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Adaptive Load Balancing in Industrial IoT Sensor Networks Using Dynamic Spanning Tree-Based Routing

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Abstract. Spanning tree-based dynamic graph routing implements a topology-aware approach for facilitating adaptive load balancing in clustered Wireless Sensor Networks (WSNs). Traditional routing methods often encounter communication constraints and energy inefficiencies resulting from fixed route choices and unequal data distribution across cluster members. The proposed framework establishes a spanning tree structure that dynamically adjusts to changes in topology, energy levels, and node density. The main goal is to enhance route selection while guaranteeing equitable workload allocation across all clusters, thereby prolonging network lifespan and reducing packet latency. The approach combines dynamic edge reconfiguration with localized decision-making, enabling real-time modifications in routing pathways according to residual energy and communication traffic. Each cluster creates an energy-weighted spanning tree that is regularly updated via distributed coordination, improving scalability and fault tolerance. Experimental assessments under diverse network settings reveal enhanced throughput, decreased transmission overhead, and stable energy usage across all nodes, confirming its appropriateness for extensive WSN implementations.

Keywords: Spanning Tree Routing, Load Balancing, Clustered Wireless Sensor Networks, Dynamic Graph Algorithms, Energy Optimization

INTRODUCTION

WSNs are essential to many monitoring and control systems, from environmental surveillance to industrial automation. Spatially distributed sensor nodes jointly perceive, process, and send data to central base stations. Energy-efficient communication and balanced traffic routing are WSN challenges, particularly with limited battery power and changeable network circumstances. Congestion, energy waste, and premature node failures result from traditional routing methods failing to adapt to network topological changes. Cluster designs are commonly used in WSNs to improve scalability and management. In such setups, Cluster Heads (CHs) gather and send data to the sink from nodes. Clustering conserves energy and decreases direct communication overhead, but inter-cluster communication is inefficient. Bottlenecks and imbalance between clusters are caused by static routing pathways, load inflexibility, and occasional route alterations. This highlights the necessity for adaptive, dynamic graph-based routing systems that preserve balance and stability over time.

A Spanning Tree Based Dynamic Graph Routing Framework for Adaptive Load Balancing in Clustered Wireless Sensor Networks is the main goal of this study. A spanning tree model that changes with node parameters like energy, traffic intensity, and connection dependability allows dynamic reconfiguration of inter-cluster pathways. The system uses an adaptive tree topology to distribute routing jobs evenly across cluster heads, improve fault tolerance, and prolong network lifespan. By assessing current metrics and shifting load, the routing system predicts performance deterioration and responds to node failures and connection degradation. Rigid routing and static cluster connections cause WSN load imbalance. Communication breakdowns and network fragmentation occur when sensor nodes near the base station or important relays use energy faster. Many cluster-based routing systems need periodic re-clustering or route rebuilding, which adds latency and overhead. Such systems cannot handle rapid traffic or topological changes without real-time reconfiguration. To circumvent these restrictions, spanning tree dynamics must be used for continuous route optimisation while maintaining data integrity and energy efficiency.

Spanning tree-based dynamic graph routing was chosen to improve route flexibility, traffic adaptation, and network lifetime in clustered WSNs. Spanning trees provide loop-free, hierarchical communication for inter-cluster routing. Real-time graph dynamics allow traffic to be diverted to different branches depending on demand

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or energy availability. Local decision-making and global coordination using adaptive spanning trees reduce communication congestion and energy consumption. It focusses on distributed control and metric-driven reconfiguration to provide a more sustainable and robust communication architecture for mission-critical sensor networks. Disaster alarm systems, environmental surveillance, combat intelligence, and smart agriculture need continual monitoring since node-level failures or load intensities may affect system performance. A graph routing strategy based on a dynamic spanning tree topology permits local modifications while preserving global connection, making it ideal for energy- and load-sensitive installations. Section 2 covers system structure, communication flow, and dynamic spanning tree creation in the proposed architecture. Section 3 discusses metric assessment methodologies and adaptive routing for traffic distribution and subtree changes. Section 4 covers implementation, simulation settings, and performance data compared to baseline protocols. Conclusion, optimisation, real-world deployment, and predictive algorithm integration are covered in Section 5.

