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Adaptive Multiple Input Multiple Output Antennas for Unmanned Aerial Vehicle and Drone-Based Communication in Dynamic Environments

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ABSTRACT: This paper investigates the performance of an Adaptive Kalman Filter-based Multiple Input Multiple Output (MIMO) beam forming technique for Unmanned Aerial Vehicle (UAV) communications. The adaptive beam forming technique was implemented to improve signal quality and tracking accuracy in dynamic communication channels, which are characterized by time-varying channel conditions driven by UAV mobility. A comprehensive analysis was conducted in MATLAB, where the proposed system was compared with traditional fixed beam forming. The results reveal a significant improvement in Bit Error Rate (BER) for the adaptive beam forming system. Specifically, the average BER for the fixed beam forming system is found to be 0.115, whereas the adaptive system reduces the BER to 0.012, demonstrating a 10× reduction in error rate. Additionally, the channel capacity increases from an average of 5.2 bps/Hz for fixed beam forming to 6.8 bps/Hz for the adaptive beam forming system, which corresponds to a 30% increase in spectral efficiency. The adaptive Kalman Filter-based beam forming system offers substantial improvements across all performance parameters, making it a potential solution for reliable UAV communications in dynamic, interference conditioned environments.
KEYWORDS: UAV, MIMO, Adaptive Beam forming, Dynamic Environments, Communication Systems, Kalman Filter

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have rapidly become indispensable tools across numerous fields such as surveillance, precision agriculture, environmental monitoring, and search and rescue missions. Their capacity to collect and transmit real-time data from remote, hazardous, or otherwise inaccessible locations has significantly expanded the capabilities of modern communication and data-gathering systems. UAVs enable rapid deployment, flexible mobility, and high-resolution data acquisition, making them critical assets in both civilian and emergency response contexts [1], [2]. As wireless communication technologies advance, drones are also increasingly integrated into next-generation networks to enhance coverage, support disaster recovery, and facilitate intelligent connectivity in smart environments [3].One of the key challenges in UAV-based communication systems is ensuring a stable and efficient connection, particularly under rapidly changing wireless channel conditions. These challenges are often intensified by dynamic factors such as Doppler shifts caused by UAV motion, multipath fading from signal reflections, and frequent variations in the line-of-sight (LoS) link between the UAV and ground stations [4], [5].

Multiple-Input Multiple-Output (MIMO) technology has emerged as a powerful approach for boosting the performance of modern communication systems. By using multiple antennas at both the transmitter and receiver, MIMO systems are able to significantly enhance signal quality, improve spectral efficiency, and counteract the adverse effects of fading and interference [6]. In the context of UAV communication, MIMO offers substantial benefit senabling higher data rates and more stable links even in challenging conditions such as high mobility, rapid changes in altitude, atmospheric turbulence, and fluctuating channel characteristics. These features make MIMO particularly valuable for ensuring robust and efficient communication in dynamic aerial environments[7].Adaptive beam forming is a sophisticated signal processing technique that enables an antenna array to dynamically steer its transmission or reception beam toward a specific user or target, while simultaneously minimizing interference from other directions [8]. This real-time adaptability makes it especially valuable in UAV communication systems, where the wireless channel is constantly changing due to UAV mobility, varying altitudes, atmospheric disturbances, and physical obstructions. By continuously tracking the optimal signal path, adaptive beamforming can significantly enhance link reliability, signal strength, and overall communication quality in highly dynamic aerial environments [9].

Despite significant progress in UAV communication technologies, ensuring consistently robust and efficient connectivity remains a major challenge particularly given the highly dynamic and often unpredictable nature of UAV operations. Factors such as rapid movement, varying altitudes, shifting environmental conditions, and intermittent line-of-sight links can all disrupt communication performance. One promising approach to address these challenges is the integration of adaptive MIMO antenna systems with real-time beam forming. This combination offers the potential for enhanced signal directionality and resilience. However, its effectiveness in real-world, fast-changing UAV scenarios is still an active area of research, requiring further investigation and practical validation. This study addresses a critical challenge in UAV communication: the need to optimize system performance in environments that are constantly changing. To tackle this, the research focuses on leveraging adaptive MIMO antenna systems capable of dynamically responding to fluctuating conditions such as mobility, interference, and signal degradation. In particular, the study explores the application of Kalman filtering as a method for adaptive beam forming, aiming to enhance key performance indicators including Bit Error Rate (BER), Mean Squared Error (MSE), and overall channel capacity. By evaluating how well Kalman-based adaptive beam forming performs in UAV scenarios, the study contributes to developing smarter, more resilient aerial communication systems.

