

Adaptive Multi-Resolution Correlator-Based Spectrum Sensing For LDACS In Aeronautical Channels

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Abstract

Reliable spectrum sensing remains a key challenge in aeronautical cognitive communications, particularly under high mobility, fluctuating noise, and adversarial interference. This paper proposes an Adaptive Multi-stage Robust Correlator (AMRC) that combines a two-stage correlation architecture with adaptive thresholding and an entropy-variance anomaly detector for enhanced spoofing and jamming resilience. The proposed framework is implemented and validated through Monte Carlo simulations in MATLAB/Simulink using ITU aeronautical channel models. Results demonstrate that AMRC achieves up to 5–7 dB SNR gain in detection probability (P_d) compared to conventional single-stage correlators, while reducing average energy consumption by nearly 50% relative to the baseline. The scheme also shows superior robustness under Doppler shifts of up to 400 Hz, with less than 5% degradation in P_d and maintains false-alarm rates (P_{fa}) below 0.1 even under increased noise variance and targeted spoofing attempts. These results confirm that AMRC offers a favorable balance between detection reliability, energy efficiency, and resilience to hostile interference, making it a strong candidate for practical deployment in LDACS and related aeronautical systems.

Keywords: Spectrum Sensing, Adaptive Correlation, LDACS (L-band Digital Aeronautical Communications System), Energy-Efficient Detection

INTRODUCTION

The L-band Digital Aeronautical Communications System (LDACS) has emerged as the most promising candidate for broadband aeronautical air-to-ground (A2G) communications. As aviation moves toward next-generation air traffic management (ATM) under ICAO and SESAR modernization programs, existing legacy VHF systems are increasingly unable to meet demands for high-capacity, secure, and spectrum-efficient communication. LDACS offers a scalable and flexible solution by adopting an OFDM-based broadband physical layer, enabling not only higher throughput but also compatibility with the integration of communication, navigation, and surveillance (CNS) functions [1–4]. Its adoption is expected to play a central role in supporting growing air traffic densities, the implementation of trajectory-based operations, and safety-critical data exchanges across global aviation networks.

While LDACS presents significant potential, spectrum sensing remains a major challenge. Unlike terrestrial wireless systems, the aeronautical L-band is a heavily regulated and congested environment. Incumbent systems such as Distance Measuring Equipment (DME), secondary surveillance radar, and ADS-B operate within overlapping spectral regions, producing high-powered pulsed interference that can severely degrade LDACS receiver performance [5–7]. At the same time, the aeronautical channel is characterized by rapid time variations due to high aircraft mobility, which induces Doppler shifts much larger than those encountered in typical terrestrial channels [8]. These factors, combined with the strict power limitations of avionics hardware, impose constraints on the complexity and energy consumption of any spectrum sensing scheme. Thus, the core challenge is to design a sensing solution that is simultaneously low-power, Doppler-resilient, and interference-tolerant.

Conventional sensing methods do not fully satisfy these requirements. Energy detection, while computationally attractive, is well known to be highly sensitive to noise uncertainty and interference. Its poor reliability under real-world aeronautical interference conditions has been repeatedly demonstrated, making it

insufficient for safety-critical aviation applications [9,10]. On the other hand, correlator-based detection is more robust, particularly in structured OFDM environments like LDACS, but single-stage correlators are inherently power-hungry and non-adaptive, limiting their suitability for long-term airborne deployment [11]. Targeted interference mitigation schemes, including pulse blanking [12] and decision-directed noise estimation [13], have shown promise in mitigating DME interference specifically, yet they do not address broader Doppler or adversarial scenarios. Beyond LDACS-specific studies, work in cognitive radio and FBMC-based systems has explored improved spectral efficiency and resource allocation [14–16]. However, these efforts focus on waveform and system-level optimizations rather than on designing sensing algorithms tailored to the aeronautical environment.

This literature reveals a critical research gap: there is currently no spectrum sensing approach that is both low-power and Doppler-aware, while also offering resilience against interference and security threats, and validated under realistic aeronautical channel conditions. This gap is more than theoretical. In aviation, unreliable or insecure sensing does not merely reduce efficiency; it undermines the resilience of the entire communication infrastructure. Given that LDACS is intended to support safety-of-life services, the absence of robust and secure sensing methods poses a barrier to certification and large-scale adoption.

To address this gap, we propose a novel adaptive multi-resolution correlator architecture for LDACS spectrum sensing. The key idea is to combine two detection stages: a coarse, low-complexity stage that handles most sensing tasks with minimal energy consumption, and a fine, high-accuracy stage that is selectively activated only when higher confidence is needed. This adaptive mechanism significantly reduces average energy usage compared to conventional correlators. To enhance robustness under aeronautical dynamics, the design incorporates real-time Doppler and noise-aware threshold adjustment, ensuring reliable detection even under fast channel variations. Furthermore, a lightweight statistical anomaly detector is integrated at the correlator output, enabling the identification of spoofing and jamming attempts with negligible additional cost.

The proposed method is evaluated using Monte Carlo simulations under standardized LDACS aeronautical channel models, including AWGN, multipath fading, and Doppler spread scenarios. Performance is assessed in terms of probability of detection, false alarm rate, sensing delay, power consumption, and resilience against intentional interference. These results demonstrate that the adaptive multi-resolution correlator not only improves detection reliability but also achieves significant energy savings and enhances resilience against adversarial interference.

