Asian Journal of Electrical Sciences
ISSN: 2249-6297 (P); 2583-7923 (E)
Vol.14 No.1, 2025, pp.47-53

DOI: https://doi.org/10.70112/ajes-2025.14.1.4269

A Novel Energy–Degree–Distance-Based Connected Dominating Set Algorithm: Performance Comparison Across Node Placement Strategies

Sujeeva Wijesiri
Department of Mathematics, University of Kelaniya, Dalugama, Sri Lanka
E-mail: sujeew@kln.ac.lk
(Received 14 April 2025; Revised 29 April 2025; Accepted 22 May 2025; Available online 27 May 2025)

Abstract - **In wireless sensor networks (WSNs), constructing an energy-efficient Connected Dominating Set (CDS) is essential for ensuring reliable communication, balanced energy usage, and extended network lifetime. Existing methods often fail to consider the impact of node distribution on CDS performance. This study proposes a CDS construction algorithm that integrates residual energy, node degree, and average neighbor distance into a unified selection metric for dominator nodes. Connector nodes are subsequently selected to ensure network-wide connectivity. The algorithm was evaluated under four deployment models: grid, triangular, random, and hybrid. Key performance indicators included CDS size, hop count, average degree, energy consumption, spectral radius, and algebraic connectivity. The proposed algorithm consistently produced compact and connected CDSs across all deployment strategies. Grid and triangular models exhibited superior performance in terms of energy efficiency and connectivity, characterized by low hop count and balanced energy consumption. Even under random and hybrid placements, the algorithm maintained robust backbone structures and outperformed baseline approaches. Spectral analysis further confirmed higher algebraic connectivity and reduced spectral radius, indicating improved robustness and communication efficiency. Overall, the proposed algorithm effectively balances energy usage and preserves connectivity across diverse node placements, offering practical insights for the design of resilient and energy-aware protocols in real-world WSN applications.**
Keywords: **Wireless Sensor Networks (WSNs), Connected Dominating Set (CDS), Energy Efficiency, Node Deployment Models, Network Connectivity.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have become critical for diverse applications, including environmental monitoring, industrial automation, smart agriculture, and battlefield surveillance [1]-[5]. These networks consist of numerous spatially distributed, battery-powered sensor nodes that collect and transmit data to a central base station. Since sensor nodes often operate in inaccessible environments where recharging is impractical, energy efficiency remains a primary concern. Node energy depletion reduces network performance and shortens network lifetime, making energy-aware network design essential.

Cluster-based routing protocols enhance energy efficiency and scalability by organizing nodes into clusters. Each cluster is managed by a cluster head that communicates with the base station, thereby reducing redundant transmissions and balancing energy usage. Connected Dominating Sets (CDSs) form virtual backbones that ensure all nodes are either in the set or adjacent to a node in the set, maintaining connectivity and enabling efficient routing.

One of the foundational studies on routing in WSNs was conducted by Guha and Khuller in 1998 [6]. They introduced the concept of CDSs using graph theory, where a CDS acts as a virtual backbone to reduce redundant transmissions and conserve energy. Their work presented approximation algorithms for constructing both unweighted and weighted CDSs, establishing a foundation for subsequent energy-efficient routing protocols.

Wan, Alzoubi, and Frieder [7] addressed distributed CDS construction for wireless ad hoc networks. Their method achieved a constant approximation factor of 8, while improving time and message complexity to O(n) and O(n log n), respectively. This approach matched theoretical lower bounds for message complexity and outperformed earlier algorithms, making it significant for scalable and energy-efficient routing in WSNs.

Cokuslu *et al.,*[8] proposed a clustering algorithm for mobile ad hoc networks (MANETs) based on Wu and Li's CDS method. By considering node degrees and applying heuristics during the marking phase, they reduced CDS size, particularly in dense networks. Although developed for MANETs, their approach is relevant to WSNs where efficient clustering and minimal overhead are essential.

Venkataraman, Emmanuel, and Thambipillai introduced DASCA [9], a clustering approach designed for scalability, energy efficiency, and robustness in WSNs. DASCA constrains cluster size and node degree to balance network load and energy usage. Simulation results demonstrated that DASCA significantly reduces energy consumption and extends network lifetime compared to HEED and LEACH.

