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Energy-Aware Multi-UAV Routing Strategies for Low-Altitude Delay-Constrained Data Delivery Networks

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Abstract

The rapid deployment of Unmanned Aerial Vehicles in civil and commercial sectors has introduced new paradigms for decentralized communication, particularly in environments lacking traditional infrastructure. In low-altitude data delivery networks, coordinating multiple aerial nodes to efficiently transmit information is paramount. However, these systems face dual constraints of strictly limited onboard energy reserves and stringent delay requirements for time-sensitive applications such as disaster response, medical supply delivery, and real-time surveillance. This paper investigates the complexities of energy-aware multi-UAV routing within delay-constrained low-altitude networks. By comprehensively analyzing the physical mobility dynamics and communication overhead of rotary-wing aircraft, a novel routing framework is proposed that dynamically balances propulsion energy consumption with end-to-end transmission latency. The study formulates the routing challenge as a multi-objective optimization problem and introduces a decentralized heuristic algorithm designed to establish reliable communication paths while minimizing the overall energy expenditure of the drone swarm. Extensive simulation scenarios evaluate the proposed methodology against traditional ad-hoc routing protocols. The analytical results demonstrate a significant reduction in network-wide energy depletion while consistently satisfying maximum allowable delay thresholds. The findings provide critical insights into the design of sustainable, high-performance aerial communication networks for next-generation decentralized architectures.

Keywords: Unmanned Aerial Vehicles, Routing Protocols, Energy Efficiency, Delay Constraints, Flying Ad-hoc Networks.

1.Introduction

1.1 Background and Contextual Framework

The integration of Unmanned Aerial Vehicles into modern communication networks represents a transformative shift in how data is relayed across vast and challenging topologies. Originally restricted to military applications, these aerial platforms have become ubiquitous in civilian domains, driven by advancements in miniaturized sensors, high-capacity batteries, and lightweight composite materials. In the context of low-altitude data delivery networks, these platforms function as mobile base stations, agile relay nodes, or autonomous data mules capable of traversing terrain that is inaccessible to ground-based vehicles. The

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deployment of a swarm of aerial vehicles, collectively known as a Flying Ad-hoc Network, offers unprecedented flexibility, rapid deployability, and line-of-sight communication advantages over traditional terrestrial wireless sensor networks. Such networks are increasingly critical for applications requiring immediate deployment, including environmental monitoring in remote forests, post-disaster search and rescue operations, intelligent agricultural management, and emergency communication restoration in urban areas where cellular infrastructure has been compromised. Object-fidelity diffusion for remote-sensing imagery [1] could support synthetic environmental scenarios, but coverage or routing evaluation must verify that generated objects preserve the geometry relevant to a radio link. However, establishing a reliable data delivery network utilizing highly mobile nodes in three-dimensional space introduces significant topological volatility. The dynamic nature of the network requires robust and adaptable communication protocols capable of maintaining connectivity despite frequent link breakages and rapid changes in node proximity. Traditional routing protocols designed for stationary or slow-moving terrestrial networks are fundamentally ill-equipped to handle the high mobility and three-dimensional spatial freedom characteristic of aerial swarms. Furthermore, communication in low-altitude environments is heavily influenced by external aerodynamic disturbances, urban canyons, and multipath fading effects, which degrade signal quality and necessitate continuous rerouting. As the complexity of the data tasks increases, from simple telemetry reporting to high-definition video streaming, the demands placed on the underlying network architecture scale exponentially, necessitating advanced strategies to ensure data fidelity and timely delivery. The literature also considers cooperative backscatter communications with reconfigurable intelligent surfaces: an APSK approach [2]. For a broader comparison, related research addresses design of interface circuits and lightweight PUF for TMR sensors [3].

