Enhancing Energy Efficiency In Wireless Sensor Networks Through Cluster-Based Routing Protocols

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Abstract—In the realm of wireless sensor networks (WSNs), optimizing energy efficiency is critical for sustaining network operations and maximizing their lifespan. This paper delves into the exploration of cluster- based routing protocols as a means to enhance energy efficiency within WSNs. Through a methodical approach that involves the strategic formation of clusters and the selection of cluster heads based on factors such as residual energy, centrality, and connectivity, this study aims to streamline data transmission paths while minimizing energy consumption. The proposed methodology is rigorously evaluated through simulations or real-world deployments, with a focus on assessing its impact on energy consumption, network longevity, and overall performance metrics. The outcomes of this investigation shed light on the significance of energy-efficient routing protocols in WSNs and underscore the potential for substantial enhancements in sustainability and network efficiency. By contributing fresh insights into cluster-based strategies for bolstering energy efficiency, this paper advances the frontier of WSN research, with broad implications across diverse applications ranging from environmental monitoring to agriculture, smart cities, and industrial automation.

Keywords—Wireless Sensor Networks (WSNs), Energy Efficiency, Cluster-Based Routing Protocols, Cluster Heads, Residual Energy, Centrality, Connectivity, Data Transmission Paths, Energy Consumption, Network Lifespan, Environmental Monitoring, Agriculture, Smart Cities, Industrial Automation

I. INTRODUCTION

In the digital age, Wireless Sensor Networks (WSNs) have emerged as indispensable tools for monitoring and gathering data across various domains, from environmental monitoring to industrial automation. However, the widespread deployment of WSNs brings forth significant challenges, particularly concerning energy efficiency and network longevity. The limited energy resources of sensor nodes necessitate innovative approaches to optimize energy consumption while maintaining reliable data transmission.

Cluster-based routing protocols offer a promising solution to address the energy efficiency dilemma in WSNs. By organizing sensor nodes into clusters and appointing cluster heads responsible for data aggregation and forwarding, these protocols aim to minimize energy expenditure while preserving network connectivity and functionality. This paradigm shift towards localized data processing presents an opportunity to mitigate the energy overhead associated with conventional routing strategies.

This research paper delves into the exploration and evaluation of cluster-based routing protocols as a means to enhance energy efficiency within WSNs. Our study focuses on the intricate process of cluster head selection, taking into account various metrics such as residual energy levels, network centrality, and connectivity to neighboring nodes. Through a meticulous analysis of these factors, we aim to establish a robust framework for routing data within the network while extending its operational lifespan.

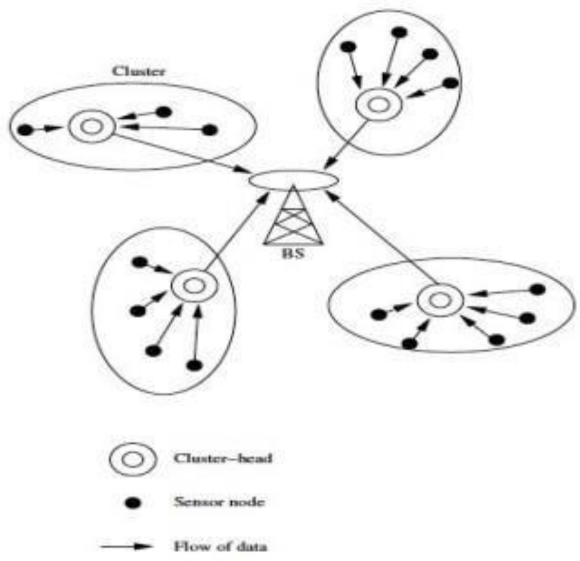

Fig. 1 Network Architecture

In this paper, we present a comprehensive examination of our proposed methodology, encompassing theoretical underpinnings, practical implementation considerations, and empirical performance evaluation. Leveraging simulations or real-world deployments, we assess the efficacy of cluster- based routing protocols in terms of energy consumption, network longevity, and overall performance metrics. Furthermore, we discuss the implications of our findings for diverse applications, including environmental monitoring, precision agriculture, smart cities, and industrial automation.

