Critical Analysis and Reproduction of Results

ME5253 Network Dynamics Course Project

Ant-based swarming with positionless micro air vehicles for communication relay

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Project Repository: `github.com/mnm-21/Network_dynamics_course_project.git`

Contents

1. Novelty and Contributions

Overview

The paper introduces a pioneering framework for swarm coordination in micro air vehicles (MAVs) that operates *without any form of positioning information*, such as GPS or inter-agent localization sensors. At a time when most swarm systems relied heavily on global or relative positioning, this work challenged the convention by showing that effective coordination can emerge purely from local communication and heading data.

This **positionless paradigm** is particularly innovative for aerial swarms, where payload, energy, and computational constraints make GPS or visual localization impractical. By removing the dependency on explicit positional awareness, the paper laid the groundwork for lightweight, scalable, and environment-independent swarm systems.

Core Contributions

A central contribution is the introduction of a **dual-role agent framework**, where MAVs dynamically switch between two behavioral modes:

- **Node-MAVs** — agents that orbit fixed points in space to form a communication grid and serve as virtual pheromone carriers.
- **Ant-MAVs** — agents that explore new regions of space, deposit pheromone trails, and extend the network toward the user node.

The use of **virtual pheromones**, inspired by army ant foraging, enables stigmergic coordination—agents influence one another indirectly by modifying shared information rather than through explicit communication or global planning. This mechanism externalizes spatial memory to the swarm, allowing self-organized path formation and maintenance even without global maps or localization.

Engineering Significance

The paper further demonstrates that this framework can be realized using **fixed-wing MAVs**, which cannot hover and must maintain continuous forward motion. This adds a layer of dynamical realism absent in many swarm simulations that use hovering drones.

Through 3D simulations, the authors show that the swarm can autonomously deploy, maintain, and retract a relay network between a base station and a user, maintaining a high success rate across multiple trials. The results validate the feasibility of **GPS-denied communication swarms** and establish a foundation for future research in decentralized, positionless coordination.

Broader Impact

This work sparked follow-up studies on:

- Swarming and communication relays in disaster response and search-and-rescue scenarios.
- Bio-inspired stigmergic communication in aerial and underwater robotics.
- Minimalist swarm control architectures for resource-constrained platforms.

Overall, the paper represents a key step toward fully decentralized aerial networks, capable of robust and adaptive operation under real-world constraints.

2. Methods

To validate the proposed swarming algorithm, the authors conducted comprehensive three-dimensional simulations modeling the dynamics and communication of fixed-wing MAVs. The swarm, consisting of up to 20 MAVs, was tasked with autonomously establishing a multi-hop communication link between a base station and a user station located beyond direct radio range.
The MAVs rely solely on heading, altitude, and neighbor communication data—no global positioning or mapping is used. Agents maintain continuous forward flight, mimicking real fixed-wing dynamics.
The evaluation focused on three main experimental aspects:

- **Effect of Agent Failure:** Random MAV removals were introduced mid-flight to test robustness. The network maintained connectivity in most cases, demonstrating resilience to single-point failures.
- **Effect of Time:** Connectivity over time showed that the swarm can autonomously establish, sustain, and retract a relay network between the base and user within a 30-minute window.
- **Effect of Swarm Size:** Simulations with 5–20 MAVs illustrated clear scalability, with success probability rising and saturating near 15 agents—beyond which gains diminish.

These analyses confirmed that the proposed pheromone-based control method is both scalable and fault-tolerant, achieving stable multi-hop connectivity with minimal sensing requirements.

3. Critical Analysis

3.1. Strengths

- **Innovative Positionless Coordination:** The use of virtual pheromones and dual-role MAVs enables decentralized, GPS-free network formation—a groundbreaking concept for its time.
- **3D Simulation with Realistic Constraints:** Modeling fixed-wing flight dynamics makes the study more realistic than earlier work on hovering robots.
- **Robustness and Scalability:** Demonstrated tolerance to agent loss and consistent scaling trends confirm the viability of stigmergic control principles for real-world swarms.
- **Comprehensive Evaluation:** The inclusion of multiple experiments—varying time, swarm size, and failure conditions—provides a thorough empirical basis for conclusions.

