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MULTI-HOP LOOKAHEAD STRATEGIES FOR ROBUST ENERGY-EFFICIENT ROUTING IN WSNS

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Abstract

When packets in routing paths travel through void or dead nodes, Wireless Sensor Networks (WSNs) lose energy over time, and impacting the sensors by reducing lifespan and degrading packet delivery performance. In order to proactively address these issues, this study suggests three routing protocols: the Game Theory Based Protocol with Three-Hop Lookahead (GTBPS-3H), the Hole Alleviation-Energy-Conditioned Mean Absolute Error (HA-ECMAE), and its two-hop extension (HA-ECMAE2H). HA-ECMAE and HA-ECMAE2H choose forwarding nodes by combining residual energy checks with Mean Absolute Error (MAE)-based position estimates to reduce location-based routing errors. By dynamically allocating leader positions throughout a three-hop neighbourhood using the Stackelberg game model, GTBPS-3H distributes the forwarding burden and reduces interactions with void and dead nodes. Simulations against the WSNEHPA [16] and ECMSE [17] baselines reveal that HA-ECMAE increases Packet Delivery Ratio (PDR) by 14% and decreases energy consumption by 15.2%, while HA-ECMAE2H increases PDR by 19% and decreases energy consumption by 18.7%, and GTBPS-3H increases PDR by 17% while extending network lifetime by 20%. These findings show [18] that when multi-hop lookahead is paired with energy-aware forwarder selection, network reliability, energy efficiency, and network lifetime improve consistently under realistic WSN conditions.

I. Introduction

WSNs are made up of battery-powered sensor nodes that gather, process, and transmit data to a base station or surrounding nodes via wireless connections. These networks enable applications such as environmental monitoring, health surveillance, disaster management, and smart infrastructure, all of which require consistent and dependable data supply.

Each sensor node operates on a fixed energy budget. A node that exhausts its energy can no longer transmit or forward packets; such a node is called a *dead node*. A *void node* is one that still has energy but has no reachable neighbour in the direction of the sink, making it unable to forward data along a useful path. Both conditions disrupt routing, waste energy on failed transmissions, and accelerate overall network failure.

Existing routing protocols handle these conditions with varying success. Many protocols improve PDR but do so at a high energy cost. Others conserve energy but route packets into void regions, causing losses that require costly retransmissions. Few protocols explicitly combine energy-aware forwarder selection with void node detection across multiple hops, which is precisely where performance gaps tend to appear.

This paper closes that gap with three protocols. HA-ECMAE selects the next-hop forwarder using MAE-based position error estimation, which limits the chance of routing toward an incorrect or unreachable node. HA-ECMAE2H extends this mechanism by evaluating candidates two hops ahead, allowing the protocol to assess path viability beyond the immediate next node. GTBPS-3H applies Stackelberg game theory within three-hop sub-regions to elect energy-aware leader nodes, distributing the forwarding responsibility across the network and avoiding dead-end paths.

All three protocols are evaluated against ECMSE [17], WSNEHPA [16], and HA-ECMSE using PDR, total energy consumption, and computational delay as performance metrics. The main contributions of this paper are:

- Three routing protocols, HA-ECMAE, HA-ECMAE2H, and GTBPS-3H, are proposed to reduce void hole formation and improve energy efficiency in WSNs.
- MAE-based next-hop selection and a two-hop lookahead mechanism are combined in HA-ECMAE and HA-ECMAE2H to improve both PDR and energy utilisation simultaneously.
- A Stackelberg game-theoretic leader election mechanism is integrated into GTBPS-3H to distribute the forwarding load across three-hop sub-regions dynamically.
- A comparative evaluation against ECMSE [17], WSNEHPA [16], and HA-ECMSE quantifies the performance gains of the proposed schemes across all three metrics.

Section II reviews related work. Section III describes the system models and protocol design. Section IV presents and analyses simulation results. Section V summarises findings and outlines future work.

II. Related Work

This section reviews prior work on WSN routing, focusing on energy efficiency, void hole mitigation, and packet delivery reliability. Butt et al. [1] addressed the void hole problem in WSNs by proposing energy-aware routing that accounts for hole regions during path selection. Their approach prioritises routes that bypass void areas, which tends to reduce unnecessary energy expenditure on failed transmissions and improve overall network longevity.

