УДК 621.39.83 doi: 10.26906/SUNZ.2025.1.235-238

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INTEGRATION OF SDR INTO UAV SYSTEMS

Abstract. The article presents an in-depth examination of how Software-Defined Radio (SDR) technology can be integrated into Unmanned Aerial Vehicle (UAV) systems to enhance communication reliability, adaptability, and security. **The aim of the article** is to demonstrate how SDR-based architectures address critical challenges such as non-stationary channels, intentional jamming, and signal spoofing by enabling real-time reconfiguration and dynamic frequency management. The flexible nature of SDR allows UAVs to rapidly modify transmission parameters, apply robust coding techniques, and switch among multiple channels to maintain resilient links. **The results obtained**: case studies and experimental data indicate that SDR-equipped UAVs significantly improve situational awareness and mission survivability. Through continuous spectrum monitoring and advanced error-correction methods, these platforms can swiftly detect and mitigate interference or jamming attempts. Moreover, the integration of machine learning algorithms further refines threat classification, facilitating accurate identification of barrage jamming, GPS spoofing, and other radio-based attacks. **Conclusions**: adopting SDR in UAV systems not only strengthens communication links but also promotes scalability and cost-effectiveness by reducing hardware dependencies. This reconfigurability, combined with AI-driven signal analysis, positions SDR-enabled UAVs as a robust solution for diverse civilian, commercial, and defense applications under evolving radio frequency threats.

Keywords: software-defined radio, UAV, jamming mitigation, communication system, signal processing.

Introduction

Unmanned Aerial Vehicles (UAVs) are low-altitude platforms used for various missions. They range from small drones to large military aircraft, differing in shape, weight, and size. Payloads like communication equipment, cameras, radars, sensors, battery capacity, and flight duration determine their configurations [1].

A standard UAV system consists of three primary components: the unmanned aircraft, the Ground Control Station (GCS), and the Communication Link (CL). The unmanned aircraft is the core element of the UAV system and is managed by the operator either through the GCS, which facilitates remote control and monitoring during flight operations, or by a Remote Controller (RC) [2] (Fig. 1).

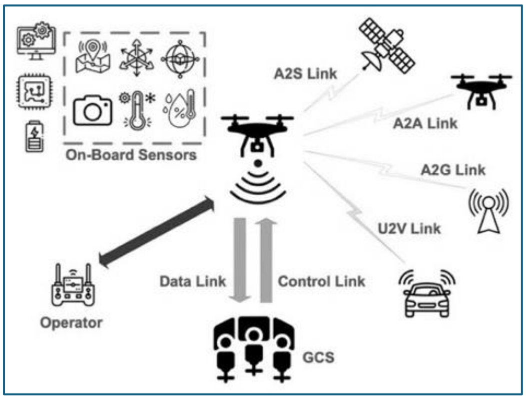

Fig. 1. High-level architecture of a UAV-based system [3]

The internal hardware architecture of an UAV includes several essential components. The Flight Controller (FC) functions as the UAV's Central Processing Unit (CPU). It is the intermediary between the software and onboard devices. The wireless communication module, which features both transmitters and receivers, enables interaction with external devices such as the Remote Controller (RC), Ground Control Station (GCS), and other UAVs if necessary [3]. Furthermore, UAVs can be equipped with a variety of sensors. To maintain stability and counteract environmental factors (such as wind and pressure variations), flight control tilt sensors, accelerometers, gyroscopes, and ultrasonic sensors for obstacle avoidance are commonly used. Additionally, UAVs may incorporate electro-optical sensors, radars, and cameras [1].

In recent years, SDR technology has been used in UAVs, either through custom-made or commercially available SDRs. Adopting SDR allows UAVs to overcome the limitations of conventional communication systems and explore new domains, including civilian, commercial, defense, and public safety. SDR provides adaptability and programmability, making it a cost-effective option which can improve the communication capabilities of UAVs [3].

SDR Overview

Software-defined radio or SDR is a communication technology that uses software-based processing to replace traditional hardware components. This approach allows for flexibility, adaptability, and upgradeability without the need to make physical changes to the hardware [4]. SDR systems use general-purpose processors (GPP), digital signal processors (DSP), or field-programmable gate arrays (FPGA) to perform tasks like signal modulation, demodulation, and channel selection (Fig. 2, 3). This enables them to operate across various frequency bands and wireless standards [5].

