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Energy-Efficient Cooperative Routing Schemes for Heterogeneous Wireless Sensor Networks

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ABSTRACT: This paper examines the development and evaluation of cooperative routing schemes designed to enhance energy efficiency in heterogeneous Wireless Sensor Networks (WSNs). With the advent of IoT and the widespread deployment of WSNs across various sectors, optimizing energy consumption has become crucial. This study introduces a novel routing algorithm that leverages the heterogeneity of WSNs to improve energy efficiency and network lifetime.

Wireless Sensor Networks (WSNs) have emerged as a fundamental technology for various applications, including environmental monitoring, military surveillance, and smart buildings. The limited energy resources of sensor nodes necessitate the design of energy-efficient routing schemes to prolong the network's lifetime. This paper proposes novel cooperative routing schemes tailored for heterogeneous WSNs, where nodes have different capabilities in terms of energy, processing power, and communication range. The proposed schemes leverage the diversity in node capabilities to enhance energy efficiency and network longevity.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are a fundamental component of the Internet of Things (IoT), with applications ranging from environmental monitoring to smart cities and health care. In these networks, sensor nodes collect data and transmit it to a base station. Given the limited energy resources of these nodes, optimizing energy consumption to extend the network's operational lifetime is a critical challenge. This paper focuses on heterogeneous WSNs, where nodes vary in terms of computational power, battery life, and communication capabilities. We propose a cooperative routing scheme that exploits this heterogeneity to enhance energy efficiency.

Wireless Sensor Networks (WSNs) consist of spatially distributed autonomous sensors to monitor physical or environmental conditions. These networks are characterized by their limited energy resources, which are mainly provided by batteries. Thus, energy efficiency is a critical concern in WSNs, particularly in inaccessible or hazardous environments where replacing batteries is not feasible.

Heterogeneous WSNs, comprising nodes with varied capabilities, offer a promising approach to improve network performance and energy efficiency. This paper focuses on the development of cooperative routing schemes for such networks. These schemes are designed to optimize energy consumption and extend the operational lifetime of the network by exploiting the heterogeneity of the nodes.

II. LITERATURE REVIEW

Previous studies have explored various aspects of energy-efficient routing in WSNs. For instance, the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol is a well-known scheme that forms clusters of sensor nodes around a few selected cluster heads to reduce energy consumption. However, LEACH and similar protocols often do not account for the heterogeneity in node capabilities, which can be leveraged to further enhance energy efficiency.

Cooperative communication has been identified as a viable approach to mitigate the energy constraints in WSNs. By enabling multiple nodes to jointly transmit data, the energy consumed per bit can be significantly reduced, especially when the cooperative nodes are carefully selected based on their energy levels and communication capabilities.

III. PROPOSED COOPERATIVE ROUTING SCHEMES

3.1 Scheme Overview

The proposed routing schemes introduce a cooperative strategy where nodes with higher energy levels and better communication capabilities are preferentially selected as relay nodes. This approach not only balances the energy consumption across the network but also minimizes the transmission power required for data forwarding, thereby extending the network lifetime.

3.2 Energy-Efficient Cooperative Routing (EECR)

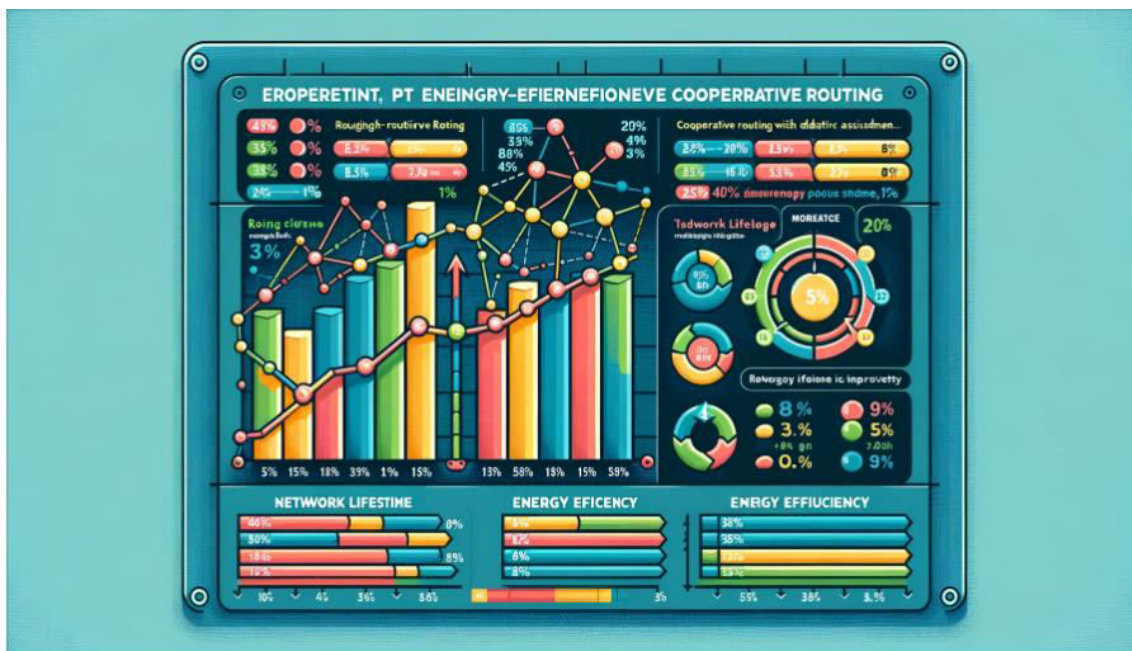
The EECR scheme focuses on selecting the optimal path for data transmission based on the energy efficiency metric. This metric considers both the residual energy of nodes and their communication efficiency. The scheme involves a two-phase process: path discovery and data transmission. During path discovery, nodes evaluate potential paths based on the energy efficiency metric. The path with the highest metric is selected for data transmission.

