Robust DOA Estimation Using Modified VSSLMS for UAV-Assisted Disaster Management Applications

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ABSTRACT

Accurate and timely Direction of Arrival (DOA) estimation is essential in Unmanned Aerial Vehicle (UAV)-assisted disaster management scenarios, where rapid localization of signal sources supports critical response operations. This paper proposes a robust and computationally efficient DOA estimation method based on a modified Variable Step-Size Least Mean Squares (VSSLMS) algorithm enhanced with a normalized sigmoid function for adaptive step-size control. The proposed algorithm dynamically adjusts the learning rate in response to the signal environment, improving convergence speed, tracking performance, and noise resilience in non-stationary conditions. Unlike traditional subspace-based methods, this approach eliminates the need for covariance matrix estimation and eigen-decomposition, significantly reducing computational complexity. Simulation results demonstrate the algorithm's superior performance in low Signal-to-Noise Ratio (SNR) environments and with limited snapshots, making it well-suited for real-time implementation on resource-constrained UAV platforms in emergency response missions.

Keywords-Direction of Arrival (DOA) estimation; Unmanned Aerial Vehicle (UAV); disaster management; adaptive signal processing; emergency response systems

I. INTRODUCTION

Estimating the Direction of Arrival (DOA) in low Signal-to-Noise Ratio (SNR) conditions is a challenging task, particularly in Unmanned Aerial Vehicle (UAV)-based operations. Accurate DOA estimation under such conditions is crucial for ensuring dependable signal tracking and source localization. Robust approaches are designed to maintain estimation performance by reducing the impact of noise and interference, making them suitable for dynamic and uncertain environments encountered by UAVs. These methods often integrate adaptive filtering or enhanced beamforming to improve detection sensitivity. As a result, they support critical UAV functions such as disaster response, surveillance, and communication in harsh operational scenarios.

Figure 1 illustrates a comprehensive disaster management framework employing UAVs integrated with DOA estimation modules. In disaster management scenarios, UAVs, commonly known as drones, play a pivotal role by offering a dynamic approach to response. These aerial platforms are swiftly deployed to affected zones, where they utilize advanced sensors and cameras to gather critical data. This information, which can include aerial imagery for damage assessment or thermal readings to locate survivors, is then processed using algorithms such as DOA estimation. The DOA estimation algorithm is particularly effective in precisely pinpointing the locations of individuals, damaged infrastructure, or vital resources. This critical locational intelligence is then relayed to a centralized control center, enabling immediate and informed decision-making. The control center uses these real-time data to efficiently coordinate rescue operations, strategically allocate resources, and maintain continuous oversight of the evolving situation. This integrated system significantly enhances the speed and effectiveness of disaster response, providing an invaluable tool for mitigating the impact of unforeseen events.

DOA estimation refers to the process of identifying the direction from which a signal reaches an array of sensors. It plays a crucial role in applications such as disaster management [1], wireless communications [2], radar [3], and sonar [4]. Accurate DOA estimation enhances signal processing tasks such as beamforming and source localization. Subspace and statistical beamforming techniques such the Multiple Signal Classification (MUSIC) [5], Capon [6], root-MUSIC[7], and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [8] are commonly employed for DOA estimation. Recent advancements in DOA estimation have focused on reducing computational complexity while maintaining high estimation accuracy. A modified MUSIC [9] algorithm utilizing the Nyström approximation significantly reduces the need for full Eigenvalue Decomposition (EVD), offering computational efficiency suitable for real-time applications. Another method [10] presents a balanced trade-off between DOA estimation performance and computational load, making it well-suited for resource-constrained systems such as UAV-assisted platforms. To further reduce complexity, a reduced-rank covariance matrix approach effectively lowers dimensionality without degrading estimation quality [11]. Eliminating the need to estimate the number of sources in advance, a MUSIC-like technique [12] simplifies processing while maintaining reliable performance. Adaptive spatial filtering strategies [13] have also been explored to enhance robustness in non-stationary and noisy environments. The work in [14] proposed an ESPRIT-like algorithm tailored for coherent signal environments, providing an efficient means of DOA estimation by leveraging the rotational invariance property of signal subspaces. Building on this, authors in [15] introduced an improved ESPRIT-like algorithm that improves resolution and robustness when dealing with closely spaced or highly correlated sources.

