

Load Balancing and Energy Optimization in Wireless Sensor – Research

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Abstract— A Wireless Sensor Network (WSN) is composed of a large number of sensor nodes deployed across a designated monitoring region to collect and transmit environmental data. Each sensor node is integrated with a compact processor, limited memory capacity, and wireless communication capability, enabling autonomous sensing and data exchange. Due to their low implementation cost, flexible deployment, and self-organizing characteristics, WSNs have become widely applicable in environmental monitoring, industrial automation, healthcare, and military surveillance systems. However, efficient energy utilization remains a major challenge because sensor nodes generally operate on limited battery resources. To address this issue, this study presents an energy-efficient Load Balancing Tree-Based Data Aggregation Scheme (LB-TBDAS) designed for grid-structured Wireless Sensor Networks. In the proposed approach, the sensing field is divided into multiple grid cells, and within each cell, the sensor node possessing the highest residual energy is selected as the Cell Head (CH). These cell heads are responsible for gathering sensing information from neighboring nodes and forwarding the aggregated data toward the Base Station (BS). For efficient routing, a tree-based communication structure is established using the Minimum Spanning Tree (MST) algorithm. During tree formation, several critical constraints are considered, including minimizing overall energy consumption, controlling network depth, and limiting the maximum number of child nodes connected to a parent node. These constraints help in achieving balanced energy dissipation across the network while maintaining reliable communication performance. During data transmission, each cell head collects and aggregates the sensed information from nodes within its grid region. The aggregated data are then transmitted through the optimized tree-based routing path toward the base station using multi-hop communication. By distributing communication load evenly among sensor nodes, the proposed LB-TBDAS effectively reduces excessive energy depletion and minimizes the hotspot problem commonly observed near the base station. Simulation analysis demonstrates that the proposed LB-TBDAS significantly outperforms conventional schemes such as GB-PEDAP and PEDAP in terms of energy efficiency and network longevity. The results indicate a substantial reduction in total energy consumption and an improvement of more than 100% in network lifetime compared to existing approaches. Therefore, the proposed scheme provides an effective and reliable solution for enhancing energy conservation and load balancing in Wireless Sensor Networks.

Index Terms— Data Aggregation, Energy Efficiency, Load Balancing, Minimum Spanning Tree (MST), Wireless Sensor Networks (WSNs).

I. INTRODUCTION

In a Wireless Sensor Network (WSN), sensor nodes are responsible for sensing environmental information, processing the collected data, and transmitting it to the Base Station (BS) through wireless communication. Rapid advancements in embedded systems and wireless

communication technologies have significantly increased the adoption of WSNs in various real-world applications. Modern sensor nodes can integrate multiple sensing components such as temperature sensors, infrared detectors, humidity sensors, and gas monitoring devices. Due to their compact size, low manufacturing cost, and flexible deployment capability, a large number of sensor nodes can be distributed over a monitoring region to collect accurate and continuous environmental information. Wireless Sensor Networks are widely utilized in several critical applications including battlefield surveillance, environmental monitoring, smart agriculture, healthcare systems, industrial automation, traffic management, and smart home technologies. In military environments, WSNs can be used for hazardous gas detection, target tracking, and human activity monitoring. Similarly, in healthcare applications, sensor nodes support patient monitoring and real-time health analysis. The increasing demand for intelligent monitoring systems has further expanded the importance of WSNs in modern communication infrastructures. Despite these advantages, energy efficiency remains one of the most challenging issues in Wireless Sensor Networks. Since sensor nodes are generally powered by limited-capacity batteries, excessive energy consumption during data transmission and reception can significantly reduce network performance and operational lifetime. In many remote or hazardous environments, replacing or recharging sensor batteries is difficult and sometimes impractical.

II. RELATED WORK

In recent years, extensive research has been carried out in the field of Wireless Sensor Networks (WSNs) to develop efficient data aggregation and routing mechanisms capable of minimizing energy consumption and improving network lifetime. Since sensor nodes generally operate using limited battery power, researchers have focused on designing communication protocols that reduce redundant data transmission, balance network load, and optimize routing performance. One of the earliest approaches introduced in WSNs is the diffusion-based data aggregation mechanism, which follows a data-centric communication model. In this approach, sensor nodes are identified based on sensed information rather than unique addresses. During data collection, a query generated by the user or Base Station (BS) propagates throughout the network. Sensor nodes that receive duplicate requests discard redundant packets, thereby reducing unnecessary communication overhead. When a node detects data matching the requested query, the sensed information is transmitted back to the BS through the established reverse communication path. The Direct Diffusion protocol utilizes neighboring sensor nodes to exchange information dynamically, making it highly suitable

