

3D AAV-DTN Communications: A Wind-Aware Approach with Dynamic Cooperative WPT

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Abstract—In this study, we propose a 3D-Aerial ONE-DTN Simulator (3D-AONE), which extends the ONE opportunistic network simulator to a three-dimensional aerial environment and integrates wind field dynamics and wireless power transfer (WPT) mechanisms for AAV-based delay-tolerant network (DTN) systems. The proposed framework enhances the original ONE simulator into a high-fidelity simulation platform for three-dimensional aerial DTNs, addressing the limitations of conventional DTN simulators that are primarily restricted to two-dimensional ground environments and lack accurate aerodynamic and energy consumption models. To overcome these limitations, a physically consistent three-dimensional Von Kármán turbulent wind field model is tightly coupled with a nonlinear rotorcraft propulsion power model, enabling an accurate representation of the relationship between fluid dynamics and AAV energy consumption. Furthermore, an infrastructure-free aerial energy cooperation mechanism based on near-field magnetic resonant coupling is introduced, allowing Charge AAVs to dynamically replenish the energy of Task AAVs. Experimental results demonstrate that the proposed framework effectively captures the impact of turbulent wind fields on AAV propulsion power consumption. The cooperative WPT experiment further verifies that Charge AAVs can replenish the energy of Task AAVs during mission execution. In addition, a communication-mode comparison under varying ground-node densities shows that WLAN provides lower average transmission delay than Bluetooth in the evaluated scenarios. Together, these results demonstrate the capability of 3D-AONE to support the joint investigation of communication timeliness and energy sustainability in dynamic multi-AAV environments.

Index Terms—Delay-tolerant network (DTN), Autonomous aerial vehicles (AAV), wind turbulence modeling, Wireless power transfer (WPT), communication and energy trade-offs.

I. INTRODUCTION

In recent years, autonomous aerial vehicles (AAVs) have been widely used in disaster response, environmental monitoring, logistics delivery, military reconnaissance, and smart city applications. Benefiting from high mobility, low deployment cost, and three-dimensional maneuverability, AAVs have become an important component of future aerial communication systems [1], [2]. In disaster areas or remote regions where communication infrastructure may be unavailable, Delay-Tolerant Networks (DTNs) have attracted increasing attention. Through the Store-Carry-Forward mechanism, DTNs enable reliable data transmission under intermittent connectivity conditions. By serving as highly mobile DTN nodes, AAVs can further enhance network coverage and improve data delivery efficiency [1], [3], [4].

Currently, The ONE (Opportunistic Network Environment) is one of the most widely used DTN simulation platforms for modeling node mobility, routing protocols, and data exchange behaviors [5]. However, the original simulator was primarily designed for ground-based environments and lacks support for three-dimensional mobility, wind field effects, and AAV energy models, limiting its applicability to AAV-DTN research [4], [6].

In aerial DTN environments, AAVs must remain airborne continuously to maintain communication coverage, making propulsion energy consumption significantly higher than communication-related power consumption. In addition, wind-induced aerodynamic drag can accelerate battery depletion. Without accurate energy models that account for stochastic wind disturbances, routing protocols may experience unexpected failures due to node energy depletion [2], [7].

Meanwhile, limited battery capacity remains a major challenge in AAV systems, restricting both flight endurance and mission range. In multi-AAV cooperative environments, energy depletion of individual AAVs may disrupt the entire communication network. Therefore, improving system lifetime through inter-AAV energy cooperation has become an important research issue [7], [8].

To address the aforementioned issues, this study extends the ONE simulator and establishes a simulation framework tailored for AAV-based DTN systems. The main contributions of this work are summarized as follows:

- A physically consistent three-dimensional aerial DTN simulation extension framework is proposed.
- Precise coupling between dynamic environmental disturbances and nonlinear flight energy consumption is achieved.
- An infrastructure-free self-organizing aerial energy cooperation mechanism is validated.

Experimental results demonstrate that the proposed 3D-AONE simulation framework can effectively model the influence of wind fields on AAV energy consumption. Furthermore, the proposed AAV energy cooperation mechanism is shown to improve both system lifetime and mission stability.

II. RELATED WORK

This section reviews prior research on AAV network simulation frameworks, wind field modeling approaches, and Wireless Power Transfer (WPT) technologies.

