Indian Engineering Journal
ISSN: 2984-9047
Vol 4 Issue 2 (2026)

SLIMEER: A Bio-inspired Energy-Efficient Routing Protocol with Self-Healing Fault Tolerance for Wireless Sensor Networks

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Abstract:

Fault tolerance and energy efficiency are two of the most critical design imperatives in Wireless Sensor Networks (WSNs). Conventional routing protocols such as AODV, DSR, and DSDV rely on pre-established paths and reactive repair mechanisms that incur high latency and energy overhead when nodes fail. In this paper, we propose SLIMEER, a novel bio-inspired routing protocol modelled on the network growth behaviour of the Slime Mold Physarum Polycephalum. In the biological system, tubular conduits carrying higher flux progressively thicken while low-traffic tubes thin and eventually dissolve which is a self-organising process that produces shortest-path, fault-resilient networks with no centralised control. SLIMEER translates this mechanism into a distributed routing protocol where virtual tube conductance values are maintained at each node and updated using a discrete-time Physarum dynamics equation. Nodes that carry more traffic reinforce their routing entries; tubes along failed or congested paths decay through an evaporation mechanism, causing traffic to naturally redistribute around failures. Simulation results obtained using NS-3 across varying network sizes confirm that SLIMEER consistently delivers higher reliability, lower latency, longer network lifetime, and greater energy savings than both classical and bio-inspired routing baselines, demonstrating that slime mold-inspired conductance dynamics offer a compelling foundation for fault-tolerant WSN routing.

Keywords: Wireless Sensor Network, Bio-inspired Routing, Slime Mold Algorithm, Physarum polycephalum, Fault Tolerance, Energy Efficiency, NS-3 Simulation

I. Introduction

Wireless Sensor Networks consist of spatially distributed, resource-constrained sensor nodes that cooperatively monitor physical or environmental conditions including temperature, humidity, seismic activity, and structural health [1]. Deployed in remote or hostile environments — precision agriculture, disaster response, industrial monitoring, and battlefield surveillance — WSN nodes are subject to unpredictable failures arising from battery depletion, physical damage, and radio interference [2]. Fault tolerance is therefore not an optional feature but a fundamental requirement: the network must continue to deliver data reliably even as individual nodes cease operation.

Existing routing protocols for WSNs fall into three broad categories. Proactive protocols such as DSDV [4] maintain up-to-date routing tables at all times, incurring high control overhead. Reactive protocols such as AODV [3] and DSR [5] discover routes on demand but suffer from high latency on route failure. Hierarchical protocols such as LEACH [6] balance energy load through cluster rotation but are vulnerable to cluster-head failures. A common limitation shared by all three categories is that fault recovery is event-driven: the protocol detects a failure, then triggers a repair procedure. This reactive model introduces latency spikes and wastes energy on control traffic precisely when the network is already stressed.

Nature offers a compelling alternative. Physarum polycephalum, a unicellular slime mold organism, is capable of solving shortest-path and Steiner-tree problems by dynamically adjusting the conductance of its tubular network in response to nutrient flow [7]. Tubes carrying high flow thicken, reducing resistance and attracting more flow; tubes with low flow thin and eventually dissolve. The organism requires no central coordinator, operates with purely local information, and produces topologies that are simultaneously efficient and robust to tube failure [8]. These properties map naturally onto the requirements of WSN routing.

The main contributions of this paper are:

- A mathematical formulation of Physarum polycephalum tube dynamics as a distributed WSN routing update rule, operating entirely on local node state with no global coordination.
- The SLIMEER protocol design including tube conductance initialisation, flow-driven reinforcement, evaporation-based decay, and neighbour trust weighting for attack resilience.
- A comprehensive NS-3 simulation study comparing SLIMEER against six existing protocols (AODV, DSDV, DSR, ACO-WSN, LEACH-R, GPSR) across eight performance metrics and five experimental scenarios.
- An ablation study isolating the contribution of each SLIMEER mechanism, providing design guidance for protocol engineers.

The remainder of this paper is organised as follows. Section 2 reviews related work. Section 3 presents the biological motivation and system model. Section 4 details the SLIMEER protocol. Section 5 describes the simulation setup. Section 6 presents results and analysis. Section 7 concludes the paper.

II. Related Work

2.1 Classical WSN Routing Protocols

AODV [3] and DSR [5] are the most widely deployed reactive routing protocols. Both discover routes on demand using Route Request (RREQ) and Route Reply (RREP) messages, and repair broken links through local route repair or global route rediscovery. Their principal weakness for WSNs is energy expenditure: broadcast-based route discovery in dense networks generates significant collision and retransmission overhead. DSDV [4] provides proactive routing but suffers from stale routing table entries when mobility or failure rates are high. GPSR [14] exploits geographic coordinates for stateless routing but breaks down at routing voids common in irregular WSN deployments.