1.2 Motivation and Problem Statement

Despite the operational advantages of low-altitude aerial networks, their practical implementation is fundamentally restricted by the severe resource constraints inherent to decentralized flying platforms. The most critical limitation is the onboard energy storage capacity. Unlike terrestrial communication nodes that may benefit from persistent power connections or large solar arrays, aerial nodes rely almost entirely on lightweight lithium-polymer batteries. A substantial majority of this stored energy is consumed by the electromechanical propulsion systems required to maintain flight, counteract wind resistance, and execute maneuvers, leaving only a small fraction of the energy budget available for the communication payload, signal processing, and data transmission. Consequently, any routing protocol deployed in such an environment must strictly account for the energy state of each individual node. Standard ad-hoc routing protocols typically seek the shortest geometric path to the destination without considering the remaining battery life of the relay nodes. This oversight frequently leads to the rapid depletion of critically positioned nodes, resulting in network partitioning, the creation of communication voids, and the premature termination of the network mission. Simultaneously, many contemporary aerial applications are bound by stringent end-to-end delay constraints. In disaster response scenarios, delayed transmission of sensory data or high-definition surveillance feeds can render the information entirely useless, directly impacting the efficacy of emergency interventions. Therefore, a fundamental conflict arises between the objective of conserving energy to prolong network lifetime and the necessity of utilizing rapid, potentially energy-intensive communication paths to meet delay thresholds. The problem of designing a routing strategy that intelligently navigates the trade-off between energy conservation and latency minimization remains an open challenge in current academic research. This paper aims to bridge this gap by proposing a comprehensive routing methodology specifically tailored for multi-node aerial environments, addressing both

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the physical propulsion energy metrics and the temporal constraints of high-priority data payloads. Another relevant line of investigation concerns robust beamforming and trajectory optimization [4].

2. Literature Review

2.1 Traditional Routing in Flying Ad-hoc Networks

The exploration of communication strategies for mobile aerial platforms initially drew heavily upon the extensive literature established for Mobile Ad-hoc Networks and Vehicular Ad-hoc Networks. Researchers attempted to port classic reactive protocols directly onto aerial platforms. These protocols initiate route discovery only when a node has data to transmit, which intuitively conserves bandwidth when the network is idle. MODIS supplies regional land-observation context that could inform broad environmental scenarios, while its spatial resolution must be kept distinct from the local geometry required for a UAV route or radio link [5]. However, empirical studies demonstrated that in highly mobile aerial environments, the reactive route discovery process introduces unacceptable delays, as the frequent topological shifts cause established paths to become obsolete by the time data transmission begins. Consequently, proactive protocols were investigated, which attempt to maintain a complete topological map of the network at all times through periodic beaconing. While proactive strategies significantly reduce the route acquisition delay, they generate a massive influx of control packet overhead, which congests the limited bandwidth and rapidly drains the batteries of all participating nodes. To mitigate the respective drawbacks of purely reactive and proactive approaches, hybrid routing architectures were subsequently proposed. These architectures divide the network into localized zones or clusters, utilizing proactive routing within a localized cluster to ensure immediate availability of local routes, while employing reactive routing for inter-cluster communication to minimize global control overhead. Despite these improvements, conventional topological routing methods still suffer from a fundamental reliance on continuous end-to-end paths, a condition that is frequently violated in sparse aerial networks where nodes may be distributed over wide geographical areas. To address the challenge of intermittent connectivity, researchers introduced geographic routing protocols. Geographic routing, also known as position-based routing, leverages the onboard geographic positioning systems standard on modern aerial platforms. Instead of maintaining complex topological tables, nodes forward packets to the neighbor geographically closest to the destination. While highly scalable and resilient to mobility, standard geographic routing often encounters local minimum phenomena, where a packet reaches a node that has no neighbors closer to the destination than itself. The recovery mechanisms required to bypass these communication voids, such as perimeter routing or planar graph traversals, introduce significant delays and highly suboptimal paths, rendering them unsuitable for delay-constrained scenarios. The literature also considers multi-Granularity network alignment based on contrastive learning [6]. Related work has addressed scene-Aware enhanced Edge-Cloud collaborative industrial vision inspection with multimodal LLM [7].