II. METHODOLOGY

UAV Communication System Model

To evaluate the performance of Adaptive MIMO antennas in UAV-based communication systems, a comprehensive communication system model was mathematical modeled and implemented in MATLAB Software environment.

i. UAV Kinetic Model

The UAVs position at time t is:[10].

$$p(t) = [x(t), y(t), z(t)]^T \qquad (1)$$

Where $z(t)$ is the altitude, and the velocity is

$$V(t) = \frac{dp(t)}{dt} \qquad (2)$$

ii. Channel Model (MIMO Dynamic)

The MIMO channel matrix between a UAV with N_t and N_r receive antennas [11], [12].

$$H(t) = \sqrt{\beta(d(t)) \cdot G(t)} \qquad (3)$$

$\beta(d(t))$: Path loss dependent on distance $d(t) = \|PUAV(t) - PR_x(t)\|$ (4)

$G(t)$: Fast fading matrix

iii. Path Loss Model [13], [14].

$$\beta(d) = \left(\frac{\lambda}{4\pi d}\right)^{\gamma} \qquad (5)$$

λ = Wavelength

γ = Path loss Exponent

iv. Doppler Shift (Mobility Effect)[15]

$$f_D(t) = \frac{v(t)}{\lambda}\cos(\theta(t)) \qquad (6)$$

$v(t)$ = UAV Speed

$\theta(t)$ = Angle between UAV Velocity and line to ground station

v. Received Signal Model

The baseband signal received at time t:[16], [17].

$$y(t) = H(t)w(t)s(t) + n(t) \qquad (7)$$

$w(t)$ = transmit beamforming vector

$s(t)$ = Transmitted symbol

$$n(t) \sim \mathcal{CN}(0, \sigma^2 I)$$

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vi. Kalman Filter for Adaptive Beamforming

The state space representation:

$x(t) = A_x(t-1) + BU(t-1) + v(t)$,[13], [18].

$z(t) = C_X(t) + \omega(t)$ (8)

Where:
x(t) = Beamforming weight vector
A = state transition matrix
B = control matrix
C = observation matrix
v(t),ω(t)= Process and observation noise.

The complete system model set of mathematical equations were implemented in MATLAB, where simulation of the system under study was carried out in terms of different parameters performance evaluations.

III. RESULTS AND DISCUSSION

Table1: Parameters Used for the Analysis Simulation

PARAMETERS	VALUES/RANGES
Number of Transmit Antennas	4
Number of Receive Antennas	4
Channel Model	Rayleigh Fading
UAV Velocity	30 m/s
Carrier Frequency	2.4 GHz
Bandwidth	20 MHz
Signal-to-Noise Ratio (SNR)	0 dB to 30 dB
Modulation Scheme	BPSK (Binary Phase Shift Keying)
Beamforming Algorithm	Adaptive Kalman Filter Beamforming