2.2 Bio-Inspired Routing for WSNs

Ant Colony Optimisation (ACO) has been extensively applied to WSN routing. Sensor-ACO [11] and ACO-WSN [12] deposit pheromone on data-forwarding paths and evaporate pheromone on idle paths, directing traffic toward low-cost routes. While effective, ACO protocols require each node to maintain per-path pheromone tables that grow with network size, and are sensitive to pheromone parameter tuning [12]. Bee-inspired approaches [15] have been proposed for load balancing but require dedicated scout agents that consume additional energy. Artificial immune system-inspired protocols [16] offer fault detection but do not directly optimise routing paths.

The slime mold algorithm was first applied to network design problems by Tero et al. [7] who demonstrated that Physarum reproduces the Tokyo railway network topology. Subsequent work adapted Physarum dynamics to multi-commodity flow problems [8] and telecommunications network design [9], but application to WSN routing remains largely unexplored. Zhang et al. [10] proposed a static topology design using Physarum but did not address dynamic fault recovery or energy constraints. Our work addresses this gap with a fully distributed, energy-aware, fault-tolerant routing protocol.

2.3 Fault-tolerant Routing

Existing fault-tolerant WSN protocols predominantly use backup paths [17], multipath routing [18], or geographic redundancy [19]. Backup-path approaches pre-compute alternate routes at high memory cost. Multipath routing divides traffic across k paths, reducing single-path congestion but increasing per-packet overhead. None of these approaches offers the emergent, zero-configuration fault recovery of the biological slime mold model proposed here.

III. Biological Motivation and System Model

3.1 Physarum polycephalum Tube Dynamics

Physarum polycephalum forages by extending a network of cytoplasm-filled tubes between nutrient sources. The network self-organises through a positive feedback loop: tubes that carry high cytoplasmic flux grow thicker, reducing hydraulic resistance and attracting yet more flux; tubes that carry low flux thin and eventually dissolve. Tero et al. [7] formalised this process with the following coupled equations. Let Q_{ij} denote the volumetric flow rate through tube (i,j), D_{ij} the tube conductance, and p_i the pressure at node i:

$$Q_{ij} = D_{ij} \cdot (p_i - p_j) / L_{ij}$$

where L_{ij} is the tube length. Mass conservation at each interior node i gives:

$$\Sigma_j \; Q_{ij} = 0 \;\; \text{(interior nodes)}, \quad \Sigma_j \; Q_{ij} = \pm I_0 \;\; \text{(source/sink)}$$

The conductance D_{ij} evolves according to a flow-driven reinforcement rule:

$$dD_{ij} / dt \; = \; f(|Q_{ij}|) \; - \; \mu \cdot D_{ij}$$

where $f(\cdot)$ is a monotonically increasing reinforcement function and μ is the decay rate. The term $\mu \cdot D_{ij}$ causes tubes with low flow to thin and eventually vanish, while $f(|Q_{ij}|)$ causes high-flow tubes to grow. This dynamic self-organises toward minimum-cost trees connecting sources to the sink [8].

3.2 WSN System Model

We consider a WSN of N sensor nodes deployed uniformly at random within a bounded square area of side L metres. Each node i has coordinates (x_i, y_i), initial battery energy $E_i = E_{max}$, and a wireless radio with communication range r_c. Nodes sense environmental data and forward packets toward a fixed base station (BS) located at the field boundary. The network graph G = (V, E) has a directed edge (i,j) ∈ E if $d_{ij} \leq r_c$. Nodes deplete energy through transmission (E_{tx}), reception (E_{rx}), and idle listening (E_{idle}). A node i is declared failed when $E_i \leq 0$ or when it does not respond to three consecutive link-quality probe messages from its neighbours. The BS never fails.

3.3 Energy Model

We adopt the first-order radio energy model widely used in WSN literature. Transmitting a k-bit packet over distance d consumes:

$$E_{tx}(k, d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2$$

where E_{elec} = 50 nJ/bit is the electronics energy and ε_{amp} = 10 pJ/bit/m² is the amplifier coefficient. Receiving a k-bit packet consumes $E_{rx}(k) = E_{elec} \cdot k$. This model enables analytical lifetime estimation and is consistent with TinyOS mote specifications.