RELATED WORKS

A framework for energy-aware routing and clustering was suggested using deep tree learning to improve routing choices in wireless sensor networks. Clustering and routing choices are constantly modified via recursive training, hence minimising energy usage and prolonging network longevity. The strategy guarantees equitable energy consumption across nodes by reducing superfluous transmissions and enhancing routing convergence using predictive learning of network behaviour and connection patterns [1]. An optimised cluster head selection approach was developed with the enhanced squirrel search algorithm to maximise the longevity of wireless sensor networks. Load balancing is accomplished by the dynamic reallocation of cluster responsibilities, guaranteeing stable communication across densely populated network areas [2]. A routing system using a minimum spanning hyper tree was created to enhance energy efficiency in sensor networks. The hyper tree model minimises unnecessary connections and identifies energy-efficient branches for routing purposes. The method accommodates topological changes and prolongs the network's operational lifetime by managing route overlap and minimising energy consumption in intermediate nodes [3]. A hybrid methodology combining machine learning-based cluster head selection with homomorphic encryption methods was presented for unattended sensor settings. Fault tolerance and data integrity are improved by the periodic reassignment of cluster heads using predictive analytics, facilitating prolonged deployments in remote or adverse situations [4].

A routing and clustering technique using advanced optimisation algorithms was developed to promote energy efficiency in wireless sensor networks. Transmission pathways are chosen based on lowest energy consumption and latency metrics, enhancing network stability and decreasing packet loss under peak traffic situations [5]. A clustering strategy that enhances energy efficiency was created using the Atomic Energy Optimisation method, aimed at achieving consistent energy consumption among sensor nodes. Simulation results validate decreased energy depletion and sustained cluster stability, even amongst fluctuating network sizes and node densities [6]. A cluster-tree routing system using the Grasshopper Optimisation system was introduced for secure data transmission in wireless sensor networks. Communication dependability is enhanced by connection trust assessment, while data aggregation is facilitated by securely transmitting packets across authenticated routes, hence maintaining integrity in multi-hop transfers [7]. An advanced Tree-Seed Continuous Optimisation technique was used to determine optimum multipath routing in wireless sensor networks. The approach facilitates fault tolerance via dynamic path switching and guarantees effective load distribution over the chosen pathways, especially in high node density situations [8].

A routing protocol, Energy-Efficient Two-Level Tree (EE-TLT), designed for energy efficiency, was developed using two-level tree-based clustering in sensor networks. The protocol improves scalability and facilitates real-time traffic via queue-aware scheduling and adaptive load balancing, hence providing optimal performance in dynamic and extensive deployments [9]. A comprehensive routing and clustering model called Edge Device Enabled Network (EDEN) was created for software-defined IoT settings, using a blend of dynamic genetic algorithms and neural network forecasts. The hybrid design improves packet delivery reliability and decreases the frequency of reconfiguration in mobile and heterogeneous networks [10]. A tree-based routing technique was developed using a combination of fuzzy C-means clustering and evolutionary algorithms to enhance routing choices in wireless sensor networks. This hybrid approach enhances routing reliability and energy efficiency in situations characterised by variable sensor concentrations [11]. A routing strategy using a dynamic minimum spanning tree was developed to enhance communication with mobile sinks. The technique persistently recalibrates spanning trees according to sink mobility patterns and node residual energy levels. It improves flexibility in mobile sink situations, ensuring dependable communication and equitable load distribution [12].

An energy-efficient ad hoc routing approach was developed for queriable sensor networks, optimising routing pathways according to energy metrics and query predictability. This method minimises duplicate transmissions, prioritises reliable routes, and facilitates energy-efficient query replies in dispersed network designs, therefore enhancing long-term data availability [13]. A routing system was established using a Rapidly Exploring Random Tree (RRT) methodology to provide obstacle-aware mobile sink trajectory planning. The method enhances data collecting efficiency in situations with topographical limitations, guaranteeing continuous connection and adaptable sink coverage over geographically dispersed sensor fields [14]. A system for clustering and routing was presented, integrating optimised scheduling with energy-efficient route selection. Cluster heads are selected based on energy and communication cost criteria, while the scheduling method reduces concurrent transmissions [15]. A balanced clustering technique was proposed to regulate cluster size distribution in wireless sensor networks. The approach guarantees consistent cluster formation by regulating cluster head selection according to node distribution density and energy thresholds [16].

