation. Once the binary data stream was generated, it was transmitted by the HackRF for broadcasting. Attacks were initiated after the UAV had been airborne for a few minutes, leading to destabilization and eventual crash. Jamming involved introducing RF noise to obstruct legitimate signal reception. Employing the GNU Radio Companion, a flowgraph was devised to emulate a jamming signal. Empirical evaluation demonstrated the effectiveness of this approach against common threats, yielding macro-averaged F1 scores of 90.57% for GPS spoofing and 94.3% for jamming.

In [66], a system was introduced that can detect and mitigate GPS spoofing attacks by integrating crowd-sourced information from mobile cellular BSs and WiFi APs, thereby enhancing GPS security for connected vehicles. This system employed mobile entities (including UAVs) equipped with GPS receivers to capture real-time environmental data and dynamically simulate mobile targets to assess GPS spoofing susceptibility. To generate GPS spoofing signals, the HackRF One was used fitted with a TCXO to ensure signal stability and accuracy during spoofing operations. GPS spoofing was orchestrated with GPS-SDR-SIM software [65], which generated GPS baseband signals to simulate both fixed and moving positions, creating realistic spoofing scenarios. Experiments involved driving a vehicle equipped with a smartphone across diverse terrains and recording various parameters every 166ms. The smartphone logged information from cellular BSs and WiFi APs, as well as GPS data. This data was used to establish a baseline for normal operation and detect anomalies indicative of spoofing. The dataset included 387,193 events recorded over a distance of more than 196km in Doha, Qatar, spanning urban, suburban, and rural areas during a 5.5-hour period. Based on the results, the system demonstrated a detection delay of around 6 seconds when using WiFi data exclusively and up to 30 seconds when using cellular network data, with a false positive rate maintained below 0.01. These metrics reflect a robust balance between timely detection and accuracy, crucial for practical deployment. GSM technology generally provided broader coverage but with higher RSS variability compared to WiFi. Combining both GSM and WiFi (WiFi+GSM) resulted in more reliable position estimates, particularly in urban areas with a higher density of anchors. This solution integrates seamlessly into existing smart navigation systems, requiring no special hardware and introducing minimal processing overhead. Its adaptability allows it to function effectively in various environments by adjusting the use of WiFi and GSM signals according to the density of available networks.

D. COUNTERMEASURES AGAINST UNAUTHORIZED UAV OPERATIONS

This subsection explores methods to address the growing threat of rogue UAVs exacerbated by advancements in autonomous flight control. Additionally, this subsection details the development and testing of mobile spoofing and jamming systems using SDR platforms to induce GPS errors and disrupt UAV navigation.

The work in [67] addressed the escalating challenges posed by the exponential growth in civilian UAV usage, exacerbated by advancements in autonomous flight control systems, which have led to a surge in accidents and hazardous incidents. To tackle this issue, a mobile spoofing system was proposed to induce location errors in targeted GPS receivers. The GPS system, with its user, space, and ground segments, served as the focal point of this work due to its widespread adoption and critical role in navigation. The proposed system utilized a low-cost SDR BladeRF x40 platform, leveraging its programmable FPGA chip and open-source architecture for efficient signal manipulation. Acting as the central controller, the SDR orchestrated the operation of the spoofing system, facilitating seamless integration and efficient execution of spoofing strategies. With its versatility and programmability, the SDR platform enabled the generation, manipulation, and transmission of fake GPS signals, crucial for inducing location errors in targeted GPS receivers. By integrating sensor data, including inputs from LIDAR, accelerometers, and magnetometers, with spoofed GPS signals, the SDR dynamically adjusted signal parameters based on the current location and orientation of a Hornet mini-UAV, ensuring precise redirection of this UAV in real-time. Moreover, NMEA (National Marine Electronics Association) messages were employed for dynamic GPS signal simulation, effectively altering the UAV's perceived location and redirecting its trajectory to designated landing areas. By adopting this method, a defensive system was implemented to divert or even assume control of unauthorized UAVs reliant on GPS information for navigation. The experimental validation of this system involved indoor and outdoor tests targeting various GPS receivers, including smartphones and evaluation kits. In addition, the L1 frequency range of the GPS system was predominantly considered, encompassing open signals for civil use and more robust, accurate signals for military applications, highlighting the vulnerabilities of both civilian and military GPS receivers to spoofing techniques. Based on the results, the efficiency of this spoofing system in deceiving GPS receivers and diverting UAVs from their intended flight paths was verified, even in scenarios where receivers had acquired initial GPS fixes.

Despite existing drone legislation, the proliferation of rogue UAV activities poses significant challenges, tarnishing the reputation of law-abiding pilots and endangering public safety. Various solutions have been proposed to address this issue, including unconventional methods such as training raptors for UAV interception or deploying non-destructive jamming devices. However, these solutions are not without drawbacks, prompting the exploration of alternative approaches such as SDR-based jamming. In response to the rising incidents involving UAVs and airplanes, the work in [68] explored the urgent necessity for countering unauthorized UAV operations, particularly within airport and airfield environments. This work employed the DJI Spark and Parrot Bebop 2 FPV UAV models, as well as a low-cost BladeRF x40 SDR platform, focusing on implementing a jammer capable of disrupting GPS navigation systems crucial for UAV autonomy. More importantly, leveraging the SDR platform and GNU Radio toolkit, various interference techniques were examined and evaluated for their spectral efficiency, energy efficiency, and complexity. Through controlled environment tests and real-world experiments, different jamming techniques were considered, ranging from barrage and tone jamming to protocol-aware congestion. These techniques exploit intentional radio interference to disrupt wireless communications, primarily targeting the PHY of wireless networks. Protocol-aware jamming emerged as the most promising solution, effectively mimicking the spectral characteristics of GPS signals to render reception virtually impossible. Real-world tests confirmed the capability of jamming to halt autonomous drone flight immediately upon activation, highlighting the potential for indirect control through spoofing signals post-jamming. Tone Jamming and Successive Pulses Jamming exhibited lower efficacy, with the former concentrating energy on the carrier frequency and the latter failing to uniformly interfere across the GPS signal bandwidth. The findings validated the efficacy of the tested approaches in halting the reliable reception of radionavigation signals, effectively neutralizing the capacity for autonomous UAV operation.

A comprehensive approach to safeguarding areas against unauthorized UAV intrusions was presented in [69]. The proposed system, built around low-cost SDR platforms, offered a portable solution capable of detecting, jamming, and spoofing GPS signals to thwart unauthorized UAV operations. This system's versatility enabled deployment in various scenarios, from protecting airports to mitigating terrorist threats or illegal activities involving UAVs. By integrating target localization capabilities with effective jamming techniques, including barrage jamming and protocol-aware jamming, the system is capable of disrupting UAV control signals and neutralizing GPS reception, thus preventing autonomous flight. Real-life tests validated the system's efficacy in halting UAV operations immediately upon activation and diverting or controlling the intruding drones. Notably, the system's security measures, including biometric authentication and communication with a supervisory entity, ensure authorized usage and accountability. The results of the real-life tests conducted to evaluate the anti-UAV system's performance were highly promising. During these tests, a DJI Phantom 3 Standard UAV was employed as the target drone, chosen due to its widespread use and representativeness of commercial drones. The anti-UAV system relied on a BladeRF x40 SDR platform, which enables versatile and efficient signal processing. This SDR technology empowered the system to dynamically adapt its jamming and spoofing techniques to counter various

