

An Adaptive Energy-Efficient Clustering and Routing Framework for Wireless Sensor Networks

Dr. P. Prabharan¹, S. Karthiga²

¹Associate Professor, Department of Computer Science and Engineering, Vivekanandha College of Engineering for Women, Tamil Nadu, India

²PG Scholar, Department of Computer Science and Engineering, Vivekanandha College of Engineering for Women, Tamil Nadu, India

Abstract—Wireless Sensor Networks (WSNs) consist of large numbers of battery-powered nodes that sense, process and forward data, often in remote environments where recharging or replacing batteries is impractical. Energy depletion therefore governs network lifetime, coverage and data reliability. Clustering and routing are the most widely studied techniques for conserving energy because they reduce redundant transmissions, enable in-network data aggregation and balance load among nodes. This survey reviews more than thirty representative works spanning classical cluster-based protocols (LEACH, HEED, EECS), heterogeneity-aware schemes (SEP, DEEC, EEHC), unequal clustering for hot-spot mitigation, chain-based, reactive and data-centric routing, fuzzy-logic approaches, metaheuristic optimisation (PSO, GA, ACO) and learning-based routing. The approaches are compared on energy efficiency, scalability, control overhead and adaptability, and their limitations are identified. Based on this analysis, a conceptual adaptive energy-efficient clustering and routing framework is outlined that combines context-aware cluster-head election, load-balanced unequal clustering, energy-aware multi-hop routing and an adaptation controller. Open research issues are also highlighted.

Index Terms—Wireless Sensor Networks, Energy Efficiency, Clustering, Cluster Head Selection, Routing Protocols, Network Lifetime, Adaptive Framework.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are collections of spatially distributed, low-cost sensor nodes that cooperatively monitor physical or environmental conditions such as temperature, humidity, vibration, pollution or movement and relay the collected data to a base station (BS) or sink [1], [2]. They underpin

applications in precision agriculture, environmental and habitat monitoring, healthcare, smart cities, industrial automation, disaster management and military surveillance. A typical node is powered by a small battery and has limited processing, memory and communication capability, and in many deployments the field is inaccessible, so the battery cannot be replaced or recharged.

Radio communication is the dominant source of energy consumption in a sensor node, and the energy needed to transmit grows rapidly with distance [3]. Sending every reading directly to a distant sink quickly exhausts the nodes and leaves the network partitioned or uncovered. Consequently, energy-efficient design of the protocol stack, and particularly of the network layer, has been the central research theme in WSNs for more than two decades [3]– [6].

Clustering is the most popular architectural answer. Nodes are grouped into clusters, each led by a cluster head (CH) that collects and aggregates the data of its members and forwards it towards the sink. This reduces the number of long-distance transmissions, removes redundant data, improves scalability and allows members to sleep when they are not sensing. The performance of a clustering scheme depends on how CHs are selected, how clusters are formed and how CH-to-sink traffic is routed. Poor choices create hot spots: CHs and relay nodes close to the sink die early, producing the “energy hole” problem and shortening the network lifetime.

A large body of protocols has been proposed, from randomised rotation of the CH role to energy-aware, heterogeneity-aware, unequal-size and optimisation-based schemes. Earlier surveys cover routing techniques [4], [5], clustering algorithms [6] and

energy-conservation mechanisms [3]. This paper complements them with a focus on the combined problem of clustering and routing and on the move towards adaptive behaviour.

The main contributions are:

- a structured review of thirty-three representative studies, grouped by the design idea they introduce;
- a comparative analysis of clustering and routing approaches in terms of energy efficiency, scalability, overhead and limitations;
- a conceptual adaptive energy-efficient clustering and routing framework derived from the gaps found in the literature; and
- a discussion of open research issues and directions for future work.

The rest of the paper is organised as follows. Section II gives the background, Section III reviews the literature, Section IV compares the approaches, Section V analyses the findings, Section VI outlines the proposed framework, Section VII discusses open issues and Section VIII concludes the paper.