The PATM algorithm by Tan, Zeng, and Bao [10] created a lightweight, adaptive backbone for ad hoc networks. PATM reduces routing overhead by constructing a minimal dominating set and embedding topology updates within data packets, with update frequency adjusted dynamically. Experiments with the DSR protocol confirmed reduced overhead and improved transmission efficiency.

Balbal, Bouamama, and Blum [11] addressed network lifetime maximization by partitioning nodes into disjoint weighted dominating sets activated sequentially in sleep-wake cycles. Their greedy heuristic outperformed recent local search methods in both solution quality and runtime. It also supports disconnected and directed graphs, with future work aimed at hybrid metaheuristic approaches.

Kim *et al.,* [12] investigated bounded-diameter CDS construction in wireless networks. They proposed centralized and distributed algorithms that optimize CDS size, diameter, and average backbone path length. The distributed method demonstrated improvements in energy efficiency and network lifespan.

Anitha and Sebastian [13] developed CDS-based clustering algorithms using (k, r)-connected dominating sets. Backbone nodes were selected based on battery level, connectivity, range, and mobility to improve stability and energy efficiency. Simulation results showed superior load balancing and fewer re-affiliations compared to traditional methods.

Hedar *et al.,* [14] proposed an adaptive scatter search algorithm (ASS-MCDS) for minimum CDS construction. Their method balances coverage and connectivity while minimizing the number of selected nodes. The inclusion of new local search and update steps enhanced performance, and benchmark tests validated its effectiveness.

Despite these advancements, many existing methods emphasize individual metrics or heuristics without jointly integrating residual energy, node degree, and spatial factors. Moreover, the impact of different node deployment patterns on CDS properties has received limited attention.

This study proposes a novel CDS construction algorithm that incorporates residual energy, node degree, and average neighbor distance into a unified selection metric. The algorithm generates compact, energy-efficient, and structurally robust CDSs across diverse node deployments, including grid, triangular, random, and hybrid models.

The objectives of this work are to design a scalable CDS algorithm that balances coverage, connectivity, and energy consumption, and to analyze the influence of node placement on CDS performance. By bridging energy-aware selection with spatial and connectivity considerations, this study addresses existing gaps and provides practical insights for designing reliable WSN backbones.

II. METHODOLOGY

This section outlines the proposed method for constructing a Connected Dominating Set (CDS) in Wireless Sensor Networks (WSNs). The approach integrates multiple node-level metrics: residual energy, node degree, and average neighbor distance into a unified selection framework. The method prioritizes energy efficiency while ensuring full coverage and connectivity among selected nodes. The methodology section includes formal definitions, algorithmic steps, and metric formulations.

A. Network Model and Definitions

The wireless sensor network is represented as an undirected graph $G=(V,E)$, where V is the set of sensor nodes and E is the set of communication links between nodes within transmission range.

1. *Domination Set (D):*
   A dominating set $D \subseteq V$ is a subset of nodes such that every node $v \in V$ is either in D or adjacent to at least one node in D; that is
   $\forall v \in V,\ \ v \in D$ or $\exists u \in D$ such that $(u,v) \in E$.
2. *Connected Dominating Set (CDS):*
   A connected dominating set is a dominating set $D \subseteq V$ such that the subgraph $I[D]$ induced by D is connected; that is for all $u, v \in D,$ there exists a path in $I[D]$ between u and v. The CDS serves as a virtual backbone for routing and communication in WSNs.
3. *Node Degree ($deg(v)$):*
   The node degree is defined as the number of nodes directly connected to it in the graph G. In a WSN, this corresponds to the number of neighboring nodes within its communication range.
4. *Adjacency Matrix (A):*
   The adjacency matrix of a graph $G=(V,E)$ with $n=|V|$ nodes is an $n \times n$ matrix $A=[a_{ij}]$, where each entry a_{ij} indicates the presence or absence of an edge between node i and node j. For unweighted graph:

$$a_{ij} = \begin{cases} 1 & \text{: if there is an edge between node i to node j} \\ 0 & \text{: Otherwise} \end{cases}$$

1. *Degree Matrix (D):*
   This is a diagonal matrix where each diagonal entry D_{ii} equals the degree of node i.
2. *Laplacian Matrix (L):*
   It is defined as $L=D-A$. It reflects the structural and connectivity properties of the network.
3. *Spectral Radius:*
   The spectral radius is the largest eigenvalue of the adjacency matrix A. It indicates the network's communication density.
4. *Algebraic Connectivity:*
   The algebraic connectivity is the second smallest eigenvalue of the Laplacian matrix L. It measures the connectivity strength of the graph.
5. *Residual Energy (E_i):*
   The residual energy of node i is the remaining battery energy of node i, normalized with respect to the maximum initial energy in the network.
6. *Average Neighbor Distance d_i:*
   The average neighbor distance is the mean Euclidean distance between node i and all of its neighbors.

