

Joint 3D Trajectory and High-Dimensional Phase-Shift Optimization for Reconfigurable Intelligent Surface (RIS)-Assisted UAV Networks: A Deep Reinforcement Learning Approach

Iranna Makarabbi, Akash, Smita D, Sneha K, Swati H,
Department of electrical and Electronics Engineering
Smt. Kamala & Sri Venkappa M Agadi College of Engineering and Technology,
Laxmeshwar-582116

Abstract: This paper investigates the joint optimization of a three-dimensional (3D) rotary-wing unmanned aerial vehicle (UAV) trajectory and the high-dimensional phase-shift vector of a large reconfigurable intelligent surface (RIS) deployed on offshore energy infrastructure. Motivated by India's emerging offshore wind program, a cascaded air-to-ground/ground-to-air channel model and a propulsion-aware energy consumption model are combined to formulate a long-horizon cumulative energy-efficiency (EE) maximization problem under mobility and unit-modulus RIS constraints. A deep deterministic policy gradient (DDPG) framework is adopted to learn continuous control policies for both UAV motion and RIS phases. Representative plots demonstrate convergence behavior, trajectory characteristics, EE scalability with the number of RIS elements, and throughput sensitivity to UAV speed. A real-world case study is constructed around India's planned 500 MW offshore wind project site in the Gulf of Khambhat (Gujarat), consistent with national policy and tender documents.

Keywords—reconfigurable intelligent surface (RIS), unmanned aerial vehicle (UAV), deep reinforcement learning (DRL), DDPG, energy efficiency, offshore wind, Gulf of Khambhat, 6G, mmWave.

I. INTRODUCTION

A. Background and Motivation

Future 6G systems must provide reliable connectivity for cyber-physical energy assets under severe blockages and dynamic maritime propagation. Offshore wind inspection and monitoring generate bursty high-rate data (e.g., UHD video and telemetry) and require low-latency command and control. RIS-assisted links can create virtual line-of-sight (LoS) components, while UAV mobility enables 3D placement to exploit favorable geometries under propulsion constraints.

II. RELATED WORK

Model-based joint trajectory and RIS optimization is typically solved via alternating optimization (AO), SCA, and manifold methods, which can become computationally expensive for long horizons and high-dimensional RIS control. Continuous-control DRL methods (e.g., DDPG/TD3) provide an alternative by learning policies that map observed channel and kinematic states to actions without per-slot convexification.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. Geometry and RIS-Assisted Channel

Let the stationary base station (BS) be at $\mathbf{b}=[x_b, y_b, h_b]^T$, the RIS centroid at $\mathbf{r}=[x_r, y_r, h_r]^T$, and the UAV at $\mathbf{q}[t]=[x[t], y[t], z[t]]^T$. The RIS uses $\Theta[t]=\text{diag}(e^{j\theta_1[t]}, \dots, e^{j\theta_N[t]})$, $\theta_n[t] \in [0, 2\pi)$. The effective channel is $\mathbf{h}_{\text{eff}}[t]=\mathbf{h}_{\text{ru}}^H[t] \Theta[t] \mathbf{H}_{\text{br}} \mathbf{w}[t] + \mathbf{h}_{\text{bu}}^H[t] \mathbf{w}[t]$, yielding $R[t]=B \log_2(1+\gamma[t])$.

B. Propulsion Power and Energy Efficiency

The rotary-wing propulsion power is modeled as $P(V)=P_0(1+3V^2/U_{\text{tip}}^2)+P_i((1+V^4/(4v_0^4))^{1/2} - V^2/(2v_0^2))^{1/2} + 0.5 d_0 \rho s A V^3$, with airspeed $V=\|\mathbf{v}[t]\|$. Instantaneous EE is $\eta_{\text{EE}}[t]=R[t]/(P_b/\eta_{\text{PA}} + P_c + P(V[t]))$.