II. BACKGROUND

A. NETWORK AND ENERGY MODEL

A WSN is commonly modelled as N static or mobile sensor nodes deployed over an $M \times M$ field with one sink located inside or outside it. Most of the surveyed work adopts the first-order radio model introduced with LEACH [7], [8].

To transmit an l -bit message over a distance d , a node spends

$$E_{Tx}(l, d) = l \cdot E_{elec} + l \cdot \epsilon_{fs} \cdot d^2, \quad d < d_0 \quad (1)$$

$$E_{Tx}(l, d) = l \cdot E_{elec} + l \cdot \epsilon_{mp} \cdot d^4, \quad d \geq d_0 \quad (2)$$

and to receive it spends $E_{Rx}(l) = l \cdot E_{elec}$, where E_{elec} is the electronics energy per bit, ϵ_{fs} and ϵ_{mp} are the free-space and multipath amplifier energies, and the crossover distance is $d_0 = \sqrt{(\epsilon_{fs}/\epsilon_{mp})}$. Aggregating k signals of l bits costs E_{DA} per bit per signal. Because the transmission cost grows with d^2 or d^4 , replacing one long hop by several short hops, and aggregating data before forwarding it, are the two basic sources of saving exploited by clustering and multi-hop routing.

B. DESIGN CHALLENGES

The main challenges are (i) the energy hole or hot-spot problem near the sink, (ii) unbalanced cluster sizes and CH placement, (iii) heterogeneity in initial energy and

in traffic load, (iv) scalability of control messages as the network grows, (v) dynamic topology caused by node failure, mobility and unreliable wireless links, and (vi) the trade-off between energy saving and delay, reliability and coverage.

C. EVALUATION METRICS

Network lifetime is usually reported through First Node Dead (FND), Half Nodes Dead (HND) and Last Node Dead (LND) rounds. The stability period (time until FND) and the instability period (FND to LND) show how evenly energy is consumed. Other metrics are total and average residual energy, energy variance among nodes, packets delivered to the sink (throughput), packet delivery ratio, end-to-end delay and control overhead.

III. LITERATURE REVIEW

CLUSTERING AND ROUTING PROTOCOLS FOR WSNs

The surveyed studies show a clear progression: randomised CH rotation, then residual-energy awareness, then heterogeneity and distance awareness, then unequal clustering for multi-hop relaying, and more recently intelligent optimisation and learning. The works are grouped below by the main idea they introduce.

A. CLASSICAL CLUSTER-BASED PROTOCOLS

^[7] W. R. Heinzelman, A. P. Chandrakasan and H. Balakrishnan introduced LEACH (Low-Energy Adaptive Clustering Hierarchy).

Each node decides on its own, using a probability, whether to act as CH in a given round, so that the burden of this role passes from node to node over time. CHs aggregate the data of their members and send it to the BS in a single hop. Their simulations show that the energy dissipated can fall to roughly one-eighth of that of direct transmission and minimum-transmission-energy routing.

^[8] The journal version of the LEACH work by W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan describes the protocol architecture in more detail and introduces LEACH-C, a centralised variant in which the BS, using location and energy information reported by the nodes, forms the clusters through simulated annealing. Better CH placement yields more balanced clusters and a longer lifetime, at the price of

reporting overhead and the need for location information.

^[9] M. J. Handy, M. Haase and D. Timmermann propose a deterministic CH-selection rule for LEACH that takes the residual energy of a node into account and stabilises the number of CHs per round. Nodes with little energy are less likely to become CHs and rounds without any CH are avoided, which postpones the death of the first node.

^[10] O. Younis and S. Fahmy introduce HEED (Hybrid Energy-Efficient Distributed clustering). CH probability is derived primarily from residual energy, while an intra-cluster communication cost, such as the average minimum reachable power, is used to break ties. The procedure runs in a constant number of iterations, produces well-distributed CHs and supports multi-hop inter-cluster routing, but the repeated message exchange adds overhead and the clusters are of roughly equal size.

