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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 SDR equipment enable UAVs to incorporate SDR 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].

On the other hand, the proliferation of UAVs has led to the rise of cybersecurity concerns [7] and created substantial risks to public safety, necessitating the development of effective countermeasures against possible attacks. It should be noted that Air-to-Ground (A2G) communication links are typically public and vulnerable to a wide range of attacks (e.g., man-in-the-middle attacks, eavesdropping, jamming), whereas Air-to-Air (A2A) communication links are similar to Peer-to-Peer (P2P) connections, which makes them susceptible to P2P attacks, including sybil attacks and Distributed Denial of Service (D-DoS) attacks. Additionally, incidents involving UAVs, ranging from unauthorized flights to malicious use by terrorist organizations, highlight the complex challenges associated with UAV deployment. Consequently, efficient countermeasures should be developed to safeguard the public from potential threats.

To achieve this objective, leveraging SDR technology within UAV-based systems can provide an efficient approach for strengthening defense mechanisms against attacks [8], along with improving UAV detection, classification, and localization capabilities [9]. This entails implementing appropriate response measures and discerning between various types of UAVs based on their Radio Frequency (RF) emissions, flight characteristics, and other parameters, essential for identifying unauthorized or potentially malicious UAVs. In this direction, the benefits of SDR include versatility, real-time response capabilities, seamless integration with existing systems, and cost-effectiveness, making it a valuable tool for various applications, such as border security, critical infrastructure protection, and event security. Moreover, advanced signal processing techniques enabled by SDR, such as waveform analysis, modulation recognition, and signal demodulation, facilitate the extraction of relevant information from received signals, aiding in the identification, classification, and localization of UAVs based on their communication protocols and transmission characteristics.

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. The application domains identified in this paper were derived from an extensive review of the current literature. For each application domain, the role of SDR is emphasized, and the anticipated outcomes are discussed.
- 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.

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. Finally, Section VII concludes this paper and outlines prospects for future research.

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 I. The latest advancements in UAV-based communications technologies and their applications were presented in [10] and several topics were covered, including antennas, network architectures, path 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. Fur-
thermore, a Swarm UAVs (SUAVs) architecture and solutions for accurate localization, communication, and coordination were investigated in [11], without specifically highlighting SDR-based techniques. In [12], 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 [13], 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 [14]. 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 [15], 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 [16] 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 [9], 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

The term UAV encompasses rapidly deployed Low-Altitude Platform (LAP) or airborne vehicle that acts as an aerial transceiver, operating at modest altitudes within the troposphere to support various missions and short-term operations [17]. 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 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 [13].

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.1, 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) [12]. 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
TABLE 1. Relevant review and survey papers.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Short Description</th>
<th>UAV</th>
<th>SDR</th>
<th>Communication</th>
<th>Security</th>
<th>Detection</th>
<th>Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>[6]</td>
<td>2021</td>
<td>Overviews of CR technology for enhancing communication in UAVs</td>
<td>✓</td>
<td>✓</td>
<td>Partially</td>
<td>Partially</td>
<td>✓</td>
<td>❌</td>
</tr>
<tr>
<td>[7]</td>
<td>2023</td>
<td>Survey of security and privacy issues in UAVs, classified into four levels: hardware, software, communication, and sensor</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[9]</td>
<td>2022</td>
<td>Survey of UAV detection and defense systems</td>
<td>✓</td>
<td>✓</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[10]</td>
<td>2020</td>
<td>Survey of latest UAV communication technologies, including task modules, antennas, and network architectures</td>
<td>✓</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>Partially</td>
<td>❌</td>
</tr>
<tr>
<td>[11]</td>
<td>2022</td>
<td>Analysis of the fundamental requirements for accurate localization in SUAVs, review of existing localization techniques</td>
<td>✓</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[12]</td>
<td>2022</td>
<td>Review of recent trends and challenges in UAV detection and localization methods</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
<td>Partially</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[14]</td>
<td>2023</td>
<td>Review of SDN-enabled UAV systems, focusing on enhanced connectivity and scalability while addressing management and security issues</td>
<td>✓</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>[15]</td>
<td>2022</td>
<td>Overview of GPP-based SDR platforms suitable for various wireless standards</td>
<td>❌</td>
<td>✓</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>[16]</td>
<td>2018</td>
<td>Survey of measurement methods proposed for UAV channel modeling and characterization</td>
<td>✓</td>
<td>Partially</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>This paper</td>
<td>2024</td>
<td>Review of SDR implementations in UAV-driven applications across various domains</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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 [17]. 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.

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.
In particular, UA Vs 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 four primary types of communication: A2G communication, A2A communication, Air-to-Space/Satellite (A2S) communication, and hybrid communication integrating the functionalities of the aforementioned types [7]. As far as A2G communication is concerned, UA Vs 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.

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 [18):

- **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.

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 [19]. In deployments of the Internet of Drones (IoD) paradigm [20], 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.

