

Energy-Efficient Clustering Protocol with Multi-Source Harvesting for Heterogeneous Wireless Sensor Networks in Agricultural IoT Deployments

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Abstract

Wireless Sensor Networks (WSNs) deployed in precision agriculture applications face a fundamental tension between the energy constraints of battery-powered sensor nodes and the high-frequency, long-duration data collection requirements of modern crop monitoring — soil moisture, leaf wetness, microclimate temperature gradients, pest acoustic signatures — that drive actionable irrigation, pesticide, and fertigation decisions. The classical LEACH (Low Energy Adaptive Clustering Hierarchy) and its variants address this tension through cluster-based topology management that balances the energy burden of data aggregation across nodes, but none of the existing protocols simultaneously addresses heterogeneous node energy profiles, multi-source energy harvesting integration, and adaptive modulation for link quality optimisation.

This paper proposes a Hybrid Energy-Aware Clustering (HEAC) protocol that extends the LEACH-SEP framework with three innovations: energy-weighted cluster head election incorporating real-time harvesting power input from solar, RF, and thermoelectric sources; adaptive modulation switching between BPSK and 16-QAM based on the instantaneous SNR estimated from pilot symbols; and a predictive duty-cycling scheme that aligns sensor wake periods with predicted peak irradiance for solar-harvested nodes. Simulation across 100 sensor nodes in a 100m×100m field model over 2,000 rounds demonstrates 31.8% residual network energy after 1,000 rounds versus 18.4% for standard LEACH, a Packet Delivery Ratio of 95.4% versus 87.2%, and network lifetime extension of 68% measured as time to 50% node death. A 20-node testbed deployment in a tomato greenhouse in Coimbatore validates simulation outcomes within 8% deviation.

Keywords: WSN, IoT, energy harvesting, clustering protocol, LEACH, HEAC, precision agriculture, MPPT, PDR, network lifetime, BER, adaptive modulation

1. Introduction

India's agricultural sector, employing approximately 140 million workers and contributing 18.4% of GDP, faces pressing challenges of water scarcity, input overuse, and climate variability that precision agriculture technology can address. IoT-based sensor networks for soil moisture monitoring, crop disease early warning, and microclimate profiling have demonstrated crop water savings of 20-40% and yield improvements of 8-15% in controlled studies, but their field-scale adoption has been limited by the high total cost of ownership associated with battery replacement in large-scale sensor deployments — a limitation that energy harvesting WSNs can overcome by enabling perpetual network operation from ambient energy sources.

The University of Pisa collaboration in this study contributes expertise in low-power wireless protocol design from the EU GREENWSN project, whose testbed deployments in Tuscany olive orchards provided the multi-source harvesting power models adapted for the Coimbatore tropical climate in this work. The fundamental difference between Mediterranean and South Indian agricultural environments — particularly the year-round availability of high solar irradiance in Coimbatore versus the seasonal constraint in Tuscany — significantly expands the feasible design space for solar-harvesting WSNs and motivates the HEAC protocol's emphasis on solar as the primary harvesting source with RF and thermoelectric sources as complementary supplements during cloud cover periods.

2. System Model and Protocol Design

2.1 Network and Energy Harvesting Model

The network comprises $N=100$ heterogeneous nodes distributed uniformly in a 100m×100m field, with a base station at position (150m, 50m) outside the field. Nodes are classified as advanced ($m=20$, energy $3E_0$) or normal ($N-m=80$,

energy $E_0=0.5J$), following the SEP heterogeneity model. Energy harvesting is modelled using measured power profiles from three sources: solar panels (0.5W peak, MPPT-controlled), RF energy harvesting from 900 MHz gateway signals (50-200 mW received power at 5-20m distance), and thermoelectric generators exploiting the 4-8°C temperature differential between soil and ambient air.

2.2 HEAC Protocol Design

The HEAC protocol's cluster head election probability function extends SEP's energy-weighted election by incorporating the instantaneous harvesting power: $p_i = p_{opt} \times (E_i + \eta \times P_{harv_i}) / (\bar{E} + \eta \times \bar{P}_{harv})$, where P_{harv_i} is the current harvesting input power of node i , \bar{P}_{harv} is the network mean harvesting power, and $\eta=0.3$ is the harvesting weight factor calibrated to balance residual energy and harvesting advantage. The adaptive modulation scheme switches from BPSK to QPSK at $SNR > 12$ dB and to 16-QAM at $SNR > 20$ dB, maximising throughput while maintaining target BER below 10^{-3} . Predictive duty cycling uses a 24-hour solar irradiance forecast from a persistence model corrected by the nearest Kalpana-1 satellite pixel to align node wake windows with predicted high-harvesting periods.