^[11] M. Ye, C. Li, G. Chen and J. Wu propose EECS (Energy-Efficient Clustering Scheme). CH candidates compete locally on residual energy, and cluster membership is decided by a weighted cost that considers both the distance of the node to the CH and the distance of the CH to the BS. This spreads the load among CHs and, in the authors' simulations, extends the network lifetime over LEACH.

B. HETEROGENEITY-AWARE PROTOCOLS

^[12] G. Smaragdakis, I. Matta and A. Bestavros present SEP (Stable Election Protocol) for two-level heterogeneous networks. Advanced nodes with extra energy are given a higher election probability than normal nodes, which prolongs the stability period before the first node dies. The scheme is limited to two energy levels and fixed election probabilities.

^[13] L. Qing, Q. Zhu and M. Wang design DEEC (Distributed Energy-Efficient Clustering) for heterogeneous networks. The election probability of a node depends on the ratio between its residual energy and the average energy of the network, so nodes with more energy serve as CHs more often. DEEC works with any number of energy levels, but it needs an estimate of the network's average energy and lifetime.

^[14] D. Kumar, T. C. Aseri and R. B. Patel propose EEHC (Energy-Efficient Heterogeneous Clustered scheme), which uses weighted election probabilities based on the energy of each node type. Heterogeneous nodes with higher energy are chosen as CHs more

often, which prolongs the stability period of the network compared with homogeneous clustering protocols.

C. UNEQUAL CLUSTERING FOR HOT-SPOT MITIGATION

^[15] C. Li, M. Ye, G. Chen and J. Wu propose EEUC (Energy-Efficient Unequal Clustering). Each tentative CH computes a competition radius that shrinks as the distance to the BS decreases, giving smaller clusters near the sink. Because CHs near the sink also relay traffic of farther clusters, their smaller clusters leave them more energy for relaying and the CH energy consumption becomes more balanced.

^[16] O. Soro and W. B. Heinzelman analyse unequal clustering in a multi-hop setting. Their analysis indicates that when clusters close to the BS are kept smaller than distant ones, the combined energy that each CH spends on collecting member data and on relaying other clusters' traffic becomes more uniform, which extends lifetime relative to clusters of equal size.

^[17] G. Bagci and A. Yazici introduce EAUCF (Energy-Aware Unequal Clustering with Fuzzy logic). A fuzzy inference system takes the residual energy and the distance to the BS as inputs and outputs the competition radius of each tentative CH, which links unequal clustering with soft-computing based decision making.

D. CHAIN-BASED, REACTIVE AND DATA-CENTRIC ROUTING

^[18] S. Lindsey and C. S. Raghavendra present PEGASIS (Power-Efficient Gathering in Sensor Information Systems). The nodes are linked into a chain so that each one talks only to its closest neighbour, and one node at a time, taking turns as leader, transmits the fused data to the BS. Cluster set-up is avoided, but delay grows with chain length, global knowledge is needed and the leader is a bottleneck.

^[19] A. Manjeshwar and D. P. Agrawal introduce TEEN (Threshold-sensitive Energy-Efficient sensor Network protocol), a reactive protocol for time-critical applications.

Nodes report only when the sensed value crosses a hard threshold or changes by more than a soft threshold, which greatly reduces transmissions. The drawback is that no data is sent if the thresholds are

never reached, so it is unsuitable for periodic monitoring.

^[20] W. Heinzelman, J. Kulik and H. Balakrishnan propose SPIN, a family of negotiation-based protocols in which nodes advertise their data with meta-data before sending it. Because a node transmits the actual data only when a neighbour request it, duplicate and redundant deliveries typical of plain flooding are avoided and energy is saved.

^[21] C. Intanagonwiwat, R. Govindan and D. Estrin present Directed Diffusion, a data-centric paradigm in which the sink floods interests, gradients are set up and data flows along reinforced paths with in-network aggregation. The approach is robust and scalable for query-driven applications but incurs overhead for interest dissemination.