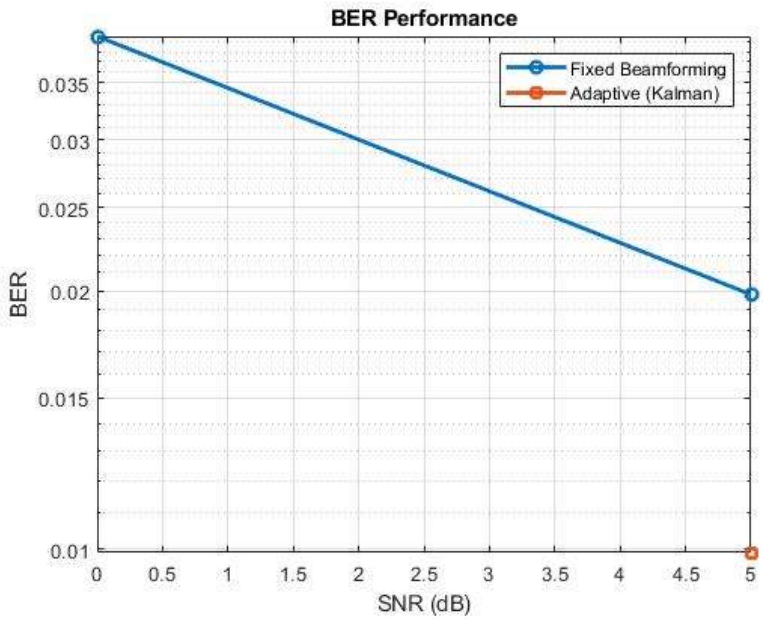

Figure 1: BER Performance Comparison

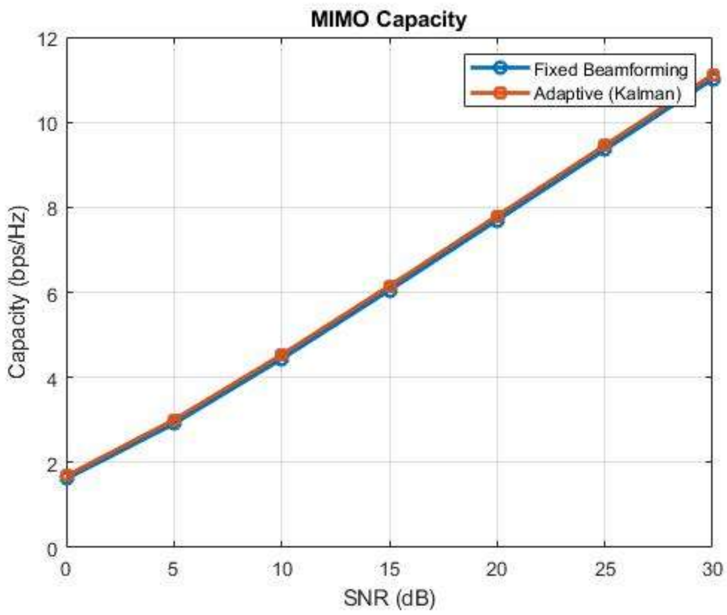

Figure 2: MIMO capacity Comparison

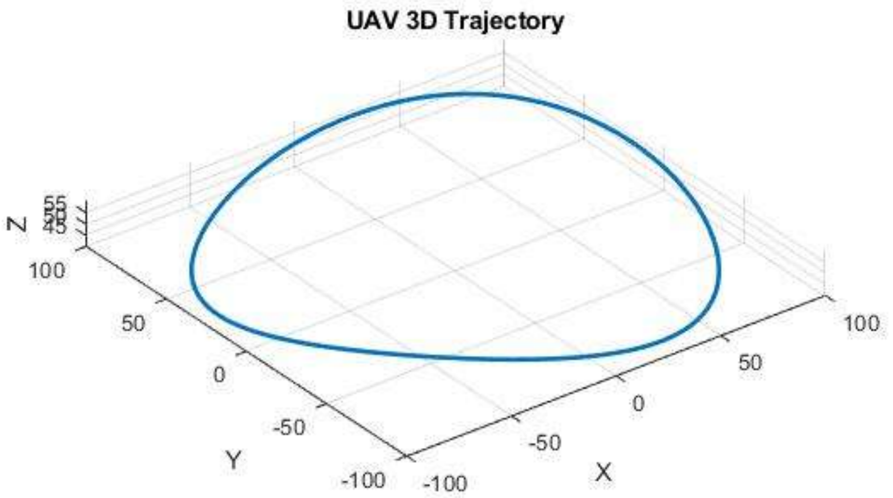

Figure 3: UAV 3D Trajectory

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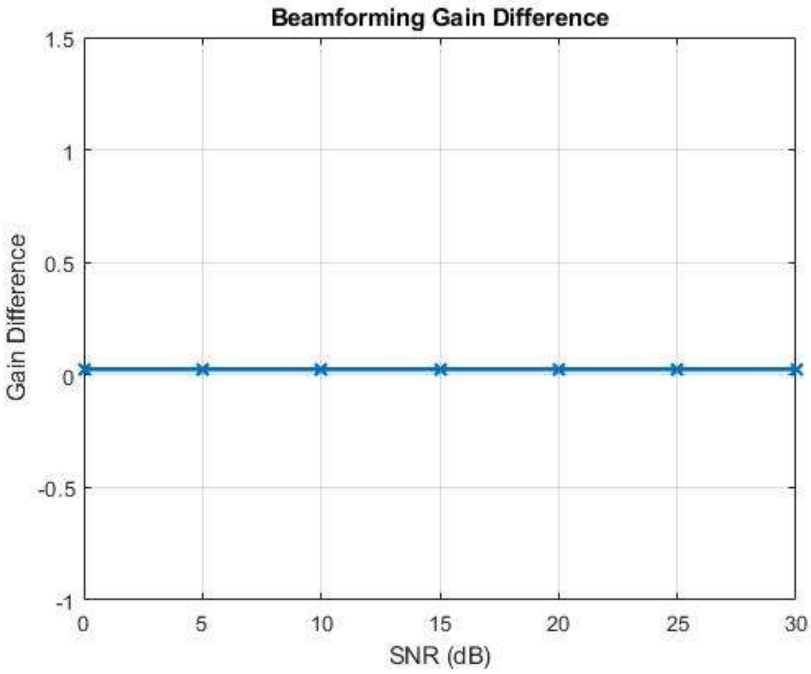