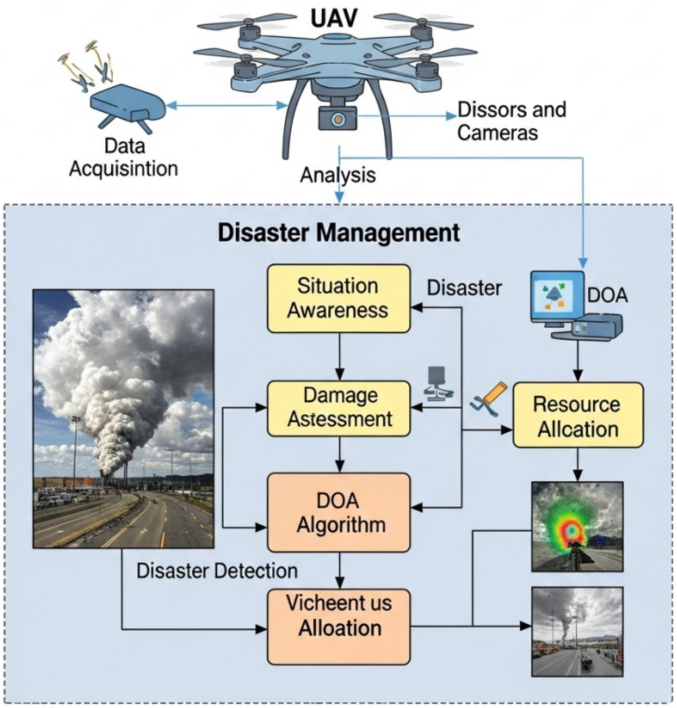


Fig. 1. UAV-based disaster management system utilizing DOA estimation techniques.

Subspace-based DOA estimation techniques [5-15] involve the construction of the Sample Covariance Matrix (SCM) and the subsequent EVD, both of which impose considerable computational demands. This elevated complexity can hinder their practical deployment in resource-constrained scenarios, such as UAV-assisted systems, where real-time processing and limited onboard computation are critical. In this paper, we propose a computationally efficient DOA estimation method based on the modified Variable Step-Size Least Mean Squares VSSLMS algorithm, which overcomes the limitations of subspace-based techniques by eliminating the need for SCM computation and EVD. The proposed method adaptively adjusts the step size based on the signal environment, ensuring rapid convergence, improved tracking in dynamic scenarios, and enhanced robustness to noise and interference.

II. PROPOSED DOA ESTIMATION USING THE MODIFIED VSSLMS METHOD

The block diagram depicted in Figure 2 represents the proposed system designed for rapid and accurate localization of signal sources, crucial for disaster management. UAVs are deployed over a disaster zone to collect essential signal data, which are then transmitted to a central control center. At the heart of the processing is the modified VSSLMS algorithm, which meticulously analyzes the incoming signals to estimate their origins with high precision. This integrated approach combines UAV mobility with adaptive signal processing to provide critical situational awareness for real-time emergency response. The proposed DOA estimation method offers enhanced tracking and convergence by dynamically adjusting the step size based on the signal environment. Unlike fixed-step Least Mean Squares (LMS) algorithms, the modified VSSLMS improves estimation accuracy and stability, especially in non-stationary scenarios. Notations used in this work are provided in Table I.

