Ant-based Swarming with Wind-Aware Replacement for Positionless Micro Air Vehicle Networks

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***Abstract*—Ant-inspired swarm algorithms enable micro air vehicles (MAVs) to self-organize into ad hoc communication networks using only local information, eliminating the need for GPS or centralized control. However, these systems remain vulnerable to wind disturbances that cause relay nodes to drift, weakening network geometry and link quality. This work enhances the classical SMAVNET framework by introducing a wind-aware replacement strategy that periodically refreshes aging nodes using local interactions. A physics-based 2D simulation incorporating stochastic wind dynamics shows that the proposed approach reduces average spatial drift by nearly 45% across swarm sizes of 5–20 MAVs compared to the baseline. Although connectivity remains idealized in simulation, the improvement in spatial coherence directly translates to higher link reliability in real deployments. The method preserves SMAVNET's simplicity and scalability while significantly improving robustness under environmental disturbances.**

***Index Terms*—Swarm robotics, micro air vehicles, communication networks, pheromone robotics, decentralized control, wind disturbances, drift mitigation**

I. Introduction

Swarm robotics enables groups of autonomous agents to collectively perform complex tasks using only local interactions, without centralized coordination or global positioning systems. In aerial domains, this paradigm offers a compelling approach for rapidly deployable communication networks, particularly in disaster zones or GPS-denied environments. One of the earliest and most influential demonstrations of this concept is the SMAVNET framework proposed by Hauert *et al.* [1], where fixed-wing micro air vehicles (MAVs) emulate the pheromone-based foraging behavior of army ants to self-organize into an ad hoc communication bridge between ground users. Each MAV acts as either an exploring "ant" or a stationary "node," relying solely on local wireless communication and simple proprioceptive sensing. The system elegantly achieves large-scale coordination without requiring position data or map-based control.

However, the original SMAVNET formulation assumes calm flight conditions and perfectly stationary nodes. In realistic outdoor environments, wind and small aerodynamic disturbances continuously displace MAVs from their nominal lattice positions. Over time, this drift alters inter-agent spacing, weakens radio links, and can eventually cause disconnections in physical deployments. Hauert *et al.* recognized this as a major limitation and suggested several possible remedies, including autopilot-level compensation, adaptive repositioning, and swarm-level refreshing. Yet none of these strategies were implemented or quantitatively validated.

This work presents a concrete realization of the swarm-level refreshing concept to mitigate drift accumulation while preserving SMAVNET's fully decentralized design. The key idea is a *wind-aware replacement mechanism*, wherein newly launched ant agents periodically replace older node agents that have remained stationary and drifted under wind influence. The replacement decision is purely local and age-based: older nodes become increasingly likely to be refreshed, while younger nodes remain fixed. This simple rule effectively renews the swarm structure over time, limiting spatial distortion without the need for global coordination.

To evaluate this mechanism, we developed a physics-based two-dimensional SMAVNET simulator that incorporates a dynamic wind model with both sinusoidal and stochastic variations in magnitude and direction. This model produces realistic low-frequency drift comparable to real-world conditions. Experiments with swarms of 5–20 MAVs under a mean wind speed of 2 m/s show that the proposed mechanism reduces average node drift by approximately 45% relative to the baseline system. Although our current model enforces continuous connectivity for clarity of analysis, the observed improvement in geometric stability would directly enhance link reliability in physical implementations where excessive drift causes intermittent loss of communication.

Overall, this study demonstrates that limited, local role refreshing can substantially improve the spatial stability of positionless aerial swarms operating in windy environments. By maintaining the simplicity and scalability of the original pheromone-based approach while increasing robustness to environmental disturbances, this extension represents a

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practical step toward real-world deployment of autonomous, self-organizing MAV relay networks.

II. Related Work Review

Early developments in swarm robotics were inspired by collective behaviors observed in nature, such as flocking, foraging, and trail formation. These systems demonstrated that global coordination can emerge from simple local interactions among agents with limited sensing and communication capabilities [2]. Early robotic implementations—such as the minimalist ground robot swarms by Nembrini *et al.* [3]—proved that coherent group motion could be achieved without centralized control, but relied on visual or relative position cues suited to ground robots with simple dynamics. Translating these ideas to aerial platforms presented new challenges: fixed-wing MAVs cannot hover, must maintain forward motion, and operate under uncertain aerodynamic conditions.