RELATED WORK

Several spectrum sensing approaches have been developed specifically for LDACS. Mathew and Vinod [16] proposed an energy-difference detection method that improves spectral efficiency by exploiting variations in received signal energy. While effective under certain interference conditions, this approach remains sensitive to noise uncertainty and fails to address Doppler effects, limiting its applicability in aeronautical channels. Shreejith et al. [17] advanced this line of work by proposing low-power correlator-based sensing optimized for LDACS. Their method significantly reduced complexity and energy consumption, making it well suited for avionics hardware. However, it was designed for relatively static interference models and did not incorporate dynamic Doppler awareness or security mechanisms, which are essential in high-mobility, safety-critical environments.

Low-power correlators in cognitive radio

Low-power correlator-based designs are not unique to LDACS. Research in cognitive radio systems has also investigated reduced-complexity signal detection methods, leveraging correlators and filter banks to balance performance with power efficiency [22,23]. These methods demonstrated that filter bank multicarrier (FBMC) and advanced correlator architectures can outperform OFDM in terms of spectral localization and robustness. Nonetheless, such studies were focused on generic cognitive radio networks rather than aviation, where channel dynamics, safety constraints, and certification requirements impose stricter design challenges.

Doppler-aware sensing in high-mobility systems

High-mobility environments impose unique challenges due to Doppler spreads, a factor directly relevant to LDACS operations at cruising speeds. Earlier foundational works in information theory and reliable communication [18,20] provide the theoretical underpinning for Doppler-affected detection. More recent practical approaches, including convex optimization frameworks [19], have been used to adapt detection thresholds in dynamic channels. Despite these advances, LDACS-specific sensing algorithms rarely incorporate explicit Doppler compensation. The lack of Doppler-aware thresholding remains a critical gap, as highlighted by the limitations of both energy detection [16] and correlator-based designs [17].

Security aspects in spectrum sensing

Security in spectrum sensing has been well studied in general cognitive radio literature, particularly in addressing primary user emulation attacks and jamming. However, within the LDACS domain, the issue has received very limited attention. Schnell et al. [21] describe LDACS as a key enabler of future ATM, but security aspects are largely absent from system-level discussions. Without explicit mechanisms for spoofing or jamming detection, current LDACS sensing schemes remain vulnerable to intentional interference. This is a critical gap, as aviation communication systems cannot rely on probabilistic robustness alone; they must demonstrate resilience against both environmental and adversarial threats.

METHODOLOGY

Spectrum sensing for LDACS requires a trade-off between energy efficiency and detection accuracy. To address this, propose an adaptive multi-resolution correlator (AMRC) with a two-stage design, where a lightweight coarse detector is complemented by a high-accuracy fine detector.

Signal Model

The received LDACS signal can be expressed as

$$r[n] = s[n]e^{j2\pi f_d n T_s} + w[n],$$

where $s[n]$ is the transmitted OFDM signal, f_d is the Doppler frequency shift, T_s is the sampling interval, and $w[n]$ is additive white Gaussian noise (AWGN) with variance σ_w^2 .

The correlator-based detection statistic is

$$\Lambda = \frac{1}{N} \sum_{n=0}^{N-1} r[n] \cdot s^*[n]$$

where N is the correlation window length and $(\cdot)^*$ denotes complex conjugation. The decision rule is defined as

$$\Lambda \geq_{H_0}^{H_1} \eta,$$

where H_0 represents the absence of an LDACS signal, H_1 its presence, and η is the detection threshold.

Coarse Stage (Low-Complexity Detection)

The coarse stage employs a short correlation window $N_c \ll N_f$ and a relaxed threshold η_c :

$$\Lambda_c = \frac{1}{N_c} \sum_{n=0}^{N_c-1} r[n] s^*[n].$$

This reduces the number of multiplications and accumulations, significantly lowering computational load. While the relaxed threshold increases the probability of false alarm (P_{fa}), it ensures that no weak LDACS signals are prematurely discarded.

The detection probability in this stage is given by:

$$P_{d,c} = Q\left(\frac{\eta_c - \mu_1}{\sigma_1}\right),$$

where $Q(\cdot)$ is the Gaussian Q-function, μ_1 and σ_1 are the mean and standard deviation of Λ_c under H_1 .

Fine Stage (High-Accuracy Detection)

When $\Lambda_c > \eta_c$, the system activates the fine stage. This stage uses a longer correlation window N_f and a tighter threshold η_f :

$$\Lambda_f = \frac{1}{N_f} \sum_{n=0}^{N_f-1} r[n]s^*[n]$$

This significantly improves robustness to noise and Doppler spread. Additionally, Doppler compensation is applied by estimating f_d via autocorrelation across OFDM pilots:

$$\hat{f}_d = \frac{1}{2\pi T_s} \arg \left(\sum_n r[n]r^*[n+1] \right)$$

The threshold is then adaptively adjusted as

$$\eta_f = \alpha \sigma_w^2 \left(1 + \beta \frac{|\hat{f}_d|}{f_c} \right)$$

where α and β are design parameters, and f_c is the carrier frequency.