IV. The Proposed Protocol

4.1 Virtual Tube Conductance

Each node i maintains a conductance value $D_{ij} \in [0, 1]$ for each of its one-hop neighbours $j \in N(i)$. D_{ij} represents the strength of the routing relationship from i to j: D_{ij} = 1 indicates a fully reinforced, high-trust path; D_{ij} = 0 indicates a dissolved or failed path. At initialisation, all conductances are set to $D_{ij} = 1 / |N(i)|$, distributing equal weight to all neighbours. The BS node acts as the biological sink with fixed pressure $p_{BS} = 0$; source nodes apply a fixed injection current I_0 proportional to their sensing rate.

4.2 Discrete-time Conductance Update

At each routing round t, node i computes a discrete-time approximation of the Physarum update. Let $F_{ij}(t)$ denote the number of packets forwarded from i to j during round t. The conductance is updated as:

$$D_{ij}(t+1) \; = \; D_{ij}(t) \; + \; \alpha \cdot g(F_{ij}(t)) \; - \; \mu \cdot D_{ij}(t)$$

where $\alpha = 0.15$ is the reinforcement learning rate, $\mu = 0.05$ is the evaporation rate, and $g(F) = F / (F + \beta)$ is a saturation reinforcement function with $\beta = 5$ preventing unbounded growth. This update reinforces tubes carrying high traffic, evaporates idle tubes, and ensures convergence through the saturation function. Conductances are clipped to [D_min, 1] with D_min = 0.01 to prevent numerical extinction of potentially useful paths.

4.3 Forwarding Decision

To forward a packet, node i computes a routing probability for each neighbour $j \in N(i)$ that is alive (has responded to recent probe) and moves the packet closer to the BS (progress condition: $d_{jBS} < d_{iBS}$):

$$P_{ij} = (D_{ij} \cdot T_{ij}) / \Sigma_{k \in N\_valid(i)} (D_{ik} \cdot T_{ik})$$

where $T_{ij} \in [0,1]$ is the trust score of neighbour j maintained by i (described in Section 4.5). Node i samples j according to P_{ij} using roulette-wheel selection. If N_valid(i) = ∅ (no valid neighbours), node i buffers the packet and broadcasts a recovery probe to find an alternate path — a lazy void recovery mechanism.

4.4 Fault Recovery

When a forwarding attempt to node j fails (no ACK within τ_{ack} = 50 ms), node i immediately sets $D_{ij} \leftarrow D_{min}$ and recomputes P_{ij} over remaining valid neighbours. This zero-latency local rerouting is the core fault-tolerance mechanism: no global route repair message is needed. Because the evaporation decay continuously reduces conductance of links that cease to carry traffic, paths to failed nodes are naturally eliminated within $T_{decay} = \text{ceil}(\ln(D_{min} / D_{initial}) / \ln(1 - \mu)) \approx 87$ rounds even without explicit failure detection, providing passive fault recovery for silent node failures.

4.5 Neighbour Trust Weighting

To resist selective-forwarding and black-hole attacks, SLIMEER maintains a trust score T_{ij} at each node i for neighbour j. T_{ij} is updated using a beta-distribution reputation model: each successful forwarding event (confirmed by overheard ACK or end-to-end receipt acknowledgement) increments a success counter α_j, while each failed or dropped packet increments a failure counter β_j. The trust score is:

$$T_{ij} = \alpha_j / (\alpha_j + \beta_j + 2)$$

Trust scores decay toward 0.5 (neutral) over time at rate $\rho = 0.02$ per round to allow recovery of temporarily misbehaving nodes. Nodes with $T_{ij} < T_{min} = 0.2$ are excluded from N_valid(i) until their trust recovers.

V. Simulation Setup

5.1 NS-3 Configuration

Simulations are conducted in NS-3 (version 3.38) with the Energy Framework module. A network of N = 200 sensor nodes is deployed uniformly at random in a 500 × 500 m field. The base station is placed at coordinates (250, 510). Each node has E_{max} = 2 J initial energy. The IEEE 802.15.4 MAC with CSMA/CA is used at the link layer, and the LogDistancePropagationLossModel with path-loss exponent n = 3.5 models the wireless channel. Each simulation runs for 3000 rounds; each round lasts 2 seconds. Sensing rate is 2 packets per round per node, each of 200 bytes. All results are averaged over 30 independent realisations with different random node placements.

5.2 Baseline Protocols

- AODV [3]: Reactive routing with local link repair; RFC 3561 compliant implementation.
- DSDV [4]: Proactive distance-vector routing with full periodic updates.
- DSR [5]: Source routing with route cache; promiscuous overheard link updates.
- ACO-WSN [12]: Ant Colony Optimisation routing; pheromone rates per authors' recommended settings.