Shenbagharaman and Paramasivan [2] proposed a secure and energy-efficient routing protocol for underwater WSNs that combines running city game optimisation with an XGBoost classifier. The game-optimisation component guides routing decisions toward energy-efficient paths, while the XGBoost module filters out malicious nodes. This work shows that combining optimisation strategies with machine learning can improve both security and energy performance in resource-constrained sensor networks.

Gopalasamy and Muthaiya [3] proposed the H-MAntnetSVM algorithm for secure packet routing in mobile ad hoc networks, targeting energy efficiency and blackhole attack detection. Their approach uses ant-colony-inspired path selection together with a support vector machine classifier to identify and exclude malicious nodes from forwarding paths. Although the work focuses on MANETs rather than static WSNs, the combination of energy-aware routing and security-oriented node evaluation is relevant to sensor network design more broadly.

Mateen et al. [4] proposed a routing scheme for blockchain-based underwater WSNs that recovers from void hole conditions by partitioning packets and redistributing the data load across relay nodes. Logical depth adjustment maintains routing balance over time. The authors report that the approach improves energy balance at the cost of higher end-to-end delay, a trade-off also observed in [3].

Qaisar et al. [5] reviewed routing challenges in WSNs and compared conventional battery-based power supplies with energy harvesting approaches, outlining the advantages and practical constraints of each. Sabor et al. [6] proposed hierarchical routing to reduce energy consumption by assigning roles to nodes according to their position in the network hierarchy, which distributes the energy burden more evenly across the deployment.

Mateen et al. [7] categorised void hole handling methods into location-based and depth-based approaches and applied Stackelberg game theory to forwarder selection in heterogeneous 5G sensor networks. Their results suggest that game-theoretic coordination among nodes can improve routing efficiency when nodes operate under energy constraints.

Hasan et al. [8] examined multipath routing protocols for multimedia traffic in WSNs and proposed activating secondary routes when primary paths become congested. This strategy tends to reduce the impact of path overload on packet delivery performance.

Huang et al. [9] presented a coordinate-assisted geographic routing scheme designed to bypass routing holes using a lightweight coordinate system. The method requires less computational overhead than face-based geographic routing, making it more practical for resource-constrained nodes.

Pawar and Agarwal [10] surveyed security threats to WSNs, including Denial of Service attacks, and evaluated defence strategies that prioritise network availability. These strategies tend to incur additional energy costs, which must be weighed against their protective benefit.

Naranjo et al. [11] proposed P-SEP, a prolong stable election protocol that classifies nodes as normal or advanced and selects Cluster Heads based on residual energy, connectivity, and distance to the sink. Rotating Cluster Head selection in this way tends to extend network lifetime by preventing premature energy depletion at individual nodes.

Ramadan et al. [12] proposed a node-power-based MAC protocol that reduces transmission energy by adapting each node's listening period. The protocol introduces higher end-to-end latency because additional control messages are required at each communication stage.

Shen and Bai [13] reviewed routing protocols for Wireless Multimedia Sensor Networks, focusing on congestion avoidance, bandwidth optimisation, and energy efficiency. Their survey identifies latency management as an unresolved challenge, particularly in applications where delay directly affects the usefulness of delivered data.

Mateen et al. [14] proposed the Minimum Delay Energy Efficient Tree flooding scheme, which constructs an optimised delay tree to balance transmission delay and energy consumption.

Simulations show that the scheme outperforms earlier flooding benchmarks; however, it does not address void hole formation, which limits its applicability in networks with uneven node deployment.

Fan and Xin [15] proposed EBPT-CRA, a clustering and routing algorithm for WSNs based on an energy-balanced path tree. The tree structure organises relay nodes to distribute energy consumption evenly across the network, and simulation results suggest that this approach extends network lifetime compared to standard clustering methods.

Taken together, these studies show that void node avoidance, multi-hop path evaluation, and energy-aware forwarder selection are closely linked. No single existing protocol combines all three mechanisms within a unified lookahead framework, which is the gap that HA-ECMAE, HA-ECMAE2H, and GTBPS-3H address.

