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Spectrum Management Methods for Enhancing UAV Resilience to Electronic Countermeasures in Complex Interference Environments

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ABSTRACT The article explores the operational resilience of Unmanned Aerial Vehicles (UAVs) amid the escalating tensions of hybrid conflicts, where the integration of drones into operational-tactical systems grants strategic importance to spectral monitoring and spectrum management. The modern electromagnetic environment in combat zones characterized by high signal density, a broad array of interference sources, and active electronic warfare systems that directly jeopardize the stability of control channels, navigation (GNSS), and intelligence data transmission for UAVs. The study provides an overview of IEEE and MIL-STD standards, along with a comparative analysis of spectrum sensing methods. The findings demonstrate that conventional solutions no longer meet contemporary challenges regarding universality and operational precision in combat scenarios, justifying the need to optimize monitoring algorithms for enhanced performance in high-interference environments.

KEYWORDS spectrum monitoring, spectrum management, UAV, EW, compressed sensing.

I. INTRODUCTION

The operational effectiveness of Unmanned Aerial Vehicles (UAVs) is determined not only by their tactical and technical characteristics (flight range, payload, stealth) but also by the critical resilience of their control loops and communication channels against Electronic Warfare (EW) interference. In modern armed conflicts, the radio frequency spectrum has become a critical operational resource, where electromagnetic dominance and ensuring Electromagnetic Compatibility (EMC) are decisive factors in command efficiency and mission success.

Within the scope of this study, spectrum monitoring treated as an agile element of the transceiver system, capable of adapting to varying operating conditions. It serves as a foundation for formulating subsequent steps regarding flexible channel switching and operating under radio interference. Threats such as jamming (interruption of control signals), spoofing (manipulation of Global Navigation Satellite System (GNSS) navigation data), and multipath propagation in urban or rugged terrain require immediate and accurate detection of spectral activity [1].

The inclusion of UAVs into multi-platform networks is of particular importance. This necessitates the harmonization of their Spectrum Management (SM) systems with general standards, ensuring compatibility with IEEE principles while maintaining the rigor of military-grade MIL-STD requirements. Consequently, the modernization and enhancement of spectrum monitoring methods for UAVs remain a priority task in military electronics and telecommunications.

II. REVIEW OF THE LITERATURE

Analysis of contemporary scientific literature indicates intensives advancement in spectrum monitoring and spectrum management within cognitive radio network (CRN) architectures leveraging UAV platforms. The primary objective inherent to such frameworks is guaranteeing resilient, adaptive, and energy-efficient connectivity amidst active electronic countermeasure conditions.

The task of spectral analysis in CRN been addressed through diverse methodologies [2, 3]. To enhance interference resilience in wireless access systems, dedicated investigations been conducted [4, 5]. An adaptive approach to spectrum monitoring with signal detection optimization in CRN thoroughly examined in [6, 7]. Additionally, a separate investigation assessed the operational efficacy of the Variable Threshold Spectrum Monitoring (VTSM) method for enhancing detection reliability in CRN [8].

The implementation of wavelet-based transformation techniques and filtering for spectrum monitoring under fading and frequency distortion conditions explored both in an independent study [9] and in research focused on spectrum monitoring within fading and frequency-distorted channels [10]. The formulation of methodologies for quantifying interference energy metrics and statistical correlation characteristics of transmitted waveforms regarding resilience to Adjacent Channel Interference (ACI) is critically important for intelligent radio systems [2, 11].

Spectrum monitoring methods in CRN, grounded in rapid computational Fourier Transform (FFT) [12], have demonstrated considerable effectiveness. Subsequent advancement within this domain incorporated the application of the Akaike Information Criterion (AIC) for spectrum monitoring [12]. In [13, 14], a solution addressing the challenge of spectral congestion was proposed through the utilization of UAVs as relay elements between licensed primary operator (PU) and opportunistic secondary operator (SU) within the foundational network infrastructure.