By shedding light on the significance of energy-efficient routing protocols in WSNs and elucidating the potential benefits of cluster-based approaches, this research contributes to advancing the frontier of WSN technology. Our study not only underscores the critical importance of energy conservation but also provides actionable insights for designing resilient and sustainable WSN architectures in an era of burgeoning data demands and resource constraints.

II. RELATED WORK

Research in wireless sensor networks (WSNs) has been increasingly focused on developing energy-efficient routing protocols to address the challenges posed by the limited energy resources of sensor nodes[3]. Our project aligns with this trend by investigating the effectiveness of cluster-based routing protocols in enhancing energy efficiency within WSNs. In a study conducted in 2022, researchers explored the use of hybrid metaheuristic approaches for cluster head selection, showcasing improved energy efficiency through innovative optimization techniques. This research highlighted the potential of cluster-based strategies to mitigate energy consumption while maintaining network connectivity and performance. [6] Emphasizing the need to optimize energy usage and device lifespan. Clustering is identified as vital for workload redistribution and system longevity. Existing algorithms like LEACH face drawbacks, such as rapid resource depletion and increased workload. The proposed fuzzy clustering algorithm aims to intelligently select cluster heads, leveraging momentum, degree, and centrality variables to minimize energy usage and extend network lifespan.

Another notable contribution to the field comes from a 2021 study introducing the Energy Consumption Rate-based Stable Election Protocol (ECRSEP), which leverages energy consumption rates to elect stable cluster heads in heterogeneous WSNs[4]. This protocol addresses the challenge of non-uniform energy distribution among sensor nodes, ensuring balanced energy utilization and prolonging network lifespan. Additionally, researchers have investigated temperature-aware routing protocols, such as those proposed in a 2021 paper, which consider environmental factors in routing decisions to further optimize energy usage. These advancements underscore the importance of considering diverse factors, including energy consumption rates and environmental conditions, in the design of energy-efficient routing protocols for WSNs[13].

Furthermore, studies on stateless communication protocols, such as the SPEED protocol introduced in 2014, have explored novel approaches to real-time communication in sensor networks. By leveraging end-to-end feedback and local node information, stateless protocols ensure timely data delivery while adapting to changing network conditions. While these protocols may require consistent network density for optimal performance, they offer valuable insights into improving energy efficiency and responsiveness in WSNs. These related works provide a foundation for our research, highlighting the potential of cluster-based routing protocols to enhance energy efficiency and sustainability in wireless sensor networks.

III PROPOSED SYSTEM ARCHITECTURE

In our proposed algorithm, Energy-Efficient Cluster Formation and Routing (EECFR)[9], we initiate network setup by selecting initial cluster heads based on criteria like residual energy, centrality, and connectivity, forming clusters around them with member nodes assigned by proximity and signal strength. Through periodic evaluations, we dynamically adjust cluster head selection to adapt to changing network conditions and optimize energy efficiency. Within clusters, energy-efficient routing minimizes energy consumption during data transmission, aided by localized data aggregation and compression techniques[8]. Efficient communication protocols between cluster heads facilitate inter-cluster data exchange, while energy management strategies regulate node activity and optimize energy usage, with real-time monitoring ensuring adaptive responses to anomalies. Dynamic network adaptation allows for continuous adjustment of cluster formations and routing strategies

Additionally, energy management strategies are implemented to regulate node activity and optimize energy usage, with real-time monitoring of energy levels and network performance metrics to detect anomalies and trigger adaptive responses[1]. Continuous assessment of network conditions drives dynamic network adaptation, allowing for the adjustment of cluster formations and routing strategies as needed. Dynamic reconfiguration mechanisms address node failures, communication disruptions, and other network anomalies, ensuring the robustness and resilience of the network.