B. Algorithm Overview

The proposed CDS construction algorithm is executed in multiple phases: metric computation, node scoring, dominator selection, and connectivity enforcement. It selects a subset of nodes that not only dominate the network but also form a connected subgraph.

1. CDS Construction Algorithm

Input

a. Adjacency matrix A
b. Node energy levels
c. Node coordinates (x_i, y_i)
d. Weights w_1, w_2, and w_3 for energy, degree, and distance
e. Energy threshold (ET)

Output (CDS)

Procedure:

1. Initialize CDS ← ∅; mark all nodes as uncovered
2. for each node i do
3. Compute $deg(i)$, d_i
4. Normalize energy, degree, inverse distance of node i
5. end for
6. for each node i with energy$(i) \geq ET$ do
7. Compute $$Score(i) = w_1 \times E_{norm}(i) + w_2 \times D_{norm}(i) + w_3 \times Dist_{norm}(i)$$
8. end for
9. while there are uncovered nodes do
10. Select node i with highest Score(i) covering most uncovered neighbors
11. Add i to CDS; update covered nodes
12. end while
13. while CDS is disconnected do
14. Identify disconnected components
15. Add intermediate nodes with Energy$(i) \geq ET$ to reconnect components
16. end while
17. return CDS

2. Scoring and Metric Normalization: Each node's score is derived from three normalized metrics:

a. *Normalized Residual Energy*

$$E_{norm}(i) = \frac{E(i)}{max_j E(j)}$$

b. *Normalized Degree*

$$D_{norm}(i) = \frac{D(i)}{max_j D(j)}$$

c. *Normalized Inverse Average Distance*

$$Dist_{norm}(i) = 1 - \frac{avgDist(i)}{\max_j\left(avgDist(j)\right)}$$

These metrics reflect energy availability, connectivity, and spatial efficiency, respectively. The weights $w_1, w_2,$ and w_3 control the importance of each component in the final score.

3. Energy Thresholding: To ensure long-term stability of the CDS, an energy threshold is applied. Nodes with normalized residual energy below this threshold are excluded from the selection process. This prevents early failure of dominators and improves network robustness over time.

C. Simulation Setup and Performance Metrics:

This subsection describes the simulation environment, node deployment strategies, network parameters, and evaluation metrics used to assess the performance of the proposed CDS construction algorithm.

1. Simulation Environment: Simulations were conducted using MATLAB to model a wireless sensor network (WSN) consisting of $N = 100$ sensor nodes uniformly deployed over a $100m \times 100m$ area. All nodes were considered homogeneous in terms of communication capability and initial energy levels. The simulation environment enabled comparative testing of the proposed CDS algorithm under varying spatial configurations and energy distributions.

2. Node Placement Strategies: Node placement strongly affects the coverage, connectivity, and energy performance of WSNs. To capture this impact, four commonly used deployment models were evaluated:

a. *Grid-Based:* Ensures uniform node distribution and ease of maintenance; suitable for structured areas such as agricultural fields and industrial zones.
b. *Triangular Grid:* Provides high coverage efficiency, useful in applications such as seismic or radiation monitoring.
c. *Random:* Represents unstructured deployments in environments such as forests or disaster-struck regions.
d. *Hybrid:* Combines a regular grid with additional redundant nodes to increase fault tolerance; commonly applied in smart cities and critical monitoring systems.