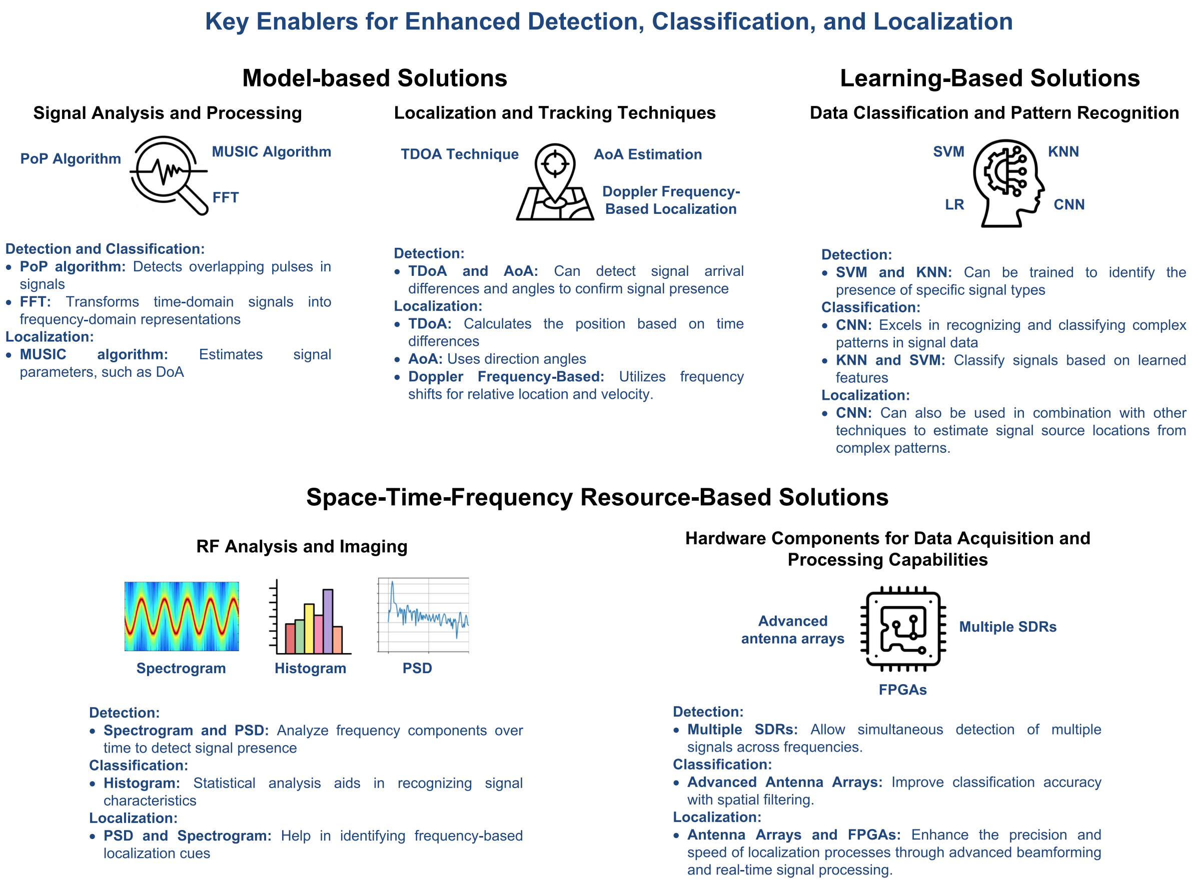

FIGURE 8. Technologies that enable advanced functionalities in SDR-assisted UAV-based operations, improving detection, classification, and localization capabilities in diverse environments.

UAV communication protocols and GPS frequencies. Also, by harnessing SDR capabilities, the system achieved precise control over signal generation and modulation, ensuring accurate disruption of UAV communications while minimizing interference with surrounding systems. Specifically, the system leveraged GNU Radio and GPS-SDR-SIM software [65] for generating and transmitting jamming and spoofing signals, respectively. The tests were conducted in a controlled rural environment to ensure safety and accuracy. Upon activating the jammer signal transmission, the UAV's behavior was immediately altered, causing it to halt its autonomous flight and hover in place. The system then initiated spoofing signals, directing the UAV towards a pre-defined forced landing site. This seamless transition from jamming to spoofing demonstrated the system's ability to neutralize UAV threats effectively. The results demonstrated the system's performance in countering a wide range of UAV operations, from autonomous flights to those controlled remotely.

VI. SDR DEPLOYMENTS FOR DETECTION, CLASSIFICATION, AND LOCALIZATION

This section explores how prior research, as summarized in Table 6, has leveraged SDR technology to improve the detection, classification, and localization capabilities of UAV-based systems. Fig. 8 depicts the technologies employed in previous studies, enabling advanced SDR-assisted UAV-based systems to detect, classify, and locate targets across diverse operational scenarios and congested RF environments. These technologies include model-based solutions, which depend on mathematical models and algorithms to interpret signals and data by using predefined models of signal behavior. In contrast, learning-based solutions utilize ML algorithms to identify patterns and make decisions based on training data. Furthermore, space-time-frequency resource-based solutions focus on optimizing resource usage across space, time, and frequency dimensions to improve system performance.

A. DETECTION AND CLASSIFICATION BASED ON SIGNAL PROCESSING

This subsection covers signal processing methodologies specifically tailored for detecting and classifying UAVs. The discussion centers on how these methodologies leverage SDR technology to enhance detection and classification capabilities.

In [70], an approach for detecting and classifying Mini/Micro UAVs was introduced, employing a hybrid strategy that merges passive RF detection methodologies with signal analysis and decoding techniques, enabled by SDR

TABLE 6. **Synopsis of Recent Research Works on SDR Deployments for Detection, Classification, and Localization**

Ref.	Year	Type of UAVs	Type of SDR	Role of SDR	Key Technologies	Outcome
[10]	2022	DJI Mavic Air, DJI Phantom 4 Pro v2.0, and DJI Mini 2	Ettus USRP X310 and Ettus USRP B200mini	Capturing RF signals (Ettus USRP X310), generation of jamming signals (Ettus USRP B200mini)	Spectrum sensing algorithms (e.g., 3EED) for UAV detection and AoA algorithms for localization.	UAV detection and defense
[70]	2024	DJI Phantom 4 Pro v1.0 and DJI Phantom 4 Pro v2.0	ADALM-PLUTO	Capturing, analyzing, and discriminating RF signals in the presence of interference	Passive RF detection, high-performance receiver chains including LNAs, high-speed ADCs, configurable AGC	Detection and classification of UAVs amidst interference signals in congested RF spectrum environments
[71]	2020	DJI Matrice M100	Ettus B200mini	Data transmission and reception	Deep CNN, RF fingerprinting	UAV identification in dynamic aerial environments
[72]	2021	Mavic 2 Zoom	Ettus USRP B210, LimeSDR	Capturing RF signals	Integrated SDR and FPGA components, ML	Drone detection sensor for anti-drone systems
[73]	2021	Parrot Bebop, Parrot AR (Elite 2.0), and DJI Phantom 3	NI USRP 2943	Capturing RF signals	Deep CNN ResNet50, LR, transfer learning from ImageNet enhanced pattern recognition	UAV detection as imagery classification
[75]	2021	Parrot Bebop, Parrot AR, DJI Phantom 3	NI USRP 2943R	Capturing RF signals	ML, RF data analysis, preprocessing (smoothing filters, FFT), ensemble learn-	UAV detection with high accuracy
[78]	2022	Intel Aero	Ettus USRP B210 and Ettus USRP B205mini	Data transmission (Ettus USRP B210) and data reception (Ettus USRP B205mini)	Signal acquisition, distributed beamforming, DoA estimation, blind signature detection, RTK	Signal localization and source detection in outdoor environments
[79]	2024	It is not specified	ADALM-PLUTO, Ettus USRP B200mini-i, USRP N210, BladeRF 2.0 micro xA4, USRP–2950R, USRP–2930	Capturing RF signals	Small-size frequency oscillators for precise localization	Accurate localization with minimal size, weight, and power consumption for UAVs in EW operations.
[80]	2024	DJI Mavic 3T-Basic Enterprise	NI USRP 2954R	Capturing RF signals	MUSIC algorithm, UCA antennas, coherent operation through calibration	UAV localization, addressing safety concerns associated with drones by accurately pinpointing their positions based on RF signals
[81]	2024	Tarot X6 hexacopter	ADALM-PLUTO	Data transmission and data reception	AoA estimation, RSSI estimation, log-distance path-loss model, PRACH-assisted method	Ground transmitter localization using UAVs
[83]	2024	DJI Mavic Air	Ettus USRP X310, Ettus USRP B200-mini	Capturing RF signals (Ettus USRP X310) and signal generation (Ettus USRP B200-mini)	MUSIC algorithm, VERT2450 antennas, DoA estimation	UAV detection and direction-finding
[84]	2022	DJI Spark	Ettus USRP X310	Capturing RF signals	SFS, WEE, PSE, SVM, RF, KNN, super-resolution estimation algorithm	UAV detection and positioning
[85]	2024	Parrot Bebop, DJI Phantom, Fimi, and DJI Mavic	Ettus USRP X310	Capturing RF signals, collecting data for CNN training	Passive monitoring, CNN for UAV classification, TDOA-based positioning	Cost-effective, scalable system for UAV classification and localization in diverse domains