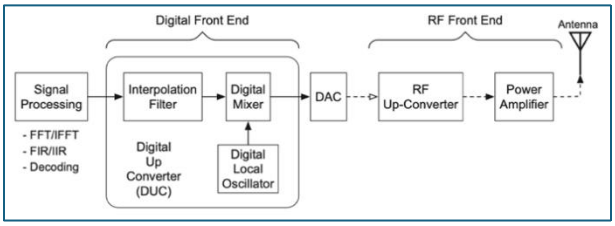

Fig. 2. SDR transmitter structure [6]

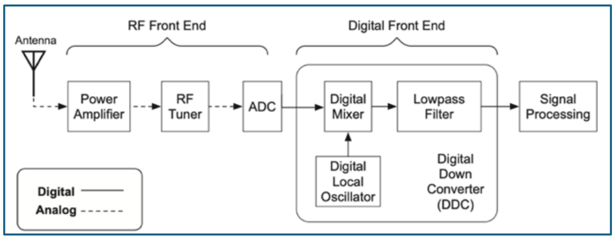

Fig. 3. SDR receiver structure [6]

The architecture of Software-Defined Radio (SDR) consists of several components first of which is the antenna. SDR antennas are usually engineered to support multiple frequency ranges and incorporates adaptive techniques such as beamforming. The RF front-end takes care of the reception and transmission of signals, converting them to and from intermediate frequencies. Analog-to-digital (ADC) and digital-to-analog (DAC) converters are used to transform analog signals into digital formats and vice versa. Their performance is often evaluated based on parameters like signal-to-noise ratio and resolution. Furthermore, the digital front-end is responsible for adjusting sampling rates and filtering signals. The baseband processing block manages coding, decoding, and modulation tasks, typically implemented using a combination of General Purpose Processors (GPP), Digital Signal Processors (DSP), and Field-Programmable Gate Arrays (FPGA) hardware [5].

SDR implementations vary in performance and efficiency. GPP-based platforms like Sora and USRP are easy to program but can be power-intensive. DSP-based solutions optimize signal processing with lower energy use, ideal for embedded applications. FPGA-based architectures offer high performance and reconfigurability but need advanced hardware skills. Nevertheless, despite power and complexity issues, SDR excels in scalability, real-time adaptability, and cost-effectiveness, making it crucial for modern wireless communication systems [5].

Adoption of SDR in UAV systems

UAVs are especially suitable for SDR equipment, which typically have lower transmission powers and simpler antenna hardware. The unobstructed line-of-sight channels available to UAVs significantly improve the performance of SDR-based communication systems (Fig. 4).

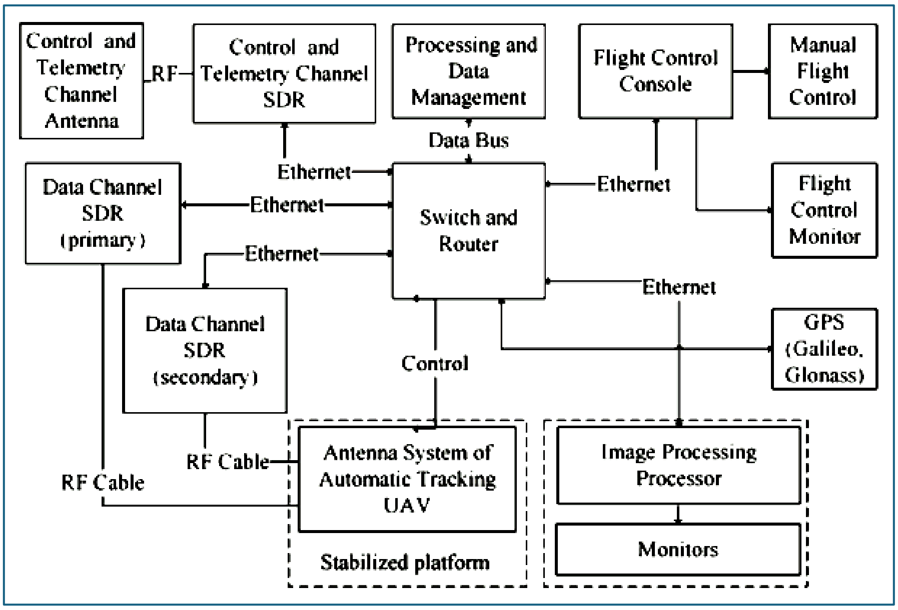

Fig. 4. The structure of the UAV control and communication system [7]