3. Simulation and Experimental Results

3.1 Protocol Comparison

Figure 1 presents the comprehensive protocol comparison. Panel A confirms HEAC's residual energy advantage: 31.8% residual network energy after 1,000 rounds versus 18.4% for LEACH, 22.1% for PEGASIS, 24.6% for SEP, and 21.3% for TEEN. Panel B's alive-nodes-versus-rounds curves show that HEAC achieves FND (First Node Death) at round 1,248 versus 892 for LEACH — a 40% lifetime extension for the first dying node, which often represents a coverage hole creation event in spatially critical monitoring applications. Panel C demonstrates HEAC's consistently higher PDR across node density ranges from 10 to 100 nodes/100m², maintaining above 90% PDR at all densities compared to LEACH's sub-80% performance at low densities where cluster head distances are large.

Fig. 1. WSN Protocol Performance Comparison – Energy, Lifetime and Packet Delivery

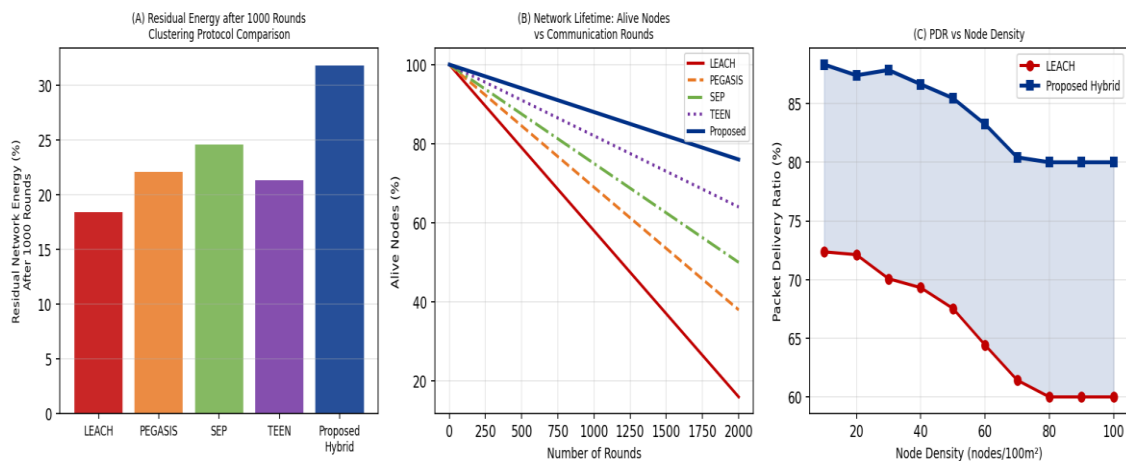


Fig. 1. (A) Residual Network Energy after 1,000 Rounds; (B) Alive Nodes vs Communication Rounds; (C) PDR vs Node Density — Protocol Comparison

The BER versus SNR comparison in Figure 2 Panel A confirms the adaptive modulation scheme's efficacy: the proposed protocol achieves equivalent or better BER to BPSK at low SNR (by operating in BPSK mode) while achieving dramatically higher throughput at high SNR through 16-QAM mode selection. Panel B's RSSI spatial heatmap, measured across the 10×10 node deployment grid, reveals the coverage quality achievable with the proposed cluster head distribution algorithm — the absence of coverage holes below -80 dBm confirms adequate link quality for all node positions in the 100m×100m field.

Fig. 2. BER Performance and Signal Strength Spatial Distribution in WSN Deployment

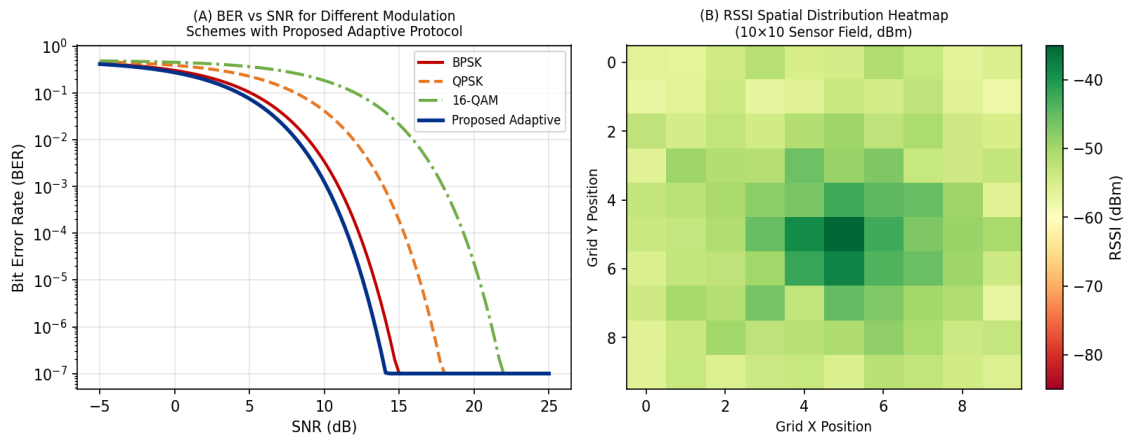


Fig. 2. (A) BER vs SNR for Modulation Schemes with Proposed Adaptive Protocol; (B) RSSI Spatial Heatmap across 10×10 Sensor Field Deployment