A. DTN Simulation Framework

Delay-Tolerant Networks (DTNs) rely on the Store-Carry-Forward mechanism [9] to enable data transmission under intermittent connectivity. The Opportunistic Network Environment (ONE) simulator [5] is widely used to evaluate routing protocols (e.g., Epidemic, Spray and Wait, Prophet). However, the original ONE simulator targets two-dimensional ground environments with simplified mobility and energy models, lacking support for three-dimensional aerial dynamics and environmental disturbances. Although other platforms like NS-3 [10] and OMNeT++ [11] support AAV network simulations, they primarily focus on communication protocol analysis rather than long-term DTN mobility behavior modeling.

B. AAV Network Simulation and Mobility Modeling

AAVs are widely deployed as mobile relay nodes in disaster-response and temporary communication scenarios to enhance network coverage [12]. Although simulation environments like Gazebo and AirSim offer precise physics engines, existing studies often assume ideal flight conditions and neglect atmospheric wind field impacts on AAV mobility and energy consumption. Consequently, developing a physically consistent AAV mobility model that tightly couples communication behaviors under a realistic DTN framework remains a significant research gap.

C. Wind Field Modeling for AAV Systems

Wind fields significantly affect AAV flight stability and nonlinear propulsion power demands. Existing wind models include the empirical Kaimal spectrum [13], which is restricted to near-ground surface layers with limited 3D spatial consistency, and the time-domain Dryden model [14], which captures flight control dynamic responses but suffers from weak spatial correlation modeling. In contrast, the Von Kármán turbulence model [15] is based on spectral theory to describe isotropic large- and small-scale vortices. By employing FFT-based spectral synthesis methods [16], it reconstructs continuous 3D turbulent flow fields with robust spatial correlation, making it uniquely suited for high-fidelity, system-level aerial simulations.

D. WPT for AAV Systems

Wireless Power Transfer (WPT) provides a promising solution for energy replenishment in endurance-critical AAV networks. WPT technologies are categorized into far-field RF/microwave broadcasting, which supports long distances but suffers from severe free-space path loss, and near-field magnetic resonant coupling [17], which features high efficiency over short distances (typically within 1–2 m). Given that near-field WPT is highly efficient and stable for short-range operations within formations, this study adopts a near-field magnetic coupling mechanism to validate an infrastructure-free, self-organizing AAV-to-AAV energy cooperation strategy in persistent aerial DTN environments.

III. SYSTEM MODEL

This study introduces the 3D-Aerial ONE-DTN Simulator (3D-AONE) framework to establish a high-fidelity simulation environment tailored for 3D aerial AAV-DTN systems. As illustrated in Fig. 1, the proposed 3D-AONE architecture comprises four core components: a three-dimensional coordinate system, an environmental wind-field model, an AAV energy-consumption model, and a cooperative WPT model.

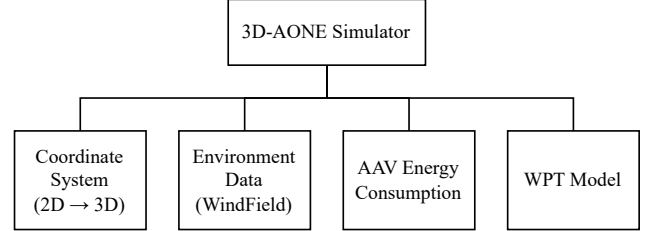


Fig. 1. System Model

A. Wind Field Model

In this study, the environmental wind field is modeled as a three-dimensional stochastic vector field to characterize the effect of atmospheric turbulence on AAV mobility and energy consumption. The wind velocity at spatial position $\mathbf{x} = (x, y, z)$ is expressed as the sum of a mean wind field and a turbulent disturbance field:

$$\mathbf{u}(\mathbf{x}) = \bar{\mathbf{U}} + \mathbf{u}'(\mathbf{x}), \quad (1)$$

where $\mathbf{u}(\mathbf{x})$ denotes the total wind velocity, $\bar{\mathbf{U}}$ is the mean wind field, and $\mathbf{u}'(\mathbf{x})$ represents turbulent fluctuations.

To construct a three-dimensional turbulent wind field with spatial correlation, this study follows the spatial turbulence generation method presented in [18]. The Von Kármán energy spectrum is employed to characterize the distribution of turbulent energy across different spatial scales and is expressed as:

$$E(k) = C \frac{\sigma^2 L^5 k^4}{[1 + (kL)^2]^{17/6}}, \quad (2)$$

where $\mathbf{k} = (k_x, k_y, k_z)$ is the wavenumber vector, $k = \|\mathbf{k}\|$ is its magnitude, σ represents the turbulence intensity, L is the integral length scale, and C is a spectrum normalization coefficient.