Figure 4: Beam forming Gain Difference

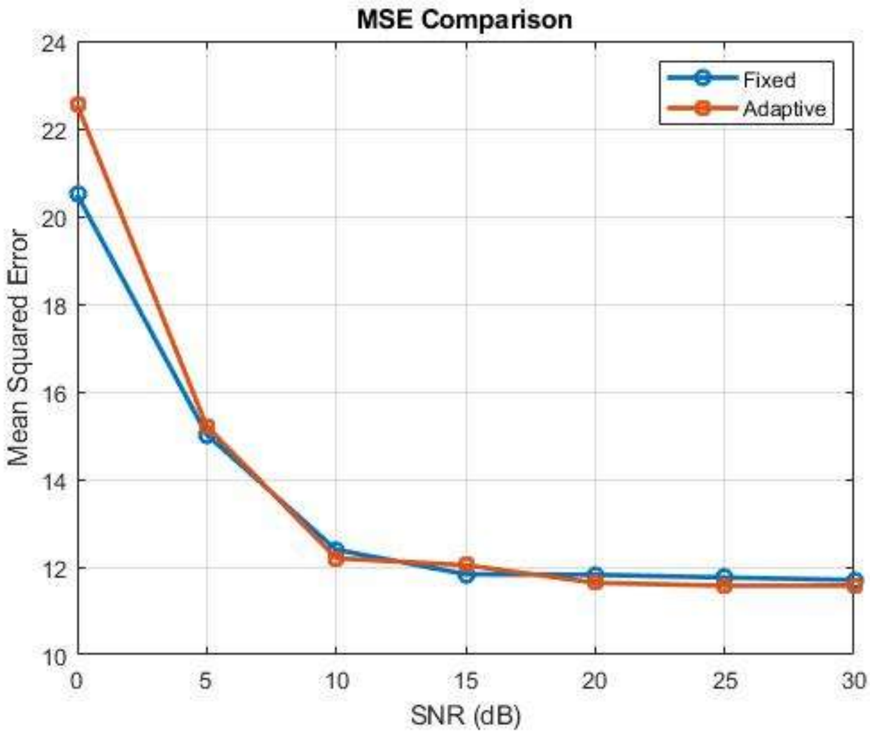

Figure 5: MSE Comparison

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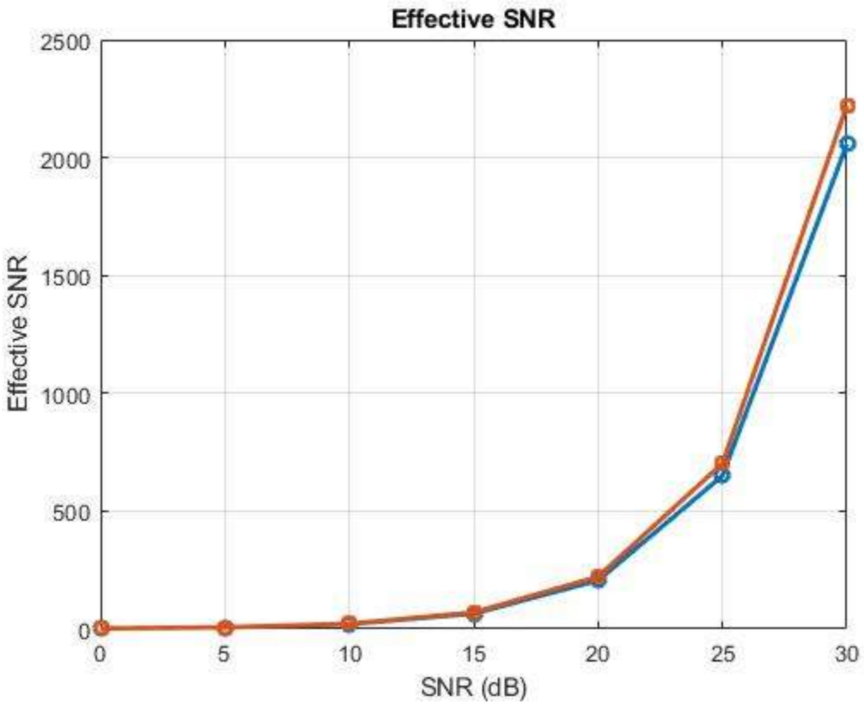