Subsequent advancement of adaptive spectrum stewardship concepts realized in a study proposing the integration of Adjusted Deep Deterministic Policy Gradient (ADDPG) with convex optimization techniques to maximize long-term secondary throughput [15]. Refinement of resource distribution strategies in Software-Defined Radio (SDR) systems examined in a paper offering a strategy that accounts for hardware limitations and enhances spectrum utilization efficiency [16].

Subsequent inquiries emphasize the fusion of Hidden Markov Models (HMM) fused alongside signal-to-noise ratio assessment protocols inside Cooperative Spectrum Sensing (CSS) frameworks [17]. In a similar vein, a tri-dimensional CR-based optimization model proposed, enabling UAVs to perform adaptive sensing via calibration to the optimal frequency contingent upon spatial positioning and current radio conditions [18, 19].

Reference [20] introduces a Multi-Agent Reinforcement Learning (MARL) framework, encompassing the training of numerous cognitive UAVs for collaborative spectrum sensing. The outlined structural design integrates both primary user activity alongside the existence of potential Electronic Countermeasure (ECM) assets. Global IEEE 1900.x series standards formalize requirements for cognitive networks; cooperation protocols coupled with adaptive spectrum orchestration [21]. These innovations constitute the technical foundation for cognitive UAVs capable of autonomously detecting and utilizing spectral voids.

A distinct investigative avenue is associated with addressing size, weight, and power (SWaP) constraints aboard UAV platforms. The potency of Compressed Sensing (CS) methodologies for wideband monitoring proven in [22, 23]. Collaborative spectrum surveillance in UAV networks demonstrates substantial enhancement in dependability regarding channel occupancy detection, as discussed in [24].

Current scholarly pathways prioritize the enhancement of energy detection amidst diminished signal-to-noise ratio circumstances. One study demonstrates performance improvement of this foundational method through the utilization of entropy metrics [25]. This approach ensures adaptive threshold tuning and rapid system response within a dynamic electronic environment.

III. ANALYSIS OF IEEE AND MIL-STD STANDARDS FOR SPECTRUM MONITORING IN WIRELESS NETWORKS

In the modern information landscape, rational SM has acquired strategic importance, particularly for military and specialized communication complexes. The extensive wireless communication infrastructure leads to a resource scarcity of the available spectral potential, which complicates the provision of reliable and resilient connectivity.

As the threat of interference grows, advanced methods of spectral control are required. In this context, standards regulating spectrum monitoring procedures and guaranteeing EMC play a vital role. Based on these standards, effective methods of spectral monitoring can selected, including dynamic frequency allocation for diverse wireless networks. This allows for significantly strengthening protection, increasing fault tolerance, and enhancing the overall network reliability.

EEE Standards and Dynamic Spectrum Access (DSA) Principles. Civil IEEE benchmarks establish the architectural framework for cognitive radio, which necessitates the transition to dynamic spectrum management methods.

IEEE 802.22 (Wireless Regional Area Networks - WRAN). Approved in 2011 and updated in 2019 [26], this standard was the primary source of the dynamic spectrum access paradigm for utilizing unused “Television White Spaces” (TVWS). For UAVs, the following embedded mechanisms are of particular importance:

1. Spectrum Sensing determines the presence of PUs to prevent interference.

2. Cooperative sensing, implemented through information exchange between nodes (the Base Station and Customer Premises Equipment), significantly enhances the survivability of spectrum occupancy detection.

3. The fundamental detection criteria focus on ensuring robust signal identification through a systematic approach that minimizes the probability of detection errors.

IEEE 1900 Series (Standard for Dynamic Spectrum Access Networks). These standards go beyond 802.22, focusing on:

1. Node Collaboration Protocols, which serve as a mechanism defining how various radio systems, including UAVs, can exchange spectrum occupancy data in a standardized manner to ensure shared access to frequency resources.

2. Universal Spectrum Management Interfaces, which involve creating standardized mechanisms for the dynamic allocation and reallocation of frequency resources within multi-UAV networks.