In [7] the authors propose an adaptive UAV communication system that uses SDR and SoC technologies to address two main challenges—non-stationary channels and intentional jamming—by incorporating real-time frequency monitoring, multi-channel links, robust coding, and directional antennas. One SDR channel continuously operates while another analyzes the spectrum for interference, enabling rapid frequency selection and modulation changes. SoC-based data processing coordinates these functions alongside advanced error-correction coding and multipath protocols to maintain reliable control and telemetry channels, as well as high-throughput data links. This approach significantly enhances UAV survivability, since multiple jamming stations would be required to disrupt both the control and data channels simultaneously.

Some studies highlight the dual role of SDR platforms in identifying threats and implementing countermeasures. The programmability of SDRs allows for advanced real-time signal processing and machine learning integration, enhancing UAV resilience in complex RF environments [3] (Fig. 5).

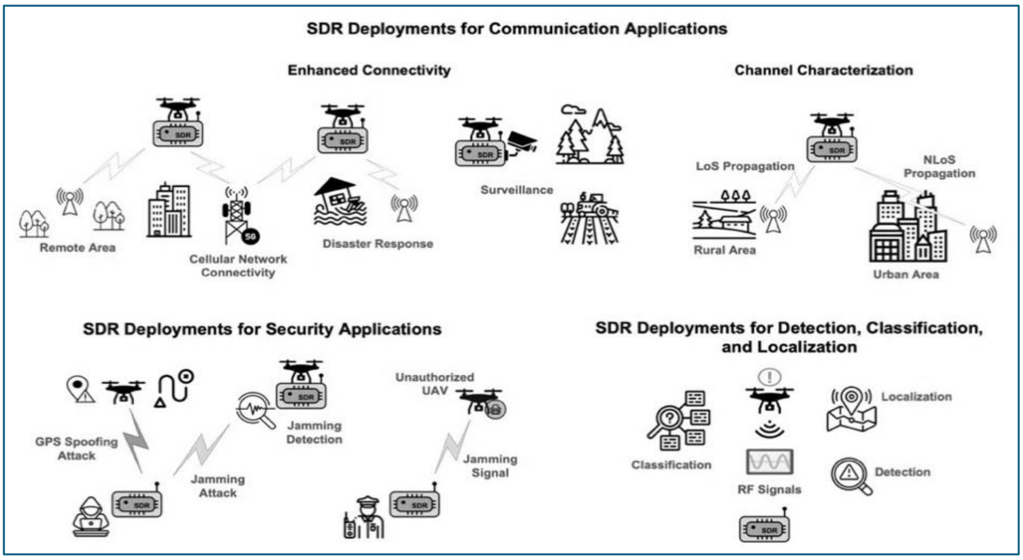

Fig. 5. Application domains and architectural frameworks of SDR-assisted UAV-based systems [3]

In [8] a study was conducted proposing a signal source identification framework in which UAVs coordinate using Blockchain-based smart contracts to detect transmitting objects in cluttered or dynamic environments. Their solution uses asymmetric key cryptography and ring signatures for privacy-preserving UAV task assignments and includes a maximum likelihood estimation scheme to derive signal parameters accurately. The results indicate that SDR-enabled UAVs can identify signal sources with high precision by combining physical-layer power data and aerial images.

In parallel, multiple approaches focus on jamming detection using ML. Li et al. [9] present a pipeline where raw I/Q samples are obtained by SDR receivers and then processed by ML classifiers, including support vector machines and deep neural networks. Various attacks, such as barrage, protocol-aware, single-tone, and successive-pulse jamming, are analyzed, with spectrogram-based CNN models showing the best results. Similarly, Alhazbi et al. [10] propose BloodHound, a deep-learning system that identifies jamming by examining shifting patterns in I/Q data. Expanding on this concept, BloodHound+ uses sparse autoencoders to detect jamming signals even in low-BER situations, providing wider defense coverage [11].