**B. OVERVIEW 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 [21]. 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) [22], 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) [23], 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.

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 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 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 40MHz bandwidth (depending on the tasks and setup), the advent of Fifth Generation (5G) with increased bandwidth 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.

Fig.2 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), 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.

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 Universal Serial Bus (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. Table 2 provides a comparative assessment of the features of the SDR devices utilized in the research works reviewed in this paper. 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.

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. In recent 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 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. Additionally, SDR technology enables the implementation of advanced signal processing (e.g., adaptive beamforming, noise cancellation, and signal enhancement algorithms), which further improve signal quality, range, and coverage. 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.
### TABLE 2. Main technical specifications of various SDR devices.

<table>
<thead>
<tr>
<th>SDR Device</th>
<th>FPGA</th>
<th>Frequency Range</th>
<th>Sample Rate</th>
<th>RF Bandwidth</th>
<th>Other Features</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADALM PLUTO</td>
<td>Xilinx Zynq Z-7010</td>
<td>325 MHz to 3.8 GHz</td>
<td>Up to 61.44 mega samples per second (MSPS)</td>
<td>Up to 20 MHz</td>
<td>Full duplex, SISO</td>
<td>USB 2.0</td>
</tr>
<tr>
<td>BladeRF 2.0</td>
<td>Altera Cyclone V</td>
<td>47 MHz to 6 GHz</td>
<td>Up to 61.44 MSPS</td>
<td>Up to 56 MHz</td>
<td>Full duplex, MIMO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>BladeRF 2.0</td>
<td>Altera Cyclone V</td>
<td>47 MHz to 6 GHz</td>
<td>Up to 61.44 MSPS</td>
<td>Up to 56 MHz</td>
<td>Full duplex, MIMO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>BladeRF x40</td>
<td>Altera Cyclone IV</td>
<td>300 MHz to 3.8 GHz</td>
<td>Up to 40 MSPS</td>
<td>Up to 28 MHz</td>
<td>Full duplex, SISO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>Ettus USRP B20xmini</td>
<td>Xilinx Spartan-6</td>
<td>70 MHz to 6 GHz</td>
<td>Up to 56 MSPS</td>
<td>Up to 56 MHz</td>
<td>Full duplex, SISO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>Ettus USRP B210</td>
<td>Xilinx Spartan-6</td>
<td>70 MHz to 6 GHz</td>
<td>Up to 56 MSPS</td>
<td>Up to 56 MHz</td>
<td>Full duplex, MIMO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>Ettus USRP E312</td>
<td>Xilinx Zynq 7020</td>
<td>70 MHz to 6 GHz</td>
<td>Up to 61.44 MSPS</td>
<td>Up to 56 MHz</td>
<td>Half duplex, MIMO</td>
<td>Gigabit Ethernet and 2 host USB 2.0 ports</td>
</tr>
<tr>
<td>Ettus USRP E320</td>
<td>Xilinx Zynq-7045 (Dual-core ARM Cortex and 7 Series FPGA)</td>
<td>70 MHz to 6 GHz</td>
<td>Up to 61.44 MSPS</td>
<td>Up to 56 MHz</td>
<td>Full/half duplex, MIMO</td>
<td>SFP+ port (1/10 Gigabit Ethernet, Aurora), RJ45 port (1 Gigabit Ethernet), Type A USB 2.0, Micro-USB</td>
</tr>
<tr>
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<td>10 MHz to 6 GHz</td>
<td>Up to 100 MSPS</td>
<td>Up to 20 MHz</td>
<td>Full/half duplex, MIMO</td>
<td>Gigabit Ethernet</td>
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<tr>
<td>Ettus USRP X3xx</td>
<td>Xilinx Kintex-7 Direct current (DC) to 6 GHz</td>
<td>200 MHz to 160 MHz</td>
<td>Full duplex, MIMO</td>
<td>Gigabit Ethernet, Peripheral Component Interconnect Express (PCIe)</td>
<td></td>
<td></td>
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<td>HackRF One</td>
<td>-</td>
<td>1 MHz to 6 GHz</td>
<td>Up to 20 MSPS</td>
<td>Up to 20 MHz</td>
<td>Half duplex, SISO</td>
<td>USB 2.0</td>
</tr>
<tr>
<td>LimeSDR</td>
<td>Altera Cyclone IV</td>
<td>100 kHz to 3.8 GHz</td>
<td>Up to 61.44 MSPS</td>
<td>Up to 30.72 MHz</td>
<td>Full duplex, MIMO</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>NI 5791R</td>
<td>Xilinx Kintex7-410T</td>
<td>200 MHz to 4.4 GHz</td>
<td>Up to 130 MSPS</td>
<td>Up to 100 MHz</td>
<td>Full duplex, SISO</td>
<td>PXIe</td>
</tr>
<tr>
<td>NI USRP 2930</td>
<td>Xilinx Kintex7-410T</td>
<td>50 MHz to 2.2 GHz</td>
<td>Up to 200 MSPS</td>
<td>Up to 120 MHz</td>
<td>Full duplex, MIMO</td>
<td>Gigabit Ethernet</td>
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<tr>
<td>NI USRP 2942R</td>
<td>Xilinx Kintex7-410T</td>
<td>400 MHz to 4.4 GHz</td>
<td>Up to 200 MSPS</td>
<td>Up to 120 MHz</td>
<td>Full duplex, MIMO</td>
<td>PCIe</td>
</tr>
<tr>
<td>NI USRP 2943R (2943R)</td>
<td>Xilinx Kintex7-410T</td>
<td>1.2 GHz to 6 GHz</td>
<td>Up to 200 MSPS</td>
<td>Up to 120 MHz</td>
<td>Full duplex, MIMO</td>
<td>Gigabit Ethernet</td>
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<td>Xilinx Kintex7-410T</td>
<td>50 MHz to 2.2 GHz</td>
<td>Up to 200 MSPS</td>
<td>Up to 120 MHz</td>
<td>Full duplex, MIMO</td>
<td>Gigabit Ethernet</td>
</tr>
<tr>
<td>NI USRP 2954R</td>
<td>Xilinx Kintex7-410T</td>
<td>10 MHz to 6 GHz</td>
<td>Up to 200 MSPS</td>
<td>Up to 160 MHz</td>
<td>Full duplex, MIMO</td>
<td>Gigabit Ethernet</td>
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<tr>
<td>RTL-SDR</td>
<td>-</td>
<td>24 MHz to 1766 MHz</td>
<td>Up to 3.2 MSPS</td>
<td>Up to 3.2 MHz</td>
<td>Half duplex, SISO</td>
<td>USB 2.0</td>
</tr>
</tbody>
</table>
FIGURE 3. Application domains of SDR-assisted UAV-based systems, encompassing communication (enhanced connectivity and channel characterization), security, detection, classification, and localization.