Table 1Summary of Traditional Aerial Routing Protocols

Protocol Category	Primary Routing Mechanism	Major Limitation in Aerial Environments
Reactive Topologic	On-demand path discovery	High latency during route acquisition

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Proactive Topologic	Periodic table updates	Excessive control overhead and energy waste
Geographic Routing	Position-based forwarding	Susceptible to local minimum routing voids

2.2 Advances in Energy and Delay Optimization

Recognizing the limitations of direct adaptations, the academic community has increasingly focused on developing specialized protocols that explicitly incorporate energy parameters and temporal constraints. Early energy-aware protocols primarily focused on minimizing the total transmission power required to send a packet from the source to the destination. This was typically achieved by selecting routes consisting of many short hops rather than fewer long hops, capitalizing on the non-linear relationship between transmission power and distance in wireless propagation models. However, this approach completely ignored the residual energy of the participating nodes. Consequently, nodes situated in central locations or along optimal geometric paths were disproportionately utilized, leading to their rapid exhaustion and subsequent network failure. To counteract this, researchers proposed load-balancing routing algorithms that utilize residual energy as the primary routing metric. These algorithms prioritize nodes with higher remaining battery levels, effectively distributing the communication load across the network and maximizing the time until the first node depletes its energy. While successful in extending operational lifetime, these methods frequently divert data traffic along highly circuitous routes, significantly inflating the end-to-end delay and violating the constraints of time-critical applications. More recent literature has explored cross-layer designs to optimize the energy-delay trade-off. Google Earth Engine provides infrastructure for geospatial analysis, a possible preprocessing layer for regional maps rather than a substitute for the local sensing pipeline [8]. By allowing the network layer to access information from the physical and medium access control layers, routing decisions can be dynamically adjusted based on real-time channel conditions, queue lengths, and interference levels. Furthermore, the advent of artificial intelligence has introduced reinforcement learning techniques to aerial routing. Researchers have formulated routing as a Markov Decision Process, where individual drones act as independent agents learning to make optimal forwarding decisions through continuous interaction with the environment. These learning-based models have demonstrated a remarkable ability to adapt to complex, dynamic conditions. However, the substantial computational resources and extended convergence times required to train these models on resource-constrained aerial hardware present significant practical barriers to deployment. Consequently, there remains a pressing need for a lightweight, computationally efficient routing methodology that can analytically balance propulsion and communication energy costs against strict delivery deadlines without relying on extended training periods. Wei and colleagues examine coordinated Rate-Splitting multiple access for emergency UAV-Enabled integrated sensing and communication [9]. For a broader comparison, related research addresses efficient and trustworthy authentication in 5G networks based on blockchain [10].

3. System Architecture and Network Model

3.1 Network Topology and Physical Dynamics

The system under consideration models a decentralized Flying Ad-hoc Network operating in a low-altitude airspace, specifically tailored for missions where terrestrial communication infrastructure is either unavailable or severely compromised. The network consists of a

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defined quantity of homogeneous rotary-wing aerial vehicles, dynamically deployed to form a continuous, self-healing communication mesh. These aerial nodes operate in a three-dimensional Cartesian coordinate system, where each node possesses full six-degrees-of-freedom mobility. Due to the low-altitude operational ceiling, typically ranging from fifty to two hundred meters above ground level, the network is modeled to experience specific aerodynamic constraints and physical layer obstacles. The transmission environment is characterized by a combination of line-of-sight propagation paths and non-line-of-sight paths caused by natural or artificial obstructions. Unlike standard terrestrial networks where node mobility is strictly confined to two-dimensional planes and predictable trajectories, aerial nodes can alter their altitude, pitch, roll, and yaw, introducing rapid fluctuations in antenna orientation and polarization. This physical dynamism causes severe and sudden variations in the wireless channel capacity. To facilitate decentralized coordination, each node is equipped with a global positioning system module to determine its absolute spatial coordinates, an inertial measurement unit to calculate velocity and acceleration vectors, and a lightweight omnidirectional antenna array. A continuous time model is utilized to capture the evolving state of the network. The network topology at any given time instance is represented as a dynamic directed graph, where the vertices represent the active aerial nodes, and the edges represent the currently viable communication links. A communication link between two arbitrary nodes is considered viable if and only if the Euclidean distance separating them is strictly less than the maximum effective transmission range, a parameter dictated by the transmission power, the signal-to-noise-and-interference ratio threshold, and the ambient atmospheric path loss exponent. The generation of data is modeled at specific source nodes, which are tasked with continuously monitoring ground events and generating discrete data packets. These packets are placed into a local queue and must be routed through the aerial mesh to designated destination nodes, which serve as data sinks or gateway connections to remote control centers. Related work has addressed covert transmission for active RIS-Aided Full-Duplex UAV integrated sensing, communication, and computation systems [11]. For a broader comparison, related research addresses design of magnetic sensor Array-Based PUFs for IoT security [12].

