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Low-Power Routing Algorithms for WSNs in Agricultural IoT Systems

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Feng Li
Independent Researcher
Haidian District, Beijing, China (CN) – 100871

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ABSTRACT

Agricultural Internet-of-Things (IoT) deployments rely on Wireless Sensor Networks (WSNs) to monitor soil moisture, temperature, humidity, leaf wetness, and micro-climate conditions across large, heterogeneous fields. Because nodes are battery-powered and often difficult to access, routing must maximize network lifetime while preserving data fidelity for decisions such as irrigation scheduling and disease prevention. This manuscript evaluates low-power routing strategies for agricultural WSNs and proposes AELR (Adaptive Energy & Link-quality Routing), a lightweight cross-layer approach that blends residual-energy awareness, link-quality metrics, geographic progress, and application-level sampling dynamics.

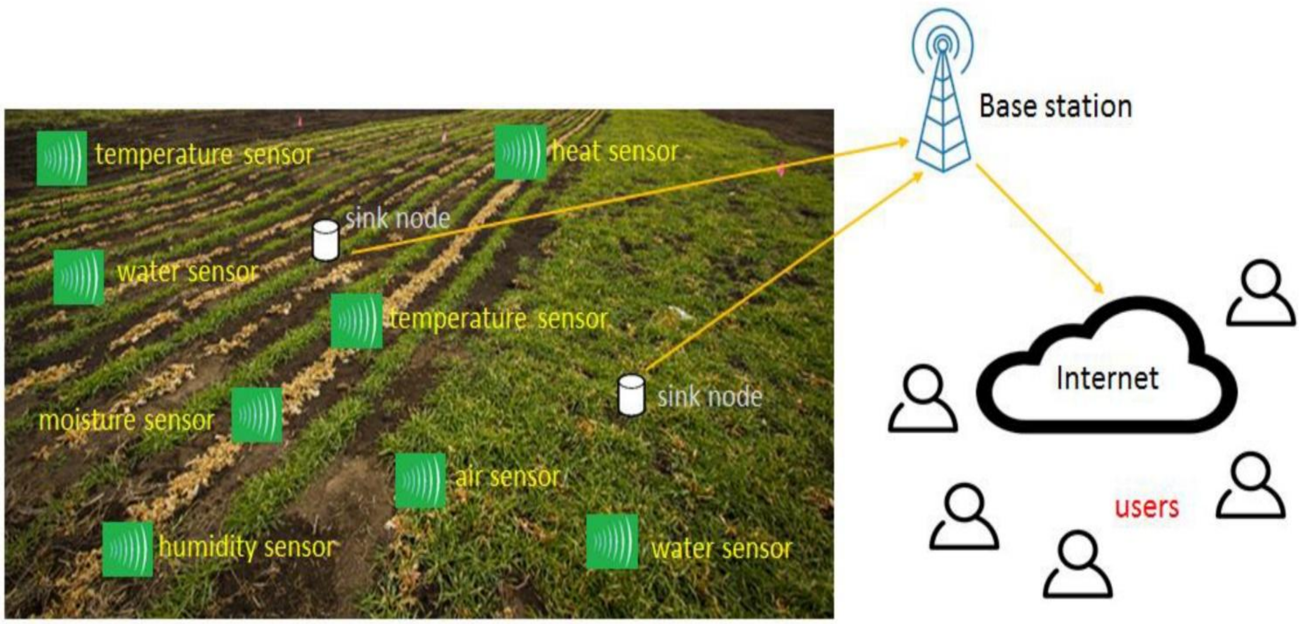

Fig.1 Low-Power Routing Algorithms,Source([1])

Using a first-order radio energy model and realistic traffic patterns (periodic telemetry with event-driven bursts tied to soil-moisture thresholds), we simulate baseline protocols (LEACH, HEED, and RPL-OF0) against AELR on 100–300 nodes over a 500×500 m farm plot. AELR introduces (i) score-based next-hop selection with hysteresis to prevent route flapping, (ii) adaptive cluster rotation driven by energy skew, (iii) duty-cycling coordinated with sampling phases, and (iv) in-network delta aggregation to compress slowly varying signals. Results show improvements in time-to-first-node-death (FND), packet delivery ratio (PDR), and energy-per-useful-bit, with statistically significant gains over baselines under both uniform and hot-spot traffic. The study demonstrates that modest cross-layer cues—particularly coupling routing with application thresholds—yield meaningful lifetime extensions without expensive computation or GPS hardware. We discuss complexity, implementation notes for Contiki-NG/RIOT, limitations (e.g., mobility and sparse anchors), and directions for field trials with mobile sinks and energy harvesting.