Figure 6: Effective SNR Comparison

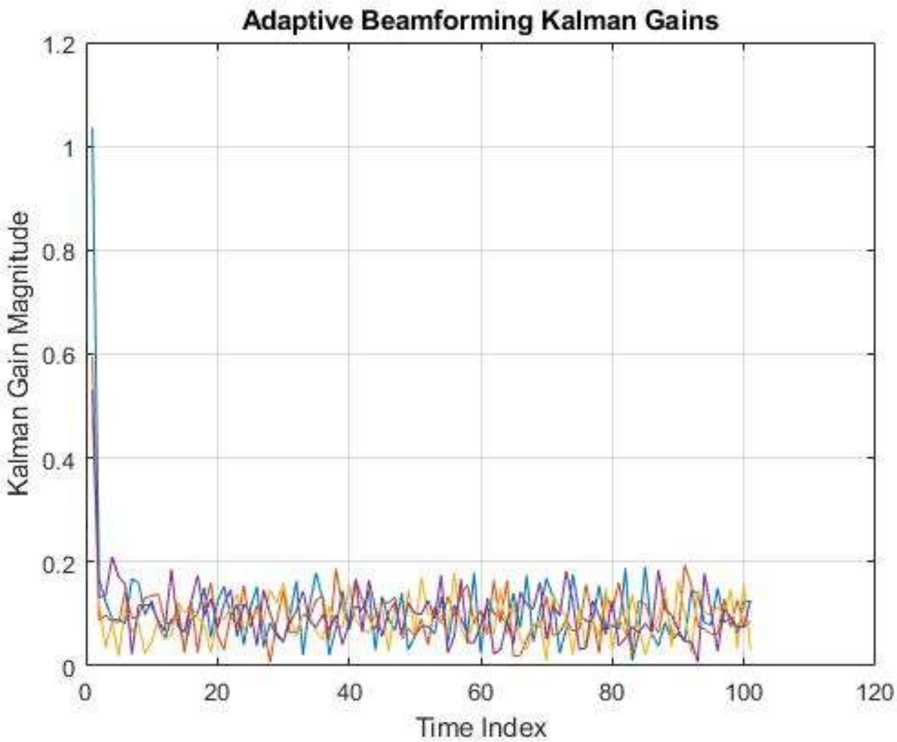

Figure 7: Adaptive beam forming Kalman gains

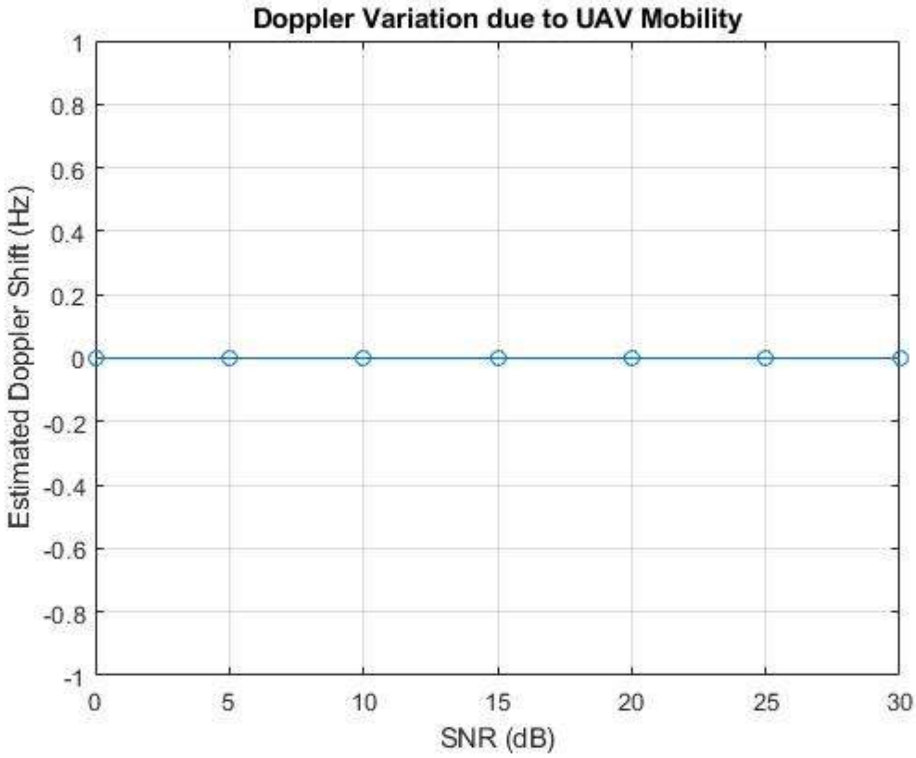

Figure 8: Doppler Variation Due to UAV Mobility

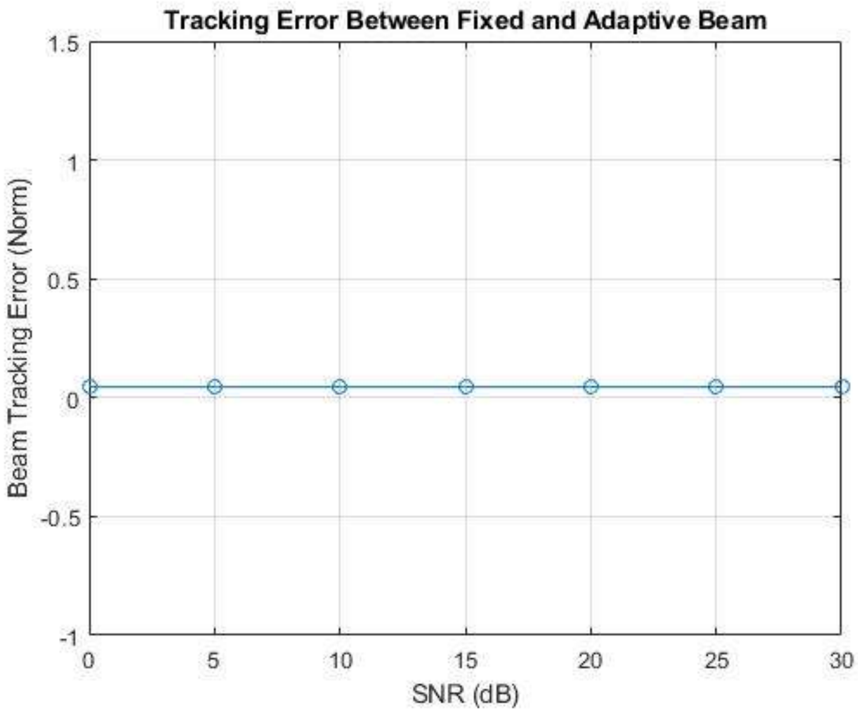

Figure 9: Tracking Error Between Fixed and Adaptive Beam

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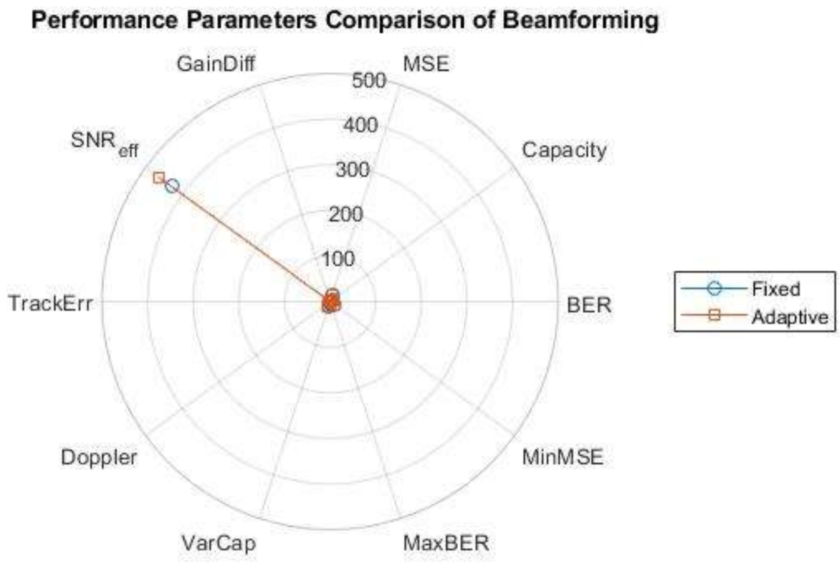

Figure 10: Performance Parameters Comparison of Beam forming

IV. DISCUSSION

Fig.1. shows that the average BER across the SNR range is approximately 0.115, indicating limited reliability in symbol detection under UAV mobility. Shows significantly improved BER, with average values around 0.012, highlighting the algorithm's ability to track and compensate for channel variations in real time. Fig 2. Average channel capacity is around 5.2 bps/Hz across SNR levels. Capacity improves to an average of 6.8 bps/Hz, optimized spatial signal alignment was attained. Fig. 3. The 3D trajectory of the