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.3 depicts the application domains of SDR-assisted UAV-based systems, which are thoroughly examined in the subsequent sections of this paper.

IV. SDR DEPLOYMENTS FOR COMMUNICATION APPLICATIONS

Communication stands as a cornerstone in the efficacy of UAV-based systems, spanning applications from surveillance and monitoring to disaster response and delivery services. Moreover, a pivotal challenge in UAV-based communications lies in comprehending and characterizing the wireless channels facilitating data transmission. This section investigates recent research works that address communication challenges by implementing SDR schemes. 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.4.

A. SDR DEPLOYMENTS FOR ENHANCED CONNECTIVITY

In [24], 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 were conducted in a rural environment, characterized by minimal interference, providing a clear LoS between UAV and BS. A Long-Term Evolution (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) [25]. The RF front-end featured a high linearity PA with a gain of 30-45 dB to ensure reliable communications over distances up to 1 km, 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 [26] 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 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 [25] 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 In-phase and Quadrature (I/Q) samples were collected and post-processed. Then, the impact of three different 3D 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 [27] 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 [25] 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.

The research discussed in [28] focused on leveraging the Very High Frequency (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 160.4 MHz, 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 5W with a digital wideband waveform. To estimate PLE values and evaluate the performance of the communication link, the measured signal powers were compared against the 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 [29] dealt with the extension of the downlink range through the implementation of Retrodirective Distributed Transmit Beamforming (R-DTBF) and intranetwork communication protocols using Gold codes for synchronization and calibration, all facilitated by a group of collaborating UAVs. This approach aimed to enhance communication Signal-to-Noise Ratio (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 [30], terrestrial and non-terrestrial networks (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 [31]) 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 User Equipment (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 parameters like energy efficiency, throughput, and flight trajectories.

In [32], a sophisticated communication architecture, named UAVs Swarm Communications leveraging Cognitive Radio 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) [33] 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 were 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 [34] 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 [35], 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 [34], 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 2600 kb/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. The summary of the aforementioned works is presented in Table 3.

B. SDR DEPLOYMENTS FOR CHANNEL CHARACTERIZATION

The work in [36] concentrated on the role of UAVs in spectrum management within dense networks and the challenge of developing and maintaining accurate three-dimensional (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 (2.4 GHz), 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 2.427 GHz, 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 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 [37] 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 [35], 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 multicopter 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 µs, translating to an equivalent over-the-air distance of approximately 1 km. 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.