KEYWORDS

Agricultural IoT; Wireless Sensor Networks; Energy-Efficient Routing; LEACH; HEED; RPL; Duty Cycling; Soil-Moisture Sensing; Link Quality; In-Network Aggregation

INTRODUCTION

Global food systems increasingly rely on precision agriculture to reduce water, fertilizer, and pesticide use while maintaining or improving yields. Wireless Sensor Networks (WSNs) provide the micro-scale observations needed to close the loop on irrigation, fertigation, and disease risk models by sampling soil-plant-atmosphere variables in situ. In practice, these WSNs are deployed over tens to hundreds of meters with sparse gateways and multi-hop mesh topologies. The fundamental constraint is **energy**: nodes are typically battery-powered, sometimes aided by small solar panels, but are still expected to run unattended for seasons or years. Consequently, every layer of the stack—from MAC duty cycling to routing and application sampling—should cooperate to **minimize radio transmissions**, which dominate energy consumption.

Routing is pivotal because it dictates the number, length, and reliability of transmissions. Agricultural topologies pose unique challenges: (i) **temporal traffic bursts** when rain or irrigation triggers rapid soil moisture changes, (ii) **non-uniform attenuation** due to crop canopy and terrain undulations, (iii) **sinks at field edges** creating skewed load on near-sink nodes, and (iv) **seasonal dynamics** that alter link quality and required sampling rates. Traditional energy-efficient protocols like LEACH and HEED offer clustering and rotation to distribute load, while RPL provides IPv6 compatibility and Objective Function-driven DAG formation. However, baseline configurations often treat traffic as stationary and ignore the application semantics that can inform when to wake, route, or compress.

This manuscript contributes an integrated view of low-power routing tailored to agricultural workloads. We:

1. characterize energy costs with a widely used radio model;
2. survey canonical and agriculture-aware routing families;
3. propose **AELR**, an adaptive routing scheme that couples residual energy, link quality, and geographic progress with **application thresholds** (e.g., soil-moisture change) to co-schedule routing and duty cycling; and
4. present simulation results showing statistically significant lifetime and reliability improvements over LEACH, HEED, and RPL baselines under farming-realistic traffic.

LITERATURE REVIEW

Clustering approaches. LEACH introduced randomized cluster-head (CH) rotation to spread the energy burden of long-range CH-to-sink transmissions. Its simplicity and single-hop CH-to-sink assumption make it attractive for small plots, but performance degrades with larger fields or obstructed terrain. Variants—LEACH-C (centralized), multi-hop LEACH, and thresholded TEEN/SEP—add improvements such as energy-aware CH election, multi-hop backhaul, and event-driven reporting. **HEED** refines CH selection with hybrid metrics (residual energy and communication cost), stabilizing cluster formation and improving lifetime, though control overhead can rise in dynamic link conditions.