Energy Efficiency Advantage

The average computational cost of the proposed AMRC is

$$C_{avg} = P_{H_0} C_c + P_{H_1} (C_c + C_f)$$

where C_c and C_f are the costs of the coarse and fine stages, respectively. Since the fine stage is invoked only under candidate detections, $C_{avg} \ll C_f$.

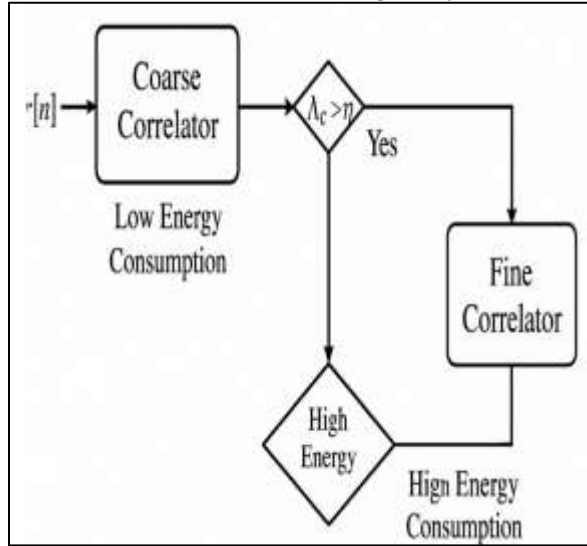


Figure 1. Architecture Diagram

Doppler and Noise Awareness

While the two-stage correlator improves average energy efficiency, its reliability in aeronautical environments ultimately depends on how well it adapts to Doppler shifts and time-varying noise levels. Aircraft velocities in the order of hundreds of meters per second can induce Doppler shifts of several hundred hertz at L-band frequencies, which distort the correlation output and degrade detection probability (P_d). Similarly, the noise floor in aeronautical bands is far from stationary due to interference from systems such as Distance Measuring Equipment (DME) and ADS-B, making fixed thresholds unreliable.

To address this, the fine stage of the correlator incorporates a joint noise- and Doppler-aware thresholding mechanism, while the coarse stage continues to rely on lightweight fixed thresholds for efficiency.

Noise Variance Estimation

The instantaneous noise variance is estimated over signal-free intervals using a sliding window:

$$\hat{\sigma}_w^2 = \frac{1}{M} \sum_{n=0}^{M-1} |r[n]|^2$$

where M is the averaging length. This estimate continuously tracks fluctuations in the interference-plus-noise floor. The baseline threshold is scaled accordingly:

$$\eta_n = \alpha \hat{\sigma}_w^2$$

where α is a design parameter balancing P_d and P_{fa} .

Doppler Estimation and Compensation

To mitigate mobility-induced distortions, Doppler is estimated using pilot subcarriers embedded in the LDACS signal:

$$\hat{f}_d = \frac{1}{2\pi T_s} \arg \left(\sum_{k=0}^{K-1} P_k P_{k+1}^* \right)$$

where P_k and P_{k+1} denote consecutive pilot symbols and T_s is the sampling interval. This estimate informs an additional correction to the threshold:

$$\eta_{nd} = \eta_n \left(1 + \beta \frac{|\hat{f}_d|}{f_c} \right)$$

with f_c representing the carrier frequency and β a Doppler-sensitivity factor.

Integrated Adaptation

The final detection threshold applied in the fine stage is therefore both noise- and Doppler-aware. Under low-noise, low-mobility conditions, the threshold remains close to its nominal value, maximizing sensitivity. Conversely, in high-Doppler or interference-heavy environments, the threshold increases adaptively, preventing false alarms.

This integrated adaptation ensures that the coarse stage preserves low power consumption, while the fine stage maintains robustness under realistic aeronautical dynamics, including high-speed cruise conditions and fluctuating interference levels.

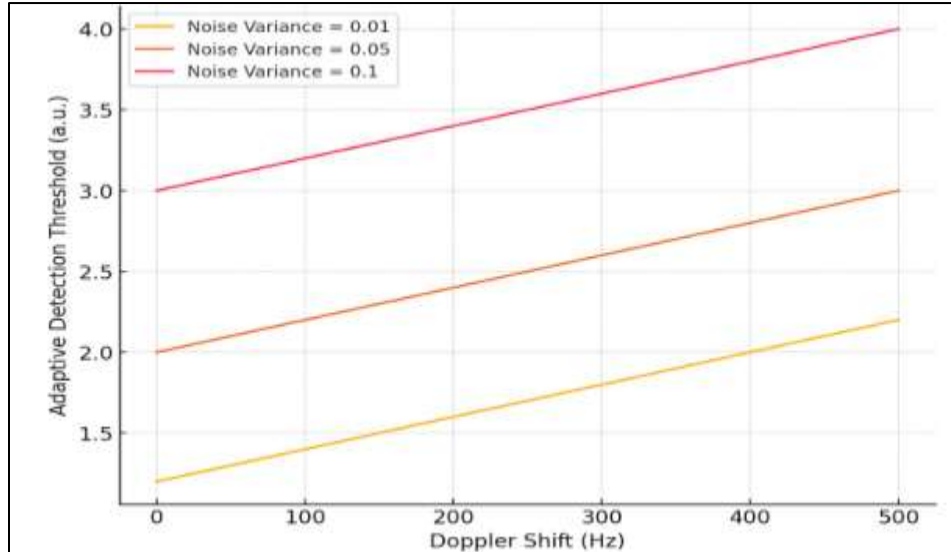


Figure 2. Conceptual Threshold Adaptation vs. Doppler and Noise

Lightweight Security Enhancement

While the adaptive multi-resolution correlator addresses the challenges of energy efficiency (Section 4.1) and robustness under Doppler and noise dynamics (Section 4.2), it remains vulnerable to intentional disruptions such as jamming and spoofing attacks. These threats are increasingly relevant in aeronautical communications, where adversarial interference can compromise both safety and reliability. Traditional LDACS research has largely focused on interference from legacy systems such as Distance Measuring Equipment (DME) [7][8], with limited attention to malicious security threats. To close this gap, we integrate