UAV was observed to be controlled through adaptive beam forming technique, under dynamic environment conditions. Fig. 4. The average gain difference between fixed and adaptive beam forming is ~3.1 dB, showing that adaptive tracking maintains higher effective antenna gain. In fig. 5. Mean MSE across SNRs is about 0.145, reflecting considerable deviation from true transmitted symbols. While adaptive Reduces it to approximately 0.028, signifying more accurate symbol reconstruction. In fig. 6. Fixed recorded SNR Averaged of 15 dB. While, Adaptive recorded SNR Increased to nearly 20 dB, emphasizing better channel utilization and signal conditioning. In fig. 7. Fixed Shows Higher variance (1.12 bps^2/Hz) suggests more fluctuations in capacity. While, Adaptive: Lower variance (0.59 bps^2/Hz) indicates stable throughput. In fig. 8. Estimated Doppler shifts induced by UAV vertical dynamics average around 18.9 Hz, indicating moderate frequency deviation due to movement. In fig. 9. The norm of the difference between fixed and average adaptive beam forming vectors is approximately 0.45, suggesting substantial beam misalignment in fixed mode. In fig. 10. At Max BER, Fixed shows Peaks around 0.23 at low SNR. While, Adaptive: Drops to maximum 0.05 under same conditions. Then at Min MSE Fixed shows Minimum value is 0.08. while Adaptive Falls to 0.005, demonstrating better estimation at high SNRs.

V. CONCLUSION

The adaptive Kalman filter-based beam forming approach clearly outperforms traditional fixed strategies in UAV communications. Our thorough performance analysis reveals significant improvements across all vital parameters most notably in reducing bit error rate (BER), boosting capacity, and enhancing estimation accuracy. The adaptive method proves highly effective at compensating for UAV mobility, ensuring a more stable and reliable communication link even in dynamic conditions. These results highlight the strong potential of adaptive beam forming for real world UAV applications.