technology. The SDR served as the backbone of the system, offering unparalleled flexibility and signal processing capabilities crucial for navigating the congested RF spectrum environment. Specifically engineered with high-performance receiver chains, including LNAs with noise figures below 1dB and direct conversion mixers, the SDR ensured optimal sensitivity and fidelity in signal reception. Moreover, the SDR featured a high-speed ADC operating at a sampling rate of 100 MSPS, enabling precise digitization of signals across a wide bandwidth. Analog and digital filtering stages, coupled with configurable Automatic Gain Control (AGC) mechanisms, further enhanced the SDR's ability to mitigate interference and maintain signal integrity. Experimental validation of the system's performance encompassed both laboratory and field tests, with rigorous assessments conducted to evaluate detection accuracy and interference discrimination. In this direction, two distinct drone models, namely the DJI Phantom 4 Pro v1.0 and DJI Phantom 4 Pro v2.0, were utilized as potential threats. These drones operate within the 2.4 GHz and 5.8 GHz ISM bands for establishing radio communication links with their remote controllers. To simulate real-world scenarios, a Wi-Fi modem was employed to generate interference signals within the ISM bands, serving to provide internet connectivity to users. Also, an ADALM-PLUTO SDR was used for RF signal processing, offering a flexible platform for RF experimentation. With a frequency range of 325 MHz to 3.8 GHz and adjustable bandwidth from 20 KHz to 20 MHz (expandable up to 56 MHz), the SDR enables reception and transmission in half or full duplex modes. In laboratory settings, controlled scenarios simulating various RF spectrum conditions were employed, while field tests provided real-world validation across urban and rural environments with varying interference levels. More specifically, the experiments entailed two primary processes; Wi-Fi signal decoding/detection and Fast Fourier Transform (FFT) calculation. The former involved analyzing samples from the receiver hardware to decode Wi-Fi beacon packets, extracting vital information such as frequency band, channel number, MAC address, and Service Set Identifier (SSID). Besides, the latter process converted time-domain samples to the frequency domain using the FFT algorithm, facilitating spectrum analysis with various resolution bandwidth options. The results revealed significant improvements in signal detection accuracy, with notable reductions in center frequency deviation achieved through the developed Pulse on Pulse (PoP) algorithms. For instance, the calculated deviation center frequency of Mini/Micro UAV signals improved from 103ppm to 61.2ppm in the presence of wideband overlapping spurious signals, showcasing the efficacy of the proposed approach. The bandwidth correction capabilities of the system further ensured precise calculation of signal bandwidths, with deviations well within acceptable limits.

In [71], the AirID framework was presented aimed to propel UAV identification technology forward by providing a comprehensive solution tailored to overcome the obstacles presented by dynamic aerial environments. At its core, AirID leveraged the capabilities of Ettus B200mini SDR, strategically deployed both on static ground units and mounted on DJI Matrice M100 UAVs. This setup allowed for collaborative identification, transforming the UAV swarm into a cohesive identification network. The role of the SDRs in the AirID framework was multifaceted acting as the backbone technology enabling the robust identification capabilities of the AirID framework. Firstly, the SDRs served as crucial components for both static ground UAV identifiers and those mounted on DJI Matrice M100 UAVs, enabling collaborative identification as an aerial swarm. Secondly, they facilitated the transmission and reception of RF signals emitted by the UAVs, capturing the I/Q samples that contained unique signatures for identification. Additionally, the SDRs played a pivotal role in implementing a deep CNN architecture, enabling the detection of these signatures at the physical layer without interrupting ongoing UAV data communication processes. The innovative approach of AirID extended beyond mere identification to tackle the complexities introduced by the ever-changing aerial conditions. One key challenge it addressed was the inherent variability in RF fingerprinting accuracy, particularly in scenarios where the environment fluctuates from one day to another. By training the CNN offline on simulated data and subsequently injecting fingerprints into the UAVs post-training, AirID ensured robust performance even amidst dynamic environmental conditions. Experimental validation affirmed the efficacy of AirID, with results demonstrating an impressive 98% identification accuracy for authorized UAVs while maintaining a stable communication Bit Error Rate (BER) of 10-4. These experiments went further to explore the impact of various factors such as distance, displacement, and interference on identification accuracy, revealing the resilience of AirID in real-world scenarios. Crucially, AirID's decision fusion algorithms, leveraging CSI, played a pivotal role in ensuring accurate identification outcomes despite challenges, such as UAV motion and interference. By intelligently combining individual identification results from multiple receivers, AirID maximized accuracy and reliability, even in the face of dynamic environmental conditions.

The sensor system presented in [72] utilized passive RF imaging techniques for drone detection and SDR technology with a continuous operational frequency range of 2.400 GHz to 2.483GHz, which is commonly associated with drone communication. This system excelled not only in cost-effectiveness but also in its combination of high performance and real-time capabilities, rendering it highly suitable for widespread deployment across a variety of applications. At the heart of this system was its pioneering hardware design, seamlessly integrating both SDR and FPGA components enabling real-time analysis of RF signals in the 2.4 GHz ISM band. This integration was vital for overcoming the real-time bandwidth limitations typically encountered with conventional SDR setups. Using affordable off-the-shelf parts enabled the system to strike a balance between cost and performance, facilitating broad deployment. Central to its effectiveness was the capacity to shift signal processing tasks from software to FPGA hardware. This approach minimized data throughput between the SDR and companion computer, enabling real-time analysis of received signals. Additionally, specific signal processing algorithms implemented in the FPGA further optimized performance, ensuring timely and accurate detection of drone signals. Experimental validation conducted in both laboratory and real-world scenarios pointed out the system's efficacy. In this respect, two SDR devices, i.e., Ettus USRP B210 and LimeSDR, were utilized as the primary SDR devices for capturing, processing, and analyzing RF signals, contributing to the evaluation of the proposed sensor system's performance in drone detection experiments. Also, the Agilent Digital Signal Generator produced an arbitrary Gaussian Frequency Shift Keying (GFSK) waveform that served as the basis for assessing the sensitivity and performance of the SDR receivers. The data acquisition aimed to record clear time-domain real-life drone signals while considering channel propagation characteristics. In this direction, the drone used as a signal source was the DJI Mavic 2 Zoom quadcopter. Comparisons with reference receivers demonstrated a notable 9dB reduction in detection sensitivity, aligning with the analog RF front-end specifications. These results affirmed the system's viability for generating ML datasets and its potential as a critical component within anti-drone systems.