for real-time data retrieval in adaptive network environments. Although this method provides efficient data dissemination, its performance is strongly influenced by the distance between sensor nodes and the Base Station, resulting in increased energy consumption in large-scale deployments. PEGASIS introduced a chain-based data aggregation approach in which sensor nodes are connected sequentially using a greedy algorithm to form a communication chain. During each transmission cycle, data are forwarded from neighboring nodes toward a designated chain leader, which finally transmits the aggregated information to the Base Station. This approach significantly reduces communication overhead by minimizing direct transmissions to the BS. Additionally, the role of chain leader rotates among sensor nodes to distribute energy consumption evenly and enhance network lifetime. To further improve energy efficiency, the Concentric Clustering and Routing Scheme (CCRS) combined cluster-based and chain-based architectures. In this scheme, sensor nodes are organized into multiple levels according to signal strength received from the Base Station. A chain structure is then established within each level using a greedy routing mechanism. By rotating the chain head periodically, CCRS achieves balanced energy utilization and reduces excessive load on individual nodes. The Two-Tier Data Dissemination (TTDD) scheme introduced a grid-based routing architecture where dissemination nodes are responsible for storing and forwarding sensing information. In TTDD, the sink node sends query messages to neighboring nodes, which subsequently forward the request toward the source node. During this process, routing paths are established dynamically, enabling efficient data delivery from source nodes to the sink while maintaining scalability in large sensor networks. Several multi-level aggregation techniques have also been proposed to reduce communication redundancy. The Multi-Level Data Aggregation Technique (MLDAT) preprocesses sensed data by filtering unnecessary or duplicate information before transmission. This approach reduces packet retransmissions, lowers communication latency, and improves bandwidth utilization. Similarly, the Hybrid Data Aggregation Algorithm (HDAA) performs intelligent real-time data processing to eliminate redundant information, thereby reducing energy consumption and communication delay while extending overall network lifetime. Tree-based data aggregation techniques have gained significant attention due to their ability to support hierarchical communication structures. In these schemes, parent nodes collect and aggregate data from their child nodes before forwarding the processed information toward upper layers of the network. The E-Span protocol constructs an energy-aware spanning tree where the node possessing the highest residual energy is selected as the root node. Parent node selection depends on both residual energy and distance to the root, enabling more balanced energy utilization. The Tier-Based Energy Efficient Protocol (TBEEP) divides the sensing region into multiple layers based on the distance between sensor nodes and the Base Station. A minimum spanning tree is then constructed using Prim's algorithm to optimize routing efficiency. By reconstructing the spanning tree in every communication round, TBEEP effectively balances network load and prolongs network operation. Energy-efficient privacy-preserving aggregation techniques have also

been explored in recent studies. The Energy-efficient and Privacy-preserving Data Aggregation (EPDA) algorithm combines aggregation trees with chain structures to secure transmitted information while reducing communication overhead. This approach minimizes energy consumption and enhances data privacy without significantly increasing network complexity. PEDAP introduced a tree-based routing protocol using the Minimum Spanning Tree (MST) concept to minimize communication energy during data transmission. In this scheme, sensor nodes aggregate and forward data through parent-child relationships toward the Base Station. By selecting communication paths with minimum transmission cost, PEDAP achieves. In recent years, extensive research has been carried out in the field of Wireless Sensor Networks (WSNs) to develop efficient data aggregation and routing mechanisms capable of minimizing energy consumption and improving network lifetime. Since sensor nodes generally operate using limited battery power, researchers have focused on designing communication protocols that reduce redundant data transmission, balance network load, and optimize routing performance. One of the earliest approaches introduced in WSNs is the diffusion-based data aggregation mechanism, which follows a data-centric communication model. In this approach, sensor nodes are identified based on sensed information rather than unique addresses. During data collection, a query generated by the user or Base Station (BS) propagates throughout the network. Sensor nodes that receive duplicate requests discard redundant packets, thereby reducing unnecessary communication overhead. When a node detects data matching the requested query, the sensed information is transmitted back to the BS through the established reverse communication path. The Direct Diffusion protocol utilizes neighboring sensor nodes to exchange information dynamically, making it highly suitable for real-time data retrieval in adaptive network environments. Although this method provides efficient data dissemination, its performance is strongly influenced by the distance between sensor nodes and the Base Station, resulting in increased energy consumption in large-scale deployments. PEGASIS introduced a chain-based data aggregation approach in which sensor nodes are connected sequentially using a greedy algorithm to form a communication chain. During each transmission cycle, data are forwarded from neighboring nodes toward a designated chain leader, which finally transmits the aggregated information to the Base Station. This approach significantly reduces communication overhead by minimizing direct transmissions to the BS. Additionally, the role of chain leader rotates among sensor nodes to distribute energy consumption evenly and enhance network lifetime. To further improve energy efficiency, the Concentric Clustering and Routing Scheme (CCRS) combined cluster-based and chain based architectures. In this scheme, sensor nodes are organized into multiple levels according to signal strength received from the Base Station. A chain structure is then established within each level using a greedy routing mechanism. By rotating the chain head periodically, CCRS achieves balanced energy utilization and reduces excessive load on individual nodes. The Two-Tier Data Dissemination (TTDD) scheme introduced a grid-based routing architecture where dissemination nodes are responsible for storing and