III. System Model

Sensor nodes in a WSN are deployed without a fixed spatial order. After deployment, each node broadcasts a hello message to discover its neighbours. A neighbour that receives this message replies with an acknowledgment, and a communication link is formed. Nodes relay data toward the sink using radio communication with optimised signal-to-noise ratios.

When a node has no reachable forwarding neighbour in the direction of the sink, a void hole forms. Packets routed into this region are lost, and the energy spent on the failed transmission is wasted. Dead nodes, which have depleted their energy entirely, produce the same effect by eliminating viable links from the routing topology.

The proposed protocols address these problems before they occur. HA-ECMAE and HA-ECMAE2H apply MAE-based position error estimation during forwarder selection to reduce misdirected transmissions. GTBPS-3H evaluates forwarding candidates up to three hops ahead, allowing it to detect and avoid void and dead nodes before committing to a path.

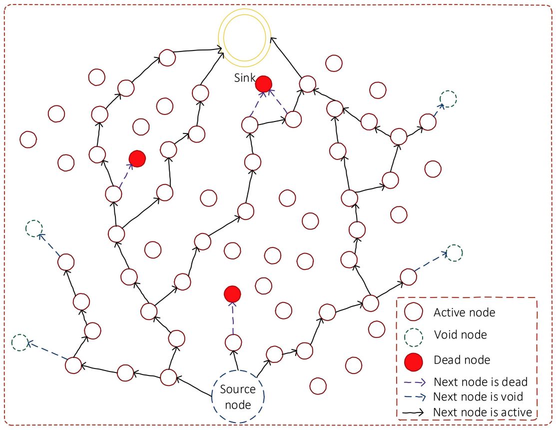

Fig. 1. System Model 1: source node at the lower boundary, sink node at the upper boundary, relay nodes randomly deployed in the intermediate region.

A. System Model I

Fig. 1 shows System Model 1. The source node sits at the lower boundary of the deployment area and the sink node at the upper boundary. Relay nodes are distributed randomly in the intermediate region. The source node performs neighbourhood discovery, evaluates candidate forwarders using predefined selection metrics, and transmits data to the best-scoring neighbour. Packets are relayed toward the sink hop by hop through intermediate nodes. HA-ECMAE checks the selected forwarding candidate against two conditions before transmitting: the node must not be a void node, and it must have sufficient residual energy to relay the packet. This one-hop pre-transmission check reduces packet loss caused by routing into dead ends. HA-ECMAE2H extends this check to cover two hops, so the protocol also verifies that a viable forwarding path exists beyond the immediate next node. This extension improves routing robustness in scenarios where the second-hop topology changes rapidly.

This study evaluates three communication scenarios under System Model 1.

1) Successful Packet Transmission: As seen in Fig. 1, data moves continuously from the source to the sink. Until delivery is finished, each relay node moves the packet one level closer to the sink.

2) Void Node Occurrence: When a node's neighbors within its communication range are unable to transfer data toward the sink, the node becomes a void. This state usually results from a sparse distribution or from nearby nodes running out of energy. The routing path breaks and the packet is deemed lost when it reaches the void node. In order to avoid wasting energy on unsuccessful transmissions, the suggested protocols identify this state during forwarder selection and remove empty nodes from the candidate list.

3) Dead Node Occurrence: A node that has used up all of its remaining energy and is unable to send or receive packets is known as a dead node. Dead nodes leave the network without a workable route to the sink and eliminate links from the routing topology. This worsens communication dependability and increases packet loss, especially in places without a backup forwarder.

HA-ECMAE and HA-ECMAE2H Protocol Design

HA-ECMAE selects the next-hop forwarder by computing the MAE for each candidate neighbour. The MAE quantifies the error between the node's estimated position and its true position; a lower MAE indicates a more reliable geographic estimate and a more predictable transmission outcome. The protocol computes a combined cost Cj = MAEij × d iOep for each candidate j, where d iOep is the estimated distance to the optimal energy point, and selects the candidate with the lowest cost that also satisfies the minimum energy threshold Etrans.

HA-ECMAE2H applies the same cost function but evaluates candidates across two hops rather than one (see Algorithm 1). Extending the evaluation window to two hops reduces void hole formation because the protocol can detect impending dead ends before the routing path reaches them.