The turbulent wind field is generated through spectral synthesis. A Gaussian random field is first constructed in the wavenumber domain and shaped according to the Von Kármán energy spectrum. A three-dimensional inverse discrete Fourier transform (IDFT) is then applied to convert the spectral representation into the physical domain.

The resulting field exhibits the prescribed Von Kármán statistical characteristics and assigns a turbulent velocity vector

to each spatial location. During simulation, the turbulent component is superimposed on the mean wind field to obtain the local environmental wind velocity. The generated wind field is subsequently discretized into a spatial representation that allows each AAV to query the wind velocity at its current position. This local wind information is used to update the AAV flight state and calculate its propulsion energy consumption.

B. AAV Energy Consumption Model

To realistically characterize the energy consumption behavior of rotary-wing AAVs, this study adopts the rotary-wing power model as the flight energy model [2]. Compared with conventional constant-power models, the adopted model considers rotor aerodynamic effects, lift requirements, and fuselage drag, enabling a more accurate representation of AAV energy consumption under different flight conditions.

The rotary-wing power model consists of three components: blade profile power, induced power, and parasite power, corresponding to rotor aerodynamic losses, lift generation, and fuselage drag during forward flight, respectively. By combining these components, the model can effectively describe the propulsion energy variation of AAVs under different flight velocities and environmental conditions.

In this model, the total propulsion power is determined by the relative wind velocity V_{rel} , defined as

$$V_{rel} = V_{aav} - V_{wind} \quad (3)$$

where V_{aav} denotes the AAV flight velocity and V_{wind} represents the environmental wind velocity. Since the propulsion demand depends on the relative airflow experienced by the AAV, headwind conditions increase propulsion power requirements, whereas tailwind conditions may reduce energy consumption. Therefore, incorporating wind field effects into the energy model enables more realistic simulation of AAV flight behavior and energy variation in practical environments.

C. WPT Model

To extend the operating time of infrastructure-free AAV-DTN systems, 3D-AONE classifies aerial nodes into Task AAVs and Charge AAVs. Task AAVs perform data collection, communication, and mission execution, whereas Charge AAVs provide mobile energy support. When the residual energy of a Task AAV falls below a predefined threshold, the system assigns a nearby Charge AAV and coordinates the two nodes so that they enter the effective range of near-field wireless power transfer.

The proposed charging mechanism adopts the near-field magnetic resonant coupling architecture reviewed in [19]. However, because both AAVs remain airborne during charging, their transmitting and receiving coils may not maintain ideal alignment. Relative displacement, attitude variation, and wind-induced hovering disturbances may produce separation, lateral, and angular errors, which reduce magnetic coupling and energy-transfer efficiency [20].

Inspired by the UAV coil-positioning concept presented in [21], 3D-AONE introduces an iterative alignment stage before energy transfer. During this stage, the relative position of the two AAVs is gradually corrected while the charging efficiency is repeatedly evaluated. Energy transfer begins only when the inter-coil distance and alignment errors remain within their allowable thresholds. The received energy is then determined by the Charge AAV's transmission power, the current transfer efficiency, and the simulation update interval. Charging terminates when the target energy is reached, the Charge AAV can no longer provide sufficient energy, or the required charging conditions are no longer satisfied.

IV. EXPERIMENTS

A. Simulation Setup

This section describes the simulation environment and system parameter settings used in this study. To evaluate the communication performance and energy consumption behavior of AAVs in Delay-Tolerant Networks (DTNs), this study integrates a three-dimensional wind field model, an AAV mobility model, and a WPT mechanism for simulation analysis.

The simulation environment includes up to two AAV nodes for mobility and energy-related evaluation, together with 30 to 150 ground communication nodes for communication-mode evaluation. The main system parameters are listed in Table I. In addition, the physical parameters of the AAVs are adopted from [2].

TABLE I
PRINCIPAL SIMULATION PARAMETERS

Parameter	Description	Value
X_{max}	Simulation area size	4500 m
Y_{max}	Simulation area size	3400 m
Z_{max}	Simulation area size	1000 m
V_{aav}	AAV velocity	10 m/s
σ	Standard Deviation of wind	1.5
L	turbulence scale of wind	100 m
$\bar{U}$	mean wind	5 m/s
E_{Task}	Task AAV Energy Capacity	720 kJ
E_{Charge}	Charge AAV Energy Capacity	3.6 MJ
P_t	Charge Power	1000 W
η	Charge Efficiency	0.95
E_{thres}	Charge Threshold	72 kJ

B. Energy Consumption under Different Wind Conditions

This experiment evaluates the propulsion-energy consumption of a single AAV under three environmental conditions: No-Wind, Steady-Wind, and Turbulent-Wind. During the experiment, the AAV follows a 1 km square trajectory while its remaining energy is continuously monitored to analyze the influence of wind fields on propulsion energy consumption.