B. ML-BASED DETECTION AND CLASSIFICATION

This subsection concentrates on the application of ML techniques for UAV detection and classification, emphasizing the use of DL and ensemble methods.

In [73], the complex issue of UAV detection was tackled, recognizing the significant security challenges they present, as exemplified by incidents, such as the Gatwick Airport disruption in December 2018. By adopting an innovative approach, the research framed UAV detection as an imagery classification problem, offering a novel perspective on an increasingly pressing concern. This approach took advantage of signal representations such as Power Spectral Density (PSD), Spectrogram, Histogram, and raw I/Q constellation, which are treated as graphical images and fed into a deep CNN ResNet50 for feature extraction. Leveraging transfer learning from ImageNet, a large-scale image database [74], the CNN was pre-trained to recognize complex visual patterns, reducing the need for extensive signal datasets and enhancing the system's ability to generalize across different UAV scenarios. Performance evaluation was conducted using a Logistic Regression (LR) ML classifier, which assesses the system's ability to classify three popular UAV models across ten distinct modes, covering various operational states such as switched on, hovering, flying with or without video transmission, and no UAV present. The evaluation was rigorous, employing techniques such as 5-fold cross-validation and an independent hold-out evaluation dataset to validate the model's accuracy and robustness. Notably, the PSD representation emerged as the most effective, achieving over 91% accuracy across the ten classifications, surpassing previous methods in the field by a significant margin. The experimental setup relied on the open DroneRF dataset, which provided a comprehensive collection of UAV signal data captured using two NI USRP 2943 devices. These high-end USRPs operated in the 1.2 GHz to 6 GHz frequency range, allowing for the capture of 40 MHz of instantaneous bandwidth each. By utilizing these two USRPs simultaneously, the system covered an 80 MHz spectrum of the Wi-Fi band, excluding channels 1 and 14. The dataset consisted of 1000 samples for each class of UAV, partitioned into training and evaluation sets to support thorough model training and evaluation. Furthermore, various signal representations were investigated in detail, including raw I/Q data, PSD, spectrogram, and histogram, shedding light on their effectiveness in capturing different aspects of UAV emissions. Through comprehensive analysis and visualization, the distinct patterns exhibited by each UAV model in different operational modes were elucidated, providing valuable insights into their RF signatures and behaviors.

By harnessing SDR, ML techniques, and RF data analysis, the work in [75] offered a sophisticated yet practical approach to discerning UAV presence, type, and flight mode with remarkable accuracy. SDR served as the primary data collection tool, with two NI USRP 2943R RF receivers capturing RF signals emitted by three types of UAVs, namely Parrot Bebop, Parrot AR, and DJI Phantom 3. These receivers, each covering different frequency bands, enabled comprehensive data acquisition and analysis. The system preprocessed the collected RF data to enhance signal quality, employing smoothing filters and FFT techniques to minimize noise and extract essential features for classification. This approach was based on a hierarchical ensemble learning framework, comprising four classifiers, each tasked with a specific aspect of UAV detection and identification. The hierarchical structure of the aforementioned framework allowed for a systematic and efficient evaluation process, ensuring precise classification at each stage of analysis. Leveraging ensemble learning techniques, such as XGBoost and K-Nearest Neighbor (KNN) algorithms, enabled the integration of multiple classifiers into a unified decision-making system, enhancing the robustness and reliability of the overall detection mechanism. Central to the system's functionality was the preprocessing of RF data, which involved cleaning, transforming, and normalizing the collected signals to enhance their quality and suitability for analysis. Through noise filtration and signal parameter optimization, the preprocessing phase established the groundwork for accurate classification and identification of UAVs amidst potentially complex and dynamic RF environments. The dataset used in the system's development comprised a diverse array of UAV types and flight modes, ensuring comprehensive training and testing scenarios. Through extensive experimentation and evaluation, the system demonstrated superior performance compared to existing methods regarding accuracy, F1 score, and recall, achieving an impressive classification accuracy rate of approximately 99%.

C. LOCALIZATION BASED ON SIGNAL PROCESSING

This subsection covers localization methods that rely primarily on signal processing techniques to detect and determine the position of UAVs. These methods utilize algorithms specifically designed to analyze and interpret signal characteristics.

In [10], the DronEnd system was presented, offering an integrated solution for drone detection and defense. This system exploited RF methods, with a focus on SDR for its flexibility and adaptability. Spectrum sensing algorithms, specifically energy detection methods, such as 3EED [76] and 3EED with an adaptive threshold [77], were employed for UAV detection within the 2.4 GHz and 5 GHz ISM bands, which are commonly used by UAVs. The SDR platforms, particularly the USRP X310, equipped with Twin-RX RF daughterboards, which serve as the backbone for signal reception, processing, and transmission. Localization of the UAV was achieved through AoA algorithms, utilizing a linear antenna system and coherent reception channels provided by the Ettus USRP X310. More specifically, the AoA algorithms exploited the phase differences of signals received from the drone using a multi-antenna system. The calibration and alignment of antennas, facilitated by the USRP X310's coherent reception channels, ensure precise localization of the UAV's position. Through calibration and processing of received signals, the system accurately determines the angle of incidence, thereby enabling precise targeting of the UAV. The jamming component, crucial for UAV annihilation, employed a directional antenna controlled by a motorized mount and powered by an Ettus USRP B200mini platform with a PA. By carrying out experimental tests, the performance benefits of the system were demonstrated, with successful annihilation of detected UAVs like DJI Mavic Air, DJI Phantom 4 Pro v2.0, and DJI Mini 2, within a 40-meter range from the system through RF jamming techniques.

In [78], a signal acquisition and source localization technique called RFEye was proposed exploiting a single UAV equipped with one omnidirectional antenna. The transmitter setup utilized a USRP B210 with a 10 dB RF amplifier and a 6dBi antenna to repetitively transmit a signal, particularly the Wi-Fi preamble, which served as the embedded signature. Moreover, the signal transmission occurred over an unused Wi-Fi channel, and the amplifier boosts the signal to 26dBm, suitable for outdoor experiments. Meanwhile, the UAV, an Intel Aero, equipped with RFEye and running Ubuntu, employed an Ettus USRP B205mini to acquire complex digital samples. These samples were streamed to the RAM disk memory over USB 3.0, enabling real-time signal processing. Distributed receiver beamforming was adopted to estimate the Direction-of-Arrival (DoA) of signals, enabling accurate localization without prior knowledge of the waveform. The SDR facilitated asynchronous signal acquisition, aligning signals from multiple positions to emulate synchronous reception. RFEye comprised four main steps; blind signature detection, asynchronous signal acquisition, DoA calculation using virtual distributed antenna arrays, and emitter position estimation. Furthermore, the UAV hovered within a 1-meter radius sphere at two nearby locations, collecting signals and aligning them in time for beamforming. Additionally, the UAV's precise positioning is facilitated by an RTK (Real-Time Kinematic) system, enhancing GPS accuracy to centimeter-level precision. Experimental results indicated RFEye's median accuracy of 1.03 m in 2-D and 2.5 m in 3-D for Wi-Fi, and 1.15 m in 2-D and 2.7 m in 3-D for LoRa waveforms, while being robust to external factors like wind and UAV position errors. Also, RFEye achieved high accuracy even in challenging NLoS scenarios, showcasing its efficacy in outdoor environments. Furthermore, Wi-Fi localization accuracy was assessed at 20 MHz bandwidth, with median errors of 4.5o in azimuth, 5.5o in elevation, and 0.63 m, 0.82 m, 2.3 m in x, y, z directions respectively. Similarly, LoRa localization exhibits median errors of 7.9o in azimuth, 8.5o in elevation, and 0.85 m, 0.78m, 2.45 m in x, y, z directions respectively, at 30dB SNR. Additionally, the impact of UAV altitude on localization accuracy was investigated, revealing minimal variation in DoA estimation and localization errors across different altitudes, with a maximum z-direction error of 1.5m at 80m altitude.