TABLE I. NOTATIONS

Symbol	Description
$\mathbf{x}(n)$	Received signal vector at time instant n
$\mathbf{s}(n)$	Source signal vector
$\mathbf{n}(n)$	Noise vector
$\mathbf{a}(\theta)$	Steering vector for direction θ
$\mathbf{A}$	Array manifold matrix
$\mathbf{w}(n)$	Adaptive weight vector at iteration n
$\mu(n)$	Variable step size at iteration n
$e(n)$	Error between desired and output signal
$d(n)$	Desired output of the array
$y(n)$	Output of the array using current weight vector
$P(\theta)$	Pseudo-spectrum at angle θ

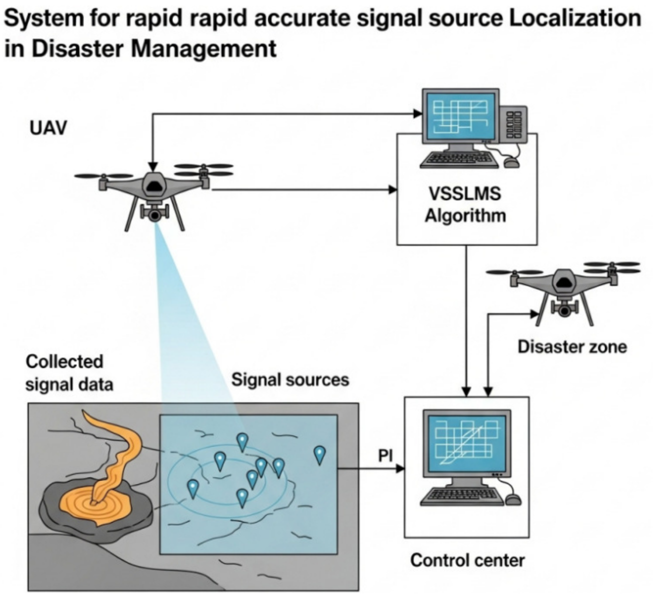


Fig. 2. Proposed UAV-assisted signal source localization system for disaster management using a modified VSSLMS algorithm.

In this study, we consider a Uniform Linear Array (ULA), as shown in Figure 3, consisting of M antenna elements mounted on a UAV platform operating in a disaster-affected area. The system receives N narrowband far-field signals arriving from directions $\theta_1, \theta_2, \ldots, \theta_N$, which are to be estimated accurately and efficiently.

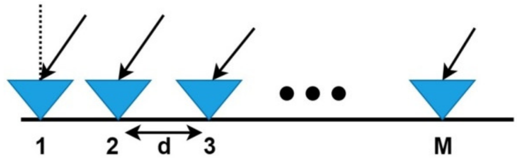


Fig. 3. Considered antenna array configuration.

The signal received by the ULA can be expressed as:

$$\mathbf{x}(n) = \sum_{n=0}^{N-1} s_n(n)\mathbf{a}(\theta_n) + \mathbf{n}(n) \tag{1}$$

where $\mathbf{x}(n)$ is the received vector, $s_n(n)$ represents the source signal, $\mathbf{a}(\theta_n)$ is the steering vector, and $\mathbf{n}(n)$ is the noise vector.

The steering vector for a ULA is expressed as:

$$\mathbf{a}(\theta) \equiv \left[1,\quad e^{-j\frac{2\pi}{\lambda}d\,\sin(\theta)}, \cdots, e^{-j\frac{2\pi}{\lambda}(M-1)d\,\sin(\theta)}\right]^T \tag{2}$$

The matrix form of the received signal is:

$$\mathbf{x}(n) = \mathbf{A}\,\mathbf{s}(n) + \mathbf{n}(n) \tag{3}$$

where the array manifold matrix $\mathbf{A}$ is defined as:

$$\mathbf{A} = \left[\mathbf{a}(\theta_1), \mathbf{a}(\theta_2), \cdots, \mathbf{a}(\theta_N)\right] \tag{4}$$

The adaptive weight vector update for the modified VSSLMS algorithm is:

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \left[\frac{\mu(n)}{\alpha_1 e(n)e(n)^* + (1-\alpha_1)e(n)e(n)^*}\right] \cdot e(n)^*\mathbf{x}(n) \tag{5}$$

where $\mathbf{w}(n)$ is the adaptive weight vector, $e(n)$ is the instantaneous DOA estimation error, $\boldsymbol{\mu}(n)$ is the variable step size, and α_1 is a shaping parameter set to 0.1.