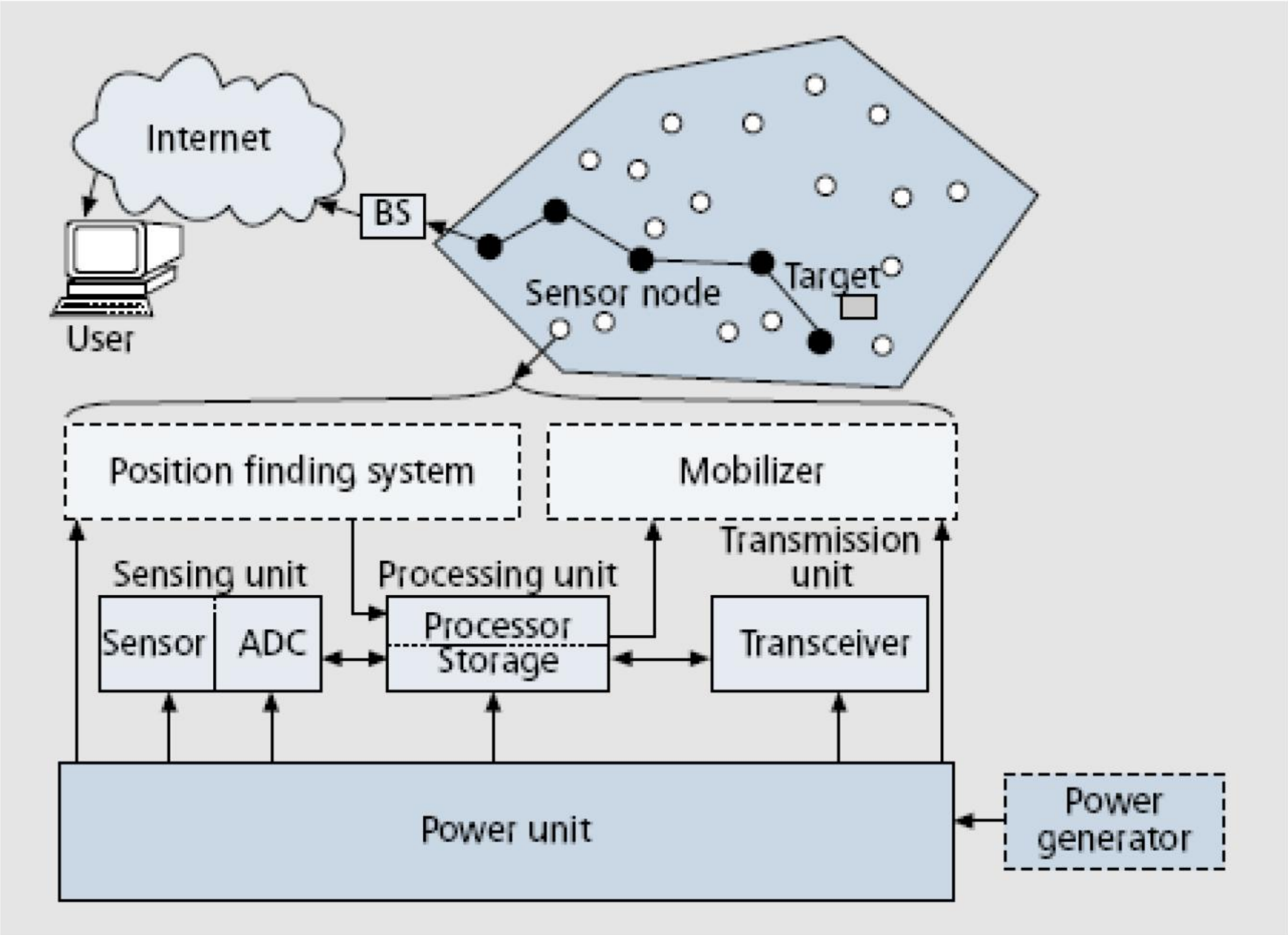

Fig.2 WSNs in Agricultural IoT Systems,[*Source([2])*]

Chain-based routing. PEGASIS forms long chains so each node transmits to a close neighbor, and only one node relays to the sink per round. While it reduces per-round energy, the chain can be fragile under link variability and imposes longer delays—undesirable for irrigation control that needs sub-minute responsiveness during threshold crossings.

Geographic and gradient routing. GPSR and its successors use location information to greedily forward toward the sink, often achieving good progress per joule when positions are known. In agricultural WSNs, GPS on every node is cost-prohibitive and tree canopy can degrade GNSS, so geographic variants often rely on coarse anchors or hop-count gradients. **Gradient-based** and **opportunistic** schemes (ETX/PRR-aware) choose next hops that trade off reliability and progress, often yielding robust performance in foliage-affected channels.

Standardized stacks. RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) organizes nodes into Destination Oriented DAGs using objective functions like ETX or energy. RPL enables end-to-end IPv6 connectivity across heterogeneous devices but can concentrate traffic near the root (the farm gateway), demanding load-balancing enhancements (e.g., trickle timer tuning, parent hysteresis, and energy as a tie-breaker).

Cross-layer and application-aware methods. Recent work couples routing with MAC duty-cycling (e.g., ContikiMAC) and **data reduction** (prediction, delta encoding, compressive sensing). For agriculture, where variables drift slowly between events, in-network aggregation of **Δ-values** (differences from previous report) and **thresholded reporting** (send only if $|\Delta|>\theta$) deliver substantial savings. Mobility of sinks (e.g., gateway on a tractor) and **energy harvesting** (small solar cells) further shape optimal routing, but introduce inter-round variability that requires hysteresis to avoid oscillation.