3. The Relevance of the IEEE 1900 Standard for UAVs lies in its ability to facilitate the formation of tactical wireless networks capable of autonomously utilizing any available frequencies, thereby providing the critically needed flexibility and system survivability under active EW conditions.

Military-Oriented MIL-STD Standards Military standards focus on EMC and physical resilience to interference, which are vital for combat systems.

MIL-STD-461G (Requirements for Spectral Purity and Interference Background). Approved in 2015 and updated in 2025 [1], this standard defines stringent electromagnetic purity and immunity standards for electronic equipment and its components. The standard is essential for a systematic spectrum monitoring system due to several key factors:

1. Radiated Susceptibility (RS) – a military requirement specifying that UAV onboard equipment must maintain full operational integrity and functional reliability within a saturated external electromagnetic environment (EME), including high-power impulsive interference.

2. The necessity for distributed spectrum monitoring arises because the MIL-STD-461G standard indirectly requires distributed spectrum systems to be capable of maintaining operational performance in contested environments, where an adversary employs FHSS and DSSS modulation modes with an extended base. This, in turn, imposes a critically high spectral component detection threshold, as well as rigorous requirements for resilience to wideband signal resilience to signal level fluctuations monitoring system.

MIL-STD-461G (Requirements for the Control of Electromagnetic Interference Characteristics). Approved in 2015 and updated in 2025 [1], this standard establishes stringent EMC requirements for subsystems and equipment. For SM and spectrum monitoring, it is critical for the following reasons:

1. RS is a military requirement specifying that UAV onboard equipment must maintain full operational capability and functionality even when exposed to intense external electromagnetic fields, including high-power pulsed interference.

2. The necessity for distributed spectrum monitoring arises because MIL-STD-461G indirectly requires SM systems to be capable of functioning in environments where the adversary employs Frequency Hopping (FH) and Direct Sequence Spread Spectrum (DSSS) techniques. This, in turn, imposes critically high requirements on the sensitivity and dynamic range of the onboard monitoring system.

Integration with STANAG 3516 to maintain NATO interoperability standards. MIL-STD-461G integrated with the STANAG 3516 standard, governing the requirements for airspace spectrum management. STANAG 3516 establishes protocols for frequency resource coordination among allied forces, allowing for the mitigation of spectrum conflict risks and the minimization of unauthorized channel bandwidth utilization [1].

In the context of the mission-specific deployment of unmanned systems, STANAG 3516 provides standardized interfaces for exchanging spectral environment data across various platforms, including ground stations, manned aircraft, and UAVs. This enables the creation of a unified spectrum monitoring network, where every network entity is capable transmitting detected signals to a centralized command center. Such an approach enhances coordination efficiency in multinational reduces the probability of "friendly fire" caused by spectral interference.

Development of a Hybrid Functional Model. The integration of civilian IEEE standards (802.22, 1900) with military standards (MIL-STD-461G and STANAG 3516) establishes a hybrid framework for effective spectrum monitoring in combat UAV systems. This model facilitates the alignment of cognitive radio agility with critical requirements for EMC and system life-cycle security.

IEEE 802.22 provides the instrumental basis for utilizing "white spaces" and adaptive spectrum access, enabling UAVs rapidly switch to vacant frequencies under interference conditions. IEEE 1900 offers collaborative monitoring protocols that enhance spectral analysis resolution by aggregating data from a distributed heterogeneous, radio monitoring network. Concurrently, MIL-STD-461G guarantees the system's resilience to electromagnetic interference (EMI), while STANAG 3516 ensures interoperability with allied forces [1, 21, 26].

IV. OPTIMIZATION OF SPECTRUM MONITORING METHODS FOR UAV COMBAT APPLICATIONS

Within the framework of combat operations conducted by UAVs at tactical and operational-tactical levels, radio frequency (RF) environmental surveillance plays a crucial role in ensuring a stable, reliable, and uninterrupted command and control (C2) link between the operator (or command center) and the UAV. This monitoring encompasses the interception and analysis of all radio communications, the detection and identification of emissions from adversary hardware (SIGINT/ELINT), and the implementation of operational ECM.