E. FUZZY-LOGIC BASED CH SELECTION

^[22] I. Gupta, D. Riordan and S. Sampalli propose a fuzzy-logic based CH election in which the BS evaluates three descriptors of each node, namely energy, concentration (number of neighbours) and centrality. The fuzzy inference handles imprecise inputs and gives a better lifetime than LEACH in the reported simulations, but the scheme is centralised.

^[23] J.-M. Kim, S.-H. Park, Y.-J. Han and T.-M. Chung present CHEF, a distributed CH election mechanism in which each node derives a chance value from fuzzy rules over its residual energy and its local distance to neighbouring nodes. A node becomes a CH if its chance is highest in its neighbourhood, avoiding the need for global information.

F. METAHEURISTIC OPTIMISATION APPROACHES

^[24] N. M. A. Latiff, C. C. Tsimenidis and B. S. Sharif use Particle Swarm Optimisation (PSO) at the BS to select CHs. The fitness function combines the residual energy of the chosen CHs with the intra-cluster distance, and the approach outperforms LEACH in terms of lifetime and data delivered in the reported experiments.

^[25] P. Kuila and P. K. Jana address clustering and routing together with PSO. The problems are first stated as linear and non-linear programs, and separate particle representations and fitness functions are then defined for the clustering step and for the routing step. The resulting algorithms are benchmarked against several existing clustering and routing protocols.

^[26] P. C. S. Rao, P. K. Jana and H. Banka propose a PSO-based CH selection algorithm whose fitness uses residual energy, intra-cluster distance and the distance to the sink. Selecting CHs by this multi-objective criterion improves energy balance and network lifetime relative to baseline protocols, although the optimisation is run centrally.

^[27] S. Hussain, A. W. Matin and O. Islam apply a Genetic Algorithm (GA) to hierarchical WSNs, encoding the CH set in a chromosome and evolving it to maximise lifetime. They report a longer lifetime than LEACH and similar protocols in simulation, at the cost of centralised computation.

^[28] T. Camilo, C. Carreto, J. S. Silva and F. Boavida propose an ant-colony based routing algorithm for WSNs. Artificial ants build paths guided by pheromone that reflects energy-related information, so that energy consumption is spread across several routes instead of a single shortest path.

G. LEARNING-BASED AND COMPLEMENTARY TECHNIQUES

^[29] M. A. Alsheikh, S. Lin, D. Niyato and H.-P. Tan survey the use of machine-learning techniques in WSNs, including routing, clustering, data aggregation and anomaly detection. They discuss how learning allows nodes to adapt to a changing environment, and they also point out the memory and computation constraints of sensor nodes.

^[30] A. Förster and A. L. Murphy present FROMS, a feedback routing scheme based on reinforcement learning for networks with multiple sinks. Nodes learn the cost of forwarding through each neighbour from feedback and adapt their routes to changes in the network.

^[31] R. Rajagopalan and P. K. Varshney survey data-aggregation techniques, including cluster-based and tree-based aggregation, and discuss the trade-off between the energy saved by aggregating data and the accuracy, latency and robustness of the result.

^[32] Z. M. Wang, S. Basagni, E. Melachrinoudis and C. Petrioli study the exploitation of sink mobility to maximise network lifetime. Because the sink changes position, different nodes take over the relaying duty over time, which eases the hot spot that forms around a fixed sink.