A dynamic routing system was created for heterogeneous wireless sensor networks using a delay-sensitive, energy-efficient methodology. The protocol facilitates adaptive topology management and minimises transmission latency, rendering it appropriate for applications necessitating rapid and energy-efficient data transfer across diverse hardware environments [17]. A clustering and routing model that enhances energy efficiency was developed using Adaptive Swarm Firefly Optimisation (ASFO) with a cross-layer expedient routing protocol. This integration minimises packet loss and guarantees load-aware routing, enhancing energy efficiency and throughput in hierarchical wireless sensor network topologies [18]. A scalable routing technique using hierarchical agglomerative clustering was presented for extensive sensor installations. Nodes are categorised into hierarchical clusters according to geographical proximity and energy parameters [19]. A routing protocol that considers energy efficiency was created with a hybrid optimisation method that integrates multi-objective genetic algorithms with cuckoo search. Load balancing is maintained by regular evaluations of node status and routing expenses, facilitating optimal performance in energy-sensitive networks.

PROPOSED METHODOLOGY

A dynamic spanning tree-based graph routing mechanism is used to load balance clustered wireless sensor networks. Initial clustering uses energy and proximity measures for sensor nodes. An edge weighted spanning tree structure based on residual energy, queue length, and connection quality selects and connects cluster heads. Node metrics are monitored to update edge weights and rebuild the spanning tree as needed. A constantly updated spanning tree structure connects these Cluster Head (CH)s based on node energy, connection quality, and traffic density. The system adapts routing by altering the spanning tree in real time to avoid overused nodes, congestion, and network load distribution. Figure 1 shows a clustered WSN with adaptive load balancing utilising Spanning Tree-Based Dynamic Graph Routing. Network topology is structured by dynamic graph initialisation. After that, adaptive load balancing distributes network load amongst cluster heads to minimise congestion. Spanning trees produce loop-free routing structures. Cluster chiefs strategically manage local sensor nodes and communicate data. Each cluster connects to a sink node using optimised spanning tree paths, removing duplication and improving transmission efficiency.

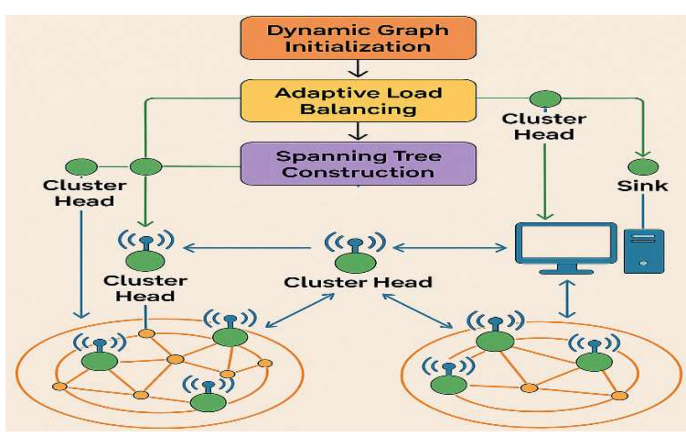

FIGURE 1. Dynamic Graph Routing Using Spanning Tree Strategy

The system has three hierarchical layers: sensing, clustering and control, and dynamic spanning tree routing. The cluster head receives environmental data from low-power sensor nodes in the sensing layer. The clustering and control layer uses distributed algorithms to cluster these nodes by signal intensity, node degree, and residual energy. Each CH aggregates data from its members after cluster formation. All CHs are logically linked via a dynamic spanning tree graph at the routing layer. This tree utilises energy-weighted edges and is updated frequently to reflect node statuses. A clustered WSN with spanning tree-based dynamic graph routing is presented in Figure 2. Green circles indicate sensor nodes, wireless symbols cluster heads. The links illustrate the network's primary (black) and secondary (orange) load-balancing routing channels. The spanning tree eliminates loops and redundancy by routing cluster member data to the sink via cluster heads. Hierarchies improve transmission efficiency and fault tolerance. Colour-coded pathways and wireless symbols make this powerful WSN system easy to trace.