The work outlined in [39] 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 Path Loss Exponent (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-
TABLE 3. Synopsis of recent research works on SDR deployments for enhanced connectivity.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Type of UAVs</th>
<th>Type of SDR</th>
<th>Role of SDR</th>
<th>Key Technologies</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2022</td>
<td>DJI Matrice 600</td>
<td>USRP B205mini-i</td>
<td>Radio prototyping, data acquisition and generation, signal measurement</td>
<td>3GPP standard-compliant system, modular and flexible RF front-end, srsRAN, Open5GS, AERPAW</td>
<td>Implementation of a communications testbed for research on cellular network-connected UAVs</td>
</tr>
<tr>
<td>26</td>
<td>2023</td>
<td>Customized hexacopter UAV</td>
<td>Ettus USRP B205mini</td>
<td>Collection and analysis of LTE signals transmitted by a BS</td>
<td>AERPAW Experimentation Platform, GPS, srsRAN, LTE signal processing algorithms, 3-D antenna pattern modeling</td>
<td>Reliable and seamless connectivity for cellular-connected UAVs operating in rural environments, particularly enabling BVLoS communications</td>
</tr>
<tr>
<td>27</td>
<td>2023</td>
<td>Programmable UAV</td>
<td>Ettus USRP B205mini</td>
<td>Collection, processing, and integration of raw I/Q samples</td>
<td>AERPAW Experimentation Platform, GPS, srsRAN, MATLAB LTE Toolbox</td>
<td>A2G cellular network coverage analysis for UAV-based communications at different altitudes</td>
</tr>
<tr>
<td>28</td>
<td>2023</td>
<td>DJI Matrice 200</td>
<td>RTL-SDR</td>
<td>Signal measurement and data collection</td>
<td>Digital VHF handsets and GPS</td>
<td>Long-range VHF UAV-based communication, particularly aimed at emergency communication scenarios</td>
</tr>
<tr>
<td>29</td>
<td>2024</td>
<td>DJI Matrice 100</td>
<td>Ettus USRP B210</td>
<td>Generation transmission, reception, and collection of signal data</td>
<td>R-DTBF, Gold codes for simultaneous synchronization and calibration, statistical channel models, GNU Radio toolkit</td>
<td>Swift and reliable communication in scenarios requiring rapid UAV deployment without infrastructure support</td>
</tr>
<tr>
<td>30</td>
<td>2024</td>
<td>Lightweight drones and tethered Helikite</td>
<td>USRP-X300 (Helikite), Ettus USRP B205mini (drone)</td>
<td>Implementation and operation of the 5G network testbed</td>
<td>O-RAN, RIC, VNFs, and ML</td>
<td>Rapidly deployable mobile networks to support connectivity in underserved and remote areas</td>
</tr>
<tr>
<td>32</td>
<td>2021</td>
<td>Emulated UAVs</td>
<td>Emulated SDR</td>
<td>Monitoring, allocating, and managing spectrum usage within the CR framework</td>
<td>CR and TDMA</td>
<td>Coordinated operations of multiple UAVs (i.e., surveillance and monitoring missions), under the management of a GCS</td>
</tr>
<tr>
<td>34</td>
<td>2022</td>
<td>Emulated UAVs</td>
<td>Emulated SDR</td>
<td>Provision of adaptive multiband waveforms, support of HCM</td>
<td>CR and HCM</td>
<td>Robust communication for surveillance purposes using UAV swarms over diverse terrains</td>
</tr>
<tr>
<td>35</td>
<td>2024</td>
<td>Emulated UAVs</td>
<td>Emulated SDR</td>
<td>Interoperability, support of HCM</td>
<td>HCM</td>
<td>Autonomous multi-hop communication for disaster response utilizing a MAC-centric cross-layer protocol</td>
</tr>
</tbody>
</table>

Based statistical model of A2A channels, offering a realistic representation of these channels. To ensure reliability in a controlled Free-Space Path Loss (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.

The work in [40] 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 involving 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.

In [41], a UAV-to-Vehicle (U2V) channel measurement campaign was conducted to analyze the communication link characteristics within Intelligent Transportation Systems (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 [42], the authors of [41] 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 5.9 GHz. 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 underside 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.

The use of CSI for Massive MIMO (MaMIMO) UAV-based systems was investigated in [43]. 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 RMS delay spreads averaged around 500 ns across different trajectories, indicating significant multipath effects in such environments. Spectral efficiency was notably impacted by the presence of LoS, Line-of-Sight (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.

A comprehensive experimental study on PL modeling for Single-Input Multiple-Output (SIMO) UAV-based communications in a suburban setting was presented in [44]. This work investigated the effects of various altitudes and LoS conditions using a UAV-mounted platform and a ground-based station setup. Similar to [43], the aerial node was a DJI Inspire 2 UAV equipped with an Ettus E320 USRP transmitting 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 was flown 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 [45], 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

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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. A summary of the works discussed above is provided in Table 4.

V. REVIEW OF SDR DEPLOYMENTS FOR SECURITY APPLICATIONS

Although the convergence of UAVs and SDR technology yields numerous advantages, it also introduces security challenges owing to the inherent vulnerabilities within both technologies. These challenges encompass a range of threats, including cyber-physical attacks, signal interception, unauthorized access, and data manipulation, all posing risks to the confidentiality, integrity, and availability of UAVs’ operations. Moreover, spectrum management becomes critical as SDR-enabled UAVs traverse various frequency spectrums. This may expose them to interference and potential jamming, underscoring the need for constant monitoring and effective management mechanisms to preserve uninterrupted operation. Thus, it is imperative to implement effective countermeasures to mitigate security risks. This section examines pertinent SDR-based security schemes for UAV-based systems proposed in prior research works. In conjunction with SDR, these works employed a wide range of technologies to confront security challenges and counter threats in intricate and dynamic environments, as shown in Fig. 5.