Aerial swarm research has traditionally focused on coverage, surveillance, or cooperative target tracking [4]–[7]. Most of these approaches depend on relative or absolute localization data, using GPS, range sensors, or map-based strategies to maintain formation [8]–[10]. Although such systems have demonstrated impressive coordination, their reliance on positioning infrastructure limits deployability in cluttered or GPS-denied environments. Moreover, localization sensors often introduce significant energy, weight, and cost overheads, which contradict the scalability and simplicity goals of swarm robotics [11], [12].

The SMAVNET project by Hauert *et al.* [1] represented a major conceptual shift toward *positionless* aerial swarms. In SMAVNET, fixed-wing MAVs form an ad hoc communication network between ground users using only proprioceptive sensing and local wireless communication. The algorithm draws direct inspiration from the foraging behavior of army ants: ant-like agents ("ant-MAVs") explore new regions while node agents ("node-MAVs") act as stationary relays, collectively forming virtual pheromone trails through localized message exchange. This minimalist approach achieved reliable communication pathways without any global position data or external beacons, and demonstrated scalability with swarm size. The system also included mechanisms for deployment, maintenance, and retraction of the network.

However, the original SMAVNET study acknowledged a critical limitation: environmental wind causes gradual drift of node agents, destabilizing the intended lattice geometry and potentially breaking communication chains. Subsequent research in bio-inspired swarming has addressed environmental adaptation in limited contexts, such as adaptive heading control or artificial evolution of control parameters [13], [14], but comprehensive methods for drift compensation in positionless aerial networks remain largely unexplored.

Beyond SMAVNET, related efforts in pheromone robotics [15]–[17] have shown that virtual chemical gradients can support distributed coordination for tasks such as foraging, search, and chain formation [18]. Yet, most of these implementations operate in structured or planar environments with negligible external disturbances. In aerial applications, environmental forces such as wind, turbulence, and updrafts introduce persistent biases that classical pheromone mechanisms do not compensate for. Recent works have attempted to introduce adaptive or hybrid control strategies to improve swarm robustness [19], [20], but these typically assume some form of position estimation, again departing from the minimalist SMAVNET philosophy.

In summary, prior research has demonstrated the feasibility of ant-inspired, positionless swarming for aerial communication relays, but its robustness under environmental disturbances remains an open problem. The SMAVNET framework provides the ideal foundation for studying this question, as it explicitly identifies wind-induced drift as a major weakness yet leaves its mitigation unresolved. Building upon this foundation, our work introduces a wind-aware replacement mechanism that refreshes aging nodes to counteract drift while maintaining the minimalist, fully decentralized architecture of the original system.

III. Proposed Problem Formulation

The original SMAVNET problem [1] considers a swarm of fixed-wing micro air vehicles (MAVs) that must autonomously deploy to form an ad hoc communication relay between two ground users without access to global position information. Each MAV acts as either an *ant-MAV*, which explores new territory, or a *node-MAV*, which remains stationary to relay data. Local coordination is achieved through short-range wireless messages encoding virtual pheromone intensity, allowing the swarm to collectively extend and maintain a communication chain from the base to the user.

Formally, let each MAV be represented as an agent a_i with position $\mathbf{x}_i(t) \in \mathbb{R}^2$ and constant airspeed v_0. Agents interact only with neighbors within a communication radius r_c. At time t, each node n_{ij} on the lattice maintains a pheromone concentration $\phi_{ij}(t)$, which evolves according to local reinforcement and decay rules as described in [1]. In ideal, wind-free conditions, these rules drive the emergence of a stable lattice-like network bridging the base and user nodes.

