An ISAC-Enabled IFF System Using AESA and FMCW Radar for Enhanced Target Identification

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Abstract

Integrated Sensing and Communication (ISAC) systems are emerging as a cornerstone for next-generation wireless networks by seamlessly combining radar sensing and communication functionalities. This paper presents a deployment oriented comparative analysis of two key radar technologies Active Electronically Scanned Array (AESA) radar and Frequency Modulated Continuous Wave (FMCW) radar within ISAC enabled Identification Friend or Foe (IFF) frameworks for enhanced target identification. AESA radar exhibits superior long-range detection, narrow beamwidth, and high angular resolution, enabling precise angle-of-arrival estimation and robust target tracking critical for defense and advanced automotive applications. Conversely, FMCW radar provides cost-effective, high-resolution short-range sensing with broader beamwidth, making it ideal for collision avoidance and indoor localization. The integrated ISAC-IFF system leverages the complementary strengths of AESA and FMCW radars to improve situational awareness by accurately classifying targets as friend or foe based on their echo signatures. Simulation results demonstrate AESA's dominance in long range and velocity estimation, while FMCW excels in close range target resolution. This study offers valuable insights for optimizing radar selection and integration in ISAC systems, advancing the development of adaptive, reliable, and precise target identification frameworks for next-generation wireless and security technologies.

Keywords– AESA, FMCW, IFF ,ISAC, radar range and echo signals.

I. INTRODUCTION

Integrated Sensing and Communication (ISAC) systems represent a significant advancement in the development of next-generation wireless networks, particularly as research progresses toward 6G technologies. ISAC systems promise to enhance spectrum utilization, increase network efficiency, and reduce the complexity of wireless hardware. By simultaneously addressing both communication and sensing tasks, ISAC opens new avenues for improving system performance while optimizing the use of available resources. However, the integration of cutting-edge technologies, such as Reconfigurable Intelligent Surfaces (RHS), offers a new paradigm in ISAC, yet remains an area that is still underexplored in the literature [1], [2].A critical component of ISAC research involves the development of robust channel models that can accurately represent real-world environments, particularly with the advent of high-frequency millimeter-wave (mmWave) and Terahertz (THz) communication systems [3], [4]. These models are essential for optimizing both communication and sensing capabilities, while addressing challenges such as interference and mobility. Advances in beamforming techniques are vital in improving ISAC system performance by enhancing signal transmission and target detection accuracy. Recent studies have highlighted the potential of hybrid beamforming methods for achieving efficient communication and radar sensing with minimal hardware complexity [5].A key technology in ISAC systems is the use of phased-array architectures, which provide scalable solutions that enable dynamic beam steering for simultaneous communication and radar sensing tasks [6]. The incorporation of RHS and metasurface technologies has further revolutionized the field by allowing for adaptive beamforming that optimizes electromagnetic wave propagation, enhancing both communication links and sensing performance [7], [8].

By integrating Reconfigurable Intelligent Surfaces (RIS), ISAC systems can dynamically control wavefronts to enable enhanced spatial coverage and effective interference suppression [9], [10]. However, despite these advancements, challenges remain in managing multi-user interference, optimizing beamforming techniques, and efficiently estimating channel conditions.In this context, the use of advanced radar technologies, such as AESA and FMCW radars, holds great potential in improving ISAC systems' performance. AESA radar, known for its higher resolution and superior beamforming capabilities, offers significant advantages in multi-target detection and tracking in ISAC applications. In contrast, FMCW radar, while more cost-effective, exhibits lower resolution and reduced precision in target localization. This paper addresses the gap between AESA and FMCW radars, comparing their performance in ISAC scenarios, particularly in terms of beamforming efficiency, target detection accuracy, and interference management. ISAC have increasingly focused on overcoming practical deployment challenges, particularly in near-field environments and intelligent surface-based systems. For instance, the issue of phase nonlinearity in near-field ISAC has been addressed through lifted super-resolution techniques, enabling high-precision sensing at short ranges [16]. In parallel, the integration of intelligent metasurfaces, such as RIS, has been identified as a transformative enabler of ISAC, providing dynamic control over electromagnetic wave propagation [17]. Data-driven approaches are also gaining traction, leveraging machine learning to adaptively optimize sensing and communication tasks in complex and dynamic environments [18]. Furthermore, the role of cognitive radar in ISAC has been emphasized as a key step toward more autonomous and context-aware systems [19]. Complementing these efforts, hybrid technologies such as spread spectrum and photonics are being explored to support high-speed, low-latency ISAC implementations in photonics-assisted architectures [20].