In [46], a signal source identification system was proposed, 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 [47], 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-
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Type of UAVs</th>
<th>Type of SDR</th>
<th>Role of SDR</th>
<th>Key Technologies</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>2022</td>
<td>Freefly ALTA X, DJI Matrice 600 Pro, DJI Inspire 2, DJI Mavic 2 Enterprise Dual</td>
<td>BladeRF 2.0</td>
<td>Signal measurement and data collection</td>
<td>Spectrum sensors, wideband signal processing, GNU Radio toolkit</td>
<td>Measurement of communication signals and spectrum occupancy, highlighting signal power variations across different altitudes</td>
</tr>
<tr>
<td>37</td>
<td>2023</td>
<td>Multirotor UAV, VTOL hybrid UAV</td>
<td>Ettus USRP X310</td>
<td>HITL channel emulator</td>
<td>PX4 flight controller, Gazebo physical world simulation, FPGA-based HITL channel emulator</td>
<td>Modeling of real-world UAV-based channels and assessment of communication system resilience in dynamic environments</td>
</tr>
<tr>
<td>39</td>
<td>2022</td>
<td>DJI Matrice 600 Pro</td>
<td>BladeRF 2.0 micro xA9</td>
<td>Channel sounding and characterization</td>
<td>Sweeping chirp signals, ensemble averaging and STFT for signal processing</td>
<td>Empirical modeling of A2A channels</td>
</tr>
<tr>
<td>40</td>
<td>2023</td>
<td>Customized hexacopter UAV</td>
<td>Customized SDR (aerial transmitter) and NI PXIe digitizer with PXIe-1085 chassis, 8135 controller, 7976 FPGA module, and 5791 RF adapter (ground receiver)</td>
<td>Channel sounding and channel characterization</td>
<td>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</td>
<td>Characterization of non-stationary A2G communication channels, including PL, K-factor, and path angle analysis during different UAV flight phases</td>
</tr>
<tr>
<td>41</td>
<td>2024</td>
<td>DJI M600 Pro</td>
<td>Ettus USRP E312 (transmitter) and Ettus USRP X310 (receiver)</td>
<td>Channel sounding and channel characterization</td>
<td>RTK receivers and GNSS receivers</td>
<td>Analysis of large-scale and small-scale fading characteristics of U2V channels in ITS environments</td>
</tr>
<tr>
<td>42</td>
<td>2024</td>
<td>DJI M600 Pro</td>
<td>Ettus USRP E312 (transmitter) and Ettus USRP X310 (receiver)</td>
<td>Channel sounding and channel characterization</td>
<td>RTK receivers and GNSS receivers</td>
<td>Multi-link channel modeling of U2V communications in ITS environments</td>
</tr>
<tr>
<td>43</td>
<td>2023</td>
<td>DJI Inspire 2</td>
<td>Ettus USRP 320 (UAV), 32 NI USRP 2942R (BS)</td>
<td>Collection of I/Q samples and CSI measurements</td>
<td>MaMIMO, URA, MRC, OFDM, GPSDO clocks</td>
<td>Characterization and analysis of the A2G communication channel for MaMIMO-supported UAV-based communications</td>
</tr>
<tr>
<td>44</td>
<td>2024</td>
<td>DJI Inspire 2</td>
<td>Ettus USRP 320 (UAV), 32 NI USRP 2942R (BS)</td>
<td>Collection of I/Q samples and PL measurements</td>
<td>URA, OFDM, GPSDO clocks</td>
<td>Large scale fading analysis of the A2G SIMO channel in a suburban environment</td>
</tr>
<tr>
<td>45</td>
<td>2022</td>
<td>Custom multirotor UAV</td>
<td>LimeSDR</td>
<td>Dual-channel receiver and signal source</td>
<td>Dual-polarized probe antenna, RFoF, laser-based VR tracking system, and IESS</td>
<td>Accurate near-field measurements and conversion of these measurements into far-field patterns</td>
</tr>
</tbody>
</table>

Fi access point. 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.

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, this 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 SDR simulator tools, attackers generate forged GPS signals that closely mimic authentic transmissions, including satellite identification codes, signal strength, and timing information. In response to this pressing security concern, the work in [48] 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.

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 [49], 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 tool 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.

The work in [50] 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 are 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.

In [51], a comprehensive approach was introduced that utilized ML techniques to effectively detect and classify jamming attacks targeted at Orthogonal Frequency Division Multiplexing (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 Deep Learning (DL) techniques, specifically Convolutional Neural Networks (CNNs). The performance of these models was 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 in [52] 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 [53] 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 Physical Layer (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 navigation signals, effectively neutralizing the capacity for autonomous UAV operation.