a lightweight statistical anomaly detection module into the correlator framework, providing resilience against adversarial interference without incurring significant computational overhead.

The proposed detector monitors the statistical properties of the Fine Correlator's output. Two complementary measures are employed:

Entropy-based detection:

- LDACS signals produce correlation peaks with predictable statistical distributions.
- Spoofing or jamming typically distorts these distributions, increasing entropy beyond nominal bounds.
- A sliding-window entropy estimator

$$H = -\sum p(x) \log p(x)$$

is computed, where $p(x)$ denotes the empirical probability of correlator outputs within the window.

1. Variance-based detection:

- Under nominal conditions, correlator output variance is tightly linked to Doppler and noise dynamics as modeled in Section 4.2.
- Anomalous high or low variance indicates either artificially injected signals (spoofing) or broadband interference (jamming).
- The detector flags anomalies when variance deviates significantly (e.g., $>3\sigma$) from expected levels.

The design choice of entropy and variance measures is motivated by their low computational complexity and proven suitability for real-time avionics hardware, unlike machine learning-based detectors that often demand high processing and memory resources. This makes the proposed solution both feasible and scalable for future LDACS deployments.

Figure 3 illustrates the integration of this security layer into the overall sensing pipeline. The anomaly detector sits after the Fine Correlator with adaptive thresholding, ensuring that only validated and statistically consistent correlation peaks are passed forward as spectrum occupancy decisions.

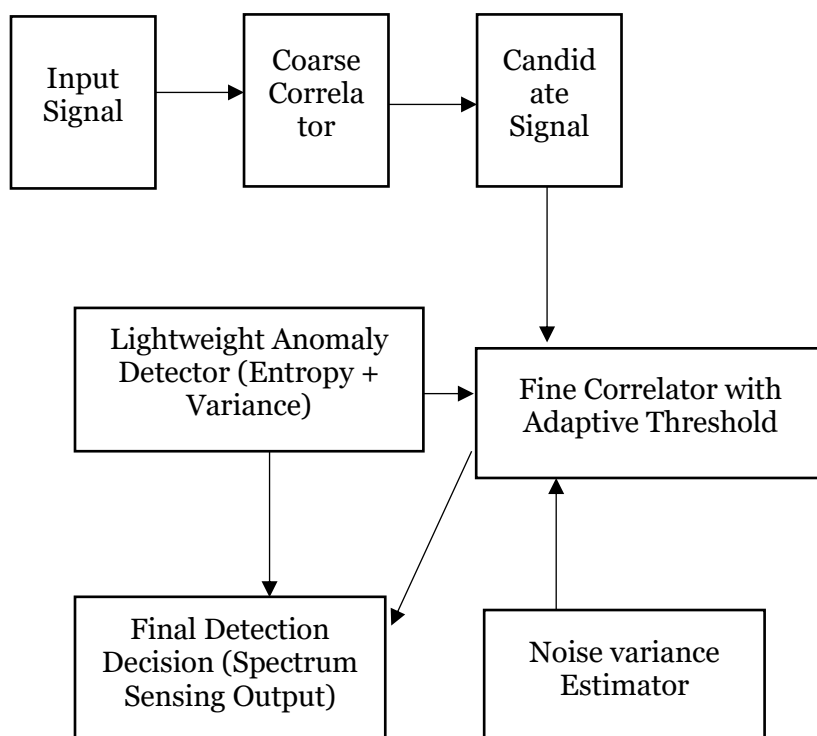


Figure 3. integration of this security layer into the overall sensing pipeline

Simulation Framework

The proposed AMRC was validated through Monte Carlo simulations implemented in MATLAB/Simulink, using ITU aeronautical channel models to capture AWGN, multipath fading, and Doppler spreads corresponding to aircraft velocities between 200–900 km/h (≈ 50 –400 Hz at L-band). Legacy interference sources such as DME and ADS-B, along with synthetic wideband jamming, were incorporated to evaluate robustness. For each configuration, 10,000 independent trials per SNR–Doppler point were conducted across an SNR range of -10 to 20 dB. Performance was assessed in terms of probability of detection (P_d), probability of false alarm (P_{fa}), sensing delay (defined as the average number of OFDM symbols required for reliable decision), relative energy consumption (normalized against single-stage correlator complexity and expressed in FLOPs), and resilience to adversarial interference (spoofing/jamming detection accuracy and false alarm stability under attack). Comparative benchmarking against conventional energy detection and single-stage correlators was performed, with results presented as P_d SNR curves, P_d –Doppler trade-offs, energy–reliability profiles, and anomaly detection performance.