A. Wind-Induced Drift

In realistic environments, MAVs experience external aerodynamic disturbances. Wind introduces a bias velocity $\mathbf{w}(t)$ that superposes with the MAV's commanded velocity, such that the actual motion is given by

$$\dot{\mathbf{x}}_i = v_0\, \mathbf{u}_i + \mathbf{w}(t) \tag{1}$$

where $\mathbf{u}_i$ is the unit vector along the MAV's heading. Even small, persistent wind components cause gradual displacement of node-MAVs from their nominal lattice positions. Because SMAVNET relies solely on local connectivity, any spatial drift can lead to (i) uneven spacing between nodes, (ii) distorted communication geometry, and (iii) eventual network fragmentation if inter-node distances exceed r_c.

In the original formulation, node-MAVs are assumed to hold their position indefinitely once deployed, with no mechanism for re-centering or refreshing. This assumption is valid in simulation but unrealistic in outdoor deployment, where accumulated drift can exceed hundreds of meters over extended durations. The problem therefore shifts from maintaining topological connectivity under ideal conditions to maintaining *spatial stability* of the network under persistent environmental disturbances.

B. Problem Objective

Given a swarm of N MAVs operating in a two-dimensional domain under stochastic wind field $\mathbf{w}(t)$, the objective is to maintain a connected relay network between base and user nodes such that:

1) The network remains connected, i.e., there exists at least one communication path from base to user through the set of node-MAVs.
2) The positional deviation of each node-MAV from its nominal lattice position is minimized over time.

We define the instantaneous drift of a node k as

$$d_k(t) = \|\mathbf{x}_k(t) - \mathbf{x}_k^*\| \tag{2}$$

where $\mathbf{x}_k^*$ is the node's ideal lattice position in the absence of wind. The overall spatial stability of the swarm over a time horizon T can then be expressed as the time-averaged drift

$$\bar{D} = \frac{1}{NT} \sum_{k=1}^{N} \int_0^T d_k(t)\, dt \tag{3}$$

The optimization goal is to design local interaction rules that minimize $\bar{D}$ without relying on global position data or centralized control.

C. Design Considerations

Any mechanism proposed to address drift must satisfy three constraints inherited from the SMAVNET design philosophy:

1) Locality: Agents can only use information obtained through short-range communication or onboard sensors; no absolute or relative position measurements are available.
2) Scalability: The control logic must scale linearly with swarm size and avoid global synchronization.
3) Minimalism: The additional behavioral complexity or communication overhead introduced to mitigate drift must remain minimal to preserve the lightweight, positionless nature of the system.

Under these constraints, the problem investigated in this paper can be stated as follows: *How can a swarm of positionless MAVs preserve the geometric stability of its relay network under wind disturbances using only local, probabilistic interaction rules?*

This formulation explicitly connects the physical phenomenon of wind-induced drift to its impact on network geometry and establishes the need for a decentralized compensation mechanism.

IV. Proposed Approach

Our approach builds upon the original SMAVNET algorithm [1], extending it to operate robustly under realistic wind disturbances while maintaining a fully decentralized, positionless framework. The proposed improvements are twofold: (1) the inclusion of a stochastic wind model that reproduces environmental drift, and (2) a probabilistic replacement mechanism that mitigates accumulated node displacement. Together, these modifications allow the swarm to self-refresh and preserve spatial stability over extended deployment times.

A. Baseline SMAVNET Behavior

In the SMAVNET framework, each MAV acts either as an *ant agent* or a *node agent*. Ant agents explore new regions of the lattice, guided by local pheromone concentrations, while node agents remain stationary and serve as communication relays. Communication between neighboring nodes is maintained through short-range wireless links within a radius r_c.

The swarm collectively constructs a lattice-like relay network by iteratively extending from the base station toward the user. When an ant agent reaches an unoccupied lattice point, it transitions into a node state, thereby extending the network. This behavior is purely local—each MAV decides its next move based only on pheromone cues and neighbor information, without any absolute position knowledge or centralized coordination.