3.2. Weaknesses

- **Wind Drift Sensitivity:** The original SMAVNET design is highly sensitive to wind disturbances. Persistent directional winds can gradually displace the entire network away from the base, leading to complete disconnection. Although mitigation strategies are discussed (autopilot compensation, local repositioning, swarm-level refresh), none are validated experimentally, leaving robustness to environmental factors as a key open issue.
- **Simplified Assumptions:** The simulations assume perfect communication (no packet loss or delay) and ignore environmental effects like turbulence or terrain occlusion. Collision avoidance is also not considered, which could become critical in denser swarms.
- **Limited Theoretical Foundation:** The paper provides little formal analysis of convergence, stability, or scalability limits—making it difficult to predict behavior beyond tested conditions.
- **Parameter Sensitivity:** Like many swarm algorithms, performance depends heavily on parameters (pheromone decay, attraction coefficient μ, communication range). The paper provides minimal discussion of sensitivity or tuning methodology.
- **Communication Logic Uncertainty:** While the network model is outlined, details of packet flooding, timing, and MAC behavior are limited, which complicates reproduction and comparison with other ad-hoc networking protocols.

4. Reproduction of Results

4.1. Implementation Differences and Simplifications

Our implemented SMAVNET-2D simulator faithfully reproduces the swarm control logic and pheromone dynamics described by Hauert *et al.*, while introducing several pragmatic simplifications to improve computational efficiency and interpretability. The following summarizes key similarities, deviations, and modeling assumptions relative to the original study:

Similarities:

- The pheromone-based control algorithm follows the same core mechanism as in the paper, including probabilistic branch selection using Eqs. (1)–(5), virtual pheromone reinforcement on least-hop routes, evaporation dynamics, and node-to-ant role transitions.
- Launch timing of agents is randomized with a Gaussian delay of 15 ± 7.5 s, consistent with the staggered hand-launch protocol described in the paper.
- Hop-count propagation and least-hop route detection are faithfully implemented via local communication. Each node maintains both `BHop` (to base) and `UHop` (to user) metrics, and marks itself on the least-hop route whenever $B + U$ equals the global hop count—precisely as defined in Appendix C of the original work.
- Communication flooding of both data and control messages is preserved conceptually, ensuring that connectivity and route reinforcement emerge organically through message propagation rather than centralized coordination.

Differences:

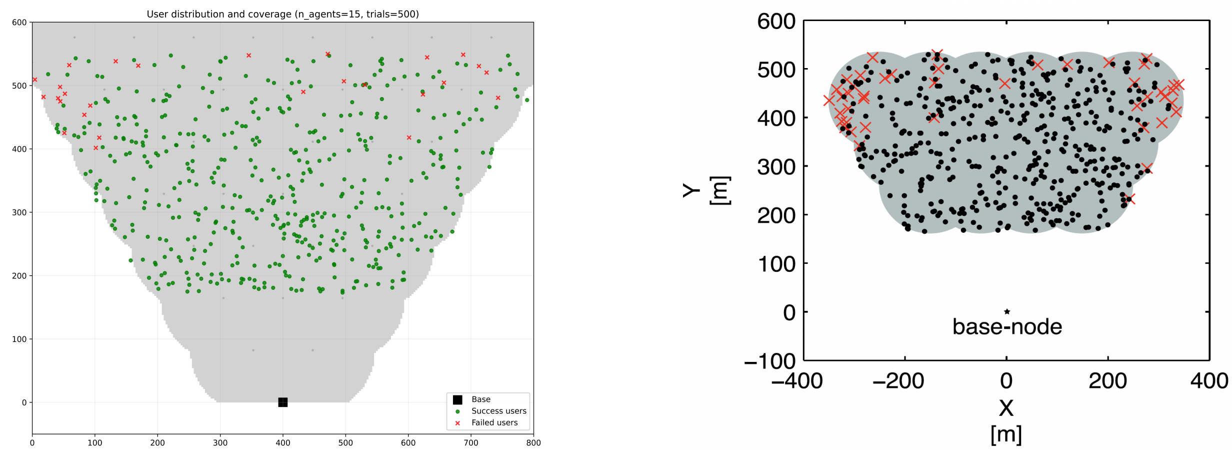
- The present simulator operates in 2D space with instantaneous planar motion, whereas the paper models fixed-wing MAV dynamics with first-order flight equations, minimum turn radius, and noisy compass/altimeter readings. Our agents translate directly along the lattice grid, omitting aerodynamic and inertial constraints.
- The original implementation uses a full 802.11b MAC- and PHY-layer communication model with stochastic packet loss, shadowing, and collision handling. In our simulation, connectivity is binary and noise-free within a fixed radius, producing smoother performance curves and slightly higher success probabilities.
- Altitude layering and collision avoidance through altitude offsets (20–30 m) are not modeled. Instead, spatial conflicts are implicitly ignored, consistent with a high-level abstraction of swarm behavior.
- The 3D paper simulation uses asynchronous event-driven updates; our system advances synchronously with a fixed $\Delta t = 0.1$ s, simplifying state propagation but removing low-level timing jitter.