Primary challenges include the computational power and energy resource constraints of the platforms, the high density and dynamic evolution of radio entities within conflict zones, the adversary's EW activities, and the necessity of ensuring rapid operational coordination with ground-based and airborne control nodes.

These constraints define strict requirements for surveillance systems: high sensitivity, reduced detection latency, interference immunity, and high adaptability [27].

Cognitive Algorithms and Adaptive Detection Thresholds.

In EW environments, where noise levels are unpredictably high and dynamically changing, a static detection threshold leads either to missed detections or to false alarms (at low thresholds). Cognitive algorithms facilitate intelligent spectrum management through the following:

Reconfigurable entropy-based thresholds. Advanced energy detection methods employ entropy metrics (e.g., Shannon entropy) to verify statistical hypotheses regarding the presence of a useful signal [25]. This approach optimizes the operation of mobile platforms by maintaining algorithmic performance within complex interference environments.

Statistical spectrum occupancy profiling and prediction. Cognitive systems analyze the historical spectral environment profile within the conflict zone. Leveraging intelligent processing algorithms and stochastic analysis, the system generates a probabilistic assessment of future interference and can proactively switch communication to backup frequencies, thereby preventing disruptions.

Cooperative Spectrum Monitoring.

The data fusion process performed by accumulating spectral data from several UAVs (local sensor nodes) and subsequently routing this information to a Processing Center, which can be deployed either at a ground control station or on a dedicated UAV-relay.

Data fusion increases the probability of detection by minimizing the impact of local interference, including shadowing, multipath propagation, and “blind zones.” In scenarios where a single UAV fails to detect a signal due to localized obstructions, other nodes positioned at higher altitudes or different locations can maintain detection, thereby enhancing overall sensing reliability. Furthermore, synchronization of measurements between interacting nodes enables the precise geolocation of hostile jamming stations, providing critical intelligence for the development of effective countermeasures [24].

Wideband Sensing and Compressed Sensing (CS).

To monitor a wide frequency band with minimal hardware costs, CS technology employed.

By leveraging CS, it is possible to set the ADC sampling rate significantly below the Nyquist rate. This directly reduces power consumption, bandwidth requirements, and hardware costs-providing a critical advantage for platforms subject to strict SWaP constraints.

CS provides a rapid, wideband spectral overview, enabling UAVs to react instantaneously to frequency-agile threats, such as frequency-hopping (FH) jamming systems.

The optimization of UAV spectral surveillance for combat applications requires high-sensitivity, adaptive, and EW-resilient solutions. Cognitive algorithms, dynamic detection thresholds, collaborative analysis, and compressed sensing methods form the foundation for designing high-efficiency onboard radio-electronic complexes for operational command and control.

The integration of these technologies enhances detection reliability, mitigates the impact of interference, and ensures proactive adaptation to jamming influences through predictive analysis within the complex electromagnetic environments of the modern battlefield.

V. COMPARATIVE ANALYSIS OF SPECTRUM MONITORING METHODS IN WIRELESS NETWORKS

A comparative assessment of various methods clarifies their respective strengths and limitations, thereby facilitating the formulation of a synergistic hybrid framework for UAV combat systems.

Energy Detection (ED).

Recognized for its minimal implementation complexity and widespread adoption, this approach functions without reliance on prior signal parameters. Such autonomy renders it exceptionally effective within electronic warfare environments characterized by undefined signal structures.

Utilizing Equation (1), the framework derives energy metrics from the acquired samples and benchmarks them against the threshold parameter λ_{ED}, thereby facilitating the differentiation of target signals from background noise [28]:

$$T_{ED} = \frac{1}{N}\sum_{n=1}^{N}(Y[n])^2 , \quad (1)$$

where N is the number of received samples, Y[n] is the n-th received sample.