Each node maintains a scalar pheromone intensity ϕ_{ij} that encodes its utility in the network. Its update rule follows the classical reinforcement–decay process, implemented in discrete form as

$$\begin{aligned} \phi_{ij}[t+1] = \phi_{ij}[t] + \phi_{\text{ant}}\, n_{\text{ants}} + \phi_{\text{internal}}\, \mathbb{I}_{\text{child}} \\ + \phi_{\text{conn}}\, \mathbb{I}_{\text{least}} - \phi_{\text{decay}}, \end{aligned} \tag{4}$$

Here, n_{ants} is the number of nearby ant agents reinforcing node (i, j), $\mathbb{I}_{\text{child}}$ indicates whether the node has at least one downstream neighbor, and $\mathbb{I}_{\text{least}}$ marks nodes on a least-hop route to the user. The constants ϕ_{ant}, ϕ_{internal}, ϕ_{conn}, and ϕ_{decay} are the reinforcement and decay coefficients implemented in the simulator.

Branch selection for active ant agents follows the Deneubourg-style probabilistic rule used in [1], reproduced below for completeness:

$$\begin{aligned} &p_L \propto (\mu + \phi_L)^2, \quad p_R \propto (\mu + \phi_R)^2, \\ &\pi_L = \frac{p_L\, c_L}{p_L\, c_L + p_R\, (1 - c_L)}, \end{aligned} \tag{5}$$

where ϕ_L and ϕ_R are the pheromone levels of the left and right candidate branches, and $c_L = (i+1)/(i+j+2)$ biases exploration based on lattice position. The agent chooses the left branch with probability π_L, ensuring balanced yet adaptive growth of the network.

B. Wind Disturbance Model

To realistically capture drift, we augment the baseline SMAVNET dynamics with a time-varying wind field $\mathbf{w}(t)$.

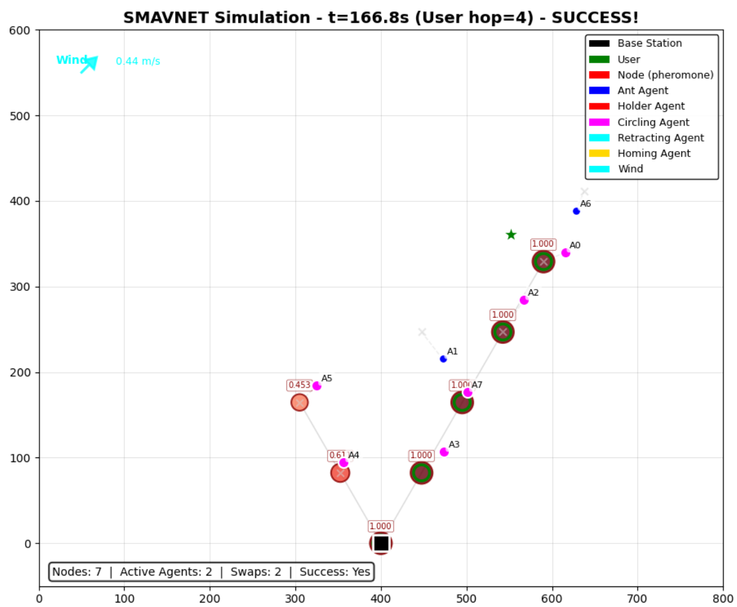

Fig. 1. Reproduction of the baseline SMAVNET behavior. The swarm autonomously forms a four-hop communication bridge between the base and user through local pheromone coordination.

Each agent therefore evolves according to the disturbed kinematic model previously defined in (1), where the commanded motion $v_0\,\mathbf{u}_i$ is superposed with an external wind disturbance. Here, v_0 denotes the constant airspeed, and $\mathbf{u}_i$ is the unit vector along the agent's instantaneous heading direction.

The wind vector $\mathbf{w}(t)$ is modeled as a combination of deterministic and stochastic components to capture both steady flow and turbulent variations:

$$\mathbf{w}(t) = w_0 \begin{bmatrix} \cos(\theta_0 + \Delta\theta(t)) \\ \sin(\theta_0 + \Delta\theta(t)) \end{bmatrix}, \tag{6}$$

where w_0 is the nominal wind speed, θ_0 is the mean wind direction, and the time-varying angular deviation is defined as

$$\Delta\theta(t) = A\sin(\omega t) + \xi(t), \tag{7}$$

with A representing the amplitude of oscillation and $\xi(t) \sim \mathcal{N}(0, \sigma_\theta^2)$ denoting a Gaussian random perturbation modeling stochastic gusts. The angular frequency ω governs how rapidly the wind direction varies over time. This hybrid formulation produces smooth low-frequency drift interspersed with short-term fluctuations, closely resembling the statistical characteristics of real outdoor wind fields.