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III. THE PROPOSED SCHEME

In Wireless Sensor Networks (WSNs), a large number of sensor nodes are deployed throughout the sensing region to continuously monitor environmental conditions and transmit collected information to the Base Station (BS). As the number of deployed nodes increases, the volume of sensed data also grows significantly. If all sensor nodes directly transmit their sensed information to the Base Station, excessive energy consumption occurs due to long-distance communication. Consequently, sensor batteries are rapidly depleted, leading to reduced network lifetime and degraded overall performance. Therefore, an efficient and energy-aware communication protocol is essential to ensure reliable

operation and prolonged network sustainability. To address these challenges, this work proposes a Load Balancing Tree-Based Data Aggregation Scheme (LB-TBDAS) for grid-based Wireless Sensor Networks. The proposed method focuses on minimizing energy consumption while balancing communication load among sensor nodes. In this scheme, sensor nodes are uniformly deployed at fixed positions within the sensing region, and the entire network area is divided into multiple grid cells. During communication, each cell selects a Cell Head (CH) based on the highest residual energy. A tree-based routing structure is then constructed among the selected cell heads, where the Base Station acts as the root node. The proposed methodology consists of three major stages: Grid Construction, Tree Structure Construction, and Data Transmission. Grid Construction Initially, the sensing area is partitioned into an $M \times N$ grid structure, where each cell has dimensions of $\alpha \times \alpha$. The coordinates of every grid cell are represented using (C_x, C_y) , while the physical location of each sensor node is denoted by (x, y) . All sensor nodes are assumed to be equipped with GPS functionality or localization mechanisms that allow them to determine their geographic position within the network. After deployment, each sensor node identifies the corresponding grid cell to which it belongs. Within every cell, the sensor node possessing the highest residual energy is elected as the Cell Head (CH). The selected Cell Head is responsible for collecting and aggregating sensing information from neighboring nodes within the same cell. To ensure balanced energy consumption, the Cell Head selection process is repeated during every communication round. This dynamic re-election mechanism prevents excessive energy depletion of a single node and distributes communication load more uniformly throughout the network. The grid-based architecture offers several advantages, including simplified routing, reduced communication overhead, and improved scalability for large-scale sensor deployments. Additionally, localizing communication within grid cells minimizes unnecessary long-distance transmissions and contributes to improved energy efficiency.

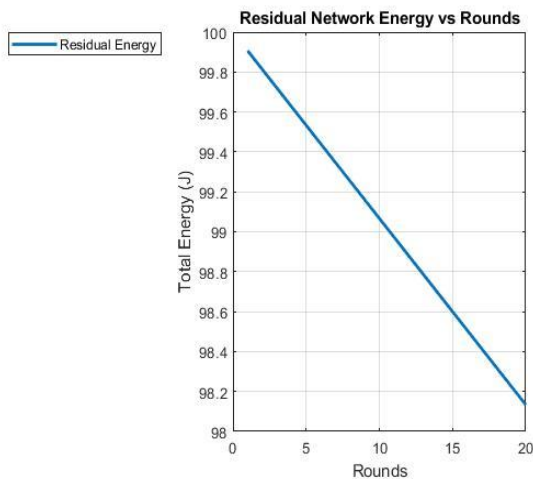
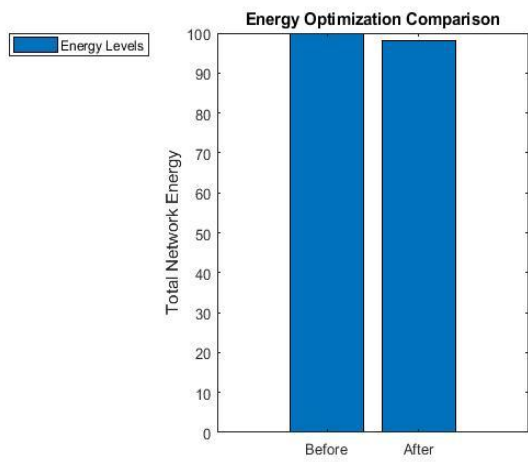
Tree Structure Construction: After selecting the Cell Heads, a hierarchical tree-based routing structure is established for efficient data aggregation and transmission. The proposed LB-TBDAS adopts concepts inspired by ZigBee network architecture, where network formation depends on parameters such as network depth and the maximum number of child nodes connected to a parent node. In the proposed scheme, the Base Station serves as the root node of the communication tree. The tree construction process follows a constrained Minimum Spanning Tree (MST) approach to ensure balanced energy utilization. Unlike conventional tree-based aggregation methods, LB-TBDAS introduces additional restrictions during tree formation to avoid excessive communication burden on individual nodes. The energy consumption model used during routing is based on transmission and reception energy calculations. The transmission cost between two nodes depends on the communication distance and packet size. The communication energy model can be represented as follows:

$$C_{osij}(K) = 2E_{elec}K + E_{amp}Kd_{ij}^2$$

IV. RESULTS

1. Energy Efficiency

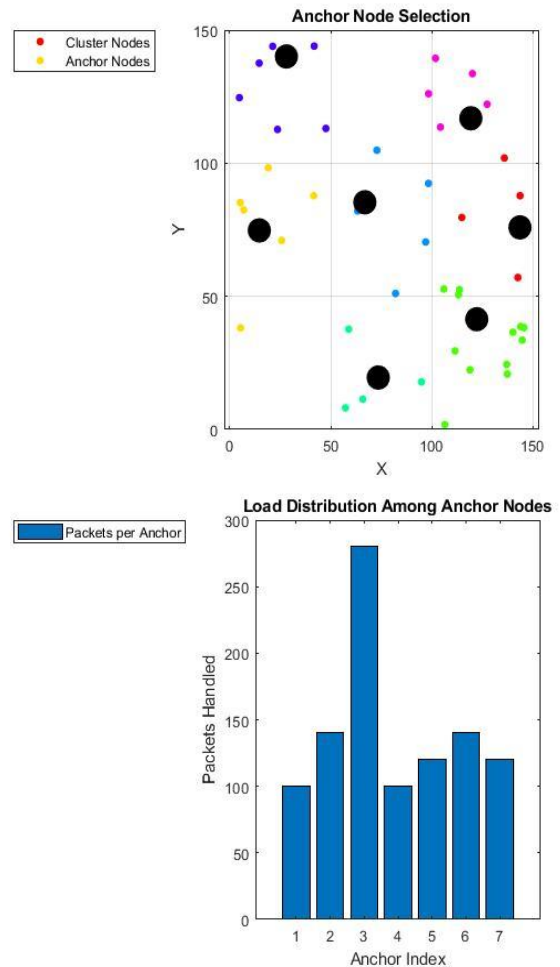
The proposed LB-TBDAS demonstrates a significant reduction in total network energy consumption compared to existing schemes such as PEDAP and GB-PEDAP. The grid-based clustering approach limits the transmission range within each cell, while the minimum spanning tree algorithm ensures that data is forwarded along the most energy-efficient paths. Additionally, the constraints on network depth and the maximum number of child nodes prevent excessively long multi-hop transmissions, which are known to consume substantial energy. As a result, the total energy consumption of LB-TBDAS is considerably lower than that of the comparative schemes, allowing the network to sustain more operational rounds before energy depletion.



2. Load Balancing

Among Anchor Nodes The load distribution analysis reveals that LB-TBDAS successfully balances the packet handling responsibilities across all anchor nodes. By imposing a strict limit on the maximum number of child nodes (C_m) that any anchor node can serve, the scheme prevents individual nodes from becoming overloaded. Furthermore, the restriction on network depth (L_m) ensures that anchor nodes located closer to the base station are not forced to relay an excessive number of packets from distant nodes. Consequently, the packet counts handled by each anchor node remain approximately uniform, effectively eliminating the hotspot problem commonly

observed in tree-based data aggregation schemes.