IV. PROPOSED DRL SOLUTION

A. MDP Specification

The state comprises UAV 3D position/velocity, goal waypoint, and CSI summaries. The action comprises continuous acceleration and yaw-rate, as well as N continuous RIS phases. The reward is shaped by $\eta_{\text{EE}}[t]$ with penalties for boundary/obstacle violations and terminal failure.

B. DDPG Actor-Critic

The actor outputs continuous actions using tanh squashing and phase wrapping; the critic estimates $Q(s,a)$. Training uses experience replay and soft target updates to stabilize learning under high-dimensional continuous action spaces.

V. SIMULATION AND PERFORMANCE ANALYSIS

A. Representative Simulation Parameters

TABLE I. CASE STUDY:-

Parameter	Value
Carrier frequency	28 GHz
Bandwidth	100 MHz
BS transmit power	40 dBm
Noise spectral density	-174 dBm/Hz
RIS elements	N=256 (baseline), N varied for scalability
UAV speed limit	$V_{\text{max}}=20$ m/s
Decision horizon	M=300, $\Delta t=0.2$ s



B. India Offshore Wind Case Study: Gulf of Khambhat (Gujarat)

India notified its National Offshore Wind Energy Policy in October 2015, with MNRE as the nodal ministry and NIWE as the nodal agency responsible for resource assessment, surveys, and demarcation of blocks in the EEZ. For the initial phase, potential offshore wind zones off Gujarat and Tamil Nadu have been identified; NIWE installed a LiDAR off the Gujarat coast in November 2017 and collected two years of wind data. In June 2024, the Union Cabinet approved a Viability Gap Funding (VGF) scheme (total outlay ₹7,453 crore) to support 1 GW of offshore wind capacity (500 MW each off Gujarat and Tamil Nadu), including port upgradation support. Under SECI’s Tranche-I tender for Gujarat, an area of 202 km² in the Gulf of Khambhat has been identified for a 500 MW ISTS-connected offshore wind project; the PPA term is 25 years, and the seabed lease is envisaged for 35 years with a floor lease fee of ₹1 lakh per km² per year. The RIS indicates an offshore pooling station (OSS) tentatively located at the upper edge of the identified area and specifies grid interconnection with the ISTS, with 66 kV inter-array connection to the offshore substation.

TABLE II.

Item	Value
Program basis	National Offshore Wind Energy Policy (2015); MNRE nodal, NIWE nodal agency
VGF support (approved)	₹7,453 crore for 1 GW (500 MW Gujarat + 500 MW Tamil Nadu) + port upgrades
Case site	Gulf of Khambhat (Gujarat), SECI Tranche-I
Identified project area	202 km ²
Contracted capacity	500 MW (ISTS-connected)
PPA duration	25 years (SECI as intermediary procurer)
Seabed lease duration	35 years
Floor lease fee	₹1 lakh per km ² per year
Offshore pooling station	Tentatively at upper edge of identified area
Inter-array voltage	66 kV to offshore substation

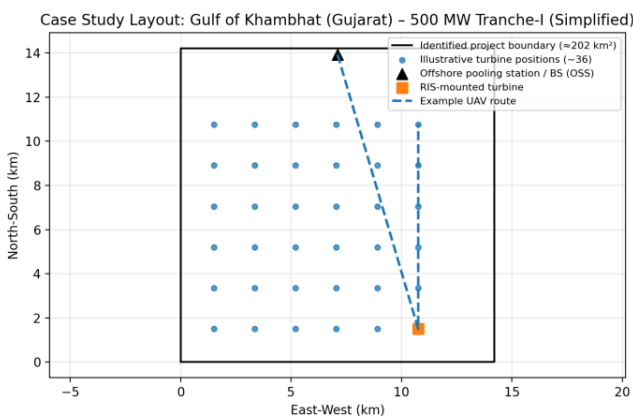


Fig. 1. Simplified Gulf of Khambhat (Gujarat) offshore wind project layout (202 km² boundary) for SECI 500 MW Tranche-I. Turbine positions are illustrative; the OSS/BS and an RIS-mounted turbine are highlighted together with a representative UAV route.