C. Wind-Aware Replacement Mechanism

The main contribution of this work is a *wind-aware replacement strategy* that counteracts node drift by periodically refreshing the network. Under persistent wind, node agents gradually deviate from their intended lattice locations, accumulating drift as defined in (2). To prevent this accumulation, newly launched ant agents are permitted to replace older nodes under controlled, local rules.

Each node maintains an internal timer measuring its age t_{age} since creation. When an ant agent encounters an occupied lattice location, it computes the replacement probability as a function of node age:

$$p_{\text{replace}} = 1 - \exp\Big[-\frac{(t_{\text{age}} - t_{\min})}{\tau}\Big], \quad \text{for } t_{\text{age}} \geq t_{\min}. \tag{8}$$

Here, $t_{\min}$ is the minimum age before a node becomes eligible for replacement, and τ controls the rate of probability growth with time. This rule is fully decentralized: each replacement event depends solely on local interaction and node lifetime, without requiring any global synchronization or drift estimation.

When a replacement occurs, the new agent assumes the node's communication role, while the displaced agent first enters homing mode and moves towards the new agent in an effort to correct its drift and then reverts to ant mode and resumes exploration. In our implementation, the new node's orbit center is anchored near its current physical position, effectively re-centering the lattice locally. This mechanism constrains long-term drift accumulation while preserving network connectivity.

D. Spatial Stability Measurement

To quantitatively assess the effectiveness of the proposed mechanism, we measure the geometric stability of the network using two complementary metrics: the instantaneous drift of each node and the time-averaged drift of the swarm. These quantities directly reflect how well the lattice geometry is preserved under persistent wind disturbances.

Let $d_k(t)$ denote the instantaneous drift of the k-th node at time t, defined as the Euclidean distance between its actual position $\mathbf{x}_k(t)$ and its ideal lattice position $\mathbf{x}_k^*$ in the absence of wind:

$$d_k(t) = \|\mathbf{x}_k(t) - \mathbf{x}_k^*\|.$$

The overall stability of the swarm over the simulation horizon T is characterized by the time-averaged drift introduced earlier in (3), which represents the mean deviation of all N node agents over time.

In the discrete simulator, this continuous measure is approximated numerically as

$$\bar{D} \approx \frac{1}{N\,M} \sum_{t=1}^{M} \sum_{k=1}^{N} d_k[t], \quad d_k[t] = \|\mathbf{x}_k[t] - \mathbf{x}_k^*\|, \tag{9}$$

where $M = T/\Delta t$ is the number of timesteps in each run, and $\Delta t = 0.1$ s is the integration interval. This discrete form corresponds directly to the implementation variables `drift_sum` and `drift_sample_count` used in the simulation. A lower value of $\bar{D}$ therefore indicates higher geometric coherence and a more stable communication topology.

In addition to overall drift, we quantify the improvement contributed by each replacement event. Let $d_{\text{pre}}^{(q)}$ and $d_{\text{post}}^{(q)}$ denote the average drift of the affected node immediately before and after the q-th replacement, respectively. The per-event reduction and its overall average are defined as

$$\Delta d^{(q)} = d_{\text{pre}}^{(q)} - d_{\text{post}}^{(q)}, \qquad \overline{\Delta d} = \frac{1}{Q} \sum_{q=1}^{Q} \Delta d^{(q)}, \tag{10}$$

where Q is the total number of replacements during a run. Positive values of $\Delta d^{(q)}$ indicate that a replacement successfully reduced the accumulated drift of that node. This event-wise measure provides finer insight into how effectively the replacement mechanism restores local network geometry and complements the global metric $\bar{D}$.