Algorithm 1 HA-ECMAE and HA-ECMAE2H Forwarder Selection

```
Input: Transmitter node T, Sink node R
Output: Successful packet delivery to R
Set current node i ← T
for iteration = 1 to N do
    if R ∈ N(i) then
        Transmit packet directly to R; break
    else
        Compute optimal energy point Oep
        Set minimum cost ← ∞
        for each neighbour j ∈ N(i) do
            Compute MAEij
            Estimate distance d  iOep
            if j is within two-hop range then
                Evaluate two-hop neighbours of j
            end if
            Compute Cj = MAEij × d  iOep
            if Cj < minimum cost and jenr ≥ Etrans then
                Update minimum cost ← Cj
                Select j as next forwarder
            end if
        end for
        if a valid forwarder is selected then
            Update i ← j; transmit packet to j
        else
            Terminate; break
        end if
    end if
end for
```

B. System Model II

Fig. 2 shows GTBPS-3H system model which is based on the game theory. As in System Model I, the source node is at the lower boundary and the sink at the upper boundary. Intermediate nodes are distributed uniformly within a three-dimensional grid that is partitioned into cubic sub-regions. This structured layout supports the Stackelberg game-theoretic forwarder selection applied within each sub-cube.

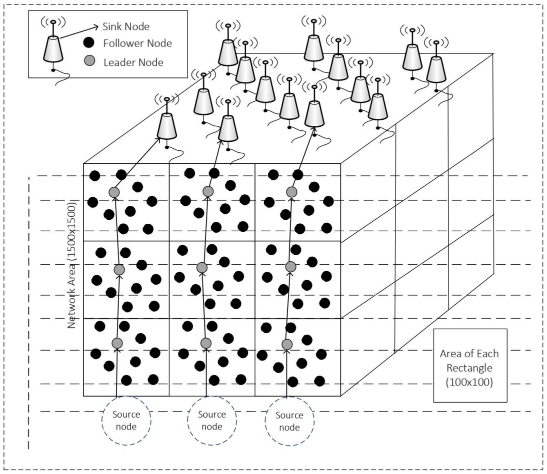

Fig. 2. System Model 2: three-dimensional cubic partitioning used by GTBPS-3H, with Stackelberg game-based leader election within each sub-region.

Each sub-cube applies the Stackelberg game model across two levels. At the first level, the nodes lies within the cube compete on residual energy. And, the node with maximum residual energy is elected as the leader and will now acts as the next forwarder for current transmission.

The chosen leader receives data from the remaining follower nodes at the second level. This cycle repeats until the leader's energy drops below the minimum threshold, at which time the leadership role is transferred to the next highest-energy node. In addition to preventing energy from collecting at any one node, rotating the leader role tends to increase each sub-region's active lifetime.

1) GTBPS-3H Protocol Design: GTBPS-3H visualizes the network as a graph with nodes as vertices and communication channels as edges. Before committing to a forwarding path, the algorithm inspects nodes up to three hops ahead for void and dead nodes, which are then excluded from candidate selection. This proactive inspection minimizes the likelihood of route failure while also distributing energy consumption more equally across the network, potentially extending total network lifetime when compared to single-hop selection alternatives.

A Stackelberg leader election procedure picks a coordinator node inside each sub-cube by optimizing a utility function that takes into account residual energy and proximity to nearby nodes.

C. Forwarder Node Selection

Both HA-ECMAE and HA-ECMAE2H select a forwarder by identifying the neighbour closest to the optimal energy point Oep that also holds enough residual energy to relay the packet. HA-ECMAE uses one-hop neighbourhood information; HA-ECMAE2H uses two-hop information, which allows it to verify that a viable path continues beyond the immediate next node.

The Euclidean distance from the transmitter to Oep is:

$$DiOep = \sqrt{[(xT - xOep)^2 + (yT - yOep)^2]} \tag{1}$$

Given slope m and DiOep, the coordinates of Oep relative to the transmitter are:

$$xOep = xT \pm DiOep / \sqrt{(1 + m^2)} \tag{2}$$

$$yOep = yT \pm (m \times DiOep) / \sqrt{(1 + m^2)} \tag{3}$$

IV. Results and Discussion

This section evaluates HA-ECMAE, HA-ECMAE2H, and GTBPS-3H through simulation and compares them with three benchmark protocols: ECMSE [17], WSNEHPA [16], and HA-ECMSE. To the best of the authors' knowledge, the three proposed protocols are reported for the first time in the literature. Performance is measured using three metrics:

- PDR: the ratio of packets successfully delivered to the sink to the total number of packets generated.
- Computational delay: the time required to process and forward packets across the network.
- Total energy consumption: the aggregate energy expended across all nodes during data transmission.