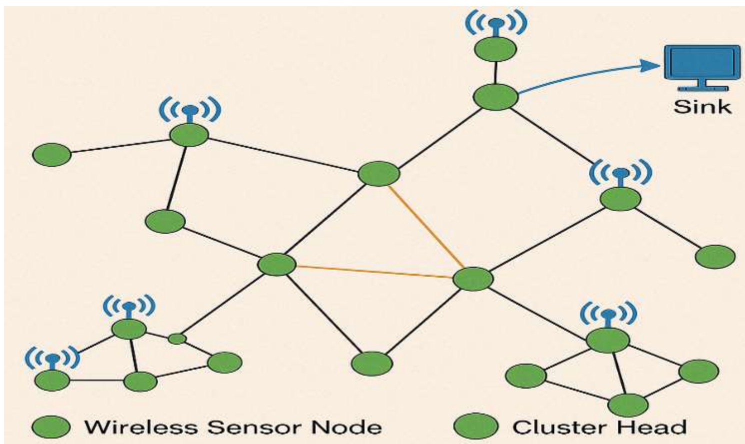

FIGURE 2. Schematic Representation of Spanning Tree Dynamic Routing in Clustered WSN

These technologies are optimised for energy-constrained, dispersed situations. A proprietary spanning tree protocol based on Ad-hoc On-Demand Distance Vector (AODV) or LEACH-based clustering algorithms regulates routing and cluster creation at the network layer. The connection layer allows low-power, short-range sensor node communication using IEEE 802.15.4. This system uses Lightweight Time Synchronisation Protocol (LTSP) to maintain coordination during dynamic re-routing. Sensor node firmware is written using TinyOS or Contiki OS, depending on hardware platform. These OSes optimise thread scheduling, radio duty cycling, and hardware abstraction. MQTT or CoAP protocols provide lightweight upstream data transfer with base stations or edge devices. The stack comprises NS-3, Cooja, and MATLAB-based custom simulators for simulations and performance testing. Energy profiling and debugging use PowerTOSSIM, Avrora, and Wireshark for packet trace analysis. The stack guarantees cross-platform interoperability, low energy overhead, and reliable communication under various traffic and environmental situations. A clustered WSN with spanning tree routing and adaptive load balancing is shown in Figure 3.

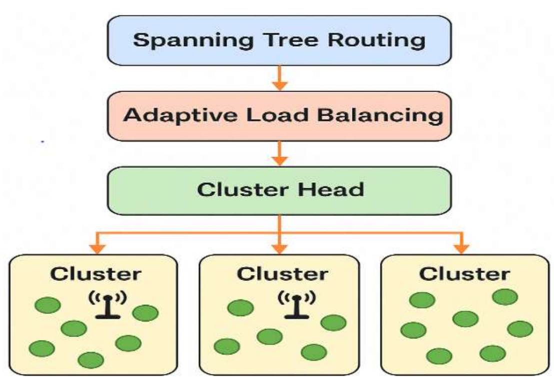

FIGURE 3. Structural Diagram of Spanning Tree Routing for Load Balancing in Clustered WSN