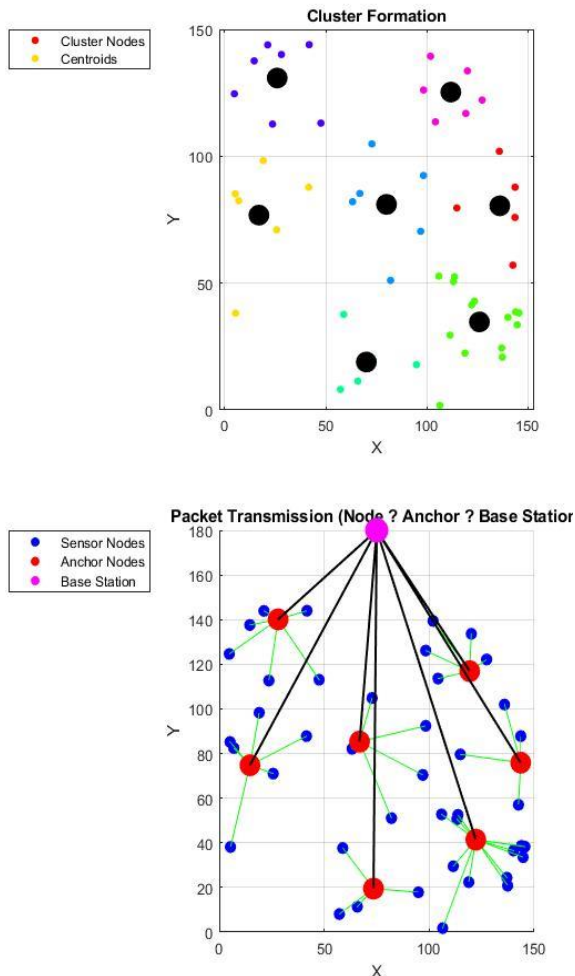
3. Network Lifetime Extension

The most compelling result of the proposed LB-TBDAS is the substantial extension of the network lifetime. Simulation results indicate that LB-TBDAS extends the operational duration of the wireless sensor network by more than one hundred percent when compared to GB-PEDAP and PEDAP. This dramatic improvement is achieved through the synergistic effect of three key mechanisms: energy-aware cell head election, constrained tree construction, and balanced load distribution. By preventing any single node from exhausting its battery prematurely, the network maintains its sensing and communication capabilities for a significantly longer period, which is particularly valuable for deployments in remote or inaccessible environments where battery replacement is infeasible.

4. Tree Depth Optimization

The tree construction phase of LB-TBDAS effectively limits the maximum depth of the data aggregation tree. Without depth constraints, leaf nodes located far from the base station would need to transmit data over many hops, leading to high cumulative energy consumption and increased latency. The proposed scheme restricts the tree depth to a predefined value L_m , which is determined based on the grid dimensions. As a result, the number of hops between any sensor node and the base station is minimized, reducing both energy consumption and end-to-end transmission delay. This optimization is particularly beneficial for large-scale grid-based WSNs where node

density is high and transmission distances vary significantly.



5. Avoidance of the Hotspot Problem

The hotspot problem, where nodes near the base station deplete their energy faster due to relaying traffic from distant nodes, is effectively mitigated by LB-TBDAS. The combination of depth limitation and child node restriction ensures that no anchor node is forced to handle a disproportionate share of relay traffic. Additionally, the periodic reselection of cell heads based on residual energy further distributes the relay burden among different nodes over time. This dynamic rotation prevents the premature failure of nodes in high-traffic regions near the base station, thereby maintaining network connectivity for a longer duration.

V. CONCLUSION

This study presented an energy-efficient Load Balancing Tree-Based Data Aggregation Scheme (LB-TBDAS) for grid-based Wireless Sensor Networks. The proposed approach utilizes a Minimum Spanning Tree (MST)-based routing mechanism to construct an optimized tree-like communication structure for efficient data transmission. Unlike conventional aggregation techniques, the proposed scheme incorporates multiple load balancing constraints during tree formation, including minimum energy consumption, controlled network depth, and limitation on the maximum number of child nodes connected to each parent node. By integrating these constraints, the proposed LB-TBDAS distributes communication load more uniformly

among sensor nodes and minimizes excessive energy depletion in specific network regions. The grid-based architecture further improves routing efficiency by organizing sensor nodes into structured cells and dynamically selecting Cell Heads based on residual energy levels. This adaptive selection mechanism contributes to balanced energy utilization and reduces the hotspot problem commonly observed near the Base Station. Simulation results demonstrate that the proposed LB-TBDAS achieves significantly better performance in terms of average residual energy, energy balancing, and network lifetime compared to existing schemes such as GB-PEDAP and PEDAP. The analysis indicates that the proposed method extends the overall network lifetime by more than 100% while simultaneously reducing total energy consumption during multi-hop communication. Therefore, the proposed LBTBDAS provides an effective and reliable solution for energy-efficient data aggregation in large-scale Wireless Sensor Networks. The scheme successfully enhances communication performance, improves network stability, and prolongs operational lifetime, making it suitable for modern monitoring and sensing applications.

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