A. Network Parameters

The simulation uses a 25,000 kbps data rate, 1.778 W transmission power, and 1,024 bits of a packet size. Path loss and transmission power remain constant throughout all experiments, ensuring consistent channel conditions across all evaluated protocols. The per-hop delivery probability within the transmission range is set to 1, which removes link-level losses so that observed performance differences reflect routing strategy rather than channel variation. Sensor nodes are deployed randomly within the network area.

B. Results and Analysis

1) Packet Delivery Ratio: Figure 3 depicts PDR as the node count increases from 150 to 550. PDR increases with node density across all protocols because increasing density provides more forwarding alternatives while decreasing the likelihood of meeting a void hole.

WSNEHPA [16] overcomes coverage gaps by dividing packets into chunks and routing them over different channels. However, this technique does not eradicate void hole problems and continues to spend energy at nodes that are unable to transmit data. ECMSE [17] achieves greater PDR than WSNEHPA by including geographic routing that accommodates for location mistakes, but its energy consumption remains higher than the recommended protocols.

When compared to WSNEHPA, HA-ECMSE and ECMSE increase PDR by 47% and 8%, respectively. Compared to ECMSE, HA-ECMAE and HA-ECMAE2H enhance PDR by an additional 9% and 19%, respectively.

GTBPS-3H has a persistent rising trend, with gains seen between 150 and 300 nodes and again between 450 and 550 nodes. This pattern demonstrates the advantage of three-hop neighbour evaluation, which enables the protocol to detect void nodes before they disturb the forwarding chain, rather than after a packet loss has happened.

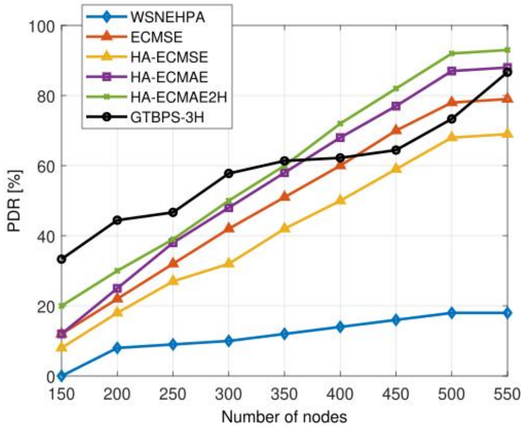

Fig. 3. PDR versus number of sensor nodes for all evaluated protocols.

2) Total Energy Consumption: Fig. 4 compares total energy consumption across all protocols as node density increases. HA-ECMAE and HA-ECMAE2H consume less energy than all three benchmark protocols throughout the evaluated range. Both protocols achieve this by combining neighbourhood-awareness with residual energy checks during forwarder selection. Checking one or two hops ahead allows the protocol to avoid transmissions that end at void or dead nodes, reducing the number of failed and retransmitted packets and lowering overall energy expenditure.

GTBPS-3H shows a near-linear decrease in energy consumption with increasing node density. This trend occurs because a denser network provides more alternative forwarding paths; the three-hop lookahead selects shorter and lower-cost routes as these options become available. The reduction in failed transmission attempts, which the pre-path inspection eliminates, accounts for the steepness of this trend relative to the benchmarks.

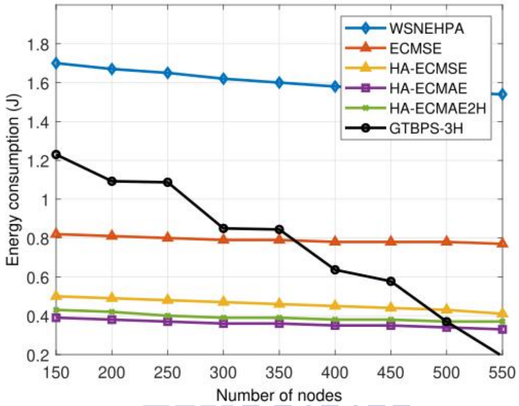

Fig. 4. Total energy consumption versus number of sensor nodes for all evaluated protocols.