The variable step size is defined as:

$$\mu(n) = \left(\frac{6}{1+e^{-\alpha\left(\|x(n)\|-\bar{x}\right)}}\right)\left(\frac{6}{1+e^{\alpha\left(\|x(n)\|-\bar{x}\right)}}\right) + \mu_{\min} \tag{6}$$

This ensures that the step size is large when the input norm is within a favorable range, enabling fast convergence, and diminishes for outlier values, enhancing stability and robustness in highly dynamic or noisy environments.

The output of the array is:

$$y(n) = \mathbf{w}(n)^H \cdot \mathbf{x}(n) \tag{7}$$

The instantaneous DOA estimation error is then defined as:

$$e(n) = d(n) - y(n) \tag{8}$$

where d(n) is the desired array output.

The sigmoid function is employed in the step-size formulation due to its non-linear, smooth, and bounded characteristics, making it ideal for adaptive systems. It provides a gradual adjustment of the step size in response to variations in the input signal norm. This behavior enhances convergence when the input is within a favorable range and improves robustness against large deviations, as it avoids abrupt changes. Compared to other non-linear functions like ReLU or tanh, the sigmoid function ensures boundedness in both gradient and output, making it particularly effective in real-time, noise-prone environments such as UAV-based disaster zones.

The array pattern is written as:

$$\mathbf{A}_P(\theta) = \left|\mathbf{w}(n)^H \cdot \mathbf{a}(\theta)\right| \tag{9}$$

Finally, the pseudo spectrum is obtained by taking the reciprocal of (9), yielding:

$$P(\theta) = \frac{1}{\mathbf{A}_P(\theta)} = \frac{1}{\left|\mathbf{w}(n)^H \, \mathbf{a}(\theta)\right|} \tag{10}$$