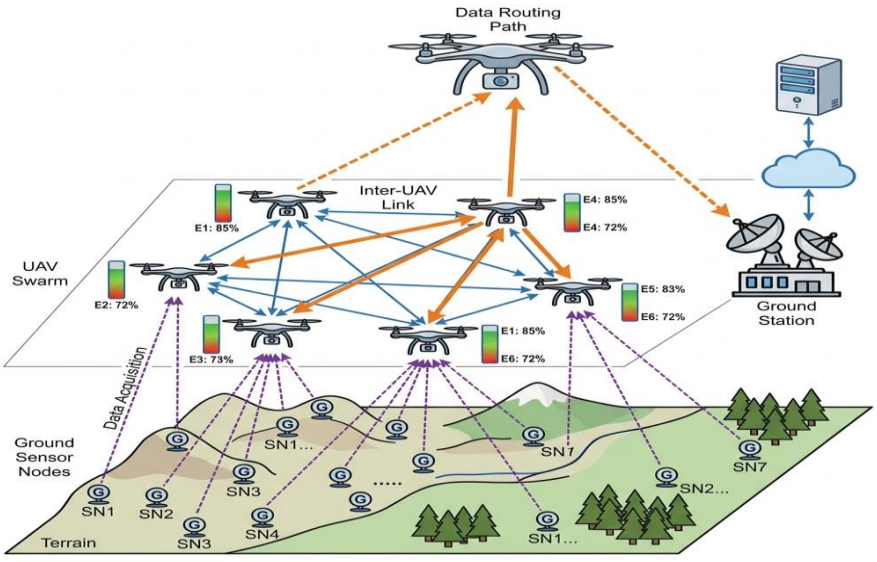


Figure 1System Architecture of Multi

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3.2 Energy Consumption and Delay Modeling

To construct an accurate routing mechanism, it is imperative to deeply formalize the dual metrics of energy consumption and transmission delay. The total energy budget of an aerial node is strictly finite and is continuously depleted by two primary independent processes: physical flight mechanics and wireless communication operations. Unlike conventional sensor networks where communication dominates energy expenditure, the energy consumed by the communication transceiver in an aerial platform is an order of magnitude smaller than the energy consumed by the rotor motors required to maintain lift and forward momentum. The physical energy consumption profile is highly non-linear and is highly sensitive to the current flight state, specifically whether the node is hovering in a stationary position or translating through the air mass. The aerodynamic power required can be mathematically modeled by aggregating the induced power needed to overcome gravity, the profile power required to overcome the drag of the rotor blades, and the parasite power necessary to push the fuselage through the air. The total physical energy consumed by a node over a specific time duration can be represented by a complex polynomial function of its velocity. The total energy expenditure can be broadly captured by the following physical formulation. Chen and colleagues examine self-calibrating MEMS accelerometers [13]. For a broader comparison, related research addresses global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals substantial health risks [14].