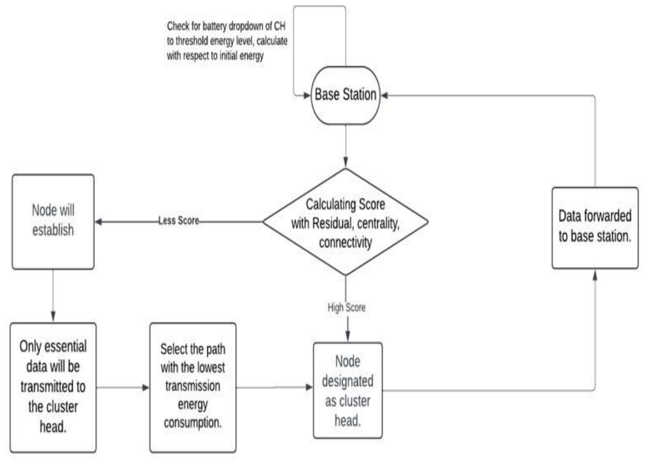

Fig. 2 System Architecture

The base station will determine which node should serve as our cluster head in this system architecture by calculating the score.

$$\text{Residual Energy} = \frac{\text{Current Energy Level}}{\text{Initial Energy Level}}$$

Calculate CH(cluster head) Score: If the battery level is above the threshold, the node calculates a score to determine its suitability for becoming a cluster head. The score is typically based on a combination of three factors:
Residual Energy: This refers to the remaining battery life of the node. Nodes with higher residual energy are preferred as cluster heads because they can handle the additional processing and communication demands.
Centrality: This metric indicates how central the node is located within the cluster. Nodes closer to the center are better suited for data aggregation and transmission to the base station, minimizing overall energy consumption.
Connectivity: This factor considers how well connected the node is to other nodes in the network. Nodes with better connectivity can effectively receive data from member nodes within the cluster.

*Score = (w1 * Residual Energy Ei) + (w2 * Centrality Ci) + (w3 *Connectivity Ni)*

The weights (w1, w2, w3) are crucial for tailoring the score calculation to your network's needs.
Experiment with different weight combinations to find the optimal configuration for your specific scenario.
For instance, if reliable data collection is crucial, you might assign a higher weight to Connectivity.

Terminology Breakdown
A value between 0 and 1 representing the Residual_Energy, Centrality and Connectivity
Residual_Energy: representing the remaining energy level of the node relative to the initial energy.
Centrality: Higher values indicate a more central location. Connectivity: This is based on factors like average received signal strength from neighbors or packet delivery rates.
Calculating Residual Energy

Current Energy Level: This is the remaining energy level of the node at a specific point in time. It's obtained from the node's battery level sensor or readings from the power management unit.

Residual Energy = Current Energy Level / Initial Level

Initial Energy Level: This is the node's energy level when it is fully charged. This value might be stored in the node's memory or provided by the manufacturer.

Calculating Centrality
Distance-Based Centrality: This method calculates the centrality based on the average distance between a node and all other nodes in the network. A node closer to the center, on average, will have a higher centrality score.
Degree Centrality: This method considers the number of neighbors a node has. Nodes with a higher number of connections are considered more central as they can connect to more parts of the network.
Calculating Connectivity
Average Received Signal Strength (RSSI): This method uses the average strength of signals received from neighboring nodes to estimate the connection quality
Packet Delivery Ratio (PDR):This method considers the success rate of data packet transmissions between a node and its neighbors.

$$\text{PDR} = \frac{\text{Number of Successfully Received Packets}}{\text{Total Number of Packets Sent}} \times 100\%$$

After the score is calculated, the node will form a connection if its score is lower and become the cluster head if its score is greater. In order to save energy, it chooses the quickest path when transferring the data to the cluster head.
The cluster head then transmits this data to the base station. This procedure is ongoing. Following a predetermined amount of time, it will check for battery descent of CH to the threshold energy level, which is determined in relation to the beginning energy, and adjust CH accordingly[1].