^[33] S. Sudevalayam and P. Kulkarni survey energy-harvesting sensor nodes and the implications of harvested energy for node and protocol design, which

opens the way to energy-neutral operation where protocols must adapt to a time-varying energy supply

IV.COMPARATIVE ANALYSIS

TABLE I. COMPARISON OF CLASSICAL CLUSTERING AND ROUTING PROTOCOLS

Protocol	Category	Key technique	Energy efficiency	Scalability	Main limitation
LEACH [7]	Distributed, cluster-based	Randomised CH rotation, local aggregation, single-hop CH-to-BS transmission	Medium	Low	Ignores residual energy; random CH number and position; single hop limits network size
LEACH-C / Det. LEACH [8], [9]	Centralised / deterministic	BS-computed clusters (simulated annealing) or energy-based deterministic threshold	Medium	Low	Location/energy reporting overhead; BS dependence
HEED [10]	Distributed, cluster-based	Residual energy plus intra-cluster cost; iterative election; multi-hop capable	High	High	Repeated message exchange; equal-size clusters
EECS [11]	Distributed, cluster-based	Local energy competition; distance-aware cluster formation	Medium	Medium	Single-hop CH-to-BS; extra set-up cost
SEP [12]	Heterogeneity-aware	Weighted election probabilities for two energy levels	Medium	Medium	Only two levels; fixed probabilities
DEEC [13]	Heterogeneity-aware	Election probability from residual-to-average energy ratio	High	Medium	Needs estimate of average energy / lifetime
EEHC [14]	Heterogeneity-aware	Weighted probabilities for node types	Medium	Medium	Depends on predefined energy classes
EEUC / UCS [15], [16]	Unequal clustering	Competition radius decreases towards sink; multi-hop CH relaying	High	High	Requires sink location; extra computation of radius
PEGASIS [18]	Chain-based	Nearest-neighbour chain with rotating leader	High	Low	High delay; global knowledge; leader bottleneck
TEEN [19]	Reactive, hierarchical	Hard and soft thresholds for event-driven reporting	High	Medium	No data if threshold not met; not for periodic sensing
SPIN / Directed Diffusion [20], [21]	Data-centric	Meta-data negotiation; interest gradients with in-network aggregation	Medium	Medium	Negotiation / interest flooding overhead

Ratings (Low / Medium / High) are qualitative and reflect how each design is generally characterised in the cited works and surveys. Reported numerical

results depend on the simulation set-up (field size, node count, sink position, energy model) and are not directly comparable across papers.

TABLE II. COMPARISON OF INTELLIGENT AND COMPLEMENTARY APPROACHES

Approach	Works	Technique	Optimisation criteria	Main limitation
Fuzzy logic	[17], [22], [23]	Fuzzy inference over node descriptors to compute CH chance or competition radius	Residual energy, centrality, concentration, distance to BS	Hand-tuned rules and membership functions; some variants centralised

Particle Swarm Optimisation	[24]– [26]	Particles encode CH sets; swarm search at the BS	Residual energy, intra-cluster distance, distance to sink	Centralised; computation and re-run cost; parameter sensitivity
Genetic Algorithm	[27]	Chromosome encodes CH set; evolved to maximise lifetime	Network lifetime, energy balance	Centralised; slow convergence
Ant Colony Optimisation	[28]	Pheromone-guided energy-aware path construction	Energy of paths, load spreading	Convergence time; control-packet overhead
Machine / reinforcement learning	[29], [30]	Learning of routing and clustering decisions from feedback	Forwarding cost, energy, adaptability	Learning overhead; limited node memory and computation
Complementary techniques	[31]– [33]	Data aggregation, mobile sink, energy harvesting	Data volume, hot-spot relief, energy supply	Accuracy/latency trade-off; path planning; hardware cost

Ratings and limitations summarise the surveyed literature; they are not results of new experiments.

V.ANALYSIS

The review shows that the clustering problem has been refined step by step. LEACH established that rotating the CH role and aggregating data locally saves a great deal of energy, but its random election ignores residual energy and CH position [7]. HEED, EECS and the deterministic variant of LEACH correct this by involving residual energy and distance [9]– [11]. SEP, DEEC and EEHC then relax the assumption of homogeneous nodes [12]– [14].

Single-hop transmission from CH to BS does not scale to large fields, and multi-hop relaying between CHs creates a new hot spot near the sink. Unequal clustering [15]– [17] addresses this directly by giving CHs close to the sink smaller clusters, and it is therefore the most important idea for large deployments.