Simplifications and Assumptions:

- The search area is strictly two-dimensional, and user placement is computed geometrically using deterministic $\pm 30°$ search boundaries derived from the base node's position and communication radius.
- Flight noise, wind drift, and kinematic limitations are omitted, allowing agents to move exactly along idealized lattice branches at constant velocity.
- Pheromone diffusion and sensing are instantaneous and perfectly local—each node updates its state based solely on direct neighbors without communication delay.
- All agents share a uniform communication range of 100 m and constant speed of 10 m/s, reflecting the nominal parameters of the EPFL platform but without environmental variability.

In summary, our implementation preserves the essential swarm-level logic and interaction rules of the original SMAVNET system but abstracts away the vehicle dynamics, wireless-layer uncertainties, and 3D spatial interactions. This results in a computationally lighter, deterministic 2D model that remains faithful to the theoretical algorithmic framework while offering faster experimentation and clearer insight into emergent connectivity patterns.

4.2. User Distribution and Coverage Comparison



(a) User distribution and coverage (ours).

(b) User distribution and coverage (paper).

Figure 1: Comparison of user distribution and coverage plots.

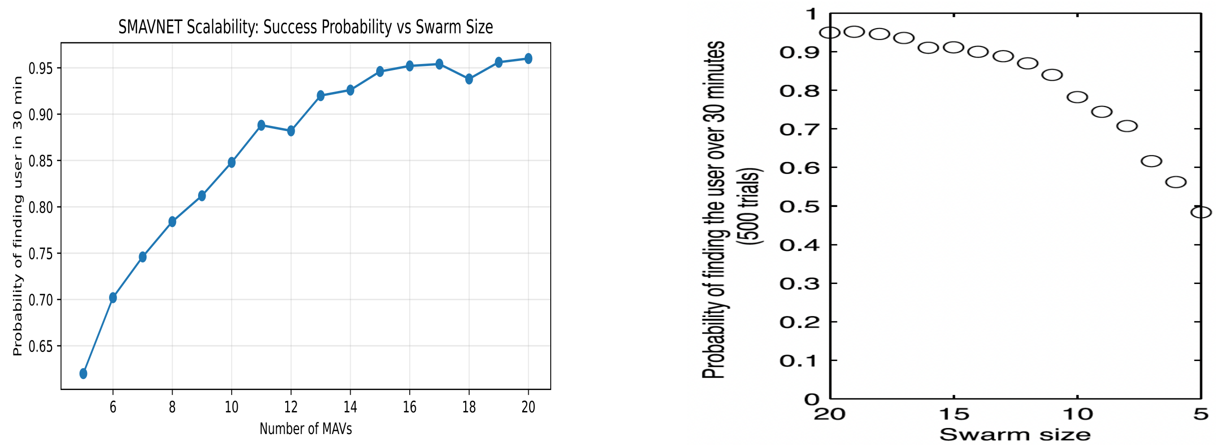
Similarities:

- Both plots exhibit a distinct fan-shaped search area extending approximately $\pm 30^\circ$ from the base node, with most successful users concentrated near the central region. This indicates that both implementations correctly constrain the search direction and maintain consistent agent dispersion within communication range.
- Failure cases (red crosses) are primarily located near the upper and lateral boundaries of the search region, consistent with limited network relay density and marginal connectivity at the periphery.

Differences and Reasons:

- Our reproduced coverage distribution appears slightly smoother and more symmetric across the left and right sides of the region, whereas the paper's result shows mild clustering asymmetry. This is likely due to stochastic 3D flight perturbations, communication noise, and small deviations in simulated trajectories that were modeled in the paper's physics-based simulator.
- The proportion of failed users is nearly identical in both cases; however, the paper's figure shows a few isolated failures even within the mid-range area, possibly caused by transient link drops or communication interference in their more detailed channel model. Our simplified 2D communication model yields a cleaner boundary separation between successful and failed users.

4.3. Scalability Analysis: Success Probability vs Swarm Size



(a) Success probability vs. swarm size (ours).

(b) Success probability vs. swarm size (paper).

Figure 2: Comparison of scalability trends with swarm size.