The work in [79] focused on utilizing SDR platforms for Doppler frequency-based localization, particularly for UAVs in Electronic Warfare (EW) applications. The proposed system, coupled with small-size frequency oscillators employed to construct a size-constrained location sensor, offered a promising approach for achieving precise localization with minimal size, weight, and power consumption, suitable for UAV applications. More importantly, the SDR platforms were crucial components in accurately determining the Doppler frequency shift for precise localization. Various SDR devices were tested and categorized into three classes according to their frequency stability, considering both those equipped with an external rubidium clock and those without. Subsequently, their effects on localization accuracy were assessed across short- and long-range scenarios. The first class, characterized by the lowest stability, encompassed devices that operate without utilizing an external frequency standard as a reference signal. Following this, subsequent classes, ranging from the second to the third, represented devices with progressively enhanced stability levels. It was further determined that the most suitable SDR devices for integration into a UAV-mounted location sensor were the Ettus B200mini-i and BladeRF 2.0 micro xA4. These devices feature compact dimensions, lightweight construction, and commendable stability parameters. The setup also considered a UAV equipped with a location sensor moving at a constant speed along a predefined trajectory, while an emitter continuously emitted a signal at a known carrier frequency. Two scenarios, short-range and long-range, with varying distances between the emitter and the UAV trajectory, were considered. Additionally, the experimental setup involved laboratory tests to measure short-term frequency stability, employing a vector signal generator as the transmitting part and various SDR platforms as receivers. Monte Carlo simulation methodology was employed to assess localization errors across different parameter combinations. Results indicated a significant reduction in location error, from 20 km to 30m for long-range and 15 km to 2 m for short-range scenarios, when using an external frequency standard. These results also revealed that higher SDR instability leads to decreased localization accuracy, with specific SDR classes showing varying levels of performance based on the magnitude of frequency instability. The third class SDRs exhibited superior accuracy, especially for scenarios with lower frequency instability.

The experimental evaluation of an SDR-assisted UAV-based localization system was detailed in [80], focusing on advanced signal processing techniques, specifically implementing the Multiple Signal Classification (MUSIC) algorithm using an SDR platform with a five-element Uniform Circular Array (UCA) for azimuthal localization. The MUSIC algorithm was exploited for its subspace-based approach to identify the AoA of RF signals. Besides, the UCA configuration addressed limitations seen with Uniform Linear Arrays (ULAs), enabling full azimuth (360°) coverage without front-to-back or end-fire region ambiguities. The system components included three NI USRPs 2954R SDRs, synchronized by an OctoClock CDA-2990, and controlled via an NI PXIe-8880 host computer, whereas calibration was achieved using a Hameg HM 8135 signal generator to ensure coherent operation among the array elements. This calibration process was crucial for achieving accurate AoA measurements, particularly in scenarios with varying signal strengths and environmental conditions. Two main scenarios were considered; close-range experiments involving a continuous sine wave target positioned within a 3m radius, and long-range experiments utilizing a commercial drone (DJI Mavic 3T-Basic Enterprise featuring a maximum transmission range of 15km) flown up to 2.5km from the receiving system. In close-range experiments, conducted within a 3-meter radius, the system demonstrated robust localization capabilities with an average error of 3.27° and low outlier percentage of 3.81%, indicating robust performance under controlled conditions. Conversely, the long-range experiments with the drone present challenges related to signal attenuation and variability in SNR over distance. Despite these challenges, the system achieved successful drone localization with an average error of 18.65°, leveraging the known operating frequency (2.46GHz) of the drone's communication link. Comparison with a professional direction-finding solution (Narda ADFA) confirmed the system's accuracy.

In [81], a method for ground transmitter localization using UAVs was proposed representing a paradigm shift in localization techniques by introducing an AoA-based approach, which diverges from conventional signal strength measures. The presented system capitalized on both traditional RSSI estimation and advanced AoA estimation techniques to achieve precise localization. For RSSI estimation, a log-distance path-loss model was employed, while AoA estimation utilized a Physical Random Access Channel (PRACH)-assisted method [82], strategically aligned with the operational characteristics of UAVs. In terms of hardware, a Tarot X6 hexacopter UAV served as the pivotal platform for data collection and localization maneuvers. Equipped with a 2x2 antenna array and a coherent receiver assembly, the UAV facilitated precise localization through data capture and processing. Furthermore, a Raspberry Pi bolstered the data acquisition process, enabling simultaneous collection of RSSI data and UAV positioning information. On the SDR front, four modified ADALM-PLUTO SDRs formed the backbone of the coherent receiver setup, operating in tandem to capture coherent samples and align received signals accurately in time. The experimental setup entailed concurrent data collection of both RSSI and AoA within the 2.4 GHz ISM band, operating amidst potential interference sources. Notably, the UAV was outfitted with the antenna array and coherent receiver assembly, engineered for optimal performance. The experimental results yielded quantitative insights into the performance disparity between the AoA-based and RSSI-based localization methodologies. Specifically, the Empirical Cumulative Distribution Function (ECDF) of the 2-D distance error was scrutinized, with the AoA approach exhibiting superior accuracy over the conventional RSSI method, albeit with inherent computational complexities and range constraints. Moreover, comparisons were drawn between the localization errors incurred by each method, providing tangible metrics for assessing their efficacy. Notably, the dataset amassed through the experimental campaign encompassed 997 data points for the AoA approach and 187 for the RSSI technique, offering a robust foundation for comprehensive analysis.

The work in [83] utilized SDR technology for detecting and estimating the DoA of RF signals emitted by a UAV. In this context, an RF-based direction-finding testbed was assessed using a DJI Mavic Air UAV operating within the 2.4–2.5 GHz ISM band. This UAV transmitted control and video signals via advanced Wi-Fi technology. The testbed incorporated the USRP X310 platform with two Twin-RX RF daughterboards, providing four phase-coherent receive channels. Moreover, a linear antenna array with four VERT2450 antennas was used to capture the RF signals, which were processed using the MUSIC algorithm implemented in the GNU Radio software environment–a well-known high-resolution DoA estimation method. The experimental setup included two scenarios; a static scenario where the UAV remained stationary, and a dynamic scenario where the UAV moved at speeds between 3km/h and 20km/h. The SDR-based testbed measured the RF signals transmitted by the UAV and compared the estimated direction with the actual UAV position recorded in the drone's flight data. System calibration was performed using a reference signal from a USRP B200-mini to ensure phase alignment across the four receive channels. The results showed an average error of 1.15 degrees in the static scenario and 1.86 degrees in the dynamic scenario, demonstrating the system's high accuracy. These results were competitive with existing drone direction-finding systems, highlighting the effectiveness of SDR and the MUSIC algorithm for UAV detection and direction-finding.

D. ML-BASED LOCALIZATION

This subsection focuses on localization techniques that incorporate ML methods for UAV detection and positioning. These methods leverage advanced algorithms to enhance the accuracy and efficiency of UAV localization by analyzing complex patterns and features within the data.