E. Implementation Details

The complete simulation was implemented in Python using the SMAVNET 2D framework developed for this study. The discrete-time integration of (1) is carried out using the update rule

$$\mathbf{x}_i[t + \Delta t] = \mathbf{x}_i[t] + v_0\,\mathbf{u}_i[t]\,\Delta t + \mathbf{w}[t]\,\Delta t, \tag{11}$$

where $\Delta t = 0.1$ s is the simulation timestep. All agents operate under identical dynamics (1) and communicate within a fixed radius $r_c = 100$ m. The base node is initialized at the origin, and the user location is randomly sampled within the upper half of the simulation area to ensure nontrivial lattice extension.

Each simulation runs for 1800 s with the parameters $w_0 = 2.0$ m/s, $A = 0.5$, $\tau = 120$ s, and $t_{\min} = 30$ s.

V. Results and Discussion

This section presents the simulation outcomes obtained using the proposed wind-aware replacement mechanism and compares them with the baseline SMAVNET behavior. All results were obtained in a 2D environment of size 800×600 m under a nominal mean wind speed of 2 m/s. Each configuration (defined by swarm size and replacement setting) was averaged over $N_{\text{trials}} = 500$ independent runs with distinct random seeds to ensure statistical robustness.

A. Baseline Reproduction

To validate our implementation, we first reproduced the original SMAVNET algorithm under calm and low-wind conditions. The swarm successfully established a communication bridge between the base and user purely through local pheromone interactions, without global positioning or centralized control. Figure 1 shows a representative run where six MAVs autonomously form a relay chain with four communication hops to the user. Each node maintains stable connectivity and correct pheromone reinforcement behavior, consistent with the results reported by Hauert *et al.* [1].

These baseline simulations confirm that the underlying controller, message propagation, and node-handling logic in our implementation faithfully reproduce the original SMAVNET dynamics, forming a solid reference for evaluating wind robustness.

B. Drift Mitigation under Wind Disturbances

We next evaluated the effect of the proposed wind-aware replacement mechanism under a mean wind speed of 2 m/s blowing in a constant direction. Figure 2 compares the average node drift, computed using (3), for swarms of different sizes both with and without replacement enabled.

Without replacement, average drift remains high, ranging from approximately 180–210 m for smaller swarms and only slightly improving for larger swarms. With replacement, the average drift drops sharply to 80–105 m, corresponding to an overall reduction of nearly 45%. This improvement is consistent across all swarm sizes tested. The results confirm that probabilistic node refreshing effectively limits long-term spatial drift accumulation, even when the total number of active agents remains constant.

Although connectivity was enforced in simulation to isolate spatial effects, the reduction in drift directly implies greater link stability in real deployments. In physical swarms, excessive drift would cause intermittent communication losses as inter-node distances exceed the communication range r_c; hence, maintaining lower drift values corresponds to higher effective connectivity over time.

C. Replacement Dynamics and Scalability

Figure 3 illustrates the average number of replacement events observed per simulation run as a function of swarm size. The number of replacements increases nearly linearly from around 7 events at 5 MAVs to approximately 20 events