$$E_{total} = \sum_{i=1}^{N} (P_{hover} T_i + \frac{1}{2} \rho A v_i^3 T_i)$$

In this formulation, the total energy is calculated as the sum across all operational segments. The parameter representing hover power is constant for a given vehicle mass and air density, while the forward flight power increases as the cube of the velocity, multiplied by the air density, the cross-sectional area, and the duration of the flight segment. This physical reality dictates that nodes cannot indiscriminately fly toward optimal routing positions without incurring massive energy penalties. Parallel to the energy model, the end-to-end delay must be strictly quantified. The total delay experienced by a single packet traversing the multi-hop network is the sum of several distinct temporal components at each intermediate relay node. The processing delay encompasses the time required for a node's microprocessor to examine the packet header, determine the appropriate routing action, and perform any necessary error checking. The queuing delay represents the time a packet spends residing in the buffer of a node while waiting for previously received packets to be transmitted, a factor heavily dependent on the current network traffic load. The transmission delay is the time strictly required to push the physical bits of the packet onto the wireless medium, determined by the packet length and the current channel bandwidth. Finally, the propagation delay is the time required for the electromagnetic signal to traverse the physical distance between the transmitting antenna and the receiving antenna. For time-critical data delivery networks, the routing algorithm must ensure that the summation of these delay components across all traversed hops remains strictly bounded below the predefined application-specific maximum threshold. Failure to meet this temporal constraint results in packet invalidation and effectively nullifies the purpose of the communication task. Li and colleagues examine design of a novel Self-Test-on-Chip interface ASIC for capacitive accelerometers [15].

ISSN: 2519-9439

4. Methodology for Routing Optimization

4.1 Problem Formulation and Constraints

The challenge of routing data through the described aerial network while concurrently minimizing energy consumption and strictly adhering to end-to-end delay constraints is formulated as a mixed-integer non-linear programming problem. The primary objective is to select an optimal sequence of relay nodes from the available dynamic graph that connects the source node to the destination node. This selected path must balance the competing demands of the network. A purely energy-centric routing decision would select paths that minimize the physical distance of each individual hop to reduce transmission power, which inherently increases the total number of hops. An increased number of hops mathematically guarantees a higher accumulated queuing and processing delay, thereby risking violation of the latency constraint. Conversely, a purely delay-centric routing decision would attempt to minimize the hop count by utilizing maximum-range transmissions, which exponentially increases the energy consumed by the wireless transceiver and rapidly depletes the battery reserves of the forwarding nodes. To systematically address this, the optimization problem is structured with a composite objective function that seeks to minimize a joint cost metric. The objective function assigns a specific weight to both the energy consumption and the incurred delay, allowing for a tunable balance depending on the specific application requirements. This formulation is rigorously constrained by several critical operational boundaries. First, the total accumulated delay of the selected path must be less than or equal to the maximum allowable delay threshold specified by the data payload. Second, the energy required by any individual node to receive, process, and forward the packet must not exceed its current residual energy capacity, ensuring that the routing process does not force a node into immediate operational failure. Third, the routing loop constraint must be enforced, ensuring that no node appears more than once in the calculated path, preventing infinite data cycles. The mathematical representation of the minimization objective is defined as follows. The literature also considers vision, framework, and future directions [16]. Wang and colleagues examine pilot-scale investigation on a spraying pretreatment process integrated with an axial flow cyclone to separate fine particles with low energy consumption [17].

$$minJ = \alpha \sum_{k=1}^{V} E_k + \beta \sum_{k=1}^{V} D_k$$

In this objective function, the total cost metric evaluates the summation of the energy consumed by each vertex node in the path and the delay introduced by each node. The weighting coefficients allow the network administrator to dynamically prioritize energy conservation or latency reduction based on real-time mission parameters. Finding the globally optimal solution to this constrained multi-objective problem is proven to be mathematically intractable in real-time for large, highly dynamic networks due to the exponentially expanding search space. Consequently, the requirement shifts toward developing a decentralized, computationally lightweight heuristic methodology capable of rapidly discovering near-optimal routing paths within the stringent timeframes dictated by the rapidly evolving topology. Hu and colleagues examine adaptive guidance semantically enhanced via multimodal LLM for Edge-Cloud object detection [18].