The system outlined in [84] capitalized on the signals shared between the UAV and its ground controller, successfully discriminating between UAV and non-UAV signals, thus enabling accurate detection even amidst environmental noise and interference. By employing SDR, this system monitored communication signals and CSI between the UAV and its controller, thereby attaining a heightened level of accuracy and adaptability crucial for combating security threats posed by UAVs. Leveraging advanced signal processing techniques, such as Empirical Mode Decomposition (EMD), Fourier Transform (FT), and STFT, the system adeptly dissected and analyzed the received wireless signals to extract essential features. Included among these features were the Signal Frequency Spectrum (SFS), Wavelet Energy Entropy (WEE), and Power Spectral Entropy (PSE), serving as distinctive markers enabling precise identification and characterization of UAV signals. Upon successful detection, spatial features, i.e., angle of azimuth and angle of elevation, were also extracted using a super-resolution estimation algorithm for UAV localization. This spatial data, coupled with multiple receiver inputs, enabled precise determination of UAV positioning within a 3-D space. The incorporation of ML algorithms, such as Support Vector Machines (SVM), random forest, and KNN, enhanced detection accuracy by discerning subtle patterns within the extracted features. The system design involved a 6-channel receiver formed by splicing three Ettus USRP X310 devices, operating at a frequency of 2.4 GHz with a sampling rate of 20 Mbit/s. Besides, the information transmission relied on a DJI Spark series UAV and OFDM signals. Experimentally, the system achieved an average detection rate of 95.58%, with median accuracies of 0.76m for 2-D positioning and 1.2m for 3-D positioning in the test environment. In Wireless Insite (WI) simulation, the median accuracies were 1.1m for 2-D positioning and 2.35m for 3-D positioning. Moreover, parameter analysis verified the system's robustness across different carrier frequencies, flight altitudes, and numbers of Receivers.

An accurate and reliable method for classifying and locating UAVs based on their RF emissions was presented in [85]. Specifically, a passive monitoring framework was presented consisting of numerous distributed receivers strategically situated across various locations, aimed at capturing RF signals emitted by UAVs during their activities. Leveraging the ubiquity of RF signals in UAV communication protocols, this framework capitalized on the inherent characteristics of these emissions to detect and classify UAVs without requiring their active cooperation or participation. The passive monitoring approach is essential for scenarios where UAVs may operate clandestinely or in non-cooperative environments, where prior knowledge or coordination with the monitoring system is not feasible. Moreover, the proposed system's detection and classification capabilities were underpinned by advanced ML techniques, particularly a CNN, tailored specifically to analyze raw RF signal data. Unlike conventional methods that rely on handcrafted features or predefined signal parameters, the CNN autonomously extracted discriminative features from the received signals, enabling robust classification of different UAV types. By training the CNN on diverse datasets encompassing various UAV signals and environmental noise, the system achieved a high classification accuracy of 88.36%, surpassing traditional ML classifiers and demonstrating its efficacy in discerning UAV signatures amidst complex RF environments. Upon successful detection and classification of a UAV signal, the system proceeded to determine the UAV's spatial coordinates using a positioning algorithm based on the Time Difference of Arrival (TDOA) technique. This process involves estimating the temporal disparities in the UAV signals received by the distributed receivers and leveraging these discrepancies to triangulate the UAV's location relative to the receiver array. The Chan algorithm [86] was employed to fuse TDOA measurements from multiple receivers and compute the UAV's precise position within the monitored area. Extensive experiments conducted in real-world wireless environments, including a campus playground, validate the system's classification and positioning capabilities, thereby affirming its practical utility and reliability. To facilitate experimentation and deployment, the system employed SDR receivers, specifically Ettus USRP X310 equipped with UBX-160 RF daughter boards, offering a wide instantaneous bandwidth of 160 MHz. Several popular drones were also chosen as targets, including Parrot, DJ Phantom, Fimi, and DJ Mavic. Synchronization among the distributed receivers was achieved through a clock source, ensuring temporal alignment of received signals essential for accurate TDOA estimation. Furthermore, the system's scalability and adaptability were underscored by its ability to accommodate additional receivers for enhanced coverage and localization accuracy, thereby catering to diverse operational scenarios and spatial requirements.

VII. LESSONS LEARNED

In this section, we summarize the key lessons learned from this paper, offering a comprehensive overview of the present state of SDR-assisted UAV-based systems.

- *SDR Deployments for Enhanced Connectivity:* The integration of SDRs in UAV-based communication systems has proven essential in addressing several critical connectivity challenges, as demonstrated by recent research. Experiments across diverse scenarios–from cellular network connectivity in rural areas to long-range VHF communication for disaster response–has demonstrated the efficacy of SDRs in extending communication ranges and ensuring robust data transmission. According to these studies, SDRs enable dynamic frequency allocation, real-time spectrum monitoring, and protocol adaptation, which are crucial for improving UAV communication across various scenarios. Previous work has also revealed that SDRs facilitate reliable BVLoS communications and extend downlink ranges through techniques such as R-DTBF. Moreover, SDRs have proven effective in enhancing long-range communication, especially in emergency and remote environments, by allowing UAVs to serve as aerial relays or establish mobile networks with lightweight, rapidly deployable setups. On the other hand, the integration of terrestrial and NTNs using frameworks such as O-RAN and HCM demonstrated the feasibility of creating adaptable and resilient networks. This approach supports rapid deployment of 5G networks and extends coverage in underserved areas, showcasing the potential for UAVs and tethered platforms to complement traditional infrastructure. Furthermore, SDR technology supports adaptive multiband waveforms and CR, which are essential for resilient UAV swarm communications and efficient disaster response. Additionally, the importance of accurate 3-D antenna pattern modeling and dynamic spectrum management has emerged as crucial factors in optimizing UAV communication links. These capabilities ensure robust performance in dynamic and challenging conditions, demonstrating the SDR's substantive role in overcoming infrastructure limitations and improving the adaptability and efficiency of UAV-based communications.