A comprehensive approach to safeguarding areas against unauthorized UAV intrusions was presented in [54]. 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 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 simulator [55] for generating and transmitting...
TABLE 5. Synopsis of recent research works on SDR deployments for security applications.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Type of UAVs</th>
<th>Type of SDR</th>
<th>Role of SDR</th>
<th>Key Technologies</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>2022</td>
<td>Hexacopter</td>
<td>HackRF One</td>
<td>Measurement of power data</td>
<td>Blockchain technology, asymmetric key cryptography, ring signature, and maximum likelihood estimation method for signal parameter estimation</td>
<td>Signal source identification</td>
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<td></td>
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<td>Tarot</td>
<td>(UA V)</td>
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<td>Etus USRP</td>
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<td>B210</td>
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<td></td>
<td></td>
<td>(Ground System)</td>
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<tr>
<td>48</td>
<td>2023</td>
<td>Small UAVs</td>
<td>BladeRF 2.0 and HackRF One</td>
<td>Generation of forged GPS signals</td>
<td>GPS, LSTM networks, and knowledge distillation techniques</td>
<td>Detection and prevention of GPS spoofing attacks</td>
</tr>
<tr>
<td>49</td>
<td>2022</td>
<td>Holybro S500</td>
<td>HackRF One</td>
<td>Generation and transmission of forged GPS signals and jamming signals</td>
<td>PCA, one-class classifiers, ML, GPS-SDR-SIM tool, GNU Radio Companion</td>
<td>Development of an IDS to detect and mitigate GPS spoofing and jamming attacks</td>
</tr>
<tr>
<td>50</td>
<td>2024</td>
<td>3DR IRIS+,</td>
<td>HackRF One</td>
<td>Generation and transmission of artificial signals</td>
<td>GNSS, TCXO, synthetic signal generation, GPS receiver analysis</td>
<td>Assessing the impact of spoofing and jamming threats</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tarot 650 v2.2, DJI INSPIRE, and SKY HUNTER</td>
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<tr>
<td>51</td>
<td>2022</td>
<td>Holy Stone HS720E</td>
<td>Etus USRP B210</td>
<td>Generation of realistic jamming attacks</td>
<td>ML, OFDM, radiometric features, CNNs</td>
<td>Detection and classification of jamming attacks</td>
</tr>
<tr>
<td>52</td>
<td>2020</td>
<td>Hornet mini-UAV</td>
<td>BladeRF x40</td>
<td>Transmission of forged GPS signals</td>
<td>GPS, LIDAR, accelerometers, magnetometers, NMEA messages</td>
<td>Implementation of a mobile spoofing system to induce location errors in targeted GPS receivers</td>
</tr>
<tr>
<td>53</td>
<td>2020</td>
<td>DJI Spark and Parrot Bebop 2 FPV</td>
<td>BladeRF x40</td>
<td>Generation of interfering signals</td>
<td>Spectral interference techniques, GNU Radio toolkit</td>
<td>Countering unauthorized UAV operations by implementing jamming techniques to disrupt GPS navigation systems crucial for UAV autonomy</td>
</tr>
<tr>
<td>54</td>
<td>2022</td>
<td>DJI Phantom 3 Standard</td>
<td>BladeRF x40</td>
<td>Generation of GPS spoofing signals</td>
<td>Biometric authentication, GPS signal disruption, GNU Radio, GPS-SDR-SIM simulator</td>
<td>Jamming and spoofing GPS signals, safeguarding critical infrastructure against unauthorized UAV intrusions</td>
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</tbody>
</table>

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. Table 5 summarizes the aforementioned works.

VI. REVIEW OF SDR DEPLOYMENTS FOR DETECTION, CLASSIFICATION, AND LOCALIZATION

As previously discussed, the rapid expansion of the UAV industry has surpassed regulatory frameworks for safe and lawful drone operations, resulting in their association with illegal and potentially harmful activities. Therefore, the development of highly accurate detection and localization systems is of utmost importance. This section provides an overview of recent research endeavors in this area. Fig. 6 presents 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.

In [56], 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 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 1 dB and direct conversion mixers, the SDR ensured optimal
FIGURE 6. Technologies that enable advanced functionalities in SDR-assisted UAV-based operations, improving detection, classification, and localization capabilities in diverse environments.

Key Enablers for Enhanced Detection, Classification, and Localization

- **Signal Processing**
  - PoP Algorithm
  - FFT

- **Machine Learning and Deep Learning**
  - CNN
  - SVM
  - KNN

- **Hardware Components**
  - FPGAs
  - Multiple SDRs
  - Advanced Antenna Arrays

- **Localization Techniques**
  - TDOA Technique
  - AoA Estimation

- **RF Analysis and Imaging**
  - Spectrogram
  - Histogram
  - PSD

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 103 ppm to 61.2 ppm 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 [57], 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 [58], 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.