These studies highlight the benefits of fine-grained data capture enabled by SDR, allowing advanced classifiers to identify jamming patterns with minimal delay. Other research extends into jammer localization, particularly Tedeschi et al. [12], who incorporate SDRs into a closed-loop control system, allowing UAV-like mobile nodes to triangulate a jamming source. By accurately characterizing the received signal strength distribution under jamming conditions, the system localizes the jammer within tens of centimeters. Another area of research investigates the GPS spoofing threat, where attackers broadcast counterfeit GPS signals via SDRs to manipulate UAV flight paths. A significant contribution toward detecting such spoofing is the lightweight model by Ren et al. [13], which employs LSTM-based knowledge distillation. Experiments show high accuracy in distinguishing genuine from forged satellite signals. Several authors discuss an Intrusion Detection System (IDS) approach that integrates radio-layer and flight-operation data [14]. This approach uses Principal Component Analysis (PCA) and one-class classifiers to analyze UAV flight logs and identify anomalies associated with spoofing or jamming. The training data can be sourced from flights, which makes the IDS architecture more generalizable and less dependent on a large labeled dataset of attacks. Additionally, integrating an IDS with Blockchain or other secure frameworks ensures the integrity of logs and detection results [8], enhancing trustworthiness and coordination when multiple UAVs or ground stations are involved.

Conclusions

While SDR-based UAV systems excel in mitigating and detecting a wide range of RF threats through customizable signal processing pipelines and robust machine learning integration, practical challenges such as power consumption, hardware constraints, and evolving regulatory frameworks remain significant. Moreover, the inherent flexibility of SDR can also be exploited by attackers, underscoring the importance of robust security measures—such as secure firmware, encryption, and vigilant oversight of open-source tools—to safeguard UAV communication channels. A multi-layered defense strategy, integrating radio-layer data with UAV telemetry and employing advanced intrusion detection systems, further strengthens resilience against jamming, spoofing, and other sophisticated attacks. By embracing collaborative threat intelligence among researchers, manufacturers, and regulatory entities, future developments in SDR-based UAV architectures can remain cost-effective, adaptable, and secure, ultimately supporting a broad spectrum of civilian, commercial, and defense applications.

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Received (Надійшла) 11.03.2025
Accepted for publication (Прийнята до друку) 04.06.2025

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Інтеграція програмно-керованого радіо з безпілотними літальними апаратами

М. О. Бікчентаєв, Б. Р. Боряк

Анотація. У статті представлено поглиблений аналіз того, як технологію програмно-визначеного радіо (SDR) можна інтегрувати в системи безпілотних літальних апаратів (БПЛА) для підвищення надійності, адаптивності та безпеки зв'язку. **Метою статті** є демонстрація того, як архітектури на основі SDR вирішують критичні проблеми, такі як нестаціонарні канали, навмисне глушіння та підміна сигналу, забезпечуючи реконфігурацію в режимі реального часу та динамічне управління частотою. Гнучка природа SDR дозволяє БПЛА швидко змінювати параметри передачі, застосовувати надійні методи кодування та перемикатися між кількома каналами для підтримки стійких з'єднань. **Отримані результати**: тематичні дослідження та експериментальні дані показують, що БПЛА, оснащені SDR, значно покращують ситуаційну обізнаність та живучість місії. Завдяки постійному моніторингу спектру та передовим методам виправлення помилок ці платформи можуть швидко виявляти та пом'якшувати спроби перешкод або глушіння. Крім того, інтеграція алгоритмів машинного навчання додатково уточнює класифікацію загроз, сприяючи точній ідентифікації загороджувальних глушінь, підміни GPS та інших радіоатак. **Висновки**: впровадження SDR у системах БПЛА не лише зміцнює канали зв'язку, але й сприяє масштабованості та економічній ефективності, зменшуючи залежність від апаратного забезпечення. Ця можливість реконфігурації, у поєднанні з аналізом сигналів на основі штучного інтелекту, позиціонує БПЛА з підтримкою SDR як надійне рішення для різноманітних цивільних, комерційних та оборонних застосувань в умовах постійно зростаючих радіочастотних загроз.

Ключові слова: програмно-визначене радіо, БПЛА, зменшення перешкод, система зв’язку, обробка сигналів.