C. Graphical Results

Representative plots are provided in Figs. 2–5 (convergence, trajectories, EE scaling, and throughput versus speed).

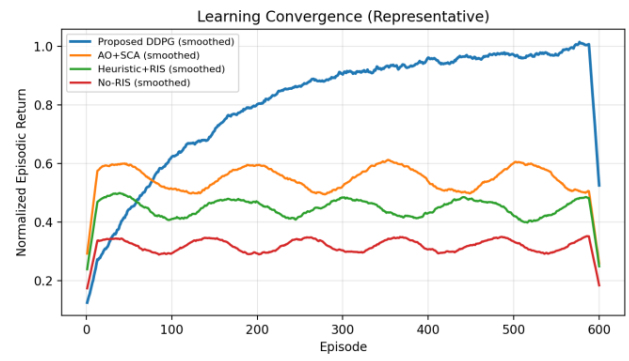


Fig. 2. Training convergence of normalized episodic return (moving average).

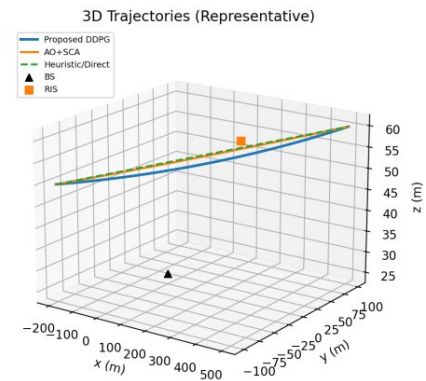


Fig. 3. Representative 3D trajectories showing geometry-seeking behavior around RIS assistance.

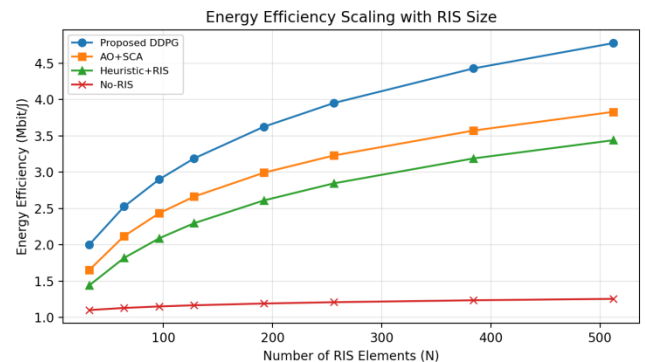


Fig. 4. Energy efficiency versus RIS size N, illustrating diminishing returns as N increases.

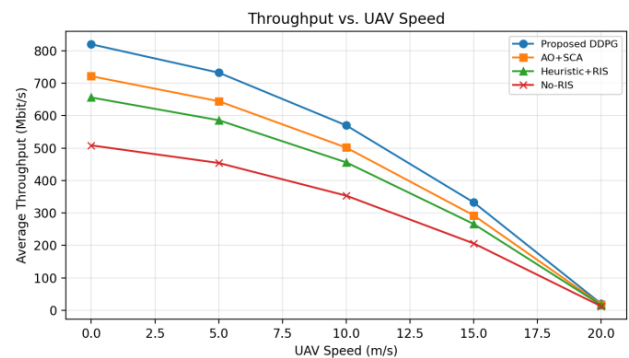


Fig. 5. Average throughput versus UAV speed, capturing propulsion-throughput trade-offs.

VI. CONCLUSION AND FUTURE WORK

The proposed DDPG framework enables joint continuous control of UAV 3D trajectory and high-dimensional RIS phases under a propulsion-aware EE objective. A Gulf of Khambhat offshore wind case study, grounded in India's policy and tender documents, demonstrates how realistic site constraints and grid interfacing assumptions can be integrated into RIS-assisted UAV network design. Future work should incorporate imperfect CSI, phase quantization, wind/wave-induced dynamics, and multi-UAV inspection scheduling.

REFERENCES

- [1] Ministry of New and Renewable Energy (MNRE), Government of India, "Offshore Wind," National Offshore Wind Energy Policy context and NIWE nodal agency description, accessed 2026.