In order to overcome the difficulties and enhance the radar's performance, we suggested using the AESA radar, which also performs admirably in ISAC multiple targets. The following sections of this work are organized as follows.The paper is structured as follows: Section II presents a detailed overview of radar-based systems, focusing on the AESA and FMCW radars. Section III evaluates the performance of the two radars and compares the results by summarizing the simulation data, followed by Section V drawing final conclusions.

II. System Overview

This section explains the transmit and receive signal expression of the FMCW radar in Subsection II-A and the AESA radar in Subsection II-B.

A. FMCW Radar

Assume that the FMCW radar employs a phase-coded signal s(t) for modulating changes in phase within a chirp signal via chirp bandwidth of B and chirp duration of T. The chip duration is $T_c = \frac{T}{N_c}$ for fast-time coding, and there are N_c, chips per chirp. Thus, the coding bandwidth is determined by the number of chips within the chirp, as $B_c = \frac{N_c}{T}$.To avoid spectrum leakage, we assume that the code bandwidth is significantly smaller than the chirp bandwidth. The transmitted FMCW waveform can be represented as:

$$x_t(t) = s(t)e^{-j(2\pi f_c t + \pi k t^2)} \tag{1}$$

The chirp slope is represented by $k = \frac{B}{T}$, while the carrier frequency is denoted by f_c. A target reflects the broadcast signal (1) at a constant speed, and it arrives with the following round-trip delay:

$$x_r(t) = \alpha_0 s\big(t - \tau(t)\big)e^{-j\left(2\pi f_c(t-\tau(t)) + \pi k(t-\tau(t))^2\right)} \tag{2}$$

The complex amplitude α_0 is proportional to the effects of target backscattering and propagation, whereas τ(t) represents the round-trip time. The following is a representation of the round-trip delay: as:

$$\tau(t) = \frac{2(R_0+\upsilon_0(t))}{c} = \tau_0 + \frac{2\upsilon_0}{c}(t) \tag{3}$$

During dechirping, the received signal is merged with the complex conjugate of the uncoded chirp signal, with c representing the speed of light, R_0 representing the range, and υ_0 representing the velocity. The dechirped signal may therefore be represented as the following [5]:

$$x_b(t) = x_r(t)e^{j(2\pi f_c t + \pi k t^2)}$$
$$= \alpha_0 s\big(t-\tau(t)\big)e^{j(2\pi f_c \tau_0 + 2\pi(k\tau_0+f_d)t - \pi k {\tau_0}^2)}$$
$$\approx \alpha_0 s(t-\tau_0)e^{j(2\pi f_b t)} \tag{4}$$

The beat frequency is represented by $f_b = k\tau_0 + f_d$. In fast-time processing, the Doppler frequency shift $f_d = \frac{2\upsilon_0 f_c}{c}$ can be ignored as it is typically much smaller than the one range cell $f_d \ll {f_s}/{N}$, where f_s is the sampling frequency of the beat signal and N is the number of fast-time samples. We incorporate all the constant terms of signal processing into $\alpha_0$without losing generality.