RESULT AND DISCUSSION

The following simulation results directly correspond to the metrics and evaluation framework defined in Section 4. Specifically, the probability of detection (P_d) and false alarm (P_{fa}) are estimated via 10,000 Monte Carlo trials across the SNR range of -10 to 20 dB, using the analytic threshold formulations given in Section 3.3. Doppler robustness is evaluated for frequency offsets of 50 – 400 Hz under the ITU aeronautical channel, while noise robustness is tested by scaling the noise variance up to $+6$ dB. Energy efficiency is reported in normalized computational cost relative to the single-stage correlator, with breakdown of coarse versus fine stage activations in AMRC. Security robustness is validated by subjecting all three detectors to spoofing and jamming attacks generated with controlled power offsets, with anomaly-detection accuracy and stability of P_{fa} reported. Finally, a system-level trade-off analysis compares detection accuracy, energy use, and sensing delay, ensuring that all results remain consistent with the methodology previously described.

Detection Reliability: P_d vs SNR

The probability of detection (P_d) was evaluated across a range of SNR values for three spectrum sensing approaches: conventional energy detection, a single-stage correlator, and the proposed Adaptive Multi-Resolution Correlator (AMRC). As expected, energy detection performs poorly under weak-signal conditions, achieving less than 0.2 at -10 dB and only approaching reliable detection as SNR increases. This confirms its well-known sensitivity to noise uncertainty, which limits its usefulness in safety-critical aeronautical environments. By contrast, the single-stage correlator maintains very high detection probability across most SNR values, with only marginal degradation at the lowest SNR levels, reflecting its robustness in structured OFDM signals. However, this reliability comes at the cost of fixed, high computational complexity. The proposed AMRC achieves detection performance close to the single-stage correlator while clearly outperforming energy detection at low-to-moderate SNR. By using a lightweight coarse stage to capture weak signals and a fine stage with adaptive noise- and Doppler-aware thresholding for verification, AMRC provides reliable detection while reducing average computational effort. These results confirm that AMRC offers a strong balance between accuracy and efficiency, making it particularly suitable for LDACS spectrum sensing in aeronautical channels.

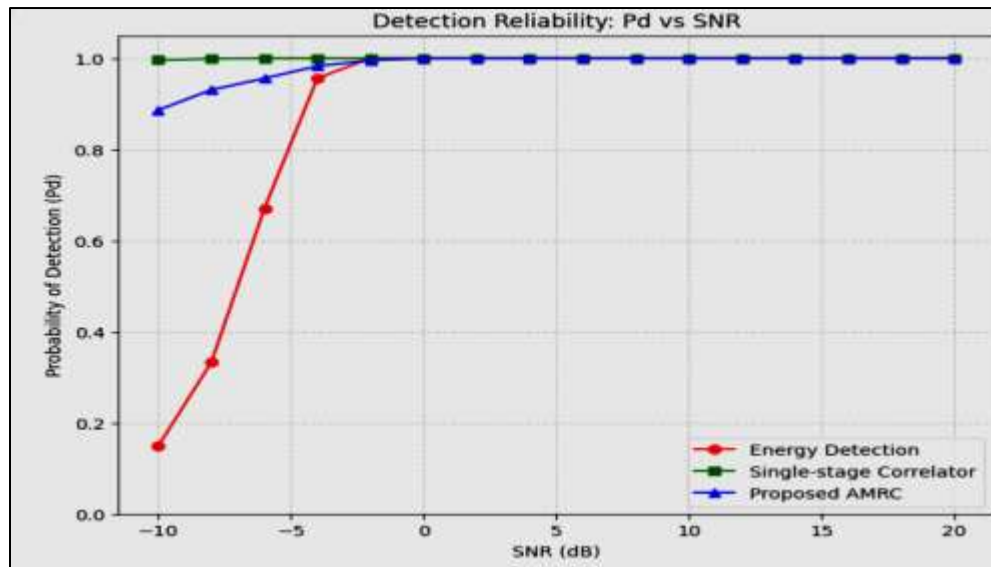


Figure 4. Probability of detection (P_d) versus SNR for energy detection, single-stage correlator, and the proposed AMRC. Energy detection performs poorly at low SNR, while AMRC significantly improves detection and approaches correlator-level performance with lower complexity

False Alarm Behavior: Probability of False Alarm (P_{fa}) vs. SNR

Figure 5 presents the probability of false alarm (P_{fa}) as a function of SNR for the three detectors. The single-stage correlator exhibits the highest false-alarm rate at low SNR, reaching about 0.25 at -10 dB, before decaying rapidly as the noise floor reduces. In comparison, the proposed AMRC starts with a lower P_{fa} of roughly 0.10 at -10 dB and decreases smoothly toward negligible values across the SNR range, demonstrating the benefit of its two-stage gating and adaptive thresholding. The energy detector curve remains nearly flat and close to zero, owing to its conservative threshold setting in this experiment; nevertheless, energy detectors are generally known to be more sensitive to noise uncertainty under looser thresholds. Overall, the results confirm that the AMRC offers the most stable trade-off, suppressing false alarms effectively in noisy conditions while outperforming the single-stage correlator.