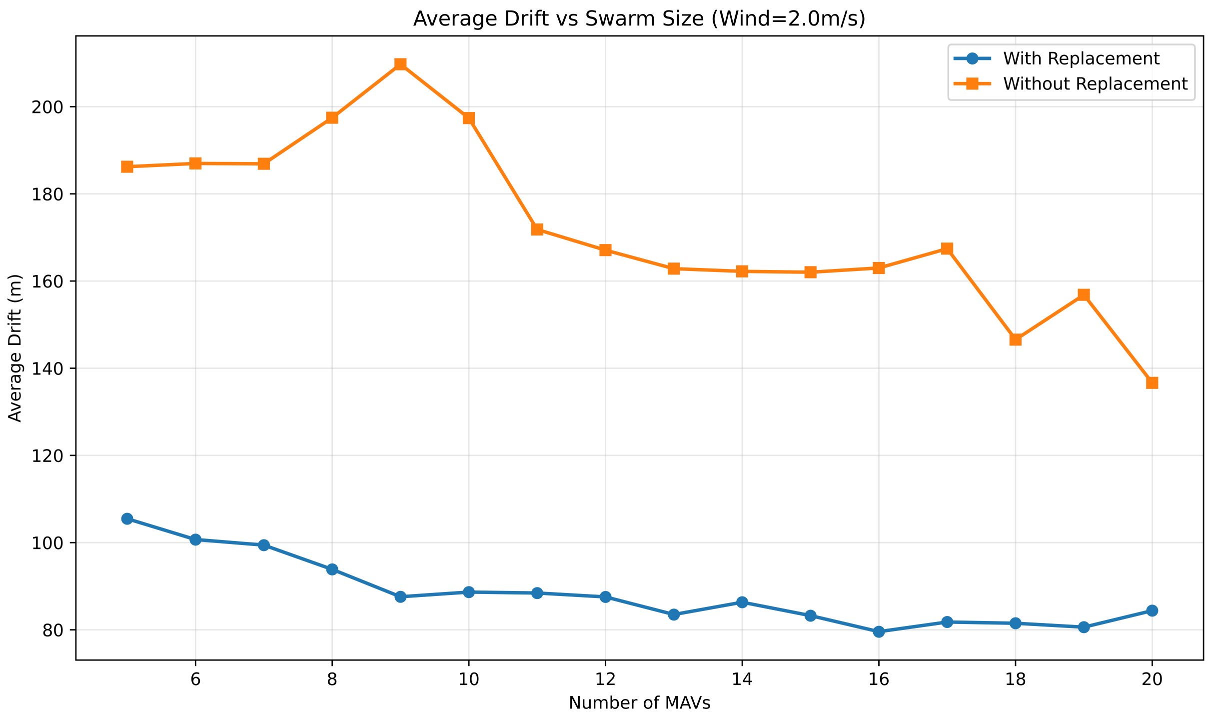

Fig. 2. Average node drift versus swarm size under 2 $\mathrm{m/s}$ wind. Each data point represents the mean of 500 independent trials. The proposed replacement mechanism consistently reduces average drift across swarm sizes, improving geometric stability by nearly 45%.

at 20 MAVs. This trend indicates that the replacement probability formulation (8) scales naturally with swarm density: larger swarms produce more encounters between ant and node agents, leading to more frequent—but stable—self-refreshing cycles.

Importantly, the absence of oscillatory or runaway replacement behavior demonstrates that the probabilistic rule maintains equilibrium. Once a sufficient number of nodes have been renewed, the system stabilizes without excessive swapping, preserving network continuity and efficiency.

D. Discussion

The results clearly demonstrate that the proposed mechanism significantly enhances the spatial stability of the positionless swarm. The reduction in average drift ($\bar{D}$) by nearly half suggests that node refreshing compensates effectively for persistent environmental disturbances.

The changed mechanism has also been designed to be fully local and positionless, relying solely on node age and local encounters. Considering the different phases of the replacement process and its communication requirements:

- Initiation: Ant agents continuously explore the lattice, as in the baseline SMAVNET. The replacement decision is made based on the agent age, using the same local communication used for pheromone exchange.
- Homing: Upon replacement, the displaced node enters a homing phase, where it uses local communication to navigate towards the new node's position.
- Reintegration: After reaching the new node's position, the displaced agent reverts to ant mode and resumes exploration. This transition is also managed through local interactions in the same manner as the baseline.

Furthermore, the near-linear scaling of replacement events with swarm size indicates that the method remains computationally lightweight and fully compatible with decentralized deployment. Larger swarms benefit from higher encounter rates, improving geometric coherence without additional communication overhead.

While the present implementation enforces continuous connectivity to isolate geometric effects, the observed stabilization strongly suggests that physical implementations would exhibit improved packet delivery and reduced link interruptions under comparable wind conditions. Future work will integrate realistic radio-link modeling and flight hardware experiments to verify this connection empirically.

Overall, the replacement mechanism fulfills the three design goals outlined in Section III: it is local, scalable, and minimalist. The swarm maintains its self-organizing nature while achieving measurable improvements in environmental robustness.