The architecture has four vertical functional tiers. Spanning tree routing delivers loop-free communication and efficient route selection at the top. Network traffic circumstances determine data flow distribution using the adaptive load balancing module below. Managing data from grouped nodes, the cluster head layer aids local coordination. Cluster heads supervise sensor node clusters at the base layer. Energy efficiency, load balance, and routing overhead are optimised by numerous methods. The main optimisation approach for spanning tree creation is energy-weighted edge selection. Intracluster data aggregation compression and sensor duty-cycling decrease duplicate transmissions and preserve node energy. Failure detection and recovery modules isolate defective nodes and redistribute responsibilities without reconfiguration using lightweight monitoring. Well-defined APIs and configurable interfaces allow third-party system or algorithm integration. This versatility makes the system appropriate for environmental monitoring, industrial automation, disaster response, and combat observation. The routing approach automatically adapts to network size and circumstances, ensuring constant performance in small farms and massive forest grids. Figure 4. Hierarchical system diagram of spanning tree-based dynamic graph routing WSN for adaptive load balancing. Top cloud units suggest remote control or data aggregation. A wireless tower-based sink node connects cluster heads to the cloud. Three multi-sensor clusters are underneath the washbasin node. Dashed orange lines are redundant channels that dynamically share communication load. Design lowers cluster congestion and optimises energy utilisation.

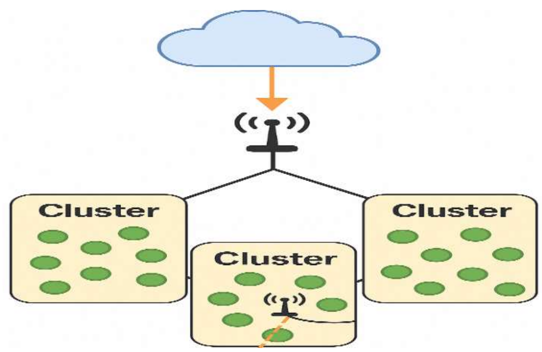

FIGURE 4. System Diagram of Spanning Tree Routing for Load Balancing in Clustered WSN

Equation for Spanning Tree Edge Weight Function

$$w_{ij} = \alpha \,.\left(1 - \frac{E_j}{E_{max}}\right) + \beta \,.\frac{Q_j}{Q_{max}} + \gamma \,.\left(1 - L_{ij}\right) \tag{1}$$

The equation defines the edge weight w_{ij} between two cluster heads i and j in the dynamic spanning tree routing graph. The weight determines whether the edge (i, j) is selected as part of the minimum spanning tree used for routing in a load-balanced and fault-tolerant manner. $\boldsymbol{E_j}$ is Residual energy of node $\boldsymbol{j}$, $\boldsymbol{E_{max}}$ maximum possible energy across all nodes, $\boldsymbol{Q_j}$ is Current packet queue length at node $\boldsymbol{j}$, $\boldsymbol{Q_{max}}$ is the Maximum queue threshold defined in the system, $\boldsymbol{L_{ij}}$ is Link quality between node i and j , α, β, γ is tunable coefficients for weighting energy, congestion, and link quality respectively. The function prioritizes nodes with higher residual energy, lower queue occupancy, and stronger link reliability. Lower values of $\boldsymbol{w_{ij}}$ indicate more desirable edges for routing. The dynamic spanning tree is constructed by minimizing total edge weight, ensuring that heavily loaded or low-energy nodes are excluded from critical paths, supporting adaptive load balancing.

Pseudo code of Dynamic Graph Tree Routing:

```
Input:
  G(V, E)         → Graph of cluster heads and interconnections
  E_residual[v]   → Residual energy of each node v ∈ V
  Q_length[v]     → Current queue length of node v
  L_quality[i][j] → Link quality between nodes i and j
  α, β, γ         → Weight tuning parameters

Output:
```

```
  T(V, E')        → Dynamic spanning tree for routing

Procedure DynamicGraphTreeRouting()
1. Initialize:
      For all edges (i, j) ∈ E:
         Compute weight w_ij using:
         w_ij = α * (1 - E_residual[j]/E_max)
             + β * (Q_length[j]/Q_max)
             + γ * (1 - L_quality[i][j])
2. Build Spanning Tree:
      Use Prim's or Kruskal's algorithm to construct T(V, E')
      minimizing ∑ w_ij
3. Monitor Network Periodically:
      For each time interval t:
         For each node v ∈ V:
            Update E_residual[v], Q_length[v], L_quality[v][*]

         Recalculate all w_ij
         Reconstruct tree T(V, E') if:
            • any E_residual[v] < threshold
            • any Q_length[v] > overload limit
            • topology changes detected (e.g., node/link failure)
4. Routing Phase:
      For every data packet p:
         Forward packet from CH to CH using T(V, E')
         If next-hop CH is overloaded or unreachable:
            Reroute via alternate subtree path
End Procedure
```