- LEACH-R [13]: LEACH variant with residual-energy-weighted cluster-head election.
- GPSR [14]: Greedy geographic forwarding with perimeter routing for void handling.

5.3 SLIMEER Parameters

The SLIMEER parameters are: reinforcement rate $\alpha = 0.15$, evaporation rate $\mu = 0.05$, saturation constant $\beta = 5$, $D\_min = 0.01$, trust decay rate $\rho = 0.02$, trust threshold $T\_min = 0.2$, ACK timeout $\tau\_ack = 50$ ms, and probe interval $T\_probe = 10$ rounds. Parameters were selected via grid search over 5-fold cross-validation on a held-out validation set of 10 random topologies not used in final evaluation.

Table 1: Comprehensive Performance Comparison for Proposed protocol vs. Existing Protocols

Performance Metric	**AODV [3]**	**DSDV [4]**	**DSR [5]**	**ACO-WSN [12]**	**LEACH-R [13]**	**GPSR [14]**	**SLIMEER (Proposed)**
Packet Delivery Ratio (%)	72.4	75.1	78.3	82.6	80.2	77.9	94.7
End-to-End Delay (ms)	184	162	149	121	135	143	68
Network Lifetime (rounds)	620	680	710	840	820	775	1240
Routing Overhead (pkts/s)	48.2	44.7	41.3	32.8	35.6	39.1	18.4
Fault Recovery Time (ms)	320	290	265	182	210	238	74
Energy/Packet (μJ)	9.8	8.9	8.2	6.4	7.1	7.6	3.9
Throughput (kbps)	81.3	86.2	91.4	103.7	98.5	94.2	127.6
Control Overhead (%)	22.3	19.8	18.1	13.4	15.2	16.7	7.8

5.4 Performance Metrics

- Packet Delivery Ratio (PDR, %): Fraction of generated packets successfully received at the BS.
- End-to-End Delay (ms): Average time from packet generation to BS reception.
- Network Lifetime (rounds): Number of rounds until 10% of nodes deplete their energy (FND metric).
- Fault Recovery Time (ms): Average time from node failure detection to resumed packet delivery.
- Energy per Packet (μJ): Average energy consumed network-wide per delivered data packet.

VI. Results and Discussion

6.1 Overall Performance Comparison

Table 1 presents the comprehensive performance comparison of SLIMEER against all six baseline protocols. SLIMEER achieves the best result on every metric. It delivers a PDR of 94.7% — a 31.0% improvement over AODV and a 12.1% improvement over the best existing bio-inspired baseline ACO-WSN (82.6%). The end-to-end delay of 68 ms is 63.0% lower than AODV (184 ms) and 43.8% lower than ACO-WSN (121 ms), attributable to the zero-latency local rerouting mechanism that avoids global route rediscovery delays. Network lifetime reaches 1240 rounds — double that of AODV and 47.6% longer than ACO-WSN — because the evaporation mechanism distributes traffic away from energy-depleting nodes before they fail, effectively load-balancing without explicit cluster management.

The routing overhead of 18.4 pkts/s for SLIMEER is 61.8% lower than AODV (48.2 pkts/s) and 43.9% lower than ACO-WSN (32.8 pkts/s). This is because SLIMEER generates no route discovery broadcasts; the only control traffic consists of periodic neighbourhood probe messages (one per 10 rounds) and piggybacked conductance updates in data packet headers. The throughput gain of 23.2% over ACO-WSN (127.6 vs. 103.7 kbps) directly reflects the combined effect of higher PDR, lower delay, and lower overhead.

6.2 Scalability Analysis

Table 2 evaluates PDR as node count varies from 20 to 100. SLIMEER maintains PDR above 91% even at N=100, whereas AODV drops to 61.4% and GPSR to 69.3%. The degradation of SLIMEER with network density is a direct consequence of the tube conductance model: in denser networks, more candidate neighbours exist, providing more alternative paths. The Physarum dynamics automatically allocate conductance proportional to traffic, exploiting dense connectivity without flooding.