Chain-based and reactive protocols reduce energy further for particular traffic patterns [18], [19], but they do not suit every application.

Metaheuristic approaches such as PSO, GA and ACO [24]– [28] find better CH placements than purely probabilistic election, yet most of them run at the BS and need global state. This costs control traffic, delays

re-clustering and makes them hard to apply in large or dynamic networks.

Fuzzy logic [17], [22], [23] is a lightweight alternative that can run locally and cope with imprecise information, although its rules are normally set manually.

Three further observations emerge. First, many studies are evaluated by simulation under an idealised radio, static uniform deployment and fixed-length rounds, which limits comparability and realism. Second, re-clustering is usually performed every round regardless of need, wasting energy on set-up messages. Third, few works treat energy, load, link quality and sink position together, or adapt their parameters when the network changes. These gaps motivate an adaptive framework

VI.PROPOSED ADAPTIVE ENERGY-EFFICIENT FRAMEWORK

Drawing on the gaps identified above, this section outlines a conceptual framework for adaptive energy-efficient clustering and routing. It combines the proven ideas of residual-energy-aware election, unequal clustering and multi-hop routing with an adaptation controller that tunes their behaviour at run time. The framework is a design proposal derived from the survey; its performance has not yet been validated experimentally.

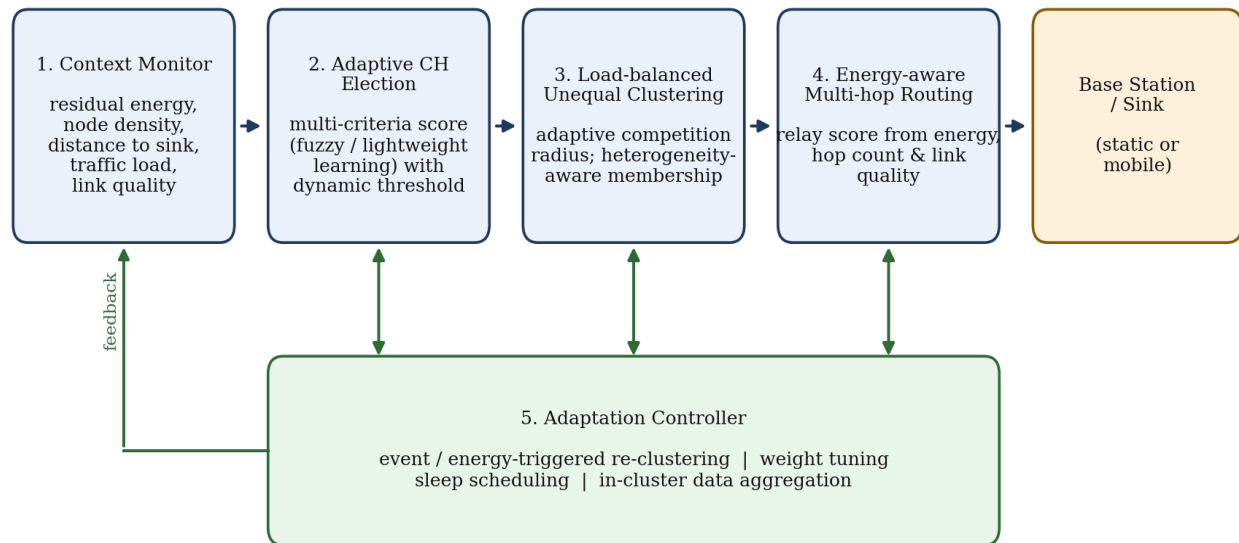


Fig. 1. Conceptual adaptive energy-efficient clustering and routing framework

A. FRAMEWORK MODULES

1)Context monitor.

Each node keeps lightweight estimates of its residual energy, local density, distance to the sink, recent traffic load and link quality to its neighbours. Information is piggy-backed on existing control packets to avoid additional overhead.