- *SDR Deployments for Channel Characterization:* The deployment of SDRs for channel characterization in UAV-based communications has been instrumental in advancing the understanding of wireless channels, guiding the design of more robust and efficient UAV-based communication systems for future applications. First, the integration of SDR technology with UAVs has proven essential for effective spectrum management, real-time channel emulation, and antenna diagnostics. For instance, UAVs equipped with SDRs, such as the Freefly ALTA X with BladeRF 2.0, facilitated the creation of accurate 3-D REMs by capturing communication signals and spectrum occupancy across varying altitudes. This highlighted the impact of altitude on signal power variations, suggesting better propagation conditions at higher altitudes due to reduced multipath effects. Second, the use of SDRs such as Ettus USRP X310in SUN allowed for realistic modeling of UAV-based channels and provided insights into the resilience of communication systems in dynamic environments. The employment of FPGA-based HITL channel emulators enabled the adaptation of channel parameters in real-time, ensuring robust communication in challenging scenarios. Third, deploying customized UAVs with advanced SDR setups, such as those used for antenna diagnostics, demonstrated the feasibility of conducting accurate near-field measurements without the need for anechoic chambers. This approach has proved beneficial for large antennas, enabling phase-coherent measurements and minimizing environmental influences. Furthermore, the characterization of non-stationary A2G channels and the exploration of U2V links in ITS environments has revealed critical insights into the impact of UAV dynamics on signal behavior. Studies utilizing SDRs for channel sounding and characterization consistently emphasized the importance of precise time synchronization, adaptive processing algorithms, and the strategic placement of antennas to enhance signal stability and quality. Lastly, the analysis of A2A communication channels underscored the significance of empirical modeling based on real-world measurements. SDR-based channel sounders provided valuable data on path loss exponents, enabling the development of realistic statistical models for A2A communications.
- *SDR Deployments for Security Applications:* Previous research revealed that SDR technology is pivotal in both strengthening and undermining security measures. On the mitigation front, innovations such as integrating Blockchain for secure UAV task coordination and advanced ML techniques for detecting jamming attacks demonstrate SDR's capacity to address complex security challenges effectively. Systems, such as BloodHound and BloodHound+, has showcased how DL and autoencoders, respectively, can significantly improve jamming detection accuracy by analyzing I/Q samples or transforming them into grayscale images for anomaly detection. Additionally, realistic channel modeling and experimental setups have highlighted SDR's role in accurately evaluating and countering GPS spoofing and jamming threats, proving its effectiveness in practical scenarios. Conversely, SDR's versatility also enables sophisticated attacks, such as GPS spoofing and jamming, which exploit UAV vulnerabilities. Notable advancements include the use of affordable SDR devices, such as HackRF One, for inducing GPS signal interference and the development of lightweight detection models to counter such spoofing attempts. The integration of SDR-based systems for detecting and neutralizing unauthorized UAV operations has illustrated their potential in safeguarding sensitive areas. Overall, while SDR technology offers robust solutions for security, it also introduces new vulnerabilities that necessitate continuous innovation and robust countermeasures to protect UAV systems from evolving threats.
- *SDR Deployments for Detection:* In the domain of UAV detection, the integration of SDR technology has proven pivotal in enhancing both detection and classification capabilities. Previous studies have pointed out several key insights into effective methodologies. In particular, combining SDR with advanced signal processing techniques, such as the use of high-speed ADCs and sophisticated

filtering mechanisms, significantly improved the system's ability to discern UAV signals amidst a noisy RF environment. In this context, SDR's flexibility in adjusting bandwidth and operational modes allows for more precise signal analysis and better handling of interference. For instance, the improved sensitivity and signal fidelity achieved through PoP algorithms has demonstrated a notable reduction in frequency deviation, underscoring SDR's role in enhancing detection accuracy. Additionally, the utilization of passive RF imaging with FPGA integration enabled real-time signal processing, which is crucial for timely UAV detection. These approaches emphasize the importance of robust signal processing and real-time analysis capabilities in enhancing detection accuracy and operational reliability.

- *SDR Deployments for Classification:* In terms of classification, the adoption of ML techniques, particularly CNNs, has substantially advanced the accuracy and efficiency of UAV classification. Previous research work has underlined the effectiveness of using signal representations, such as PSD and spectrograms, processed through CNNs to identify UAVs across various operational states. Moreover, transfer learning from large-scale image databases, such as ImageNet, has facilitated more accurate and generalized recognition, reducing the need for extensive datasets and improving classification performance. Additionally, the use of hierarchical ensemble learning frameworks further enhanced classification accuracy by integrating multiple classifiers, each focusing on specific aspects of UAV signals. This comprehensive approach, coupled with detailed preprocessing and noise reduction techniques, achieved impressive classification results with accuracy rates exceeding 99%. These findings emphasize the significant role of sophisticated ML algorithms and signal representations in achieving high levels of accuracy in UAV classification, demonstrating a shift towards more advanced and reliable methods in the field.
- *SDR Deployments for Localization:* The exploration of SDR-based localization systems has yielded numerous insights and lessons learned. The DronEnd system has indicated that utilizing SDR platforms, such as the USRP X310, alongside sophisticated AoA algorithms with coherent reception, can effectively localize UAVs by analyzing phase differences in received signals. Specifically, this system successfully detected and neutralized UAVs within a 40-meter range using RF jamming. Another approach has capitalized on monitoring communication signals between UAVs and ground controllers, employing advanced signal processing techniques and ML algorithms to enhance detection accuracy and localization, achieving a 95.58% detection rate and precise 3-D positioning. Moreover, passive monitoring frameworks have shown the ability to classify UAVs based on RF emissions without active cooperation by utilizing CNNs for feature extraction and TDOA for localization, achieving high classification accuracy and robust performance in diverse environments. Furthermore, techniques such as RFEye, which involved UAV-based signal acquisition and DoA estimation, have proved effective even in challenging conditions, obtaining high localization accuracy. Doppler-based localization has highlighted the influence of SDR frequency stability on accuracy, with improved performance observed in devices equipped with external frequency standards. Additionally, systems employing MUSIC algorithm and UCA configurations have demonstrated robust performance in both close-range and long-range scenarios, though improvements are necessary for handling signal attenuation over distance. Lastly, the combination of AoA with RSSI methods in UAV-based ground transmitter localization has revealed that AoA techniques offer superior accuracy, albeit with increased computational complexity. Overall, these systems have pointed out the critical role of advanced signal processing and ML in enhancing system performance and accuracy.

VIII. FUTURE RESEARCH DIRECTIONS

The paradigm of SDR-assisted UAV-based systems confronts a spectrum of challenges and critical impediments, as shown in Fig. 9. Therefore, several avenues for future research and development in this field can be identified as follows:

- *Communication Aspects:*
- *Hardware Optimization and Energy Consumption:* Looking forward, research efforts should concentrate on optimizing hardware and developing energy-efficient hardware architectures, particularly focusing on SDR architectures and FPGA models tailored specifically for UAV applications. This involves adopting low-power design techniques and incorporating energy-harvesting components to prolong operational life. Future research directions may involve optimizing internal parameters, such as dynamically adjusting processing power based on real-time signal requirements, thus enhancing resource efficiency and conserving energy. Implementing advanced hardware and accelerators can significantly improve specific signal processing tasks and minimize processing latency, offering a balance between performance and power consumption. Furthermore, expanding the capabilities of FPGAs for broader data pre-processing through techniques, such as pre-filtering and data compression, can reduce the load on subsequent processing stages and minimize overall energy use.
- *Algorithmic Techniques and Signal Processing:* Advancements in this field should prioritize refining algorithmic techniques, such as using adaptive filtering algorithms, to substantially enhance signal clarity and processing efficiency. Exploring ML and DL approaches, for instance, implementing CNNs for pattern recognition, opens new avenues for processing complex signals. Additionally, enhancing robustness under