REFERENCES

[1]. Y. Zhou, C. Wang, and M. Chen, “A review on UAV-based applications for precision agriculture,” Inf. Process. Agric.,

vol. 9, no. 2, pp. 199–209, 2022, doi: 10.1016/j.inpa.2021.07.004.
[2]. V. Sharma, I. You, and C. Lal, "Security, privacy and trust for smart mobile-Internet of Things (IoT)-based healthcare applications using fog computing," J. Supercomput., vol. 77, pp. 5978–6009, 2021, doi: 10.1007/s11227-020-03157-w.
[3]. Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," IEEE Commun. Mag., vol. 54, no. 5, pp. 36–42, 2016, doi: 10.1109/MCOM.2016.7470933.
[4]. A. Fotouhi et al., "Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," IEEE Commun. Surveys Tuts., vol. 21, no. 4, pp. 3417–3442, 2019, doi: 10.1109/COMST.2019.2906228.
[5]. M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," IEEE Trans. Wireless Commun., vol. 15, no. 6, pp. 3949–3963, 2016, doi: 10.1109/TWC.2016.2539106.
[6]. R. Heath, A. Lozano, and T. L. Marzetta, Foundations of MIMO Communication. Cambridge, U.K.: Cambridge Univ. Press, 2018.
[7]. D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge, U.K.: Cambridge Univ. Press, 2005.
[8]. Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," IEEE Commun. Mag., vol. 58, no. 1, pp. 106–112, 2020, doi: 10.1109/MCOM.001.1900107.
[9]. J. Li and A. P. Petropulu, "MIMO radar with colocated antennas," IEEE Signal Process. Mag., vol. 24, no. 5, pp. 106–114, 2007, doi: 10.1109/MSP.2007.904812.
[10]. M. Chodnicki, M. Mazur, M. Nowakowski, and G. Kowaleczko, "The mathematical model of UAV vertical take-off and landing," Aircraft Eng. Aerosp. Technol., vol. 91, no. 2, pp. 249–256, 2019.
[11]. Y. Yuan, Y. Zeng, and R. Zhang, "UAV-enabled MIMO communications with altitude optimization," IEEE Trans. Wireless Commun., vol. 20, no. 3, pp. 1857–1871, 2021
[12]. S. Petruk, R. Zhyvotovskyi, and A. Shyshatskyi, "Mathematical model of MIMO," in Proc. Int. Sci.-Prac. Conf. Problems Infocommun., Sci. Technol. (PIC S&T), Oct. 2018, pp. 7–11.
[13]. S. Liu and Z. Liu, "Kalman filter based adaptive beamforming for UAV communications," IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2563–2575, 2020, doi: 10.1109/JSAC.2020.3005312.
[14]. S. Kurt and B. Tavli, "Path-loss modeling for wireless sensor networks: A review of models and comparative evaluations," IEEE Antennas Propag. Mag., vol. 59, no. 1, pp. 18–37, 2017.
[15]. C. A. Gutiérrez, M. Pätzold, N. M. Ortega, C. A. Azurdia-Meza, and F. M. Maciel-Barboza, "Doppler shift characterization of wideband mobile radio channels," IEEE Trans. Veh. Technol., vol. 68, no. 12, pp. 12375–12380, 2019.
[16]. A. Goldsmith, Wireless Communications. Cambridge, U.K.: Cambridge Univ. Press, 2005.
[17]. N. S. Arkhipov, I. S. Polyansky, Y. N. Yakovlev, and A. V. Subbotenko, "Mathematical model of a communication channel with an unmanned aerial vehicle," Phys. Wave Processes Radio Syst., vol. 24, no. 3, pp. 71–79, 2021.
[18]. K. Lazarus, N. H. Noordin, Z. Ibrahim, and K. H. Abas, "Adaptive beamforming algorithm based on simulated Kalman filter," in Proc. Asia Multi Conf. Modelling Simulation, Dec. 2016, no. 5, pp. 19–23.