2)Adaptive CH election. Each tentative CH computes a multi-criteria score, for example

$$S_i = w_1(E_{res,i}/E_{avg}) + w_2(1 - d_{i,BS}/d_{max}) + w_3\rho_i + w_4LQ_i \quad (3)$$

where $E_{res,i}$ is the residual energy, E_{avg} the estimated average energy, $d_{i,BS}$ the distance to the sink, ρ_i the normalised local density and LQ_i the link quality. The score may be obtained by a fuzzy inference system, in the spirit of [17], [22], [23], or by a simple weighted sum, and a dynamic threshold prevents nodes with low scores from becoming CHs. The weights w_k are tuned by the adaptation controller.

3)Load-balanced unequal clustering.

The competition radius is reduced for CHs close to the sink, following the idea of EEUC [15],

$$R_c(i) = [1 - c \cdot (d_{max} - d_{i,BS})/(d_{max} - d_{min})] \cdot R_0, \quad 0 \leq c \leq 1 \quad (4)$$

and the membership of a node is decided by a cost that includes its distance to the CH and the residual energy of that CH, as in EECS [11], so that clusters are balanced for heterogeneous nodes [12]– [14].

4)Energy-aware multi-hop routing.

A CH selects the next-hop relay among neighbouring CHs closer to the sink using a score that combines the residual energy of the relay, the remaining hop count and the link quality, so that traffic is spread over several relays instead of loading a single shortest path.

5)Adaptation controller.

Instead of re-clustering every fixed round, the controller triggers re-clustering when a CH's residual energy falls below a fraction of the average energy, when load imbalance between clusters exceeds a limit, or when an event such as node failure or sink movement is detected. It also adjusts the weights w_k , schedules sleep for members with redundant sensing coverage [3] and enables in-cluster data aggregation [31].

Extensions such as a mobile sink [32] and harvested-energy awareness [33] can be plugged in through the same context information.

B. PLANNED EVALUATION

The framework should be evaluated by simulation against LEACH, HEED, DEEC and EEUC, with FND, HND, LND, residual energy, energy variance, packet delivery ratio, delay and control overhead as metrics. Scenarios should vary the node density, the sink position, the degree of energy heterogeneity and the link model, and the results should be averaged over several random deployments.

VII.OPEN ISSUES AND FUTURE DIRECTIONS

Several issues remain open. (i) Realistic channel models: most protocols are evaluated under ideal radio links, whereas interference, fading and asymmetric links change the real cost of a route. (ii) Lightweight intelligence: learning and optimisation need to be made light enough for resource-constrained nodes, or distributed between nodes and the sink. (iii) Mobility and dynamics: protocols should handle mobile nodes, mobile sinks and node failures without costly global re-clustering. (iv)

Energy harvesting: protocols must adapt to a time-varying energy supply [33]. (v) Security and trust: CH election and routing are attractive targets for attackers, and secure, energy-efficient designs are needed. (vi) Benchmarking: common simulation settings, open test-beds and real-deployment evaluation are needed so that protocols can be compared fairly. (vii) Integration with IoT and edge computing architectures.

VIII.CONCLUSION

This paper has surveyed clustering and routing approaches for energy-efficient wireless sensor networks, from LEACH and its energy-aware and heterogeneity-aware successors to unequal clustering, fuzzy-logic, metaheuristic and learning-based schemes.

Randomised rotation and local aggregation form the basis of energy saving, residual-energy and distance awareness make CH selection more reliable, and unequal clustering with multi-hop relaying is the key to mitigating the hot-spot problem in large networks.

Centralised metaheuristics yield good CH placement but are costly, whereas fuzzy and learning-based methods offer lighter ways to adapt. Existing work only partly addresses joint, adaptive handling of energy, load, link quality and sink position. The conceptual adaptive framework presented here, built from a context monitor, adaptive CH election, load-balanced unequal clustering, energy-aware multi-hop routing and an adaptation controller, is a step in this direction, and its validation by simulation and real deployments is the natural next step.

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