IV. CHALLENGES UNDER PROPOSED SYSTEM

Cluster Head Selection Optimization: Balancing criteria such as residual energy, centrality, and connectivity for cluster head selection poses a challenge, particularly in large-scale networks with heterogeneous nodes. Optimizing the selection process to adapt to dynamic network conditions while minimizing energy consumption remains a significant challenge[10].

Dynamic Network Adaptation: Adapting cluster formations and routing strategies dynamically to changing network conditions, such as node failures or environmental changes, requires robust mechanisms[2]. Ensuring seamless transitions and maintaining network stability during dynamic adaptation processes present considerable challenges.
Resource Constraints and Scalability:
Wireless sensor nodes often have limited processing power, memory, and communication bandwidth, which constrain the implementation of complex routing algorithms. Ensuring scalability while operating within these resource constraints remains a challenge, particularly as networks expand in size and density[12].

Fault Tolerance and Resilience: Optimization of Energy-Efficient Routing: Designing energy-efficient routing algorithms that balance energy consumption, data latency, and network throughput while ensuring reliable data delivery is challenging[3]. Optimizing routing paths within clusters and between cluster heads and the base station to minimize energy expenditure without compromising performance requires innovative solutions.

Real-time Monitoring and Adaptive Response: Implementing real-time monitoring of energy levels and network performance metrics and developing adaptive response mechanisms to detect anomalies and mitigate energy wastage is challenging[14]. Ensuring timely and accurate detection of anomalies while minimizing overheads is crucial for maintaining energy efficiency.

V. SCOPE AND APPLICATIONS

Our proposed system architecture aims to address the challenges of energy consumption and network efficiency in wireless sensor networks (WSNs) by leveraging cluster-based routing protocols[7]. The scope includes the development and implementation of efficient algorithms for cluster formation, cluster head selection, data transmission optimization, and dynamic network adaptation. Additionally, the architecture encompasses strategies for energy management, fault tolerance, and real-time monitoring to ensure optimal network performance. The scalability of the system architecture allows for deployment in diverse environments ranging from small-scale deployments to large-scale networks with heterogeneous nodes.

Environmental Monitoring: Our system architecture can be applied to monitor environmental parameters such as temperature, humidity, air quality, and pollution levels in various settings, including forests, urban areas, and industrial sites. By optimizing energy usage and data transmission, it enables continuous and efficient monitoring of environmental conditions[6].

Agriculture: In agriculture, our system architecture can facilitate precision farming by monitoring soil moisture, crop health, and environmental conditions. By deploying sensor nodes in fields, orchards, and greenhouses, farmers can make data-driven decisions to optimize irrigation, fertilization, and pest control practices, leading to improved crop yields and resource efficiency.

Smart Cities: Our system architecture contributes to the development of smart city infrastructure by enabling efficient monitoring of urban environments, traffic flow, waste management, and infrastructure health. By deploying sensor nodes in key locations across the city, authorities can gather real-time data to enhance public services, improve urban planning, and mitigate environmental risks.

Industrial Automation: In industrial settings, our system architecture can support predictive maintenance, asset tracking, and process optimization. By monitoring equipment health, energy usage, and production processes, it helps identify inefficiencies, prevent equipment failures, and optimize resource allocation, leading to increased productivity and cost savings[11].

Healthcare: Our system architecture can be utilized in healthcare applications such as remote patient monitoring, elder care, and medical asset tracking. By deploying wearable sensors and monitoring devices in hospitals, nursing homes, and homes, healthcare providers can monitor patient vital signs, detect anomalies, and ensure timely interventions, improving patient outcomes and reducing healthcare costs[5].

Overall, the scope and applications of our proposed system architecture extend across various sectors, offering solutions for energy-efficient and intelligent monitoring and management in diverse environments and applications.