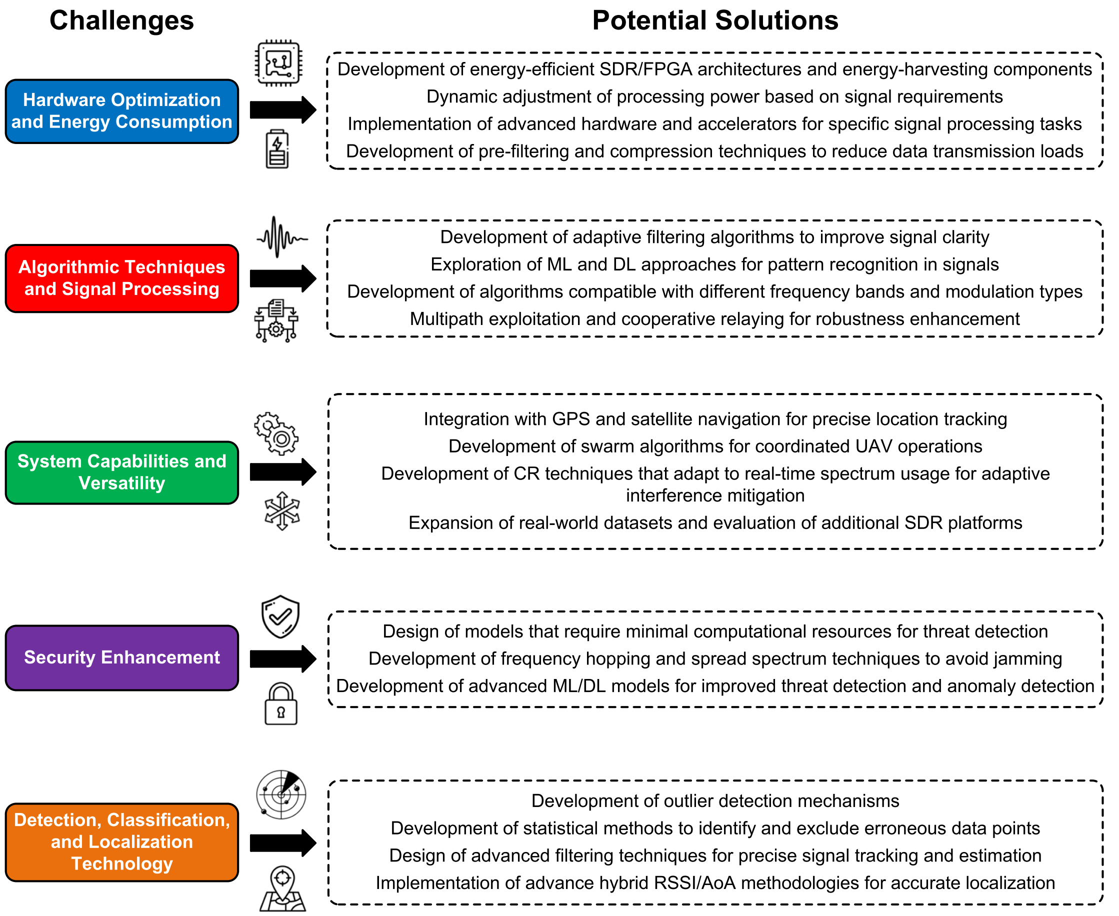

FIGURE 9. **Challenges of SDR-assisted UAV-based systems and corresponding solutions to overcome these challenges.**

NLoS conditions through techniques, such as multipath exploitation and cooperative relaying, can improve the reliability and performance of UAV communication systems in challenging environments. Extending the applicability of these algorithms to various RF signals ensures compatibility with different frequency bands and modulation types, broadening their utility.

- *System Capabilities and Versatility:* Future research endeavors may focus on strengthen the capabilities of SDR-assisted UAV-based systems to address evolving challenges and ensure effectiveness across diverse operational scenarios. This includes advancements in 3-D positioning by integrating GPS and other satellite navigation systems, allowing for precise location tracking. For applications requiring coordinated efforts, developing swarm algorithms for multi-UAV tracking ensures efficient and synchronized operations. Moreover, adaptive interference mitigation, through CR techniques that adjust to real-time spectrum usage, helps maintain robust communication in dynamic environments. Moreover, expanding datasets and evaluating additional SDRs by collecting extensive real-world data and testing across multiple platforms provide comprehensive insights and validate system performance under various conditions.
- *Security Enhancements:* Security remains a critical concern in SDR-assisted UAV systems, necessitating enhancements in threat detection and mitigation. Developing lightweight detection models that require minimal computational resources ensures that threat detection can be performed without significantly impacting system performance. Moreover, research efforts should focus on Refining jamming and anti-jamming techniques, such as using frequency hopping and spread spectrum methods, which can effectively prevent and counteract jamming attacks. Further research avenues also involve the development of advanced ML and DL models for improved threat detection and reduced false alarm rates in complex RF environments. This includes exploring anomaly detection through unsupervised learning methods. These advanced models can significantly enhance the system's ability to identify and respond to security threats in real-time, thereby safeguarding the UAV and its operations.
- *Detection, Classification, and Localization Technology:* Future research endeavors in UAV detection, classification, and localization technology are poised to expand system capabilities to address evolving challenges and ensure efficacy in diverse operational scenarios. Efforts are directed towards fortifying UAV detection systems

against rogue UAVs through outlier detection mechanisms, such as statistical methods to identify and exclude erroneous data points, thus ensuring airspace integrity. In addition, promising avenues for exploration include the expansion of FPGA capabilities for broader data preprocessing and offloading software algorithms to minimize detection latency. Future research is expected to concentrate on refining algorithmic techniques for signal processing and exploring innovative approaches (e.g., ML and DL), to enhance system performance and versatility for signal classification tasks. Further advancements involve the development of advanced filtering techniques, such as Kalman filters, to achieve precise signal tracking and estimation, crucial for accurate navigation and positioning. Finally, identified limitations of UAV-enabled localization technologies can be addressed by advancing hybrid RSSI/AoA methodologies, which offer enhanced localization accuracy, particularly for applications requiring precise geolocation and tracking of UAVs and their targets.

IX. CONCLUSION

In this paper, a wide range of research works has been reviewed that utilized SDR platforms, predominantly FPGA-integrated ones, in UAV-based systems. Based on previous work, this paper has underlined the significance of accurate simulation frameworks and flexible platforms in optimizing performance. Furthermore, this paper has highlighted that addressing challenges, such as developing accurate 3-D radio environment maps and investigating large-scale channel propagation statistics, contributes to laying the groundwork for robust communication systems. Based on works on A2G cellular network coverage, beamforming techniques, and channel characterization, this paper has also emphasized the importance of understanding propagation features. Additionally, this paper has indicated that the establishment of resilient UAV swarms and the use of CR to tackle spectrum limitations constitute significant efforts aimed at bolstering network flexibility and adaptability.

In the context of security, the scalability, real-time response capabilities, and cost-effectiveness of SDR-based solutions has made them indispensable tools for safeguarding airspace, critical infrastructure, and public safety. This paper has indicated that the integration of SDR platforms into UAV operations enables the generation and transmission of jamming signals, as well as the simulation of GPS signals to induce location errors, addressing challenges posed by rogue UAV activities. Additionally, this paper has mentioned that SDRs can efficiently capture and analyze RF signals amidst interference, thus ensuring robust signal integrity and communication resilience. This paper has also underlined that leveraging ML techniques improves the detection of GPS spoofing and jamming attacks, bolstering UAV security in critical operations and adverse conditions. As discussed in this paper, innovative lightweight detection models, such as those utilizing LSTM networks, offer promising solutions by effectively identifying GPS spoofing attacks, ensuring the security and reliability of UAV operations. Moreover, this paper underlined that intelligent IDS, integrated with SDR platforms, can enhance UAV defensive capabilities by detecting and mitigating attacks. Through the utilization of Blockchain technology, SDR, and UAVs, signal source identification systems promise accurate discernment of signaling objects in cluttered environments while ensuring stringent security and privacy protocols. In conclusion, addressing security challenges posed by the convergence of UAVs and SDR technology requires a multifaceted approach.

On another front, this paper has pointed out the effectiveness of SDR-equipped UAV-based systems in detecting and distinguishing between different types of UAVs based on their RF emissions and flight characteristics. The utilization of advanced signal processing techniques facilitated by SDR, coupled with the integration of ML algorithms, has further enhanced the accuracy and reliability of UAV detection and classification but also enabled precise localization in both 2-D and 3-D spaces. As evidenced by experimental validations across diverse scenarios, including congested RF spectrum environments and dynamic aerial conditions, SDR-enabled systems offer unparalleled performance and reliability in UAV detection and classification, thus ensuring safer and more secure integration of UAVs into modern society. Finally, the integration of SDR platforms for Doppler frequency-based localization, particularly in UAVs for EW applications, has shown promising results.

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