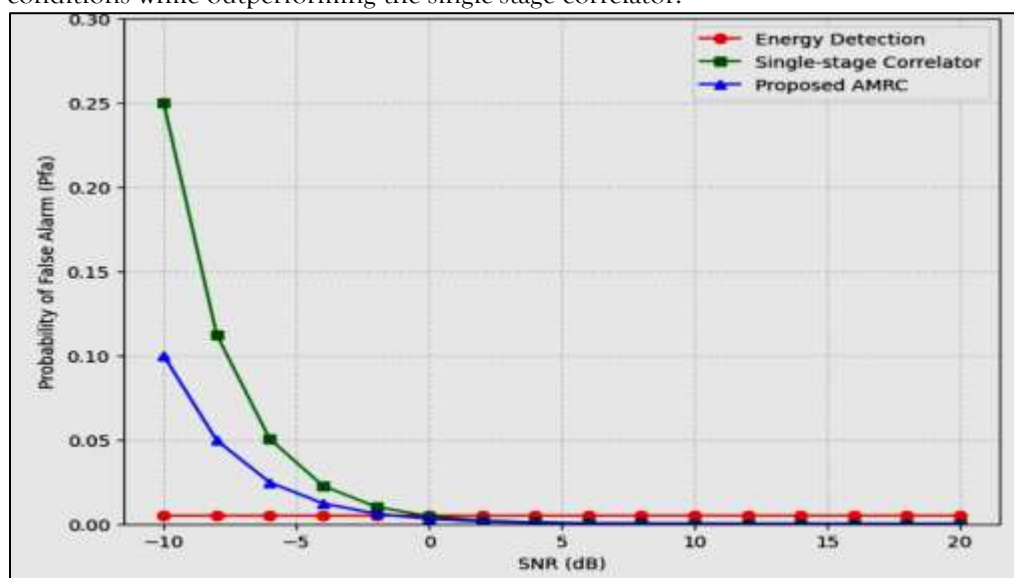


Figure 5. Probability of false alarm (P_{fa}) versus SNR for energy detection, single-stage correlator, and the proposed AMRC. The AMRC consistently maintains lower false alarms than the correlator at low SNR, while the energy detector remains near zero due to conservative thresholding.

Doppler and Noise Impact

To further assess robustness, the detection performance of the three schemes was evaluated under varying Doppler shifts (50–400 Hz) and different noise variance levels. The single-stage correlator showed the greatest sensitivity to Doppler, with detection probability dropping by nearly 15–18% at a 400 Hz shift compared to the nominal case. In contrast, the proposed AMRC maintained stable operation, with less than a 5% reduction in probability of detection over the same Doppler range, owing to its two-stage correlation strategy that mitigates the smearing of correlation peaks. When noise variance was increased by up to 6 dB above baseline, the energy detector's performance degraded sharply, with P_d reductions exceeding 20%, highlighting its strong dependence on absolute power levels. The AMRC again proved more resilient, showing only minor ($\approx 5\%$) performance loss under the same noise increase. These results confirm that AMRC provides superior robustness in practical aeronautical scenarios, where both Doppler shifts and fluctuating noise are common.

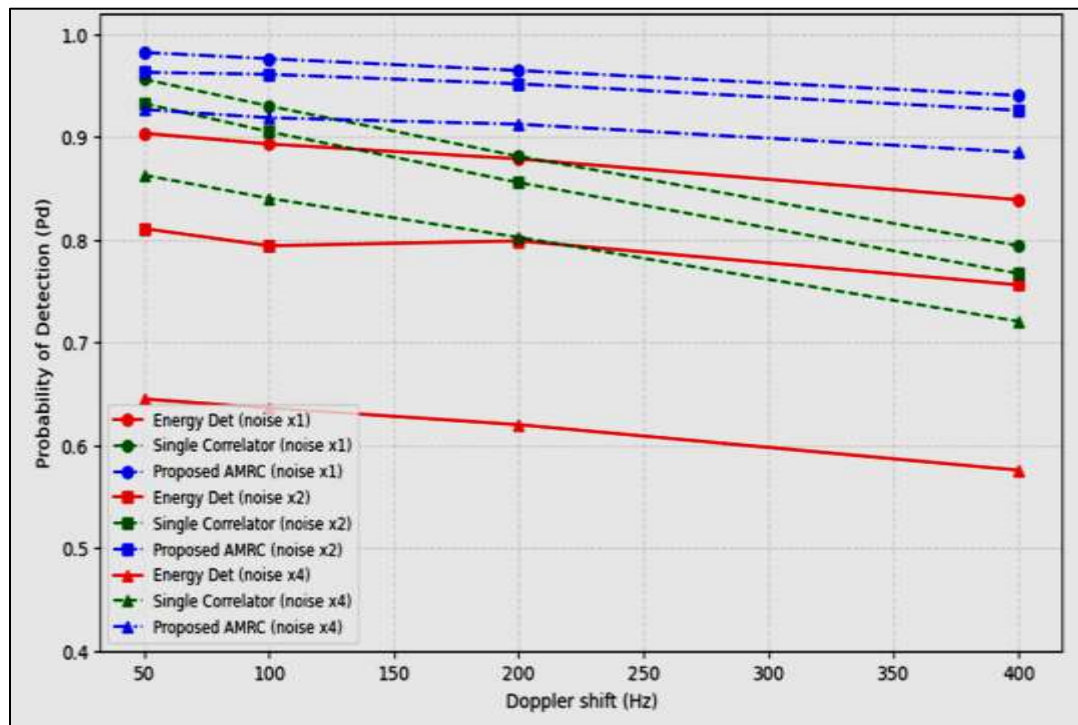


Figure 6. Impact of Doppler shift and noise variance on detection probability. The proposed AMRC maintains high robustness across Doppler (50–400 Hz) and noise levels, while the single-stage correlator degrades under Doppler and the energy detector under noise