To gauge the efficacy of ED, Receiver Operating Characteristic (ROC) profiles employed, mapping the trade-off juxtaposing the likelihood of signal acquisition against the inclination toward erroneous alert generation.

Visualized within Fig. 1 the ROC trajectories for an adaptive energy detector, wherein the discrimination threshold undergoes real-time modulation predicated upon the Signal-to-Noise Ratio (SNR). Employing distinct adaptation coefficients for each SNR regime enables a comparison of the robustness and fidelity inherent to the signal identification mechanism across varying interference scenarios.

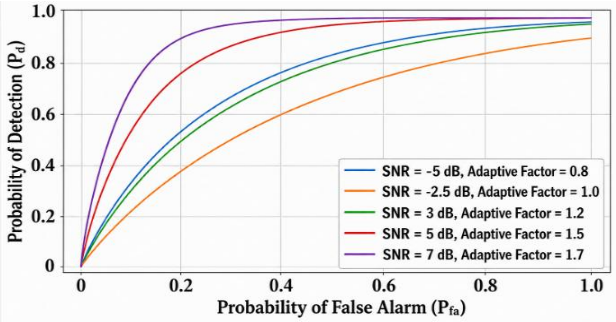

FIG. 1. ROC curves for frequency spectrum monitoring with an adaptive energy detector threshold.

An examination of the data outlined in Fig. 1 confirms that adaptive threshold tuning within the energy detector enhances the probability of detection while sustaining or even diminishing the incidence rate of false positive declarations relative to static thresholding methods.

A primary constraint hindering onboard UAV implementation stems from its pronounced susceptibility noise uncertainty. In regions of active interference, background noise levels fluctuate dynamically, leading toward a heightened propensity for erroneous alerts or detection failures. Consequently, this necessitates the adoption of entropy-based adaptive thresholds [25].

Waveform-Based Monitoring (WFB).

The WFB method applied exclusively for identifying transmissions within networking architectures characterized by known structures (pilot signals, preambles, or synchronization sequences).

Unlike the ED method, the WFB detector's operation relies upon deriving the cross-correlation metric involving the inbound waveform r(n) and an a priori known reference template s(n). The calculation of the corresponding decision metric T performed according to expression (2):

$$T = \left|\sum_{n=0}^{N-1} r[n]\cdot s^{*}[n]\right| , \quad (2)$$

where N is the number of samples, s^*(n) is the complex conjugate of the template.

The paramount advantage of WFB lies in its capacity to attain elevated levels of detection likelihood (P_D) with minimal false alarm probability (P_{fa}), as vividly illustrated by the ROC profiles depicted in Fig. 2.

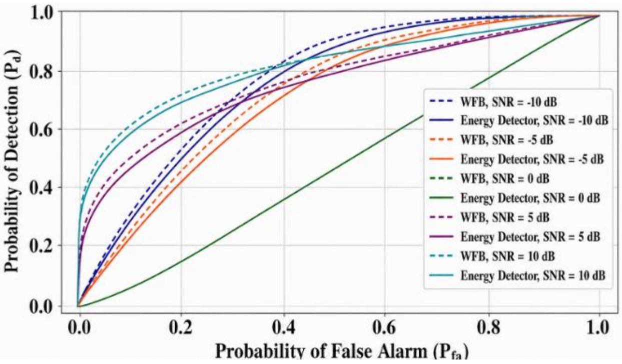

FIG. 2. Comparison of WBS and ED methods.

WFB (blue curve) provides a significantly higher trajectory on the graph than ED (orange curve). This proves that due to correlation processing, WFB has greater responsiveness to faint transmissions and maintains operational efficacy within low SNR conditions.

Cyclostationary Feature Detection (CSD).

The CSD methodology exploits a fundamental statistical attribute intrinsic to numerous beneficial transmissions within communication frameworks – the embedding of periodic elements or cyclostationary correlations that recur at a designated cyclical frequency α. These cyclostationary traits are typically absent across both natural background and synthesized noise.