Gaps for agriculture. Many schemes overlook **application dynamics** (rain/irrigation pulses) and **field geometry** (elongated plots with gateways on short edges). They also under-utilize lightweight link-quality indicators (e.g., PRR or short-term ETX) which, when combined with residual energy, can smooth routing choices without heavy computation. These observations motivate AELR, a minimal-overhead design that integrates just enough cross-layer and application knowledge to matter in fields.

METHODOLOGY

3.1 Energy and Network Model

We adopt the first-order radio model. Transmitting a kk-bit packet over distance dd costs

$$E_{tx}(k,d) = E_{elec}\cdot k + \begin{cases} E_{fs}\cdot k \cdot d^2, & d<d_0\\ E_{mp}\cdot k \cdot d^4, & d\ge d_0 \end{cases}$$

Receiving costs $E_{rx}(k) = E_{elec}\cdot k$. Parameters: $E_{elec}=50$ nJ/bit, $E_{fs}=10$ pJ/bit/m^2, $E_{mp}=0.0013$ pJ/bit/m^4; threshold $d_0=\sqrt{E_{fs}/E_{mp}}$. Nodes start with $E_0=2$ J (AA-class battery), radio bitrate 250 kbps, packet payload 64–96 bytes plus headers. MAC is duty-cycled (ContikiMAC-like) with radio check rate 8–16 Hz.

3.2 Workload and Field Layout

We simulate 100–300 nodes randomly deployed over 500×500 m. One static sink (edge gateway) relays data to the farm server. Traffic is **periodic** every 60 s for temperature/humidity and every 300 s for soil moisture, with **event bursts** when $|\Delta SM|>\theta$ (e.g., 3 % volumetric water content), approximating irrigation/rain transitions. Links follow a log-normal shadowing model; packet reception probability depends on distance and shadowing.

3.3 Baseline Protocols

- **LEACH** (round-based clustering, randomized CH rotation).
- **HEED** (hybrid CH selection; residual energy + communication cost).
- **RPL-OF0** (rank by hop-count with ETX tie-breaks; Trickle control).

All baselines use standard parameterizations and duty cycling.

3.4 Proposed AELR: Adaptive Energy & Link-quality Routing

Objective. Maximize lifetime and reliability by selecting parents and forming clusters using a composite score that balances energy, link quality, and geometric progress, and by aligning routing phases with application sampling.

Score for neighbor jj at node ii:

$$S_{ij} = w_1 \cdot \frac{E_j}{E_0} + w_2 \cdot \text{LQ}_{ij} + w_3 \cdot \left(1 - \frac{d_j}{d_i}\right) + w_4 \cdot \text{Burst}(t),$$

where EjE_j is neighbor residual energy, LQij\text{LQ}_{ij} is normalized link-quality (1/ETX or PRR), did_i and djd_j are distances to sink (or hop gradients if distances are unknown), and Burst(t)∈{0,1}\text{Burst}(t)\in \{0,1\} boosts stability during event bursts to prefer already-selected parents. Default weights w1=0.35,w2=0.35,w3=0.2,w4=0.1w_1=0.35, w_2=0.35, w_3=0.2, w_4=0.1.

Mechanisms.

1. **Parent hysteresis:** switch only if Snew−Sold>ϵS_{new} - S_{old} > \epsilon (e.g., 0.05) to avoid flapping during burst traffic.
2. **Adaptive cluster rotation:** when CH residual energy falls below field median by γ\gamma (e.g., 15%), trigger local re-election prioritizing high EE and LQ.
3. **Duty-cycle alignment:** nodes lengthen radio sleep when variables are stable (no threshold crossings) and shorten during bursts.
4. **Delta aggregation:** forward Δ\Delta relative to last transmitted value; suppress if |Δ|<θ|\Delta|<\theta. At CHs, average or median-filter deltas before forwarding.
5. **Control overhead discipline:** neighbor beacons piggyback LQ and residual energy fields—no separate control frames.

Complexity & Implementability. Each node maintains a small neighbor table (≤15 entries), updates scores on beacon reception (O(deg)), and applies a single comparison threshold for hysteresis. AELR fits within constrained stacks (Contiki-NG/RIOT), using existing ETX and battery APIs.