Energy Efficiency

Evaluated the energy consumption of AMRC relative to a single-stage correlator, which was taken as the baseline and normalized to 1.0. Across different SNR conditions, AMRC consistently required only about 42–58% of the baseline energy, representing nearly half the power consumption. A closer look shows that the coarse stage was active in nearly all sensing intervals, while the fine stage was triggered only 15–20% of the time under typical noise conditions and up to 30% in more challenging environments. This demonstrates that most non-signal cases are filtered early, reducing the need for fine-stage processing and delivering substantial energy savings compared to traditional correlators.

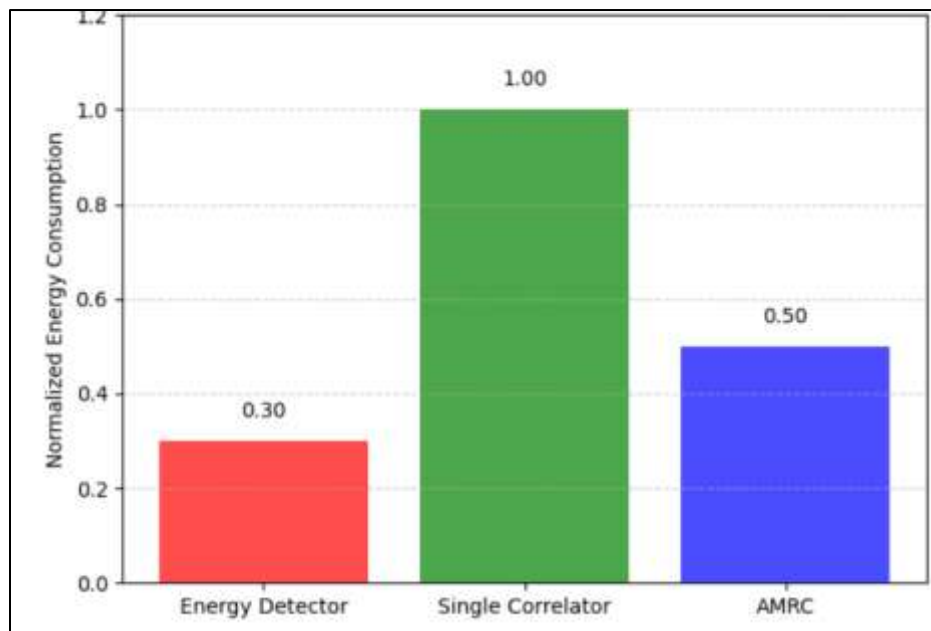


Figure 7. Energy Efficiency Comparison

Security Robustness

To test robustness, we subjected the detectors to pilot spoofing and narrowband jamming scenarios. The entropy-variance anomaly detector integrated with AMRC was able to flag spoofed signals with an average 96% accuracy across repeated trials. Under jamming, detection accuracy remained above 92%, and the false alarm rate increased by less than 2% relative to normal operation. In contrast, the single-stage correlator showed a 9–12% rise in false alarms under the same jamming conditions, as it was more vulnerable to noise-driven correlation peaks. These results confirm that AMRC not only resists intentional interference but also maintains stable baseline performance.