In contrast to ED and WFB (predicated on familiarity with the specific waveform architecture), CSD utilizes statistical properties of modulation and coding. This makes it a robust mechanism toward the discernment and classification of emissions. The calculation of the test statistic [28], executed in alignment with equation (3), enables the architecture to verify signal occurrence through the localization of distinctive peaks at non-null cyclical frequency domains α:

$$\mathrm{SCF}_y^{\alpha}(f) = \lim_{n \to \infty} \frac{1}{n} \sum_{n=1}^{N} y(n)\, y^{*}(n-\tau) e^{-j2\pi\alpha n} . \quad (3)$$

The expression (3) lays the groundwork for assessing the method's empirical attributes. To demonstrate the findings of its application, Fig. 3 presents a graph illustrating the capability of CSD in scenarios featuring low SNRs, where other methods, particularly ED and MF, lose accuracy or cannot implemented owing to the lack of an accurate waveform model.

The CSD method – a singular methodology for detecting weak signals in complex radio channels, which guarantees efficient functionality without the prerequisite of knowing the exact signal waveform configuration. By exploiting cyclostationary properties of signal statistics, CSD upholds superior resilience against real noise and congested radio spectra. It outperforms the conventional energy-based detector amidst reduced signal-to-noise ratio conditions and yields enhanced ROC profiles.

Matched Filtering (MF).

The MF methodology stands as the theoretically supreme framework for signal identification, utilized exclusively when sophisticated transmission indicators regarding the primary user are accessible (encompassing waveform structure, amplitude-frequency properties, and phase details).

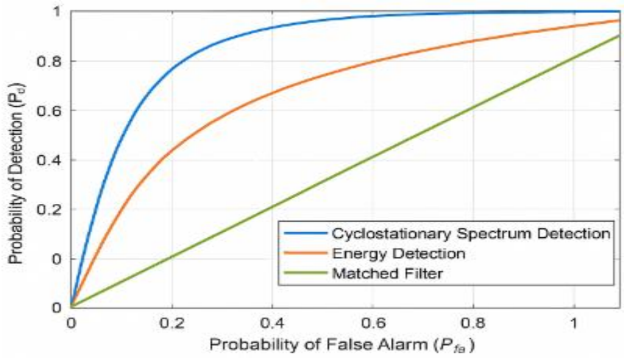

FIG. 3. Comparison of CSD, ED and MF methods.

The core concept underlying the matched filter centers on the maximization SNR attained at the filter's output junction. Such a linear entity possesses an impulse response that constitutes a temporally inverted and shifted reproduction of the intended signal structure.

The Rate of false positives (P_{fa}) and detection likelihood (P_D), associated with MF, may be mathematically derived utilizing the statistical attributes inherent to the decision-making statistic. Under the presumption of a Gaussian distribution premise, said likelihoods computed via the Q-function [28], as mathematically represented within equations (4) and (5):

$$P_{fa} = Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right), \quad (4)$$

$$P_{fa} = Q\left(\frac{\lambda - \mu_1}{\sigma_0}\right), \quad (5)$$

where Q is the Q-function, α is the detection threshold and μ and σ are the mean and standard deviation of the output signal under hypotheses H_0 (noise only) and H_1 (signal present), respectively.

Calculation results and visualization of ROC curves at low SNR (e.g., -3 dB) prove that MF constitutes the most efficacious methodology (Fig. 4).

Matched filtering depicts the uppermost trajectory within the graphical representation, demonstrating superior detection likelihood (P_D) across any specified false positive rate (P_{fa}). This corroborates its optimality. Cyclostationary detection (CD) exhibits intermediate performance, as it demonstrates enhanced adaptability to statistical transmission attributes. ED manifests the lowest efficacy under diminished signal-to-noise ratio circumstances.

The principal benefit inherent to the MF lies in its capacity to deliver the maximally attainable probability of signal identification under a predetermined false positive rate constraint.