Fig. 2 presents the remaining-energy trajectories under the three evaluated wind conditions. In the no-wind case, the absence of environmental airflow results in an approximately linear decrease in the remaining energy under the prescribed flight trajectory.

In the steady-wind and turbulent-wind cases, the available energy decreases more rapidly than in the no-wind case. The

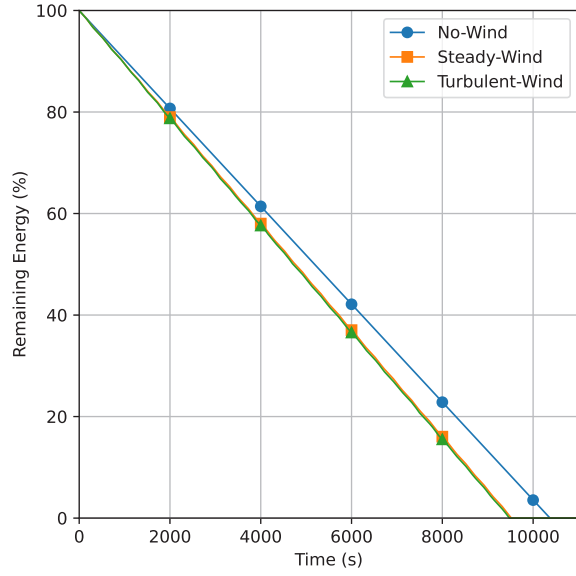


Fig. 2. Comparison of AAV energy consumption under different wind conditions.

two wind-affected cases exhibit similar overall trends, with small differences resulting from variations in the local wind velocity and direction encountered along the flight path. These variations alter the relative airflow experienced by the AAV and consequently affect its estimated propulsion power.

Overall, the results show that the modeled wind conditions alter the AAV energy-consumption trajectory. The experiment therefore confirms the functional coupling between the wind-field query mechanism and the propulsion-energy model within 3D-AONE.

C. AAV Energy Cooperation

This experiment further analyzes the system benefits achieved by incorporating the WPT-based energy cooperation mechanism, as illustrated in Fig. 3. The system architecture consists of two types of AAV nodes: Task AAVs responsible for task execution and Charge AAVs responsible for energy replenishment. Considering the maximum travel distance within the simulation area, the charging threshold of the Task AAV is configured as 10% of its maximum battery capacity. In practical scenarios, this threshold can be dynamically adjusted according to environmental conditions.

As shown in Fig. 3, when the remaining energy of the Task AAV falls below the predefined threshold, a Charge AAV is dispatched to rendezvous with the Task AAV and initiate energy transfer. The energy level of the Task AAV subsequently increases, demonstrating that the implemented WPT mechanism can provide in-mission energy replenishment under the evaluated conditions.

The results show that the Task AAV can receive energy from the Charge AAV without returning to a fixed charging station. Within the evaluated scenario, the mechanism restores

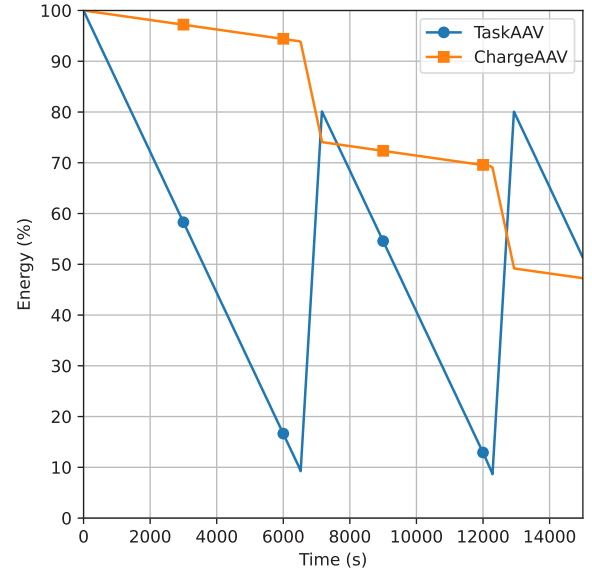


Fig. 3. Cooperative energy transfer among AAVs.

the Task AAV's energy before complete depletion and supports continued mission execution.