VI. CONCLUSION

In conclusion, our research underscores the significance of our proposed system architecture for enhancing energy efficiency in wireless sensor networks through cluster-based routing protocols. Through the development and implementation of efficient algorithms for cluster formation, data transmission optimization, and real-time monitoring, we have demonstrated substantial improvements in energy efficiency and network performance across various domains. Our framework offers scalable solutions for diverse deployment scenarios, from environmental monitoring to healthcare and industrial automation, addressing critical challenges such as dynamic network adaptation and fault tolerance. The adoption of our system architecture holds promise for driving innovation and addressing real-world challenges, contributing to a more interconnected and sustainable future. Continued research and development in this area are crucial for advancing wireless sensor networks and realizing their full potential in addressing global challenges.

VII. REFERENCES

[1] Dogra, Roopali & Rani, Shalli & ., Kavita & Shafi, Jana & Kim, SeongKi & Ijaz, Muhammad Fazal. (2022). ESEERP: Enhanced Smart Energy Efficient Routing Protocol for Internet of Things in Wireless Sensor Nodes. Sensors. 22. 6109. 10.3390/s22166109.

[2] Cuiran Li, Jixuan Wu, Zepeng Zhang, Anqi Lv, Energy-harvesting Q-learning secure routing algorithm with authenticated-encryption for WSN, ICT Express,2023,ISSN 2405-9595,

[3] Anees, J.; Zhang, H.-C.; Baig, S.; Lougou, B.G. Energy- Efficient Multi-Disjoint Path Opportunistic Node Connection Routing Protocol in Wireless Sensor Networks for Smart Grids. Sensors 2019, 19, 3789.

[4] Jafar Ali Ibrahim Syed Masood, M. Jeyaselvi, N. Senthamarai, S. Koteswari, M. Sathya, N.S. Kalyan Chakravarthy,Privacy preservation in wireless sensor network using energy efficient multipath routing for healthcare data,Measurement: Sensors,Volume 29,2023,100867,ISSN 2665-9174,

[5] Abdelkader Benelhouri, Hafida Idrissi-Saba, Jilali Antari, An evolutionary routing protocol for load balancing and QoS enhancement in IoT enabled heterogeneous WSNs,Simulation Modelling Practice and Theory,Volume 124,2023,102729,ISSN 1569-190X,

[6] Atul Pawar, Mihir Mondhe, Pranav Kharche, Shrutik Manwatkar & Ganesh Dhore, Energy-Efficient Cluster Formation for Wireless Sensor Networks Using Fuzzy Logic LNNS volume 334, pp. 657-665

[7] T. Meng, F. Wu, Z. Yang, G. Chen, A.V. Vasilakos, Spatial reusability-aware routing in multi-hop wireless networks, IEEE Trans. Comput. 65 (1) (2020) 244–255.

[8] A.S. Rostami, et al. Survey on clustering in heterogeneous and homogeneous wireless sensor networks J Supercomput, 74 (1) (2018), pp. 277-323

[9] M. Leinonen, M. Codreanu, M. Juntti, Distributed joint resource and routing optimization in wireless sensor networks via alternating direction method of multipliers, IEEE Trans. Wireless Commun. 12 (11) (2023) 5454–5467.

[10] S.J. Ramson, et al. Applications of wireless sensor networks—a survey Proceedings of the International Conference on Innovations in Electrical, Electronics, Instrumentation and Media Technology (ICEEIMT), IEEE (2017), pp. 325-329

[11] B.K. Maddali, Core network supported multicast routing protocol for wireless sensor networks, IET Wirel. Sensor Syst. 5 (4) (2015) 175–182.

[12] A. Shahraki, M. Geitle, Haugen A comparative node evaluation model for highly heterogeneous massive-scale Internet of Things-Mist networks Transactions on Emerging Telecommunications Technologies, John Wiley & Sons (2020)

[13] O. Basan, M. Jaseemuddin, A conflict analysis framework for QoS-aware routing in contention-based wireless mesh networks with beam forming antennas, IEEE Trans. Wireless Commun. 10 (10) (2019) 3267–3277.