B. AESA Radar

AESA radar, using phased-array, principles where the transmitted and received signals are both processed through beamforming. AESA focus on the beamforming and array response characteristics central to AESA operations. The transmitted signal from an AESA radar is formed by applying phase shifts to each element in the array to steer the beam towards a desired direction θ. If we denote the baseband signal to be transmitted as s(t), the transmitted signal x(t) for an array with N elements is given by:

$$x(t) = \sum_{n=1}^{N} w_n s(t)\, e^{j(2\pi f_c t + \phi_n)} \tag{5}$$

Here, d_n is the location of the n-th element in the array, $w_n$is the amplitude weighting applied to the n-th element, f_c is the carrier frequency, $\phi_n = -kd\sin\theta$ is the phase shift applied to the n-th element to steer the beam towards θ, and $k = \frac{2\pi}{\lambda}$ is the wave number, where λ is the wavelength of the transmitted signal.The backscattered signal is received by the radar after the transmitted signal bounces off a target at angle θ and range R. The received signal r(t) at each element includes both the propagation time delay and the Doppler shift, if the target is moving. The received signal at the m-th element in an array of N receiving elements can be represented as follows:

$$r_m(t) = \alpha\, s\left(t\frac{2R}{c}\right) e^{j(2\pi f_c t - 2\pi f_d + \psi_m)} \tag{6}$$

Where α represents the reflection coefficient (amplitude and phase) of the target,$\tau = \frac{2R}{c}$is the round-trip propagation delay for range R(with ccc as the speed of light),$f_d = \frac{2\upsilon}{\lambda}$ is the Doppler frequency due to target radial velocity υ,$\psi_m = -kd_m\sin\theta$ is the phase shift for the mmm-th element due to the target's angular position θ, and $s\left(t-\frac{2R}{c}\right)$is the time-delayed version of the transmitted signal accounting for the two-way travel time.

$$r_m(t) = \alpha s(t-\tau)e^{j(2\pi f_c t - 2\pi f_d + \psi_m)}$$
$$\approx \alpha s(t-\tau)e^{j(2\pi f_b t + \psi_m)} \tag{7}$$

The beat frequency f_b is the difference between the instantaneous frequencies of the sent and received signals when the received signal $r_m(t)$ and the transmitted signal s(t) are combined.

III. Results and Discussion

This section examines numerical results and provides a knowledge of the FMCW and AESA radar's, Then, using the simulation settings listed in Table 1, compare the performance of AESA radar against FMCW radar at various targets.

TABLE1

SIMULATION PARAMETERS

Parameters	**Symbols**	**Values**
Speed of Light	c	3×10^8
Carrier Frequency	f_c	77GHz
Wavelength	$\lambda = {}^{c}/_{f_c}$	3.89 mm
Bandwidth	B	150MHz
Chirp Duration	T	5.5ms
Sampling Frequency	$f_s = {}^{N_c}/_{T}$	186.18kHz
Target Angles	θ-target	[-10°, 5°, 20°]
Beam Steering Angle	θ	30°
Element Spacing	${}^{\lambda}/_{2}$	1.44mm