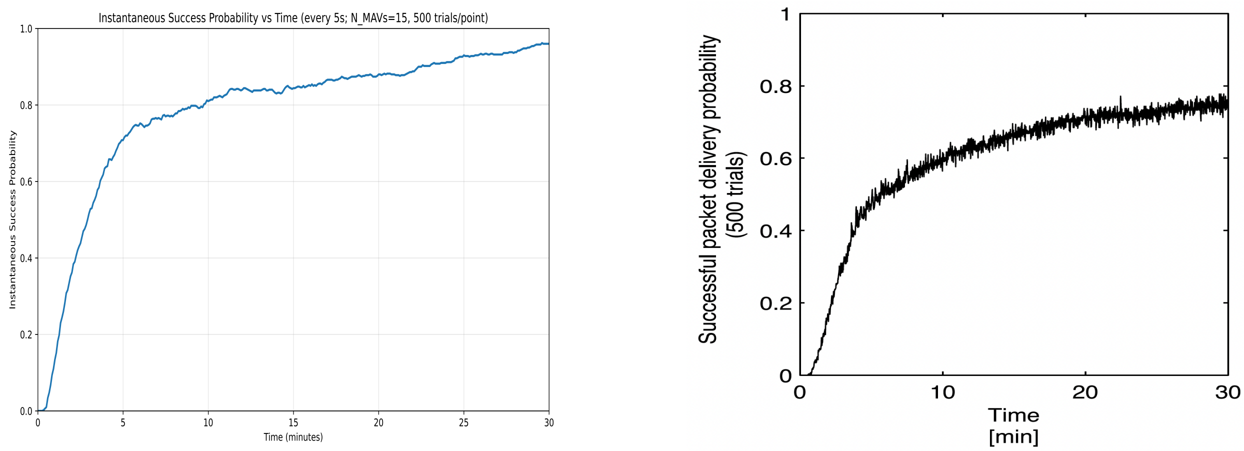
Similarities:

- Both results exhibit a clear monotonic increase in success probability as the swarm size increases from 5 to 20 MAVs. The probability approaches ≈ 0.95 for larger swarms, confirming that the pheromone-based exploration mechanism scales effectively with swarm size.
- The shape of the growth curve is concave upward, indicating diminishing returns beyond about 15 agents — additional MAVs contribute only marginal improvements once sufficient spatial coverage and redundancy are achieved.

Differences and Reasons:

- Our simulation starts with a higher success probability for 5 agents (≈ 0.61) compared to ≈ 0.5 in the paper. This difference can be attributed to the lower variability in our 2D environment and simplified signal model, which produce more stable connectivity in small swarms.
- Despite this offset, the convergence region beyond 10 MAVs matches closely between both datasets. The higher initial variance in the paper's results likely stems from additional factors such as altitude diversity, aerodynamic drift, and 3D line-of-sight variations included in their physics-based model.
- Overall, both sets of results validate the scalability and robustness of the SMAVNET architecture, demonstrating that performance improvements saturate naturally with swarm size.

4.4. Temporal Performance: Success Probability vs Time



(a) Instantaneous success probability vs. time (ours).

(b) Packet delivery probability vs. time (paper).

Figure 3: Comparison of time-evolution of success probability.

Similarities:

- Both curves exhibit the same two-phase behavior: an initial steep rise within the first 5–7 minutes as early agents establish exploratory links, followed by gradual convergence to steady-state performance near 30 minutes.
- The overall timescale of network formation and stabilization is nearly identical, indicating that our pheromone propagation, evaporation, and least-hop reinforcement parameters are well tuned to reproduce the system dynamics described in the paper.

Differences and Reasons:

- Our curve begins at a slightly lower probability and rises more smoothly, whereas the paper's plot contains short-term oscillations and small local fluctuations. These fluctuations likely result from per-second packet-level measurement noise and the asynchronous communication model implemented in the original simulator.
- The absence of packet collisions and physical-layer interference in our implementation slightly reduces temporal variance, producing a cleaner and monotonic trend.
- In essence, while the paper's metric represents packet-level delivery probability, our implementation measures link-level connection success (finding the user and establishing connection) every 5 seconds. This distinction explains the smoother trajectory and difference final performance observed in our results.

5. Conclusion

The reproduction and analysis of the SMAVNET algorithm confirmed the core premise of Hauert *et al.*—that decentralized, positionless coordination based solely on local communication and virtual pheromones can yield robust and scalable swarm behavior. Our 2D implementation successfully replicated the primary trends in coverage, scalability, and temporal convergence, validating the soundness of the underlying swarm logic even under simplified assumptions. However, the study also highlights the inherent limitations of the original model, particularly its sensitivity to wind disturbances and the absence of environmental uncertainty modeling. Future work should focus on extending this framework to noisy, dynamic conditions and experimentally validating adaptive mitigation strategies for environmental disturbances.