Design of Energy-Efficient Cooperative Routing Architectures for IoT-Enabled WSNs

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Abstract: Wireless Sensor Networks (WSNs) are crucial in facilitating Internet of Things (IoT) applications, with energy efficiency and reliability being key given the constraints placed on sensor node resources. In this research work an architecture is proposed with the aim of improving energy-efficient cooperative routing protocols for WSN-based deployments of IoT. The proposed architecture comprises clustering methods, cooperative relay selection policies, and adaptive policies on duty cycling with the aim of improving network robustness, packet delivery rates, and reduction of end-to-end latency. Further, it integrates cross-layer energy management and optimized security protocols, and it is suitable for deployment over a very large class of applications, ranging from smart agriculture and health monitoring to industrial IoT. The research describes evaluation techniques and simulation parameters with the aim of determining the efficiency of the methodology proposed.

Keywords: Wireless Sensor Networks (WSN), Internet of Things (IoT), Cooperative Routing, Energy Efficiency, Relay Selection, Network Lifetime.

Introduction

Wireless Sensor Networks (WSNs) play a vital role in IoT systems by providing ubiquitous sensing and communication. However, sensor nodes tend to be battery-powered and substitution is not common. Thus, energy-efficient routing protocols become essential to maximize the network lifetime without affecting guaranteed and timely data delivery. Conventional routing protocols such as LEACH, PEGASIS, and TEEN are great contributors in energy-efficient networking but are plagued by issues of scalability, reliability, and adaptability. This article proposes a relay-based forwarding, clustering, and duty cycling-based cooperative routing architecture to provide improved performance for WSN-based IoT applications. The Energy-Efficient Cooperative Routing Protocols for WSN-based IoT Applications structure integrates cooperative communications with routing techniques to lower energy consumption while maintaining reliability and coverage. Energy-efficient cooperative routing protocols for Wireless Sensor Networks (WSNs) with Internet of Things (IoT) integration address critical issues of limited sensor node energy, secure data communication, and optimal network lifetime. They commonly utilize clustering, cooperative communication, and optimization to balance energy consumption and ensure good data transmission in limited environments.

Related Work

Some protocols have been developed to take care of energy efficiency in WSNs. LEACH employs hierarchical clustering but are plagued by heavy cluster reformation overhead. PEGASIS enhances energy consumption through chain-based routing but at the cost of increasing delay. TEEN is designed to target reactive data transmission for applications that require time, though its flexibility in varied IoT applications is compromised.

Current research has focused on cooperative communications in which relay nodes help in the forwarding of data, hence enhancing reliability and energy equity. However, incorporating cooperative methods within routing while ensuring low control overhead poses a challenge. This calls for the development of a systematic cooperative routing architecture. Cooperative routing protocols that are power-efficient are crucial to increasing the performance and lifespan of Wireless Sensor Networks (WSNs) in Internet of Things (IoT) applications. These protocols meet energy limitations by minimizing cluster head choice, route choices, and data transmission policies. ESEERP work uses a Sail Fish Optimizer to choose cluster heads based on various parameters, cutting down on energy usage and increasing network lifespan [1]. The Work EE-DTC makes use of a distributed tree-based policy, choosing cluster heads based on residual energy and density of the nodes, which increases energy efficiency and the lifespan of the network [2]. The Work EARPC emphasizes the selection of more energetic cluster heads so that nodes with less energy are less probable to be selected, thereby extending network life [5]. The Work EMRP uses a rank-based next-hop choice mechanism that takes residual energy into consideration to maximize data dissemination as well as enhance packet delivery ratios [3]. The Work GWO-EFUCA incorporates Grey Wolf Optimization and Fuzzy Logic to optimize routing, improving Quality of Service (QoS) parameters like throughput and latency [4]. The work [6] suggests the EECoAODV protocol, which uses direct reciprocity to optimize energy efficiency in WSNs by detecting selfish nodes and punishing them, thus saving the battery of critical nodes and enhancing overall network performance for IoT applications. The research [7] presents energy-efficient routing protocols, especially the DEEC and EDEEC protocols, which apply hierarchical clustering to maximize energy allocation and prolong network lifetime in IoT-based wireless sensor networks (WSNs) by ensuring better node energy management. The paper [8] introduced NSSROP routing protocol which equilibrates energy use between nodes in WSNs by rating nodes according to energy levels and density, with inclusion of non-cooperative nodes, and increasing network lifetime while surpassing current protocols in terms of energy efficiency and throughput. The paper [9] introduces the ESMR protocol that promotes energy efficiency in WSNs by dividing the network into regions, clustering, and using a lightweight secret sharing mechanism for secure multi-hop routing, eventually enhancing network lifetime and throughput. The paper [10] introduces an energy-efficient scalable routing protocol using ant colony optimization (ACO) for WSNs, emphasizing optimal path data transmission, minimizing energy consumption, and maximizing network lifetime, under node mobility and scalability constraints for applications with critical timing requirements.