Table 1 shows the functional links between major components of clustered wireless sensor networks' spanning tree-based dynamic graph routing architecture. Each row represents a logical or physical module, whereas columns show communication and decision-making steps. Checkmarks indicate direct participation in topology identification, route calculation, load distribution logic, and message relaying. This mapping identifies task ownership, interdependencies, and routing. This structure simplifies modular interaction analysis and determines which components are involved in adaptive routing changes caused by network oscillations or traffic imbalances by isolating each layer's contribution. ✓ represents the Involved / Active / Contributing, ✗ means Not Involved / Inactive / Irrelevant.

TABLE I. Communication Layer Interaction Mapping

Component	Topology Discovery	Path Calculation	Load Distribution	Tree Update Logic	Message Forwarding
Sensor Node	✓	✓	✓	✗	✓
Cluster Head	✓	✓	✓	✓	✓
Spanning Tree	✓	✓	✓	✓	✗
Control Message	✓	✓	✓	✓	✓
Aggregation Unit	✗	✗	✓	✗	✓

RESULTS AND DISCUSSION

For real-world clustered wireless sensor installations, the system provides resilient, scalable, and energy-efficient routing. The system distributes soil moisture, temperature, and humidity sensors throughout broad farmlands, dynamically balancing communication load between cluster heads to save battery life in agricultural monitoring. The system provides low-latency, high-reliability communication using dynamically modified channels to monitor machines throughout plants. Figure 5 shows a bar chart comparing five wireless sensor nodes (Nodes A–E) on energy, latency, throughput, packet loss, and load. Nodes are clusters of bars with various colours expressing measurements. The actual values are shown above each bar for clarification.

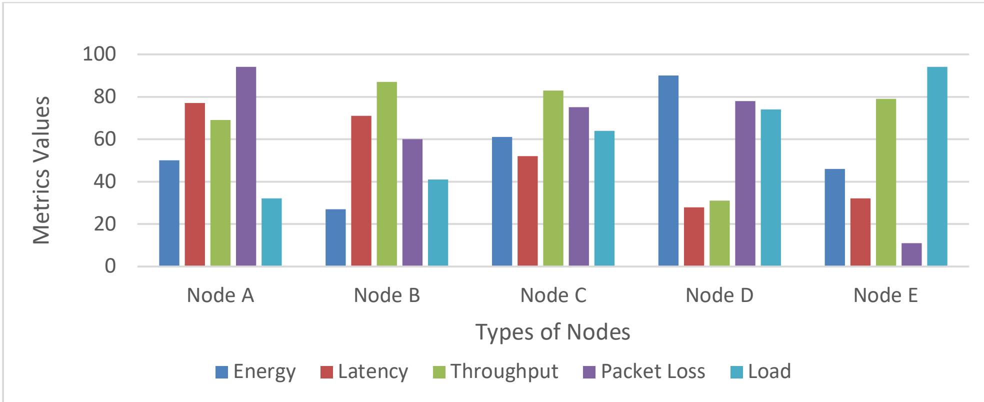

FIGURE 5. Bar Chart Representation of Node Performance Metrics

Future enhancements seek to boost intelligence, flexibility, and performance in different deployments. Machine learning approaches for predictive route selection minimise spanning tree reconstruction frequency, boosting efficiency under varying load circumstances. Based on prior network behaviour, reinforcement learning agents may help cluster heads choose optimum forwarding techniques. IPv6 over 6LoWPAN allows IoT ecosystem integration. SDN frameworks may facilitate reconfiguration and administration of complex sensor infrastructures in future system versions, enhancing scalability and responsiveness. Table 2 shows how network events affect routing dynamics in a spanning tree-based graph. A wireless sensor network trigger situation is shown in each row. The columns show if the spanning tree is recalculated, clusters are reorganized, message delay characteristics change, or energy burden is reallocated. This organized overview shows how inputs affect routing system adaptation.