VI. Conclusion

This work extends the SMAVNET framework by introducing a wind-aware replacement mechanism that enhances the robustness of positionless micro air vehicle (MAV) swarms operating under environmental disturbances. Building upon the

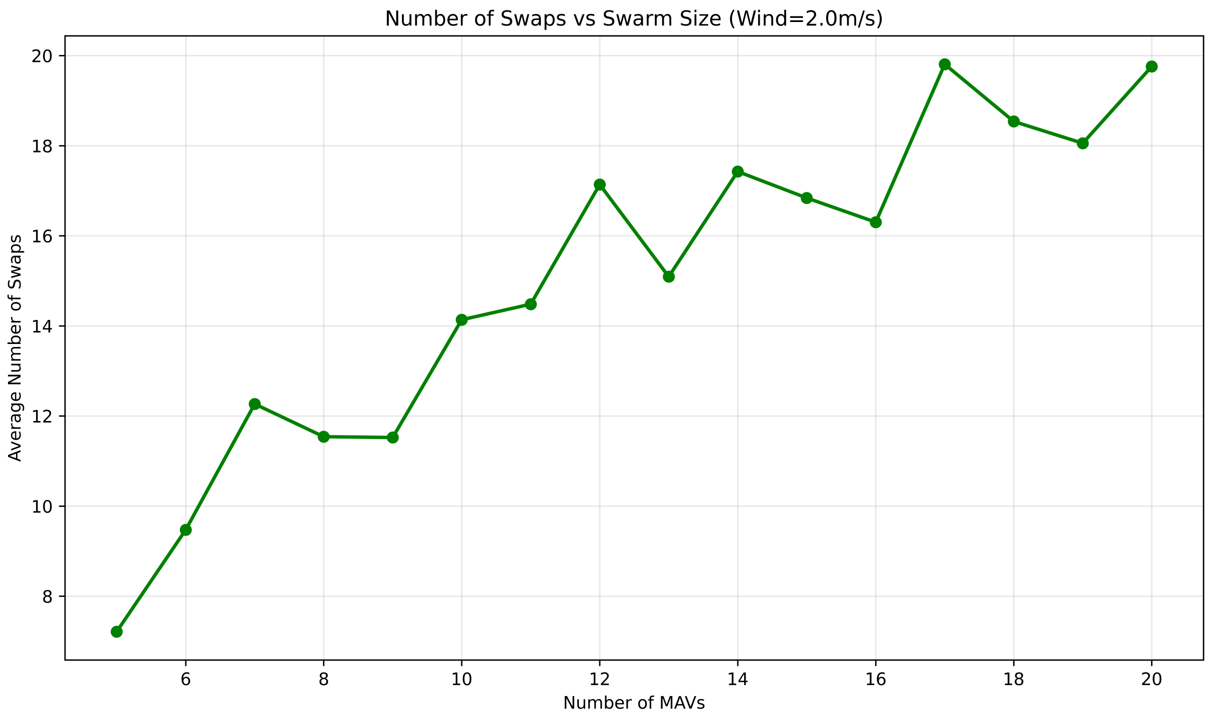

Fig. 3. Average number of node replacement events versus swarm size under 2 $\mathrm{m/s}$ wind. Each datapoint is averaged over 500 trials. The number of swaps increases approximately linearly with swarm size, confirming scalability and stable self-refreshing dynamics.

original ant-inspired deployment and communication model, we formulated the problem of wind-induced drift and proposed a local, probabilistic node-refreshing strategy to mitigate long-term spatial deviations.

Simulation results demonstrated that the proposed mechanism r educes average node drift by nearly 45% across swarm sizes ranging from 5 to 20 MAVs, while maintaining stable and scalable replacement dynamics. These findings confirm that environmental drift, a major limitation identified in the original SMAVNET design, can be effectively counteracted without compromising the minimalistic and decentralized nature of the system.

Beyond geometric stability, reduced drift directly translates to improved link reliability and longer network lifetimes in physical deployments. Future work will focus on integrating realistic communication-layer modeling and GPS-denied flight tests to empirically validate these effects. Further extensions could explore adaptive replacement policies that consider link quality and local topology, enabling fully autonomous, resilient, and self-healing aerial communication swarms.

VII. Supplementary Material

Github repository with simulation code and data: link
Presentation video: Drive Folder with presentation video

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