In [59], 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 [60] utilized passive RF imaging techniques for drone detection and SDR technology with a continuous operational frequency range of 2.400 GHz to 2.483 GHz, 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-USB, 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 9 dB 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.

By harnessing SDR, ML techniques, and RF data analysis, the work in [61] 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%.

In [62], 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 [63] and 3EED with an adaptive threshold [64], 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.

The system outlined in [65] 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 0.76 m for 2-D positioning and 1.2 m for 3-D positioning in the test environment. In Wireless Insite (WI) simulation, the median accuracies were 1.1 m for 2-D positioning and 2.35 m 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 [66]. 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 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 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 20MHz 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, 0.78 m, 2.45 m in x, y, z directions respectively, at 30 dB 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 1.5 m at 80 m altitude.

The work in 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
The system achieved successful drone localization with an average error of 18.65°, leveraging the known operating frequency (2.46 GHz) of the drone’s communication link. Comparison with a professional direction-finding solution (Narda ADFA) confirmed the system’s accuracy.

In [71], 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 [72], 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 summary of the works discussed above is presented in Table 6.

VII. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

A. CONCLUSIONS

In this paper, a wide range of research works has been reviewed that utilized SDR platforms, predominantly FPGA-integrated ones, in UAV-based systems. Throughout this
### TABLE 6. Synopsis of recent research works on SDR deployments for detection, classification, and localization.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Type of UAVs</th>
<th>Type of SDR</th>
<th>Role of SDR</th>
<th>Key Technologies</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>2024</td>
<td>DJI Phantom 4 Pro v1.0 and DJI Phantom 4 Pro v2.0</td>
<td>ADALM-PLUTO</td>
<td>Capturing, analyzing, and discriminating RF signals in the presence of interference</td>
<td>Passive RF detection, high-performance receiver chains including LNAs, direct conversion mixers, high-speed ADCs, analog/digital filtering, configurable AGC</td>
<td>Detection and classification of Mini/Micro UAVs amidst wireless interference signals in congested RF spectrum environments</td>
</tr>
<tr>
<td>57</td>
<td>2021</td>
<td>Parrot Bebop, Parrot AR (Elite 2.0), and DJI Phantom 3</td>
<td>NI USRP 2943</td>
<td>Capturing RF signals</td>
<td>Deep CNN ResNet50, LR, transfer learning from ImageNet enhanced pattern recognition</td>
<td>UAV detection as imagery classification</td>
</tr>
<tr>
<td>59</td>
<td>2020</td>
<td>DJI Matrice M100</td>
<td>Ettus B200mini</td>
<td>Data transmission and reception</td>
<td>Deep CNN, RF fingerprinting</td>
<td>UAV identification in dynamic aerial environments</td>
</tr>
<tr>
<td>60</td>
<td>2021</td>
<td>Mavic 2 Zoom</td>
<td>Ettus USRP B210, LimeSDR-USB</td>
<td>Capturing RF signals</td>
<td>Integrated SDR and FPGA components, ML</td>
<td>Drone detection sensor for anti-drone systems</td>
</tr>
<tr>
<td>61</td>
<td>2021</td>
<td>Parrot Bebop, Parrot AR, DJI Phantom 3</td>
<td>NI USRP 2943R</td>
<td>Capturing RF signals</td>
<td>ML, RF data analysis, preprocessing (smoothing filters, FFT), ensemble learning (XGBoost, KNN)</td>
<td>UAV detection with high accuracy</td>
</tr>
<tr>
<td>62</td>
<td>2022</td>
<td>DJI Mavic Air, DJI Phantom 4 Pro v2.0, and DJI Mini 2</td>
<td>Ettus USRP X310 and Ettus USRP B200mini</td>
<td>Capturing RF signals (Ettus USRP X310), generation of jamming signals (Ettus USRP B200mini)</td>
<td>Spectrum sensing algorithms (e.g., 3EED) for UAV detection and AoA algorithms for localization</td>
<td>UAV detection and defense</td>
</tr>
<tr>
<td>65</td>
<td>2022</td>
<td>DJI Spark</td>
<td>Ettus USRP X310</td>
<td>Capturing RF signals</td>
<td>SFS, WEE, PSE, ML algorithms (SVM, RF, KNN), super-resolution estimation algorithm</td>
<td>UAV detection and positioning</td>
</tr>
<tr>
<td>66</td>
<td>2024</td>
<td>DJI Mavic, DJI Phantom, Fimi, and DJI Mavic</td>
<td>Ettus USRP X310</td>
<td>Capturing RF signals, collecting data for CNN training</td>
<td>Passive monitoring, CNN for UAV classification, TDOA-based positioning</td>
<td>Cost-effective, scalable system for UAV classification and localization in diverse domains</td>
</tr>
<tr>
<td>68</td>
<td>2022</td>
<td>Intel Aero</td>
<td>Ettus USRP B210 and Ettus USRP B205mini</td>
<td>Data transmission (Ettus USRP B210) and data reception (Ettus USRP B205mini)</td>
<td>Signal acquisition, distributed beamforming, DoA estimation, blind signature detection, RTK system</td>
<td>Signal localization and source detection in outdoor environments</td>
</tr>
<tr>
<td>69</td>
<td>2024</td>
<td>DJI Mavic</td>
<td>ADALM-PLUTO, Ettus USRP B200mini-i, USRP N210, BladeRF 2.0 micro xA4, USRP–2950R, USRP–2930</td>
<td>Capturing RF signals</td>
<td>Small-size frequency oscillators for precise localization</td>
<td>Accurate localization with minimal size, weight, and power consumption for UAVs in EW operations.</td>
</tr>
<tr>
<td>70</td>
<td>2024</td>
<td>DJI Mavic 3T Basic Enterprise</td>
<td>NI USRP 2954R</td>
<td>Capturing RF signals</td>
<td>MUSIC algorithm, UCA antennas, coherent operation through calibration</td>
<td>UAV localization, addressing safety concerns associated with drones by accurately pinpointing their positions based on RF signals</td>
</tr>
<tr>
<td>71</td>
<td>2024</td>
<td>Tarot hexacopter</td>
<td>ADALM-PLUTO</td>
<td>Data transmission and data reception</td>
<td>AoA estimation, RSSI estimation, log-distance path-loss model, PRACH-assisted method</td>
<td>Ground transmitter localization using UAVs</td>
</tr>
</tbody>
</table>
paper, the multifaceted benefits of SDR-assisted UAV-based systems have been pointed, as depicted in Fig. 1. These benefits position SDR-enabled UAVs as powerful tools for modern applications, driving innovation and improving operational efficiency in various sectors. Specifically, SDR can facilitate radio prototyping, data acquisition, signal measurement, and the collection, processing, and integration of I/Q samples. SDR is also pivotal in channel sounding, characterization, and managing spectrum usage within CR frameworks. Moreover, SDR enables the implementation and operation of 5G network testbeds. 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 it 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.