Figure 1 illustrates the visual layouts of these placement strategies, and Table 1 summarizes their application areas and *benefits.*

3. Network Parameters: Unless otherwise specified, the following parameters were applied across all simulation scenarios:

a. *Number of Nodes:* 100
b. *Communication Range:* 20 m
c. *Initial Energy:* Random values between 0 and 1, normalized by the maximum observed energy
d. Weight Vector: $w = [w_1, w_2, w_3]$ set to $[0.4, 0.3, 0.3]$, assigning the highest priority to residual energy, followed by degree and inverse average neighbor distance
e. *Energy Threshold:* A cutoff value of 0.3 (normalized), allowing only nodes with at least 30% of the maximum initial energy to be considered for CDS inclusion

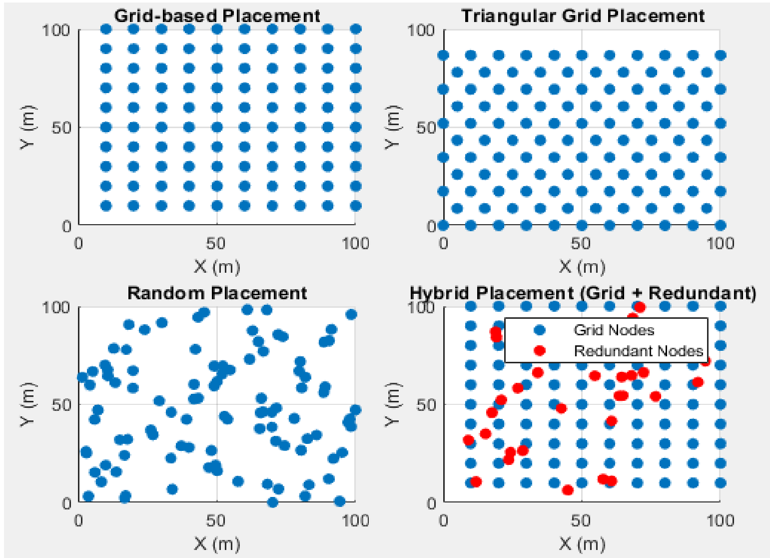

Fig. 1 Visualization of four node placement strategies in wireless sensor networks

TABLE I SUMMARY OF NODE PLACEMENT STRATEGIES AND THEIR KEY CHARACTERISTICS

Placement Type	Typical Use cases	Key benefits
Grid-based	Agriculture, industrial areas	Uniform coverage, easy maintenance
Triangular Grid	Surveillance, seismic, radiation zones	Maximum efficiency, full coverage
Random	Forests, disaster zones, remote terrain	Easy to deploy in harsh environments

4. Performance Metrics: The effectiveness of the proposed CDS construction algorithm was evaluated using the following metrics:

1. *CDS Size:* The total number of nodes selected for the CDS. Smaller CDS size implies higher structural efficiency.
2. *Spectral Radius:* The largest eigenvalue of the adjacency matrix of the CDS subgraph, indicating the intensity of inter-node connectivity.
3. *Algebraic Connectivity:* The second smallest eigenvalue of the Laplacian matrix. Higher values suggest improved network robustness.
4. *Average Degree:* The mean number of neighbors per node, reflecting overall network density.
5. *Average CDS Degree:* The mean connectivity among CDS nodes, indicating the strength of the virtual backbone.
6. *Average Hop Count in CDS:* The mean number of hops between nodes in the CDS, serving as a measure of routing efficiency.
7. *Total CDS Energy:* The sum of the residual energy of all CDS nodes, assessing long-term operational viability.
8. *Energy Efficiency:* The ratio of total CDS energy to the total network energy, representing the relative cost of maintaining the backbone.

5. Simulation Procedure: For each node placement scenario, the adjacency matrix was generated based on the communication range. Node energy levels and spatial coordinates were initialized accordingly. The proposed algorithm was then executed to construct the CDS. Once the CDS was formed, all performance metrics were computed and compared across the deployment models.

III. RESULTS AND DISCUSSION

This section presents the performance evaluation of the proposed Connected Dominating Set (CDS) construction algorithm under four node placement strategies. The algorithm was assessed using structural and energy-related metrics to evaluate its effectiveness across diverse network configurations. Figure 2 shows the resulting CDSs for each node placement strategy, and Figure 3 illustrates comparative performance across Grid, Triangular, Random, and Hybrid deployments.

A. CDS Size and Network Coverage

The size of the CDS varies significantly across the placement strategies. The Triangular Placement yields the smallest CDS with 19 nodes, indicating efficient backbone selection to maintain full coverage. In contrast, the Random Placement produces the largest CDS with 32 nodes, reflecting redundancy due to irregular node distribution.