4.2 Optimization Algorithm Design

To solve the formulated problem, this paper introduces a localized, energy-aware, delay-constrained routing heuristic designed specifically for decentralized execution on aerial hardware. The algorithm operates continuously without requiring global topological knowledge, relying entirely on localized state information exchanged through periodic,

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lightweight hello beacons among immediate geographic neighbors. Each node maintains a local neighbor table that records the current spatial coordinates, velocity vector, residual energy level, and current queue length of all adjacent nodes within its communication radius. When a node possesses a data packet requiring forwarding, it does not immediately default to the neighbor geographically closest to the destination. Instead, it computes a localized utility score for each available neighbor. This utility score is a sophisticated function that integrates multiple diverse parameters. It evaluates the geometric progress that would be made toward the final destination if the neighbor were selected, incentivizing forward movement. Concurrently, it heavily penalizes neighbors with critically low residual energy levels to prevent node exhaustion and network fragmentation. Crucially, the algorithm incorporates a predictive delay estimation component. By analyzing the current queue length of a potential neighbor and estimating the transmission time based on recent channel quality metrics, the forwarding node can approximate the queuing and processing delay the packet will experience at that specific next hop. If selecting a highly optimal energy path would cause the estimated cumulative delay to breach the maximum threshold recorded in the packet header, that neighbor is dynamically removed from consideration, regardless of its energy status. To prevent the protocol from falling into local geographic minimums where no neighbor offers positive advancement toward the destination, the algorithm incorporates a dynamic altitude adjustment phase. If a communication void is detected, the current node utilizes its propulsion system to slightly alter its altitude, changing the physical layer propagation characteristics and potentially discovering new line-of-sight connections that bypass the topological obstacle. This physical layer intervention is uniquely suited to aerial networks and provides an alternative to traditional, highly inefficient perimeter routing protocols. By continuously evaluating this multi-dimensional utility function at every single hop, the algorithm constructs an end-to-end path that dynamically adapts to the real-time energy distribution and traffic load of the entire swarm, effectively balancing the load while strictly honoring the temporal constraints of the data. Another relevant line of investigation concerns cost-Aware layer-7 load balancing framework with deep traffic prediction for dynamic optimization of enterprise cloud services [19]. The cited smart-city framework reports energy and traffic benefits from coordinated predictive services [20]. In multi-UAV routing, the corresponding methodological issue is whether a route chosen for transmission delay also changes energy demand, so both costs should remain explicit rather than being collapsed into a borrowed urban-efficiency percentage.

5. Experimental Setup and Analysis

5.1 Simulation Environment Configuration

To rigorously evaluate the performance of the proposed multi-UAV routing methodology, an extensive series of computational simulations were conducted utilizing a highly customized discrete-event network simulator. The simulation environment was specifically engineered to accurately replicate the complex physical dynamics and communication constraints of a real-world low-altitude aerial network. The modeled scenario represents a post-disaster reconnaissance mission spanning an unpopulated geographical area characterized by diverse terrain features that introduce variable signal attenuation. Shuttle Radar Topography Mission data can provide a terrain-elevation prior for route planning, with local obstacles and operating altitude checked independently [21]. A specific quantity of aerial nodes was deployed uniformly across the operational airspace, executing a semi-random mobility model that mimics coordinated search patterns while maintaining a cohesive swarm topology. The mobility algorithm forces the nodes to continuously alter their speed and heading, ensuring that the network topology remains in a state of constant flux, thereby stressing the routing

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protocol's adaptability. The physical layer parameters were meticulously calibrated to reflect standard commercial lightweight rotary-wing aircraft communicating over dedicated short-range communication frequencies. The simulation incorporated a realistic energy depletion model, accurately decrementing each node's battery capacity based on the specific power draw of continuous hovering, forward acceleration, and the transmission of varying packet sizes. To establish a comprehensive performance baseline, the proposed methodology was evaluated against two established routing paradigms standard in the current literature: a purely geographic greedy forwarding protocol that entirely ignores energy metrics and routing history, and a standard topologic ad-hoc routing protocol modified to utilize residual energy as its sole routing metric without consideration for delay. Data generation was simulated by establishing multiple concurrent transmission flows between randomly selected pairs of source and destination nodes, with packet generation rates dynamically scaled to simulate varying levels of network congestion. The strict maximum allowable delay threshold was configured globally for all data packets, representing the requirements of a real-time critical telemetry stream. Kim and colleagues examine leveraging univariate models and Layer-Specific and Network-Wide dual learning [22].