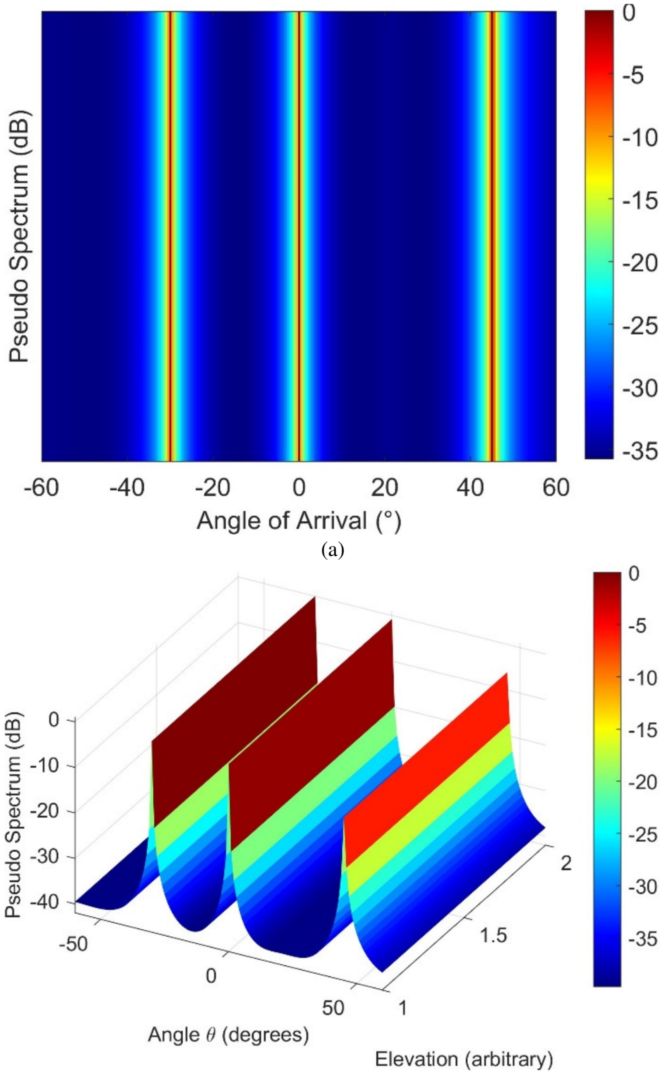
III. RESULTS AND CRITICAL ANALYSIS

In this section, we critically analyze the simulation results obtained for the proposed robust DOA estimation method utilizing the modified VSSLMS algorithm within UAV-assisted disaster management applications. The evaluation focuses on key performance metrics, including estimation accuracy, convergence speed, robustness to noise and non-stationary environments, and computational efficiency. The modified VSSLMS approach is compared against conventional LMS-based methods and, where relevant, subspace-based algorithms such as MUSIC. A UAV with a ULA of $M = 8$ antenna elements and an inter-element spacing of half a wavelength ($d = \lambda/2$) was modeled through simulations in a MATLAB environment. $N = 3$ uncorrelated narrowband signals that impinged from far-field sources at known DOAs, −30°, 0°, and 45°, were taken into consideration. To evaluate the performance under various noise situations, the SNR was adjusted between -5 dB and 20 dB.

A. Spatial Spectrum Analysis

Figures 4 and 5 illustrate the spatial spectrum results obtained for two different scenarios using the modified VSSLMS algorithm. In Figure 4, the DOAs of −30°, 0°, and 45° correspond to well-separated sources. The resulting 2D and 3D spatial plots display sharp and clearly defined peaks with minimal sidelobes, indicating precise DOA resolution.

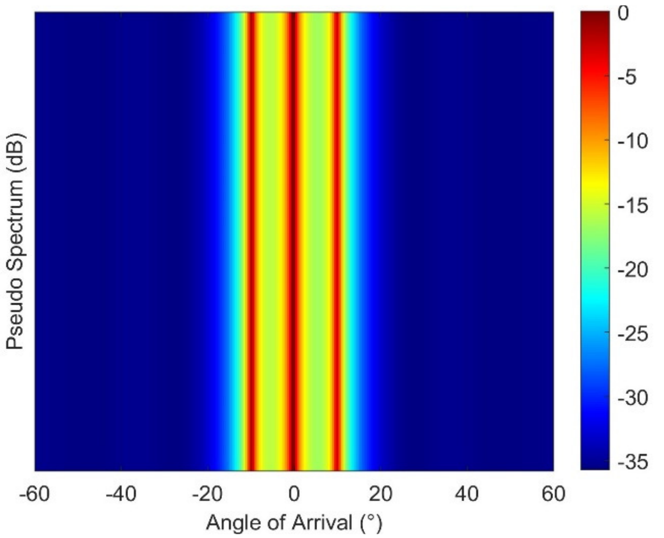
Conversely, Figure 5 demonstrates the algorithm's ability to resolve closely spaced sources at −10°, 0°, and 10°. Despite the proximity of the sources, the modified VSSLMS successfully distinguishes each DOA with high resolution and reduced interference leakage. Overall, the results in Figures 4 and 5 validate the robustness of the proposed algorithm under varying signal environments. Whether the sources are widely separated or closely spaced, the modified VSSLMS consistently achieves reliable DOA estimation.



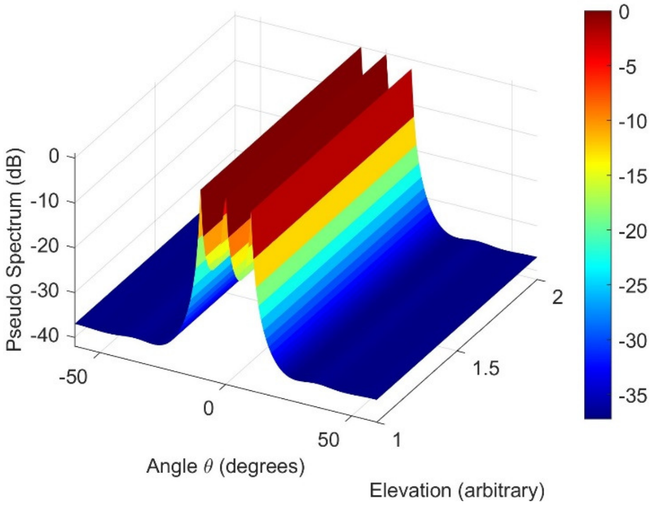
(a)

(b)

Fig. 4. Spatial spectrum for the estimation of well-separated targets using the modified VSSLMS with DOAs = −30°, 0°, and 45°: (a) 2D plot, (b) 3D plot.