The Grid and Hybrid Placements result in intermediate CDS sizes of 25 and 27 nodes, respectively. A smaller CDS is generally preferred, as it reduces control overhead and energy consumption during communication. The structured nature of the triangular layout likely contributes to improved spatial efficiency and reduced CDS size.

B. Spectral Radius and Algebraic Connectivity

Spectral metrics provide insight into the robustness of the CDS. The Triangular Placement records the highest spectral radius (21.24) and algebraic connectivity (1.014), indicating a strong and well-connected backbone. In contrast, the Random Placement shows a high spectral radius (19.27) but very low algebraic connectivity (0.303), suggesting that although many links exist, the overall structure is fragile and prone to fragmentation.

The Grid Placement exhibits a lower spectral radius (15.59) with moderate algebraic connectivity (0.65), reflecting a reasonably stable but less densely connected structure. The Hybrid Placement has a spectral radius of 21.09, comparable to the triangular layout, but lower connectivity (0.58), indicating moderate cohesion within the CDS.

Overall, the results show that structured node placements enhance connectivity and fault tolerance, while random or semi-structured deployments reduce backbone resilience.

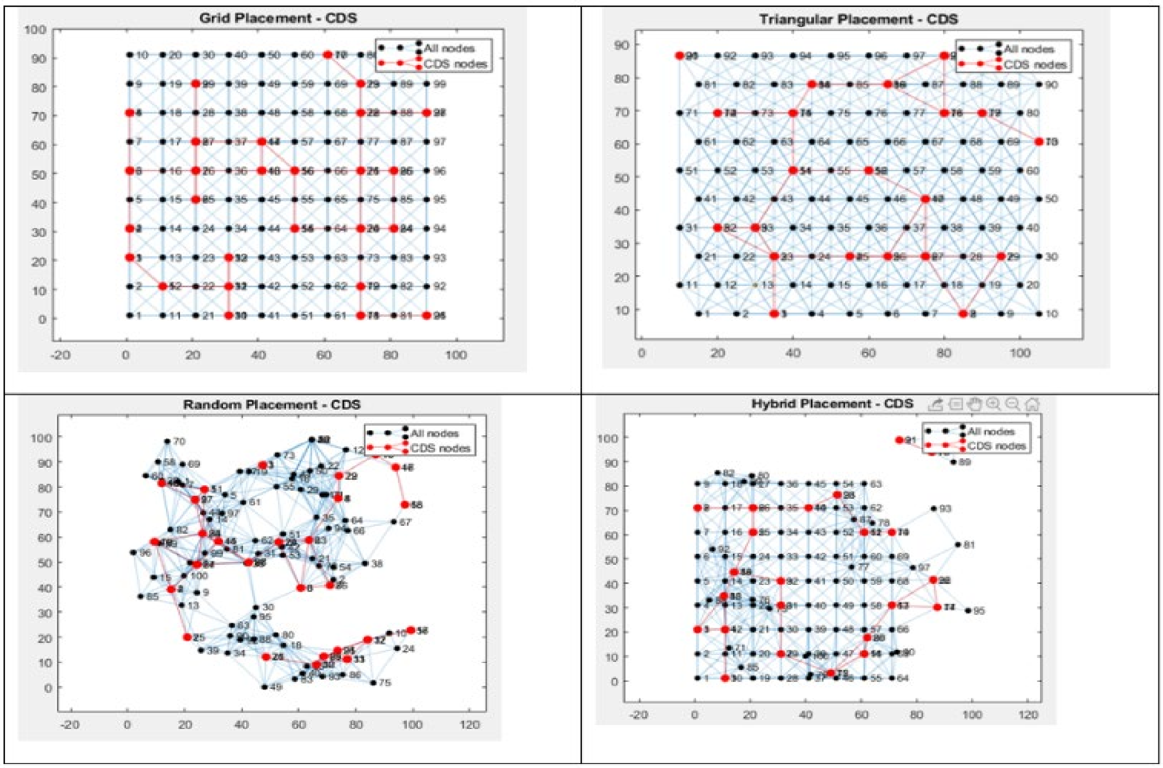

Fig. 2 Connected Dominating Sets for the four different node placement strategies.

```
--- Grid Placement ---
CDS Size: 25
Spectral Radius: 15.5922
Algebraic Connectivity: 0.6507
Average Degree: 10.04
Avg CDS Degree: 10.80
Avg Hop Count in CDS: 3.39
Total CDS Energy: 20.09
Energy Efficiency (CDS energy / total): 38.01%
```

```
--- Triangular Placement ---
CDS Size: 19
Spectral Radius: 21.2367
Algebraic Connectivity: 1.0142
Average Degree: 13.64
Avg CDS Degree: 14.79
Avg Hop Count in CDS: 2.75
Total CDS Energy: 15.79
Energy Efficiency (CDS energy / total): 29.87%
```

```
--- Random Placement ---
CDS Size: 32
Spectral Radius: 19.2738
Algebraic Connectivity: 0.3031
Average Degree: 10.34
Avg CDS Degree: 11.63
Avg Hop Count in CDS: 3.51
Total CDS Energy: 24.01
Energy Efficiency (CDS energy / total): 45.42%
```

```
--- Hybrid Placement ---
CDS Size: 27
Spectral Radius: 21.0914
Algebraic Connectivity: 0.5827
Average Degree: 11.96
Avg CDS Degree: 11.59
Avg Hop Count in CDS: 3.37
Total CDS Energy: 20.71
Energy Efficiency (CDS energy / total): 39.18%
```

Fig. 3 Performance metrics of the Connected Dominating Set for four wireless sensor network node placement strategies.

C. Degree and Hop Count Analysis

The average degree and hop count provide further insights into node connectivity and routing efficiency. The Triangular Placement again performs best, achieving the highest average degree in the full network (13.64) and within the CDS (14.79), along with the shortest average hop count (2.75). This indicates dense connectivity and efficient communication paths among dominator nodes.

In comparison, the Random Placement reports average degrees of 10.34 (network-wide) and 11.63 (within CDS), with a longer average hop count of 3.51, suggesting more communication steps and potential delay. The Grid and Hybrid Placements yield intermediate results, reflecting moderate levels of connectivity and routing efficiency. These findings reinforce that denser, structured deployments offer superior performance in terms of connectivity and transmission latency.

