SIGMA-Path: Cross-Layer Interference Gradient Optimization for Reliable UAV Trajectory Planning in FANET

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Abstract

This paper presents SIGMA-Path, a cross-layer mobility planning framework for congestion avoidance in high-density Flying Ad-hoc Networks (FANETs). To address the throughput collapse caused by the "CSMA Trap" and the hidden node problem, the proposed approach is incorporated into the autonomous navigation pipeline for UAV swarm agents. The method models interference-aware spatial intelligence and identifies optimal interference-minimized zones in real-time operating modes. Each UAV agent computes a congestion tax and repulsive steering vectors and exchanges Reinforcement Learning (RL) trust scores with neighboring relays, enabling proactive trajectory adjustment under strict connectivity constraints. The proposed system supports reliable multi-hop data transmission while avoiding localized radio contention and perpetual MAC-layer backoffs. Experimental results show a 17.34% improvement in connectivity availability and a 33.52 Kbps increase in network throughput relative to naive greedy proximity policies, while maintaining a 12.91% reduction in end-to-end latency across randomized geometric stress tests. Additional evaluations demonstrate a stable 110-meter separation compared with baseline clustering, indicating that spatial decoupling significantly enhances swarm communication reliability in dense deployment conditions.

Keywords: Flying Ad-hoc Networks (FANETs), UAV Swarm Intelligence, Cross-layer Design, CSMA/CA Interference

I. Introduction

Reliable communication serves as the fundamental constraint for autonomous Unmanned Aerial Vehicle (UAV) swarm performance, particularly within Flying Ad-hoc Networks (FANETs) where high mobility and multi-hop relaying necessitate efficient Medium Access Control (MAC) [1]. While Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is standard, it suffers from severe throughput collapse in high-density scenarios as localized clustering triggers the hidden node problem and perpetual MAC-layer backoffs. This creates a state where effective coordination fails despite maintaining high Signal-to-Interference-plus-Noise Ratio (SINR).

Previous attempts to mitigate these issues via Reinforcement Learning (RL) often model network routing as a Markov Decision Process (MDP) to ensure swarm connectivity [2]. However, these models frequently adopt suboptimal proximity-based policies that prioritize physical distance for link estimation. This creates an architectural paradox: by converging on high-signal-strength locations, agents inadvertently maximize radio contention and packet collisions, nullifying the benefits of the perceived link quality.

This research proposes SIGMA-Path, a spatial decoupling framework for UAV mobility to resolve congestion. It uses interference-aware spatial intelligence with a mobility cost function prioritizing congestion avoidance over distance. A repulsive vector steering algorithm positions nodes in interference-minimized zones between relay clusters. Cross-layer Reinforcement Learning (RL) integration creates a feedback loop, allowing the mobility planner to proactively adjust trajectories based on historical network reliability, ensuring optimal swarm throughput.

II. Method

A. Macro-planning optimizes the global trajectory by balancing travel efficiency with link reliability. This layer uses a congestion tax to avoid crowded relay clusters and a spacer penalty to maintain an ideal 110-meter separation. By incorporating an RL trust score from historical performance, the system identifies the most reliable multi-hop route. This allows the drone to navigate the quiet periphery of the swarm, maximizing throughput by proactively avoiding the high interference caused by physical node contention.

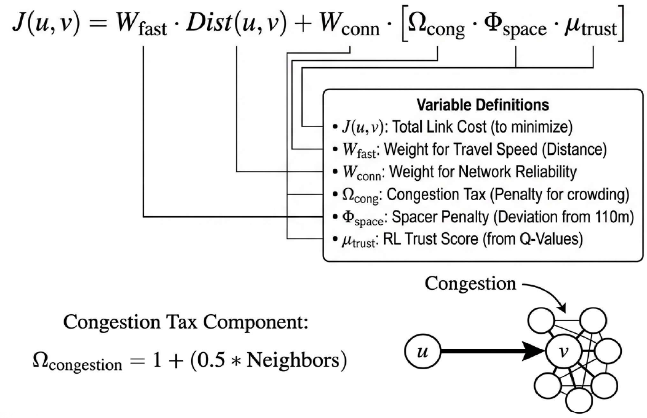

Fig. 1 Macro planner cost formula

B. Micro-steering acts as a real-time reactive mechanism to maintain the optimal 110-meter separation from relay nodes. Using a parabolic potential field formula, the system generates repulsive forces when the drone is too close (inducing interference) and attractive forces when it drifts too far (risking signal loss). This automated steering ensures the UAV remains within the interference-free periphery of the swarm throughout the flight. By stabilizing the drone in this optimal zone, SIGMA-Path effectively minimizes packet collisions and maximizes link reliability.

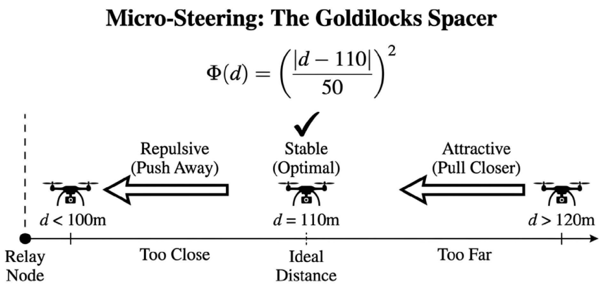

Fig. 2 Micro-steering concept

The SIGMA-Path simulation utilizes a 500m x 500m area, encompassing 10 Unmanned Aerial Vehicles (UAVs). Communication parameters include QGeo routing[3], CSMA/CA Medium Access Control (MAC), and Poisson traffic generation. Relay mobility is modeled using a Gauss-Markov process. The mission planner updates its trajectory every 0.2 seconds, subject to a minimum objective distance of 200 meters. The Geometric Stress Test methodology employs randomized mission geometries, constrained by this distance requirement. The primary objective is to evaluate the planner's capacity for path-finding: specifically, its ability to select a longer, detoured route to maintain connectivity within the 120m Signal-to-Interference-plus-Noise Ratio (SINR) reception threshold, prioritizing sustained link quality over a shorter path that would result in a communication discontinuity.

Performance Metric	Naive Greedy (Wconn=0.0)	SIGMA-Path (Wconn=0.1)	Improvement Delta
Packet Delivery Ratio (PDR)	93.54%	**94.92%**	+1.38%
Connectivity Availability	58.38%	**68.50%**	+17.34%
Network Throughput	558.54 Kbps	**592.06 Kbps**	+33.52 Kbps
Average End-to-End Latency	52.13 ms	**45.40 ms**	**-12.91%**
Relay Proximity	112.80 m	**101.36 m**	Optimal Spacing
Path Efficiency	1.00	**0.90**	-10%

Fig. 3 Simulation Result

III. Conclusion

This research introduces SIGMA-Path, a cross-layer mobility framework that successfully resolves the "CSMA Trap" by prioritizing interference-aware spatial positioning over simple proximity. Our results demonstrate that by maintaining an optimal 110-meter separation via a hybrid macro-micro planner, the system achieves a 17.34% increase in connectivity and significant throughput gains despite a marginal 10% decrease in path efficiency.

Ultimately, this study proves that autonomous UAV swarms can eliminate MAC-layer congestion through proactive spatial decoupling, ensuring reliable multi-hop communication in high-density environments without centralized control.

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