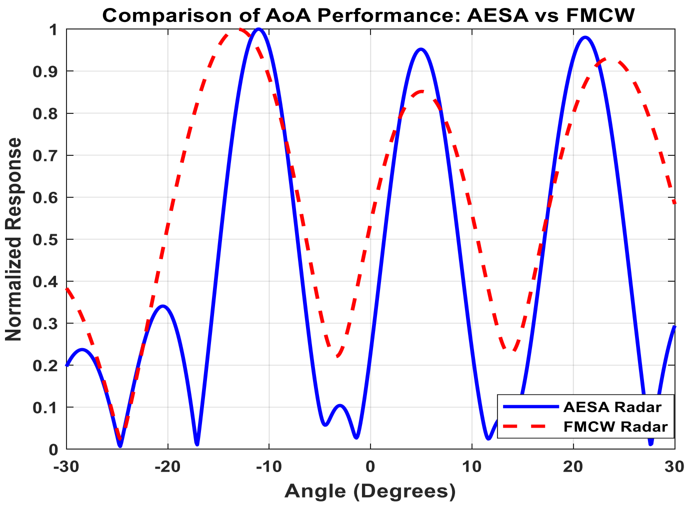

Fig.1 Comparison of AoA Performance

The comparison of the Angle of Arrival (AoA) performance between the AESA and FMCW radar systems, as shown in Fig._1, highlights significant differences in angular resolution and precision in target location estimation. The AESA radar exhibits significantly sharper response peaks, indicating higher angular resolution and, consequently, more accurate AoA estimations. This sharpness is a direct result of the system's ability to focus the radar beam more narrowly, which improves its precision in detecting the target's angle. In contrast, the FMCW radar shows broader response peaks, signifying lower resolution and less precision in estimating the exact location of the target. The primary distinction between the two systems lies in their beamforming capabilities. The AESA radar's advanced beamforming allows it to achieve narrower beams, enabling better focus on specific angles with higher precision. Additionally, the narrower beamwidth enhances the system's ability to reject interference, improving overall performance. Conversely, the FMCW radar produces a wider main lobe due to its simpler design, leading to reduced accuracy in AoA estimation. This broader beam results in less precise angular measurements, making FMCW less suitable for high-precision target tracking applications. AESA outperforms FMCW in terms of angular resolution and precision. AESA achieves sharper response peaks due to its superior beamforming capabilities, which allow for narrower beams, better target localization, and improved interference rejection. This makes AESA ideal for high-accuracy applications like military and advanced automotive systems. In contrast, FMCW radar, with its broader beams and lower resolution, is more suitable for short-range, cost-effective applications where precision is less critical.

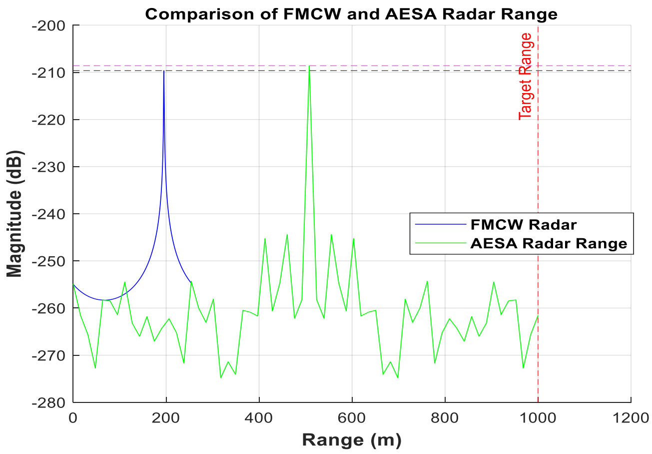

Fig.2 Compare the performance of FMCW and AESA

Fig.2 shows the performance of FMCW and AESA to estimate the range at 1km.FMCW radar demonstrates strong performance in detecting targets at short ranges (up to 200 meters) with a high peak magnitude, but experiences a significant drop in signal strength at longer distances, especially beyond 600 meters. Its ability to detect long-range targets, such as those at 1k meters, is limited due to signal attenuation. AESA radar exhibits superior performance in detecting long-range targets, successfully identifying the target at 1k meters with a noticeable peak. However, its performance at shorter ranges (200-600 meters) is less consistent, showing fluctuations in signal strength. AESA's electronic beam – forming enhances its long-range detection capabilities but introduces more system complexity. FMCW radar is well-suited for short-range precision, while AESA radar is optimal for long-range detection. The trade-off lies between FMCW's simplicity and effectiveness at shorter ranges versus AESA's capability for long-range sensing, albeit with higher complexity and cost.