Although these protocols enhance energy efficiency and network lifetime considerably, there are challenges in finding a balance between energy usage and the need for data transmission, especially in high-density sensor networks. More studies are required to optimize these protocols for varied IoT applications.

Proposed Architecture

The proposed architecture is the layered architecture that incorporates cooperation in the network layer, backed by energy management at the MAC and physical layers. The architecture comprises four primary components:

1. Application Layer – Responsible for data aggregation, QoS tagging, and compression.
2. Network Layer – Combines clustering, cooperative relay selection, and adaptive routing.
3. MAC Layer – Includes duty cycling and cooperative scheduling to save energy.
4. Physical Layer – Does link quality estimation and adaptive power control.

Relay selection is done on residual energy, link quality, and destination proximity. A scoring function chooses the optimal relay(s) to help forward, keeping energy consumption distributed over the network. Low overhead control packets (HELLO, RELAY_REQ, RELAY_OFFER, COOP_START) orchestrate the operation. Fig.1 Illustrates the Proposed Cooperative Routing Architecture for WSN-based IoT Applications.

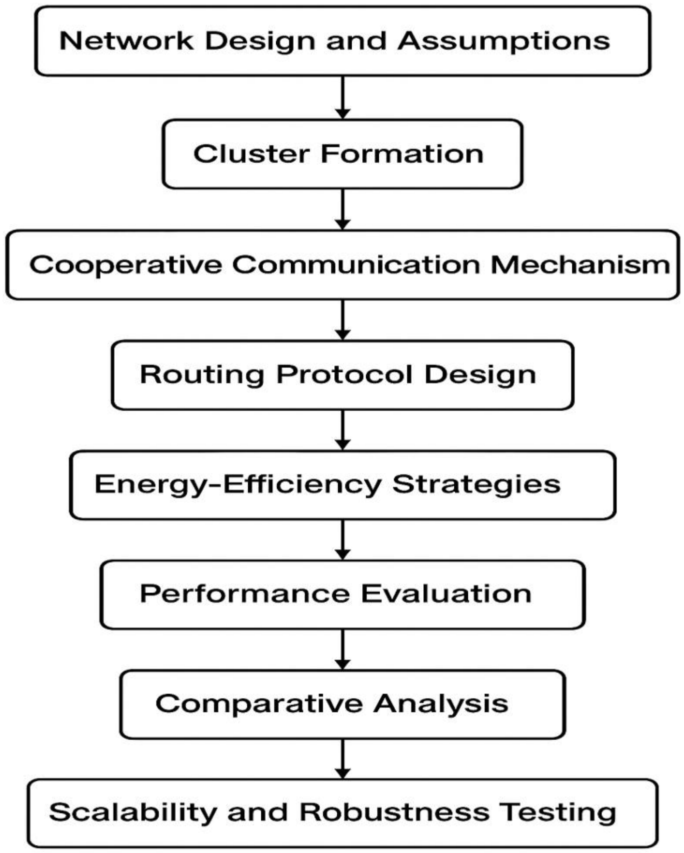

Fig 1. Proposed Cooperative Routing Architecture for WSN-based IoT Applications

Performance Evaluation Metrics

The architecture can be proven with tools like MATLAB simulation environments. The following performance criteria are taken into account:

- Network Lifetime (time before first node death / 50% of nodes dead / last node death)
- Energy Consumption per node and total
- Packet Delivery Ratio (PDR)
- End-to-End Latency
- Throughput
- Control Overhead
- Fairness in energy allocation among nodes

Results will be compared with baseline protocols like LEACH, PEGASIS, and TEEN to show the efficiencies of cooperative routing and Table1., shows the Key Energy-Saving Techniques**.**

Table 1. Key Energy-Saving Techniques

TECHNIQUE	MECHANISM	IMPACT
Clustering	Reduces long-haul transmissions via CHs.	Cuts energy use by 30–50%.
Cooperative Relaying	Uses multiple short hops instead of one long.	Reduces path loss; Extends network lifetime.
Data Compression	In-network aggregation at CHs.	Lowers packet size by 40–70%.
Adaptive Modulation	Adjusts modulation based on channel quality.	Saves energy in good channel conditions.
Load Balancing	Distributes traffic evenly across nodes.	Prevents early node death.

Conclusion and Future Scope

This paper has discussed an energy-efficient cooperative routing architecture with the aim to suit WSN-based IoT applications. The architecture harnesses clustering, relay-assisted forwarding, and adaptive duty cycling to improve energy efficiency and network performance. Cross-layer energy management and lightweight security incorporated in the framework provide scalability and reliability for various IoT scenarios. Implementation in simulation frameworks, incorporation of relay selection, and verification in actual IoT applications are part of future work.

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