(a)



(b)

Fig. 5. Spatial spectrum for the estimation of closely spaced targets using the modified VSSLMS algorithm with DOAs = −10°, 0°, and 10°: (a) 2D plot, (b) 3D plot.

B. Direction of Arrival Estimation Accuracy

Figures 6 and 7 illustrate the variation in DOA estimation accuracy, measured by the Root Mean Square Error (RMSE), for all algorithms, with respect to SNR and the number of snapshots. As expected, the RMSE decreases consistently with an increase in both SNR and the number of snapshots. We compare the performance of the proposed method with state-of-the-art methods, including MUSIC [5], root-MUSIC [7], ESPRIT [8], modified MUSIC [16], and Nyström MUSIC (NMUSIC) [17]. As shown in Figure 6, the proposed modified VSSLMS algorithm demonstrates superior accuracy across the entire SNR range (−5 dB to 20 dB), consistently outperforming traditional subspace methods by maintaining lower RMSE, particularly under low SNR conditions. This performance highlights the algorithm's resilience in noisy and unpredictable environments typical of disaster scenarios. Moreover, Figure 7 illustrates that as the number of snapshots increases, the estimation accuracy improves for all methods. Nevertheless, the modified VSSLMS consistently achieves lower RMSE with fewer snapshots, indicating faster convergence and enhanced tracking performance with limited data, a critical advantage in time-constrained emergency deployments.

C. Computational Complexity

In real-time UAV-assisted operations, computational efficiency is vital. Recent efforts, such as the Unitary Root-MUSIC with Nyström approximation [18], have reduced the computational load in 3D sparse array processing by avoiding full eigen-decomposition while maintaining high resolution. Similarly, adaptive Nyström-based spectral analysis in coprime arrays [19] offers efficient DOA estimation by approximating large covariance matrices, significantly lowering complexity in structured array configurations. Compared to these, our proposed VSSLMS-based method eliminates subspace processing altogether, enabling even faster and lighter implementation suitable for UAV-embedded systems.

Figure 8 presents a normalized comparison of the computational complexity among the evaluated algorithms, providing a clear perspective on their relative resource requirements. The results indicate that the modified VSSLMS algorithm achieves the lowest computational burden, primarily because it avoids the eigen-decomposition and spatial smoothing steps that are mandatory in several classical approaches. Following the modified VSSLMS in terms of efficiency is NMUSIC, which leverages matrix approximations to reduce complexity. In contrast, algorithms such as MUSIC, root-MUSIC, and modified MUSIC involve full eigen-decomposition, leading to significantly higher resource consumption. This makes modified VSSLMS particularly well-suited for embedded systems on-board UAVs where processing power is limited, and latency must be minimized.

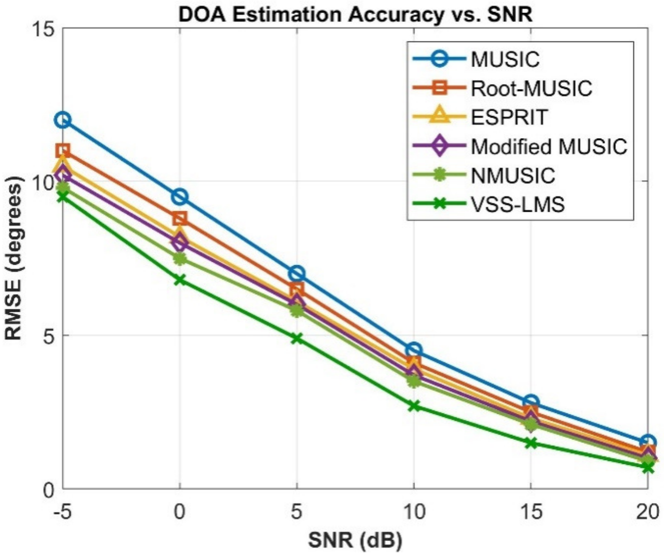


Fig. 6. RMSE versus SNR for the proposed modified VSSLMS algorithm and baseline DOA estimation methods.