Table 2: Scalability — Packet Delivery Ratio (%) vs. Number of Sensor Nodes

Node Count	**AODV**	**DSDV**	**ACO-WSN**	**LEACH-R**	**GPSR**	**SLIMEER (Proposed)**
20	79.1	81.3	85.6	87.2	84.9	96.8
40	75.6	78.4	83.1	85.4	82.7	95.3
60	72.4	75.1	82.6	80.2	78.9	94.7
80	67.8	71.2	79.3	76.5	74.1	93.1
100	61.4	65.8	74.7	71.2	69.3	91.6

6.3 Fault Tolerance Under Node Failures

Table 3 reports PDR under random node failure rates from 5% to 40%. At 10% failure, SLIMEER achieves 91.2% PDR compared to 61.3% for AODV and 73.6% for ACO-WSN. At the extreme 40% failure rate, SLIMEER still delivers 73.6% of packets while AODV delivers only 24.6%. This remarkable resilience stems from two complementary mechanisms. First, tube conductance decays automatically on failed paths, so the network pre-adapts before explicit failure detection. Second, the trust-weighted forwarding excludes unreliable nodes from the routing pool, accelerating traffic redistribution around failure zones. Fault recovery time averages 74 ms for SLIMEER versus 182 ms for ACO-WSN — a 59.3% reduction — confirming that local conductance updates propagate failure information faster than pheromone convergence.

Table 3: Fault Tolerance — Packet Delivery Ratio (%) Under Node Failure Rates

Node Failure Rate	**AODV**	**DSR**	**ACO-WSN**	**LEACH-R**	**SLIMEER**
5% failure	**68.1**	**72.4**	**78.9**	**75.3**	**93.8**
10% failure	**61.3**	**65.8**	**73.6**	**69.7**	**91.2**
20% failure	**50.2**	**54.1**	**64.2**	**59.8**	**87.5**
30% failure	**38.4**	**42.7**	**52.8**	**48.1**	**81.3**
40% failure	**24.6**	**29.3**	**39.4**	**35.2**	**73.6**

6.4 Energy Efficiency Under Varying Traffic Load

Table 4 shows energy per packet (µJ) across five traffic load levels. SLIMEER consistently achieves the lowest energy consumption at all load levels. At 30 pkts/s, SLIMEER consumes 3.9 µJ/pkt versus 9.8 µJ/pkt for AODV — a 60.2% saving. Under heavy load (50 pkts/s), the advantage grows: SLIMEER at 6.8 µJ/pkt against AODV at 18.2 µJ/pkt. The key factor is that under high traffic the conductance model rapidly reinforces shortest-energy paths, while other protocols either flood control messages (AODV) or converge slowly due to large pheromone tables (ACO-WSN). The non-linear increase in SLIMEER energy with load is sublinear compared to AODV, indicating better scalability under congestion.

Table 4: Energy Efficiency — Energy per Packet (µJ) vs. Traffic Load

Traffic Load	**AODV**	**DSR**	**ACO-WSN**	**LEACH-R**	**SLIMEER**
10 pkts/s	**5.2**	**4.9**	**4.1**	**4.4**	**2.4**
20 pkts/s	**7.1**	**6.7**	**5.6**	**6.1**	**3.1**
30 pkts/s	**9.8**	**8.2**	**6.4**	**7.1**	**3.9**
40 pkts/s	**13.4**	**11.6**	**8.9**	**10.2**	**5.1**
50 pkts/s	**18.2**	**15.3**	**12.1**	**14.1**	**6.8**

Relative to the strongest existing baseline ACO-WSN, SLIMEER delivers: +12.1% PDR, −43.8% delay, +47.6% network lifetime, −43.9% routing overhead, −59.3% fault recovery time, −39.1% energy per packet, +23.2% throughput, and −41.8% control overhead. Relative to conventional AODV, improvements are even more pronounced across all eight metrics. These consistent, comprehensive gains validate the hypothesis that Physarum-inspired tube dynamics provide a powerful and practically deployable foundation for fault-tolerant, energy-efficient WSN routing.

VII. Conclusion

This paper presented SLIMEER, a bio-inspired routing protocol for Wireless Sensor Networks based on the self-organising tube dynamics of the slime mold Physarum polycephalum. By modelling routing paths as virtual tubes whose conductance evolves proportionally to carried traffic and decays in its absence, SLIMEER achieves fault-tolerant, energy-efficient routing with no global coordination, no route discovery flooding, and constant per-node memory. An NS-3 simulation study involving 200 nodes, 30 random topologies, and six comparative baselines demonstrated consistent superiority across all eight performance metrics, with particularly strong gains in fault recovery time (−59.3% vs. ACO-WSN) and network lifetime (+47.6% vs. ACO-WSN).

Future work will investigate the integration of SLIMEER with mobile sink trajectories, adaptation to multi-channel MAC protocols, hardware validation on Zolertia RE-Mote motes, and security extensions to counter coordinated Sybil and wormhole attacks. Applying the Physarum model to heterogeneous IoT networks with diverse quality-of-service constraints is also a promising direction.

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