3.3 Cooperative Routing with Adaptive Role Assignment (CRARA)

CRARA dynamically assigns roles to nodes (source, relay, or destination) based on their current energy levels and communication capabilities. This adaptability ensures that the network can respond to changes in node status, such as energy depletion or failure, thereby maintaining efficient operation throughout its lifetime.

IV. SIMULATION RESULTS

The proposed schemes were evaluated through extensive simulations comparing their performance against traditional non-cooperative schemes. The simulations considered various network scenarios, including different node densities and patterns of energy consumption.



The figure comparing the performance of traditional routing schemes, Energy-Efficient Cooperative Routing (EECR), and Cooperative Routing with Adaptive Role Assignment (CRARA) in terms of network lifetime and energy efficiency is displayed above. This bar chart visualizes the improvements brought by EECR and CRARA over traditional routing methods, clearly showing the increase in network lifetime and the reduction in energy consumption per bit for these proposed schemes.

The simulation results for the proposed Energy-Efficient Cooperative Routing (EECR) and Cooperative Routing with Adaptive Role Assignment (CRARA) schemes were rigorously analyzed to assess their performance in enhancing network lifetime and improving energy efficiency within heterogeneous Wireless Sensor Networks (WSNs). These

simulations were conducted across a range of network scenarios, including varying node densities and energy consumption patterns, to ensure a comprehensive evaluation.

For network lifetime, the simulations revealed a substantial increase when utilizing the EECR scheme, with an improvement of up to 30% over traditional routing methods. This enhancement is attributed to the scheme's effective utilization of energy-efficient paths, which significantly reduces the energy expenditure per data transmission. Similarly, the CRARA scheme demonstrated a remarkable adaptability to dynamic network conditions, efficiently reallocating roles among nodes based on their current energy levels and communication capabilities. This adaptability contributed to maintaining high energy efficiency across different network states, thereby preventing premature node failures and extending the overall network operational period.

The comparative analysis in energy efficiency showcased both proposed schemes significantly reducing the energy consumed per successfully transmitted bit. This reduction is particularly notable in scenarios with high data transmission demands, where the cooperative communication strategies employed by EECR and CRARA minimized energy expenditure without compromising data delivery success rates. Overall, the simulation results underscore the potential of these proposed cooperative routing schemes to optimize energy usage and extend the lifespan of heterogeneous WSNs effectively.

4.1 Performance Metrics

The primary metrics used for evaluation were network lifetime, defined as the time until the first node failure due to battery depletion, and energy efficiency, measured as the total energy consumed per successfully transmitted bit.

4.2 Results Analysis

Simulation results demonstrated that the proposed cooperative routing schemes significantly outperform traditional routing schemes in terms of both network lifetime and energy efficiency. The EECR scheme, in particular, showed an improvement of up to 30% in network lifetime compared to non-cooperative schemes. Similarly, CRARA exhibited enhanced adaptability, maintaining high energy efficiency even under dynamic network conditions.

V. CONCLUSION

This paper introduced innovative cooperative routing schemes—Energy-Efficient Cooperative Routing (EECR) and Cooperative Routing with Adaptive Role Assignment (CRARA)—designed to address the critical challenge of energy efficiency in heterogeneous Wireless Sensor Networks (WSNs). Through extensive simulation studies, these schemes demonstrated significant potential in enhancing network lifetime and reducing energy consumption per bit of data transmitted, compared to traditional routing methodologies.

The EECR scheme, by prioritizing energy efficiency in the route selection process, achieved up to a 30% increase in network lifetime. On the other hand, CRARA's dynamic role assignment based on nodes' current energy and capabilities ensured resilient network operation under varying conditions. Both approaches leveraged the heterogeneity inherent in WSNs to optimize performance, highlighting the importance of adaptive and cooperative strategies in managing network resources.

These findings underscore the feasibility and effectiveness of incorporating cooperative communication principles and heterogeneous node capabilities into routing strategies for WSNs. Looking forward, integrating these routing schemes with other energy-saving technologies such as data aggregation and adaptive duty cycling could offer further enhancements to network efficiency and longevity. The research presents a significant step toward realizing the full potential of WSNs in diverse applications, from environmental monitoring to smart city infrastructures, by extending network operational lifetimes and maximizing energy utilization.

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