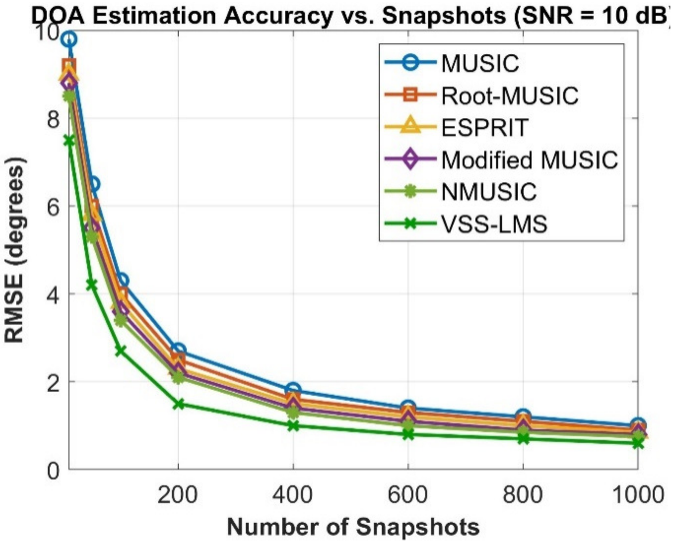


Fig. 7. RMSE versus the number of snapshots for the proposed modified VSSLMS algorithm and baseline DOA estimation methods.

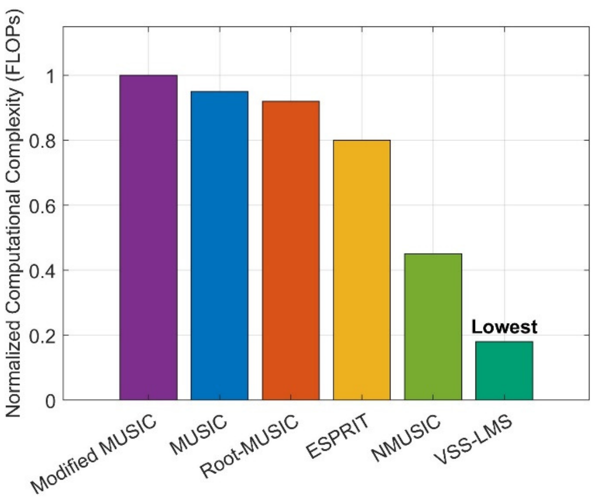


Fig. 8. Normalized computational complexity of the proposed modified VSSLMS algorithm and baseline DOA estimation methods.

In the context of embedded UAV systems, the proposed method offers significant advantages. The algorithm avoids the computational bottlenecks associated with subspace-based DOA estimators, such as EVD or matrix inversions. Its core operations, comprising scalar multiplications and vector updates, are inherently low-complexity and suitable for real-time processing on UAVs with limited onboard computation capabilities. As such, the algorithm is practical for deployment in embedded environments where power, weight, and latency constraints are critical.

IV. CONCLUSION

This study presents a robust and computationally efficient Direction of Arrival (DOA) estimation approach based on the modified Variable Step-Size Least Mean Squares (VSSLMS) algorithm, tailored for Unmanned Aerial Vehicle (UAV)-assisted disaster management scenarios. By adaptively adjusting the step size in response to dynamic signal environments, the proposed method achieves rapid convergence and high estimation accuracy, even under low Signal-to-Noise Ratio (SNR) and closely spaced signal conditions. Simulation results demonstrate that the modified VSSLMS algorithm not only outperforms traditional subspace-based techniques in terms of accuracy but also significantly reduces computational complexity, making it well-suited for real-time deployment on resource-constrained UAV platforms. The algorithm's ability to operate effectively with fewer snapshots further reinforces its applicability in urgent and volatile disaster zones where time and resources are limited. By integrating the modified VSSLMS into UAV systems, emergency responders can benefit from enhanced situational awareness, faster source localization, and improved decision-making in critical missions.

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