3) Computational Delay: Fig. 5 compares computational delay across all protocols. HA-ECMAE, HA-ECMAE2H, and GTBPS-3H all produce lower delay than the benchmark protocols. Checking forwarding candidates one or two hops ahead reduces the frequency of dead-end routes, which eliminates the retransmission cycles and recalculation overhead that dead-end paths produce.

GTBPS-3H achieves the lowest delay of all evaluated protocols. Inspecting up to three hops ahead allows GTBPS-3H to select valid forwarding paths more consistently, which minimises invalid transmission attempts and their associated processing cost. The result is a lower and more stable average delay across all tested node densities.

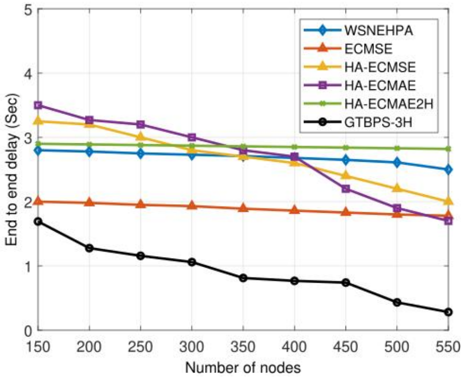

Fig. 5. Computational delay versus number of sensor nodes for all evaluated protocols.

C. Protocol Trade-offs

Each protocol balances PDR, energy consumption, and computational delay differently. The simulation results reveal the following trade-offs.

- WSNEHPA [16] uses multipath transmission to limit computational delay, but produces the lowest PDR and the highest energy consumption across all tested node counts. Routing packets across multiple overlapping paths increases the total number of transmissions, which accelerates energy depletion and limits long-term network viability.
- ECMSE [17] improves PDR by using location-error-aware geographic routing, but incurs higher energy consumption and computational delay than the proposed protocols because its forwarder selection does not account for void or dead node conditions.
- HA-ECMSE reduces computational delay through more selective forwarder evaluation but does not incorporate residual energy into the selection cost, which leads to higher energy consumption compared to HA-ECMAE.
- HA-ECMAE improves both PDR and energy efficiency over HA-ECMSE by incorporating the MAE metric into the cost function. This introduces a modest trade-off in routing precision but reduces misdirected transmissions, producing a net gain in both delivery performance and energy use.
- Among all evaluated protocols, HA-ECMAE2H and GTBPS-3H obtain the maximum PDR and energy efficiency. The trade-off is greater computational complexity per routing step, as considering two or three hops ahead takes more processing than single-hop selection. This overhead increases with node density, which may limit its utility in installations with strong real-time latency requirements.

V. Conclusion and Future Work

This paper proposed three routing protocols for WSNs: HA-ECMAE, HA-ECMAE2H, and GTBPS-3H. All three target the dual problem of void hole formation and excessive energy consumption, which are among the primary causes of premature network failure in WSN deployments.

HA-ECMAE applies MAE-based forwarder selection with a one-hop lookahead and achieves a 14% PDR improvement and a 15.2% reduction in energy consumption relative to the ECMSE baseline. HA-ECMAE2H extends this to a two-hop lookahead, improving PDR by 19% and reducing energy use by 18.7%, which reflects a measurable gain in routing robustness and a lower retransmission rate. GTBPS-3H uses Stackelberg game-theoretic leader election within three-hop sub-regions to distribute forwarding responsibilities dynamically, extending network lifetime by 20% and improving PDR by 17% compared to WSNEHPA.

Each proposed protocol outperforms WSNEHPA and ECMSE on at least two of the three evaluated metrics. The main trade-off common to all three protocols is that multi-hop lookahead evaluation adds processing overhead per routing step, which may limit applicability in deployments that require strict worst-case latency guarantees.

In order to lower the computational cost of multi-hop assessment while maintaining accuracy, future research will investigate incorporating lightweight machine learning models into the forwarder selection stage. A fuller picture of protocol scalability under more demanding WSN settings might also be obtained by expanding the assessment to mobile node deployments and diverse traffic loads.

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