D. Adaptive Communication and Energy Scheduling

This experiment investigates the communication-performance characteristics that can support adaptive mode selection between low-power Bluetooth and high-bandwidth WLAN in AAV-DTN systems. The two communication modes represent different operational priorities. Bluetooth provides an energy-conscious communication option with relatively limited transmission range and data rate, whereas WLAN provides wider communication coverage and higher data-transfer capability for time-sensitive or data-intensive transmissions. By comparing their average transmission delays under different ground-node densities, this experiment provides a communication-performance basis for incorporating mode selection into future energy-aware communication strategies.

Fig. 4 compares the average transmission delay of Bluetooth and WLAN for networks containing 30 to 150 ground communication nodes. As the number of ground nodes varies, the delay values of both communication modes exhibit moderate fluctuations. Nevertheless, WLAN maintains a lower average transmission delay than Bluetooth at each evaluated ground-node density. This tendency is consistent with the higher configured data rate and wider communication range of WLAN, which provide additional opportunities for message forwarding and buffer offloading under the evaluated simulation settings.

The communication-mode comparison and the cooperative WPT experiment address complementary aspects of persistent AAV-DTN operation. Communication-mode selection influences message-delivery timeliness and communication-related energy demand, whereas the WPT mechanism provides in-mission energy replenishment when the residual energy of a

Task AAV becomes insufficient. Although the two mechanisms are evaluated separately in the present experiments, their integration within 3D-AONE provides a functional basis for future adaptive communication and energy-scheduling strategies that balance transmission performance, energy availability, and mission continuity.

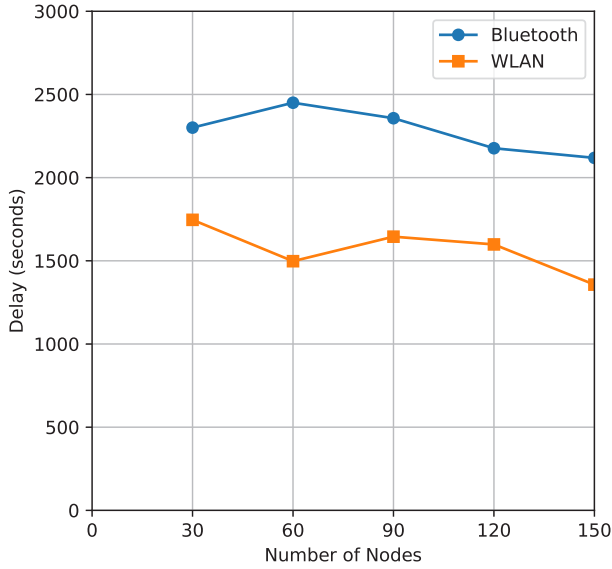


Fig. 4. Average transmission delay for different numbers of ground nodes

V. CONCLUSION

This study introduces the 3D-Aerial ONE-DTN Simulator (3D-AONE), an integrated simulation framework that extends the conventional ONE simulator to three-dimensional aerial environments. The framework incorporates three-dimensional mobility, environmental wind fields, rotary-wing propulsion energy estimation, cooperative wireless power transfer, and configurable Bluetooth and WLAN communication modes. These extensions enable the ONE simulator to represent environmental, energy, and communication characteristics relevant to AAV-based DTN operations.

Experimental results show that steady and turbulent wind conditions produce distinct AAV energy-consumption trajectories by changing the relative airflow experienced by the vehicle. The cooperative WPT experiment demonstrates that a Charge AAV can replenish the energy of a Task AAV during mission execution, thereby supporting continued operation under the evaluated scenario. In the communication-mode evaluation, WLAN consistently exhibited lower average transmission delay than Bluetooth across the tested ground-node densities, indicating its potential to better support delay-sensitive data delivery under the evaluated AAV-DTN settings. Collectively, these results demonstrate that 3D-AONE can evaluate wind effects, in-mission energy replenishment, and communication-performance characteristics within a common simulation framework.

In summary, 3D-AONE provides a unified environment for studying multi-AAV communication and energy-management

behaviors under dynamic environmental conditions. The current evaluations establish the functional feasibility of the individual simulation components and illustrate their complementary roles in communication timeliness, energy availability, and mission continuity. The proposed platform can therefore serve as a foundation for future cross-layer studies on adaptive communication-mode selection, cooperative charging, routing, and energy-aware mission management in aerial DTN systems.

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