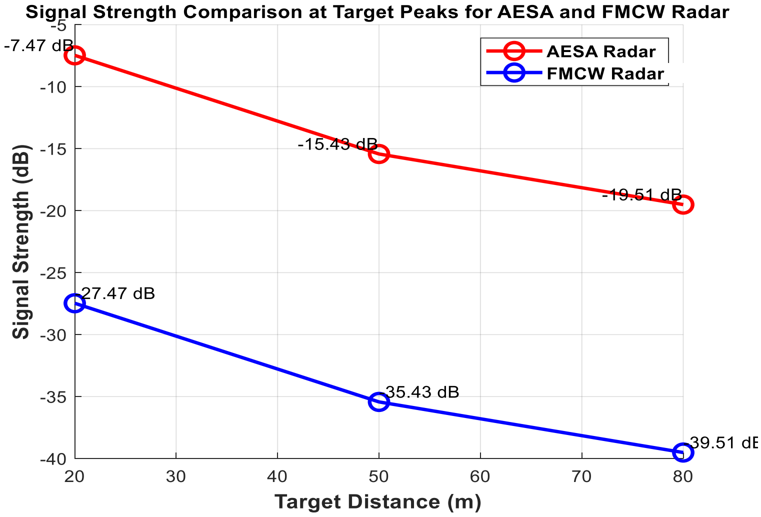

Fig.3 Comparison plot for AESA and FMCW in multiple targets at 20m, 50m and 80m.

Then varying range below 100m for multi targets at 20m,50m and 80m. Fig. 3 shows that the results of the comparative analysis AESA and FMCW radar systems reveal significant differences in signal strength as a function of target distance. At a target distance of 20 meters, the AESA radar exhibits a signal strength of approximately 0 dB, indicating effective performance in close-range detection. In contrast, the FMCW radar records a lower signal strength of around -40 dB, suggesting limited efficacy at this range. As the target distance increases to 50 meters, the AESA radar maintains a positive signal strength, whereas the FMCW radar continues to decline, reaching approximately -48 dB at 80 meters. This trend demonstrates that the AESA radar consistently outperforms the FMCW radar, particularly at greater distances. The results underscore the superiority of the AESA system for applications requiring long-range detection capabilities, making it suitable for critical operations such as air traffic control and military surveillance. Conversely, the FMCW radar may be better suited for short-range applications, where its lower signal strength may still yield effective results. By the integrated communication performance of the system the target is identified as friend or foo based on the received echo signal, which is extended for military applications. Overall, the comparison reveals in Table 2 that AESA radar offers superior performance in AoA estimation accuracy, owing to its higher array gain, better beamforming capabilities, and narrower beamwidth. While FMCW radar is more cost-effective and suitable for short-range, less demanding tasks, AESA radar outperforms it in precision-sensitive applications, providing better performance in terms of angular resolution and target localization accuracy.

TABLE 2 DEPLOYMENT-ORIENTED COMPARISON OF AESA AND FMCW RADARS IN ISAC

Parameter	**AESA Radar**	**FMCW Radar**
Beamwidth	Narrower (higher resolution)	Broader (lower resolution)
Main Lobe Width	Narrower (higher angular accuracy)	Wider (lower angular accuracy)
Application	High precision (e.g., military, automotive)	Cost-effective for short-range (e.g., collision avoidance)
Range	Long Range	Short Range
Performance	Higher AoA estimation accuracy	Lower AoA estimation accuracy

IV. CONCLUSION

This paper explored the integration of AESA radar within ISAC frameworks, comparing its performance against FMCW radar in various operational scenarios. Through numerical simulations and analytical evaluations, AESA radar demonstrated superior beamforming capabilities, higher angular resolution, and improved long-range detection compared to FMCW radar. The findings highlight AESA's potential for high-precision target tracking and interference mitigation, making it an ideal candidate for advanced military, surveillance, and automotive applications.Furthermore, the study emphasizes the role of ISAC in enhancing situational awareness through integrated sensing and communication functionalities. By leveraging AESA's electronic beamforming, ISAC systems can achieve real-time, high-accuracy target identification, facilitating applications such as IFF (Identification Friend or Foe) in defense systems. While FMCW radar remains a viable choice for short-range, cost-effective solutions, AESA radar proves essential for applications demanding high precision and extended range capabilities.Future work will focus on optimizing AESA-based ISAC architectures by incorporating deep learning techniques for adaptive beamforming and interference management. Additionally, real-world validations through experimental setups will further refine the practical feasibility of these advancements, ensuring robust and scalable deployment in next-generation wireless and radar systems.

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