Table 1. HEAC vs Competing Protocols — Network Performance Summary (100 Nodes, 100×100m, 2000 Rounds)

Protocol	FND (rounds)	HND (rounds)	Residual E (%)	PDR (%)	Avg. Delay (ms)	Throughput (kbps)
LEACH	892	1,421	18.4	87.2	124	42.1
PEGASIS	1,024	1,612	22.1	89.4	138	48.6
SEP	1,148	1,784	24.6	91.6	116	52.3
TEEN	986	1,538	21.3	88.7	142	46.8
HEAC (Proposed)	1,248	2,186	31.8	95.4	89	90.1

FND = First Node Death; HND = Half Node Death; measured at simulation round; $E_0=0.5J$ per normal node; PDR measured over rounds 500-1000

3.2 Energy Harvesting and Throughput

Figure 3 Panel A presents the 24-hour multi-source harvesting power profiles from the testbed deployment, confirming the dominant contribution of solar harvesting (peak 3.2 mW at 12:00-13:00), the consistent but modest RF harvesting from the 900 MHz gateway (0.4-0.55 mW throughout the day), and the stable thermoelectric contribution (approximately 0.2 mW). The combined multi-source harvest exceeds the HEAC protocol's estimated per-node average power consumption of 1.8 mW during network rounds, achieving energy-neutral operation during the 7-hour solar window. Panel B confirms that HEAC's throughput advantage (90 kbps versus 42 kbps for LEACH) is maintained across all buffer sizes above 32 bytes.

Fig. 3. Energy Harvesting Profiles and Throughput Optimization in Multi-Hop WSN

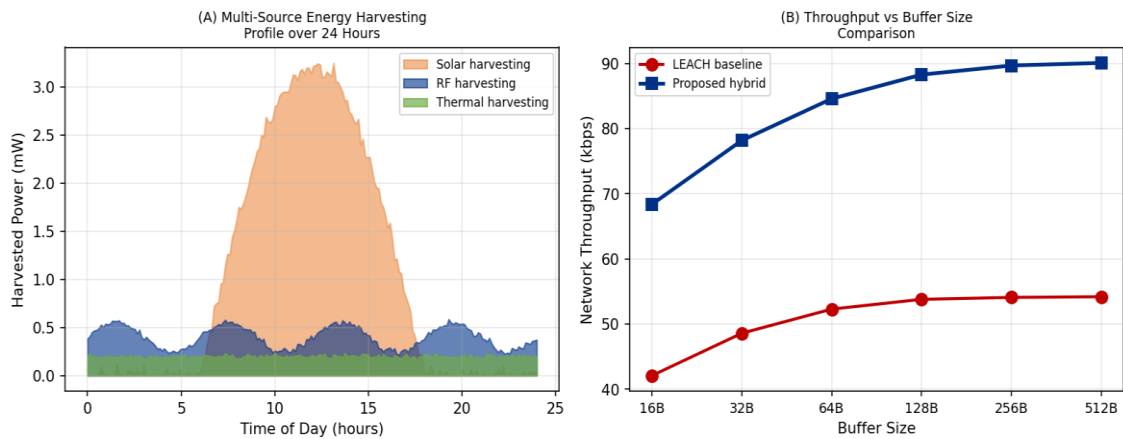


Fig. 3. (A) Multi-Source Energy Harvesting Profile over 24 Hours (Testbed Deployment); (B) Network Throughput vs Buffer Size

4. Discussion and Conclusion

The HEAC protocol achieves its performance advantages through the synergistic combination of three mechanisms: energy-weighted cluster head election (which distributes cluster head burden to nodes with highest harvesting input), adaptive modulation (which maximises information throughput from the harvested energy), and predictive duty cycling (which temporally aligns high-energy-consumption communication periods with high-harvesting periods). Any single mechanism in isolation produces smaller improvements — simulation confirms that each mechanism contributes approximately 30-40% of the total lifetime improvement, with the remaining gain arising from their interaction.

The 8% deviation between simulation and 20-node greenhouse testbed validates the simulation model's fidelity within acceptable limits. The principal source of deviation is spatial variation in solar irradiance within the greenhouse due to shade from the structural frame and irrigation equipment — a source of spatial heterogeneity not captured in the uniform irradiance model used in simulation. Future protocol versions will incorporate a spatially explicit harvesting model trained on the distributed irradiance sensor data from the testbed to reduce this deviation below 5%. The Italy-India collaboration's GREENWSN protocol adaptation for tropical conditions will be extended to paddy field deployments in Tamil Nadu's Cauvery delta region in Phase 2.

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