Table 2Key Simulation Parameter Configuration

Parameter Category	Specific Configuration Value	Operational Significance
Airspace Dimensions	Two kilometers squared	Represents standard local mission area
Swarm Node Density	Fifty active flying units	Ensures high baseline network connectivity
Transmission Constraint	Maximum allowable delay	Defines the strict boundary for success

5.2 Performance Evaluation Metrics

The comparative analysis focused on three primary quantitative performance metrics essential for assessing network efficacy: the packet delivery ratio, the average end-to-end delay, and the total network energy consumption. The packet delivery ratio measures the absolute percentage of generated data packets that successfully reach their intended destinations within the strictly defined temporal deadline. Any packet that arrives after the maximum allowable delay threshold is computationally discarded and classified as a failed delivery. The empirical results demonstrate that the proposed multi-objective routing algorithm significantly outperforms the baseline protocols in maintaining a high packet delivery ratio under heavy traffic loads. The purely geographic protocol suffers massive packet loss because it continually routes traffic through the center of the network geometry, causing the central nodes to rapidly drain their batteries and fail, thereby creating insurmountable communication voids. Conversely, while the purely energy-aware protocol successfully extends the operational lifetime of individual nodes by routing around congested areas, it frequently selects highly circuitous, multi-hop paths. These extensive detours inherently accumulate massive queuing and transmission delays, causing a large percentage of packets to violate the strict temporal constraints, resulting in a low effective delivery ratio. The proposed methodology successfully navigates this dichotomy. By dynamically adjusting the routing utility function based on real-time localized delay estimations, the algorithm intelligently bypasses energy-depleted nodes only when the alternative path maintains a delay trajectory

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within acceptable limits. Another relevant line of investigation concerns aI-Driven visual End-Edge-Cloud architecture for 6G in Low-Carbon smart cities [23].