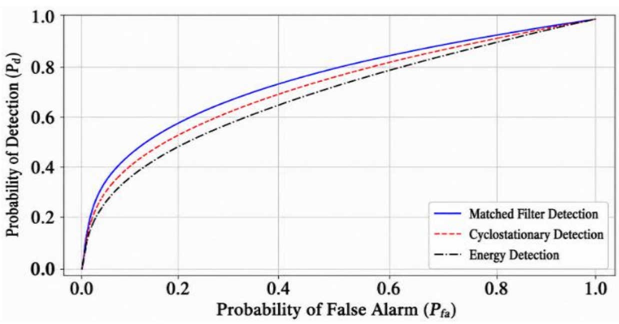

FIG. 4. Comparison of ROC curves for MF, CD and ED methods.

Correlation-based Frequency Spectrum Monitoring (CFSM).

A correlation-based spectrum monitoring methodology employed for detecting weak transmissions within high-noise environments. The methodological principle relies upon quantifying the degree of correspondence between the inbound waveform $r(t)$ and the predetermined template $s(t)$.

The derivation of the continuous cross-correlation metric executed in accordance with equation (6), enabling the architecture numerically evaluate the extent of statistical interdependence linking the acquired waveform with its canonical temporal representation:

$$\mathrm{C}(\tau) = \int_{-\infty}^{\infty} r(t)s(t-\tau)dt, \tag{6}$$

where $\mathrm{C}(\tau)$ is the correlation function, $r(t)$ is the received signal, $s(t)$ is the reference signal, τ is the time delay between the signals.

The derivation of the discrete cross-correlation metric, executed in alignment with equation (7), enables the architecture to undertake computational analysis of captured samples for extracting timing characteristics of the transmission and facilitating its identification amidst interference [28]:

$$\mathrm{C}[n] = \sum_{k=0}^{N-1} r[k]s[k-n], \tag{7}$$

where $r[k]$ and $s[k]$ are the signal values at discrete time points, N is the number of samples.

Fig. 5 depicts ROC profiles that facilitate the assessment of CFSM performance relative to the energy-based detection approach.

At SNR = -10 dB and -5 dB (blue and orange curves), the correlation-based methodology significantly outperforms ED, demonstrating elevated detection probability metrics under equivalent false alarm rate constraints. This corroborates the superiority of CFSM within complex interference-prone environments.

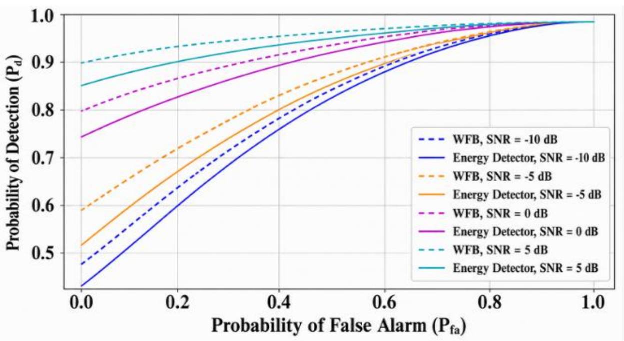

FIG. 5. Comparison of correlation-based and energy-based monitoring methods at various SNR levels.

Comparative analysis indicates that CFSM demonstrates superior efficacy under diminished signal-to-noise ratio conditions owing to structural signal comparison, whereas ED becomes competitive solely at elevated SNR levels. Consequently, for achieving elevated precision levels within dynamic radio environments, it is advisable to employ hybridized and adaptive methodologies that integrate the strengths of both correlation-centric, as well as energy-centric approaches.

VI. CONCLUSION

Effective organization of spectrum monitoring within combat UAV systems necessitates a multifaceted strategic framework that merges technical excellence with tactical dependability and guaranteed resilience under electronic warfare conditions.