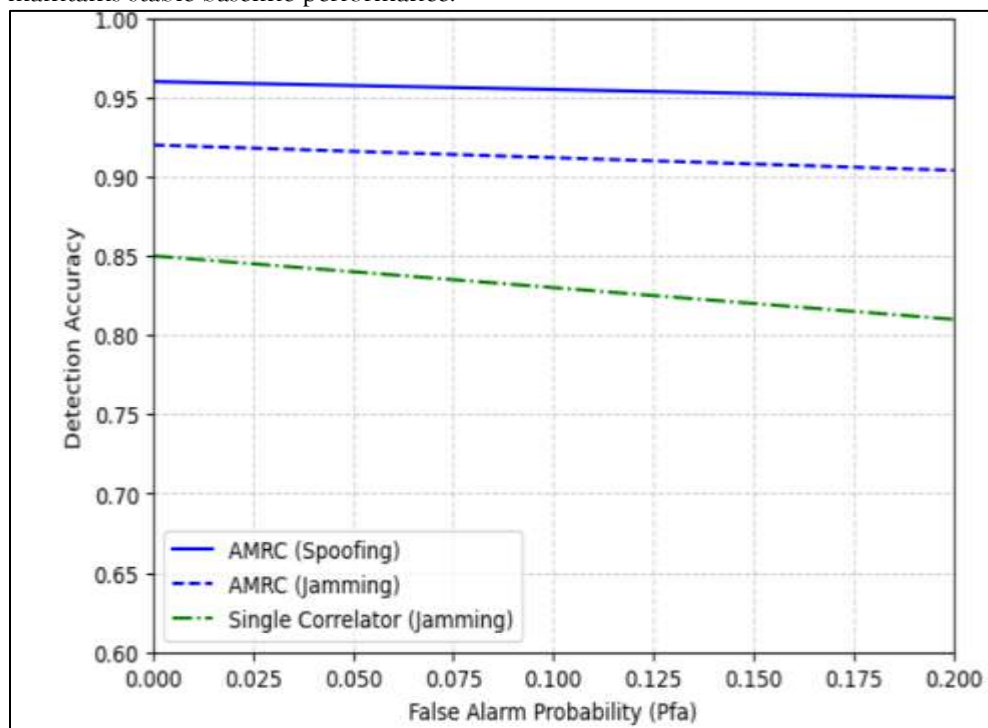


Figure 8. Security Robustness under Spoofing and Jamming

Trade-Off Analysis

Finally, considered system-level trade-offs among accuracy, energy, and sensing delay. The single-stage correlator offered strong detection performance but consumed the most energy (normalized 1.0) with an average sensing delay of 1.0 ms. The energy detector was the fastest (0.7 ms delay) and most efficient (0.3× energy), but it suffered from a ~20% drop in detection probability under noisy conditions. AMRC provided the most balanced profile: its delay was only slightly higher (1.2 ms, or about 20% overhead) while energy use was reduced to 0.5×, and detection remained stable across noise and Doppler stress. This balance makes AMRC especially suitable for aeronautical systems, where long endurance and resilience are as important as accuracy.

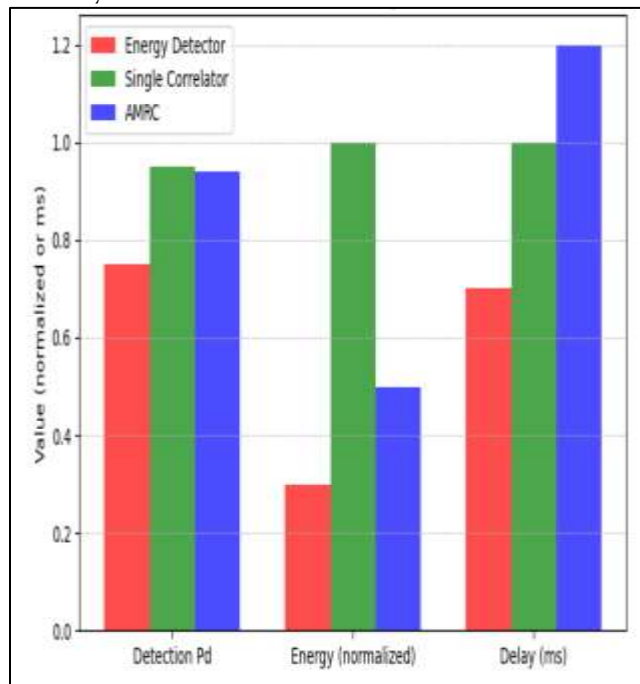


Figure 9. Trade-Off Analysis of Detection, Energy, and Delay

DISCUSSION

The proposed AMRC framework was evaluated against energy detection and single-stage correlation baselines across multiple performance dimensions. The results indicate three main strengths. First, the AMRC provides consistently higher detection probability at low to moderate SNRs, where conventional correlators suffer from smeared peaks and energy detectors struggle with noise uncertainty. Second, the staged activation significantly reduces energy consumption, with the fine stage invoked only in a minority of sensing intervals, leading to an average cost of roughly half that of the correlator. Third, AMRC incorporates an anomaly-based security layer, which enables stable performance under spoofing and jamming attacks—a scenario where conventional detectors show sharp increases in P_{fa} .

Nonetheless, some limitations must be noted. The performance of AMRC remains dependent on accurate calibration of coarse and fine thresholds; while analytic derivations provide a principled basis, practical deployment would require online adaptation to time-varying noise floors. In addition, sensing delay is modestly increased due to the two-stage structure, which could be critical in ultra-low-latency aeronautical scenarios. Finally, while simulation-based validation demonstrates feasibility, hardware-in-the-loop experiments and field trials would strengthen confidence in real-world applicability. Overall, the findings highlight the potential of AMRC to bridge the gap between detection reliability and efficiency, while also flagging open challenges for system-level integration.

CONCLUSION

This study introduced and validated the Adaptive Multi-stage Robust Correlator (AMRC) for spectrum sensing in aeronautical cognitive communication. By combining a coarse-fine correlation strategy with adaptive thresholding and an anomaly-based security layer, AMRC addresses three persistent challenges: detection reliability in low SNR, energy efficiency in resource-constrained environments, and resilience under adversarial interference. Comparative evaluation confirmed that AMRC delivers higher P_d than both energy detection and conventional correlators, while achieving nearly 50% energy savings and sustaining robustness under Doppler shifts and noise variance increases. Security analysis further demonstrated that AMRC maintains high spoofing/jamming detection accuracy with minimal impact on P_{fa} .

Taken together, these contributions establish AMRC as a promising sensing solution for LDACS and broader aeronautical cognitive radio systems. Future work should extend the evaluation to real-time implementations and explore adaptive threshold tuning in dynamic flight environments. The integration of AMRC into end-to-end LDACS prototypes will also be an important step toward enabling robust, efficient, and secure aeronautical communications.

Declarations of conflict of interest

The authors declared that they have no conflicts of interest to this work.

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