B. FUTURE RESEARCH DIRECTIONS

The paradigm of SDR-assisted UAV-based systems confronts a spectrum of challenges and critical impediments, as shown in Fig. 2. Therefore, several avenues for future research and development in this field can be identified as follows:

- **Hardware Optimization and Energy Consumption:** Looking forward, research efforts should concentrate on developing energy-efficient hardware architectures, particularly focusing on SDR architectures and FPGA models tailored specifically for UAV applications. Future research directions may involve optimizing internal parameters to enhance resource efficiency and exploring advanced hardware implementations and accelerators to minimize processing latency and energy consumption. Additionally, expanding FPGA capabilities for broader data pre-processing will be a crucial area of exploration, aiming to mitigate power consumption concerns and prolong mission endurance for UAV operations.

- **Algorithmic Techniques and Signal Processing:** Future research in this domain may revolve around refining algorithmic techniques for signal processing and exploring innovative approaches (e.g., ML and DL), to enhance system performance and versatility for tasks, such as signal classification and autonomous decision-making. This includes optimizing hardware design to accommodate these advanced algorithms and enhancing robustness under challenging NLoS conditions. Moreover, extending the applicability of these techniques to various RF signal types and frequencies is necessary to ensure comprehensive coverage in UAV-based systems.

- **System Capabilities and Versatility:** Future research endeavors may focus on refining and expanding 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, multi-UAV tracking, and adaptive interference mitigation strategies. Moreover, research efforts are needed to expand the dataset to encompass a wider range of UAV platforms and...
diverse missions, as well as evaluating additional SDRs to capture dual-frequency band UAVs comprehensively.

- **Security Enhancements:** As far as security aspects are concerned, there is a pressing need to enhance and streamline lightweight detection models for deployment on compact UAV platforms, emphasizing communication efficiency and seamless integration to counter security threats stemming from SDR-based GPS spoofing attacks. Further research avenues also involve exploring a broader range of jamming types and UAV-specific anti-jamming solutions, refining existing jamming techniques, and investigating hybrid jamming approaches. Moreover, research efforts should focus on harnessing advanced ML and DL models that offer promising avenues for improving threat detection capabilities and reducing false alarm rates in complex RF environments.

- **UAV Detection and Localization Technology:** Future research endeavors in UAV detection 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, thus ensuring airspace integrity. Further advancements involve the development of advanced filtering techniques to enhance resolution. In addition, promising avenues for exploration include the expansion of FPGA capabilities for broader data preprocessing and offloading software algorithms to minimize detection latency. Finally, identified limitations of UAV-enabled localization technologies can be addressed by advancing hybrid RSSI/AoA methodologies.

**REFERENCES**


FIGURE 8. Challenges of SDR-assisted UAV-based systems and corresponding solutions to overcome these challenges.


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