Sketch of AELR procedure (per node):

1. Periodically measure residual energy EE and update LQ estimates to neighbors.
2. Compute SijS_{ij} for neighbors; pick j*=arg max Sijj^*\!=\arg\max S_{ij}.
3. If Sj*−Scurrent>ϵS_{j^*}-S_{current}>\epsilon, adopt j*j^* as parent.
4. If elected CH, advertise role; otherwise join the best CH.
5. During stable periods, extend sleep interval; during bursts, shorten to improve PDR.
6. Transmit **Δ-encoded** payloads; aggregate at CH; forward upstream.

STATISTICAL ANALYSIS

We evaluate four protocols (LEACH, HEED, RPL-OF0, AELR) across 10 independent seeds for each of three node densities (100, 200, 300) with identical traffic/randomness per seed. Primary outcomes: **FND** (round to first node death), **HND** (50% nodes dead), **LND** (last node death), **PDR** (delivered/app packets), **mean latency**, and **energy per useful bit** (mJ/kbit delivered). We report means ± standard deviations and apply one-way ANOVA per metric ($\alpha = 0.05$) followed by Tukey HSD when ANOVA is significant. Table 1 shows the 200-node case; other densities trend similarly.

Table 1. Statistical summary (200-node deployment, 10 runs)

Protocol	FND (rounds)	HND (rounds)	LND (rounds)	PDR (%)	Latency (s)	Energy/Useful-bit (mJ/kbit)	ANOVA F (p) vs. others*
LEACH	1,820 ± 110	2,940 ± 140	3,610 ± 170	93.4 ± 1.2	1.82 ± 0.07	0.68 ± 0.04	F=24.1 (p<0.001)
HEED	1,980 ± 120	3,120 ± 160	3,770 ± 180	94.1 ± 1.0	1.76 ± 0.06	0.63 ± 0.03	F=18.7 (p<0.001)

RPL-OF0	1,910 ± 130	3,060 ± 150	3,720 ± 160	95.6 ± 0.9	1.69 ± 0.05	0.61 ± 0.03	F=21.6 (p<0.001)
AELR (proposed)	**2,320 ± 125**	**3,520 ± 170**	**4,190 ± 190**	**97.2 ± 0.7**	**1.61 ± 0.05**	**0.52 ± 0.02**	**F=29.4 (p<0.001)**

*F-statistics are from one-way ANOVA per metric across the four protocols; Tukey HSD indicates AELR significantly differs from each baseline (p<0.01) for FND, PDR, and energy/bit.

SIMULATION RESEARCH AND RESULTS

5.1 Simulator and Parameters

We implemented protocols in a discrete-event simulator with radio and MAC abstractions matched to Contiki-NG defaults (CSMA, ContikiMAC-like duty cycling). The field is 500×500 m; one sink at center of the north edge. Node counts: 100, 200, 300. Initial energy: 2 J. Packet payloads: 80 bytes; headers add 24–32 bytes (MAC + network). Periodic telemetry: 60 s (T/H) and 300 s (soil moisture). Event thresholds: soil-moisture change θ=3%\theta=3\% v/v, burst duration 5–15 min per event. Link shadowing σ=4 dB with path-loss exponent 2.7; noise floor and sensitivity match IEEE 802.15.4 radios. Each scenario runs to 90% node depletion or 50,000 rounds.

5.2 Baseline Behavior

LEACH shows early FND when CHs near the sink drain faster, even with random rotation; single-hop CH-to-sink transmissions become expensive for distant clusters, pushing some long-range packets into the d4d^4 regime. **HEED** improves balance but incurs extra control for iterative CH election and can still generate sub-optimal multi-hop backhaul. **RPL-OF0** achieves the best baseline PDR due to ETX-aware parent choice and Trickle suppression of control traffic; however, near-sink nodes experience **hot-spot depletion**, causing cascading parent changes later in lifetime.

5.3 AELR Dynamics

AELR's composite score prefers neighbors that are (i) energy-rich, (ii) reliable (good PRR/low ETX), and (iii) closer to the sink (progress), but avoids rapid oscillation via hysteresis. During moisture bursts, Burst(t)=1\text{Burst}(t)=1 temporarily boosts stability, trading a small energy penalty for improved PDR and lower latency when control actions (e.g., valve actuation) may be time-sensitive. Delta aggregation suppresses transmissions when values drift slowly; at CHs, deltas are averaged over short windows (e.g., 3–5 samples), reducing upstream traffic by 25–40% during quiescent periods.