1. An imperative necessity been established regarding the deployment of DSA protocols aligned with IEEE-802.22 and IEEE 1900 specifications, alongside EMC requirements outlined in MIL-STD-461G. This convergence facilitates the engineering of a spectrum management system that combines efficient detection of available channels (white spaces) with high resilience against direct EW impacts.

2. Spectrum monitoring efficiency in combat UAV systems bolstered via the integration of CS paradigms, which reduces SWaP demands and ensures rapid wideband scanning. Further improvements achieved through integrating cognitive components, including entropy-based adaptive detection thresholds, significantly enhancing threat identification reliability [25].

3. Findings derived from the juxtaposition of spectral surveillance techniques indicate that incumbent conventional techniques do not afford the requisite adaptability and operational accuracy for comprehensive coverage of all critical UAV combat scenarios. Energy Detection exhibits critically low efficiency under intense radio interference conditions, whereas waveform and correlation-based approaches rely heavily on prior knowledge of exact signal parameters, which is impractical when countering unpredictable threats. Meanwhile, the cyclostationary detection method, despite high interference resilience, limited by implementation complexity and sensitivity to precise cyclic frequency estimation.

To ensure enhanced fidelity and robustness of surveillance within spectrally congested hostile environments, it is imperative to formulate cutting-edge composite spectrum monitoring methods and adaptive implementation algorithms that synthesize the strengths of diverse methodologies, thereby ensuring adaptive management of UAV frequency resources.

AUTHOR CONTRIBUTIONS

S.K., G.C. – conceptualization, methodology, investigation; V.L., H.S. – supervision writing-review and editing.

COMPETING INTERESTS

The authors declare no conflict of interest.

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Методи управління спектром для підвищення стійкості БПЛА до радіоелектронної протидії в складних завадових умовах

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АНОТАЦІЯ У статті досліджується операційна стійкість безпілотних літальних апаратів (БПЛА) в умовах ескалації гібридних конфліктів, де інтеграція дронів в оперативно-тактичні системи надає стратегічного значення спектральному моніторингу та управлінню спектром. Сучасна електромагнітна обстановка в зонах бойових дій характеризується високою щільністю сигналів, широким спектром джерел завад та активним застосуванням систем радіоелектронної боротьби (РЕБ), що створює безпосередню загрозу стабільності каналів управління, навігації (GNSS) та передачі розвідувальних даних БПЛА. Метою роботи є аналіз та визначення перспективних методів спектрального моніторингу й управління спектром, здатних забезпечити адаптивну роботу радіоелектронних систем БПЛА в умовах інтенсивних радіоперешкод. У роботі представлено огляд підходів до спектрального зондування, зокрема енергетичного виявлення, виявлення за формою сигналу, циклостаціонарного виявлення, узгодженої фільтрації та кореляційного аналізу. Проаналізовано можливості використання когнітивних алгоритмів, адаптивних порогів, кооперативного моніторингу та стисненого вимірювання для підвищення ефективності широкосмугового контролю спектра. Окрему увагу приділено аналізу вимог стандартів IEEE 802.22 та IEEE 1900, а також MIL-STD-461G і STANAG 3516, що визначають підходи до динамічного доступу до спектра, когнітивного радіо, електромагнітної сумісності та управління спектром. Проведений порівняльний аналіз показує, що традиційні методи спектрального моніторингу мають обмеження щодо адаптивності, точності та оперативності роботи в динамічному середовищі з високим рівнем завад. Використання стисненого вимірювання дає змогу здійснювати широкосмуговий моніторинг зі зниженням вимог до частоти дискретизації, енергоспоживання та апаратних ресурсів. Результати дослідження обґрунтовують доцільність поєднання методів когнітивного радіо, адаптивного моніторингу, кооперативного аналізу та стисненого вимірювання для підвищення стійкості БПЛА до радіоелектронної протидії та забезпечення ефективного управління частотними ресурсами в складних завадових умовах.

КЛЮЧОВІ СЛОВА моніторинг спектра, управління спектром, БПЛА, РЕБ, стиснена вибірковість.