TABLE II. Routing Transition Event Matrix

Trigger Event	Topology Impact	Tree Recalculation	Cluster Realignment	Message Delay Shift	Energy Redistribution
Node Failure	✓	✓	✓	✓	✓
Link Congestion	✗	✓	✗	✓	✓
Metric Threshold Drop	✓	✓	✓	✓	✓
Scheduled Rebalance	✗	✓	✓	✗	✓
Topology Expansion	✓	✓	✓	✗	✓

Figure 6 shows a heatmap of five sensor nodes' performance indicators across five categories. Each cell displays a metric value, colour-coded from yellow to red, with numerical values. The heatmap structure quickly identifies patterns, outliers, and performance bottlenecks. Nodes with high metrics across all measures may be cluster chiefs. High-latency or packet-loss nodes might be omitted from crucial routing pathways.

Wireless sensor network applications benefit from the proposed system's operational and performance. Dynamic spanning tree routing and adaptive load balancing lengthen network lifespan, eliminate imbalanced energy use-related node failures, and enhance end-to-end dependability. The technology improves data transmission under energy and bandwidth constraints and self-heals after node or connection failures. Decentralised decision-making and local cluster activities decrease communication overhead. The system is compatible with several sensor platforms and protocols, making it applicable in many contexts. It provides real-time environmental knowledge for disaster management, smart agriculture, and remote monitoring. Adaptability to changing network circumstances makes the system robust, cost-effective, and simple to maintain. Overall, these benefits allow more efficient, autonomous, and scalable sensor network deployments in civilian and industrial use cases, enabling long-term, energy-conscious mission-critical operations.

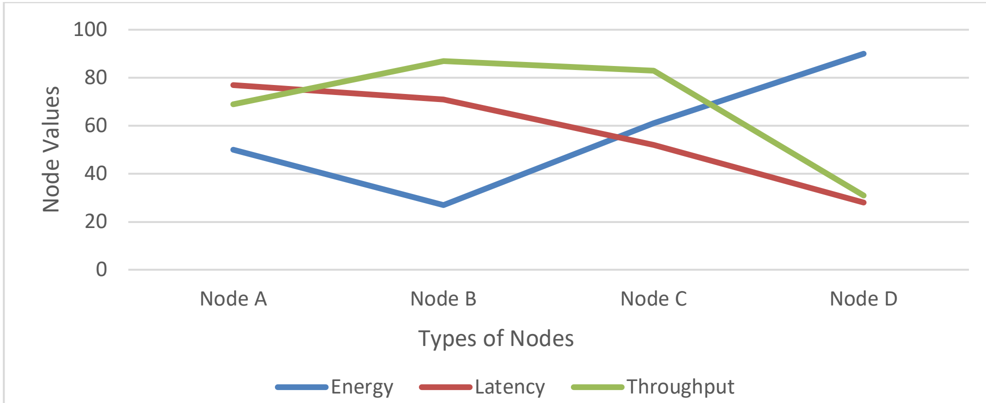

FIGURE 6. Clustered Metric Distribution of Heatmap of Node Metrics

CONCLUSION

Dynamic graph routing based on spanning trees for adaptive load balancing in clustered wireless sensor networks offers significant enhancements while also posing many technological hurdles. Dynamic topological alterations resulting from node failures or mobility induce synchronization delays in tree rebuilding. Regular modifications to the spanning structure elevate communication overhead, especially in congested networks with limited energy resources. The computational cost of sustaining effective routing networks under limited memory circumstances restricts implementation on resource-constrained sensor nodes. The efficacy of load balancing is significantly influenced by precise residual energy calculation, which might vary owing to inconsistent sensing and transmission requirements. Integration with real-time traffic models is constrained, diminishing responsiveness under sporadic data situations. Security problems, including erroneous data injection during three updates, remain unresolved. Future improvements include the integration of machine learning for predictive routing determinations, multi-tree coordination for redundancy, and cross-layer optimization methods for enhanced resource utilization. Deployment in heterogeneous wireless sensor network settings provides opportunities for assessing resilience across various application areas.

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