D. Energy Consumption and Efficiency

Energy efficiency is critical in WSNs, particularly for battery-powered nodes. The Triangular Placement demonstrates the lowest total CDS energy usage (15.79 units) and the highest energy efficiency, with the CDS consuming approximately 30% of the network's total energy.

In contrast, the Random Placement records the highest energy consumption (24.01 units), with nearly 45% of total energy used by the CDS, indicating greater overhead and inefficiency. The Grid and Hybrid Placements show intermediate energy usage (~20 units) and moderate efficiency levels (38-39%). These results suggest that CDSs formed under well-structured deployments not only require fewer nodes but also preserve network energy more effectively, contributing to longer operational lifespans.

E. Summary

The comparative evaluation shows that the Triangular Placement consistently delivers the best outcomes across all metrics, including CDS size, spectral robustness, routing efficiency, and energy efficiency. The Random Placement performs the worst overall, highlighting the limitations of unstructured deployments in CDS formation. The Grid and Hybrid Placements yield moderate performance but fall short of the triangular layout in both efficiency and connectivity.
These findings suggest that integrating the proposed algorithm with structured node placement-particularly triangular configurations-can significantly improve backbone quality and enhance network sustainability in WSNs.

IV. CONCLUSION

This study proposed a novel energy-aware Connected Dominating Set (CDS) construction method that integrates node energy levels, degree, and average neighbor distance into the selection process. The algorithm was evaluated under multiple node placement strategies, demonstrating that structured deployments-particularly triangular arrangements-consistently yielded more efficient CDS formation in terms of connectivity, routing performance, and energy utilization.

Although the approach proved effective in static environments with idealized energy assumptions, its performance in dynamic or real-time conditions remains untested. Furthermore, the absence of direct comparisons with existing CDS algorithms limits the benchmarking scope. These limitations suggest future research directions, including the integration of adaptive behavior, refinement of energy models, and expansion of simulations to larger and more realistic network scenarios.

The key takeaway from this work is that coupling a carefully weighted CDS construction method with structured node placement can significantly enhance the energy efficiency and robustness of wireless sensor networks. This finding contributes practical insights to sustainable WSN design and provides a foundation for further exploration into dynamic, energy-aware network backbones.

Declaration of Conflicting Interests
The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author received no financial support for the research, authorship, and/or publication of this article.

Use of Artificial Intelligence (AI) - Assisted Technology for Manuscript Preparation
The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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