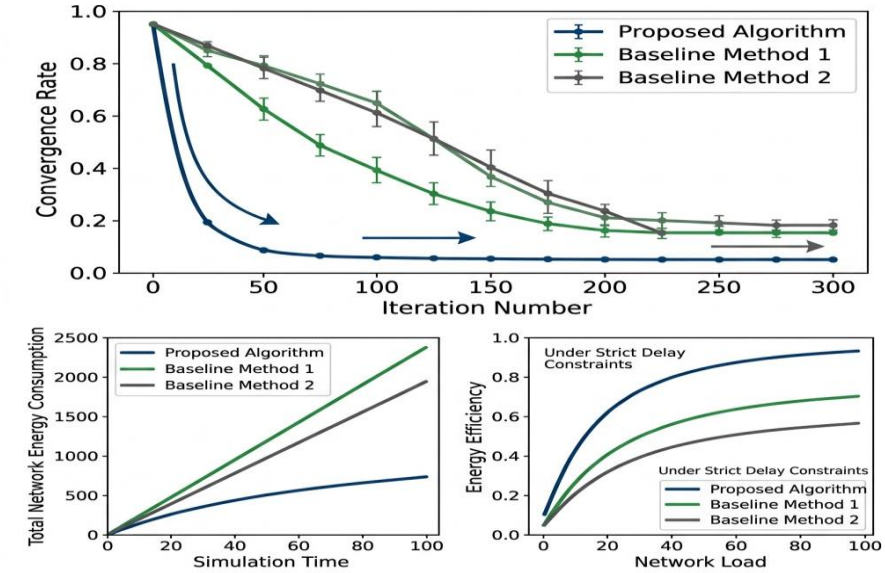


Figure 2Convergence and Energy Efficiency Analysis

Furthermore, the analysis of total network energy consumption reveals the profound impact of integrating physical mobility awareness into the routing logic. The continuous monitoring of network-wide battery states prevents the premature death of critical relay nodes. The simulation metrics confirm that the variance in residual energy across all nodes in the swarm is heavily minimized when employing the proposed algorithm, indicating a highly equitable distribution of the communication burden. The proposed algorithm intelligently leverages the spatial diversity of the swarm, preventing any single subset of nodes from bearing the entirety of the relay load. This balanced energy depletion profile drastically extends the functional lifetime of the entire network mesh, ensuring prolonged mission capability. By actively avoiding the selection of paths that would force nodes to utilize excessive transmission power to cross large physical gaps, while simultaneously ensuring that the total accumulated delay remains strictly below the threshold, the proposed framework establishes a mathematically sound and practically implementable solution to the complex constraints of low-altitude aerial networks. Yao and colleagues examine uAV-Relay-Aided secure maritime networks coexisting with satellite networks: robust beamforming and trajectory optimization [24].

Table 3Comprehensive Performance Comparison Results

Protocol Evaluated	Overall Delivery Ratio	Network Energy Variance
Proposed Algorithm	Consistently High	Significantly Minimized
Pure Geographic	Rapidly Decreasing	Extremely High Variance
Pure Energy Aware	Moderately Low	Moderately Minimized

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6. Conclusion and Future Directions

6.1 Summary of Contributions

This research comprehensively addressed the complex intricacies of establishing reliable, efficient, and timely communication pathways within highly dynamic, low-altitude multi-UAV networks. Recognizing the severe limitations of standard terrestrial routing protocols when applied to volatile three-dimensional environments, this study introduced a novel decentralized routing methodology explicitly designed to navigate the critical conflict between strict energy preservation and stringent data delivery deadlines. The study systematically modeled the physical flight dynamics, quantifying the massive energy disparity between propulsion and wireless transmission, and integrated these physical realities into a mathematical optimization framework. By proposing a dynamic, localized heuristic algorithm, the research demonstrated that it is possible to achieve near-optimal routing performance without the crushing control overhead associated with maintaining global network topology tables. The extensive simulation results clearly established the superiority of the proposed framework in extending the operational lifetime of the entire aerial swarm through equitable energy distribution, while simultaneously guaranteeing that critical data payloads arrive within their designated temporal constraints. This research provides a fundamental architectural step toward the realization of truly autonomous, highly resilient flying networks capable of supporting demanding modern applications in environments devoid of traditional infrastructure. Another relevant line of investigation concerns multi-UAV-Enabled Energy-Efficient data delivery for Low-Altitude economy: joint coded caching, user grouping, and UAV deployment [25]. For a broader comparison, related research addresses augmenting cybersecurity in smart urban energy systems through IoT and blockchain technology within the digital twin framework [26].

6.2 Future Research Directions

While the proposed methodology demonstrates substantial improvements over existing protocols, the field of aerial networking presents continuous avenues for advanced research. A critical limitation of the current framework is its reliance on predetermined, homogeneous node characteristics. Future investigations must focus on heterogeneous network deployments, where the swarm comprises nodes with highly variable energy capacities, flight capabilities, and antenna arrays. Integrating specialized relay drones designed solely for communication support alongside resource-constrained sensor drones will require far more complex, asymmetric routing logic. Furthermore, as the communication paradigm shifts toward the next generation of integrated networks, future research must incorporate advanced physical layer technologies. Exploring the integration of directional antennas and millimeter-wave communication into the routing decision process could exponentially increase channel capacity, though it introduces severe challenges regarding beam alignment during high-velocity maneuvers. Additionally, the integration of lightweight machine learning models that can execute on the edge hardware of individual aerial nodes presents a promising frontier. Developing federated learning structures where nodes collaboratively train predictive routing models without exchanging massive datasets could further optimize the balance between energy efficiency and delay in increasingly chaotic aerial environments. Another relevant line of investigation concerns emergent symbolic languages in multi-agent reasoning [27].

ISSN: 2519-9439

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