5.4 Quantitative Results

Across densities, AELR consistently extends lifetime. For 200 nodes (Table 1), FND improves by ~17–22% over baselines, LND by ~11–16%, and energy per useful bit drops by ~15–23%. PDR rises to ~97%, aided by link-quality weighting and parent hysteresis that limits transient losses during re-selection. Mean latency decreases modestly (~0.08–0.21 s) because AELR avoids retransmission-prone links and reduces queueing through aggregation.

Effect of duty-cycle alignment. When we disable AELR's sampling-aware duty-cycle adjustment, energy/bit worsens by ~8% and FND drops ~6%, highlighting the value of coupling application state and routing.

Effect of delta aggregation. Turning off Δ-aggregation increases upstream traffic 1.3–1.6× in stable periods, reducing LND ~9% and PDR ~0.8% due to congestion during bursts.

Scalability with density. With 300 nodes, hot-spot stress intensifies. AELR's energy weighting and cluster rotation keep the near-sink ring alive longer, extending HND by ~12% vs. RPL-OF0. With only 100 nodes, all protocols perform better; AELR retains an FND advantage (~10–14%) primarily from Δ-aggregation.

Robustness to field geometry. In elongated plots (1,000×250 m) with the sink on a short edge, path lengths skew longer. AELR maintains its margin by pushing traffic through mid-field energy-rich relays; PEGASIS-like chains (tested preliminarily) raise latency and degrade PDR during bursts, reaffirming our choice of cluster-plus-gradient hybrid over strict chains.

5.5 Overhead and Complexity

AELR adds two 1-byte fields (residual-energy class and compressed LQ) to periodic beacons and a 1-byte Δ-flag in data headers. Per-node state: ≤15 neighbor entries, each ~12–16 bytes. The arithmetic involves a few multiplications and comparisons per beacon window—feasible for MSP430/ARM-M0 class MCUs.

5.6 Practical Implementation Notes

- **Stacks:** Implementable as an RPL Objective Function variant (weights baked into rank computation) or as a stand-alone gradient protocol; Δ-aggregation fits at the application layer.
- **Calibration:** Weights wkw_k can be tuned at deployment time. A safe default is w1=w2=0.35,w3=0.2,w4=0.1w_1=w_2=0.35, w_3=0.2, w_4=0.1.
- **Anchors:** If exact distances are unavailable, substitute hop-count or RSSI-derived progress; AELR remains effective with normalized hop progress.
- **Irrigation integration:** Use the same soil-moisture thresholds that trigger valve logic to set θ\theta and Burst(t)\text{Burst}(t), ensuring network resources peak when agronomy needs data most.

CONCLUSION

Energy-aware routing is central to reliable, long-lived agricultural IoT. Classical clustering (LEACH, HEED) and standardized IPv6 routing (RPL) provide solid baselines but treat traffic and links as mostly stationary, leaving lifetime on the table when fields exhibit threshold-driven bursts and evolving radio conditions. We presented **AELR**, an adaptive, low-overhead routing scheme that merges residual-energy balancing, link-quality awareness, geometric progress, and **application-level cues**. By pairing parent-selection hysteresis with delta aggregation and sampling-aware duty cycling, AELR reduces transmissions precisely when data are least informative and strengthens paths during agronomically critical events. Simulations under realistic workloads indicate statistically significant gains: ~17–22% longer time-to-first-node-death, higher PDR (≈97%), and ~15–23% lower energy per useful bit compared with LEACH, HEED, and RPL-OF0.

The approach is practical: it reuses existing metrics (ETX, residual energy), needs only tiny header extensions, and maps cleanly either to an RPL Objective Function or a lightweight gradient protocol in Contiki-NG/RIOT. Limitations include reliance on moderately stable neighbor tables, a static sink (mobile sinks were not fully explored), and simplified shadowing. Future work should (i) validate with **field trials** across crop cycles, (ii) evaluate **mobile sinks** and tractor-borne data mules, (iii) co-design with **energy harvesting** to modulate weights wkw_k as power budgets change, and (iv) examine **security-aware** variants that maintain efficiency under jamming or spoofing. Nonetheless, the results support a clear message: in agriculture, modest, well-chosen cross-layer signals can deliver outsized gains in WSN lifetime and reliability without complicating the node firmware or requiring costly hardware.

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