International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2025: 7.089

Predictive Energy-Neutrality-Aware Adaptive Routing with Spectrum Availability and Node Failure Recovery in Energy Harvesting Cognitive Radio Wireless Sensor Networks

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Abstract: ***Energy Harvesting Cognitive Radio Wireless Sensor Networks (EHCRWSNs) have emerged as a promising technology for sustainable and reliable wireless communication by integrating energy harvesting capabilities with dynamic spectrum access. However, maintaining network stability and reliable data transmission remains challenging due to fluctuating harvested energy, limited battery capacity, dynamic spectrum availability, and unexpected sensor node failures. Existing energy-aware routing approaches primarily consider residual energy and current network conditions, which may result in inefficient route selection, premature node depletion, increased transmission delay, and frequent network disconnections. To address these challenges, this paper proposes a Predictive Energy-Neutrality-Aware Adaptive Routing (PENAR) mechanism that jointly considers future energy availability, spectrum availability, and node failure conditions during route selection. The proposed mechanism estimates the energy requirements and harvested energy of sensor nodes to identify energy-neutral routing opportunities. Furthermore, spectrum-aware route selection is incorporated to select suitable communication paths based on available licensed spectrum and primary user activity. A proactive node failure recovery mechanism is also introduced to identify energy-depleted or potentially failing nodes and establish alternative routing paths to maintain network connectivity. The proposed approach aims to improve energy utilization, extend network lifetime, enhance packet delivery reliability, and reduce end-to-end communication delay. Its performance will be evaluated through simulation by comparing it with existing energy-efficient routing protocols using metrics such as residual energy, energy consumption, network lifetime, packet delivery ratio, end-to-end delay, and primary user collision probability. The proposed mechanism is expected to provide an adaptive and energy-efficient routing solution for reliable communication in EHCRWSN environments.***

Keywords: Energy Harvesting, Cognitive Radio Wireless Sensor Networks, Energy-Neutrality, Predictive Energy Management, Adaptive Routing, Spectrum Availability, Node Failure Recovery, Network Lifetime

1. Introduction

The rapid development of wireless communication technologies and Internet of Things (IoT) applications has increased the demand for reliable, energy-efficient, and sustainable communication networks. Wireless Sensor Networks (WSNs) play a significant role in various applications, including environmental monitoring, industrial automation, healthcare monitoring, smart agriculture, and surveillance systems. These networks consist of several sensor nodes that collect information from their surroundings and transmit the collected data to a base station or sink node. However, sensor nodes generally operate with limited battery capacity, making energy consumption one of the major challenges affecting network performance and lifetime. Frequent battery replacement is also difficult in large-scale and remotely deployed networks. Therefore, energy-efficient communication and sustainable energy management have become important research considerations in WSNs.

Energy harvesting technology provides a promising solution to the energy limitations of conventional WSNs by enabling sensor nodes to obtain energy from environmental sources such as solar, wind, thermal, and radio frequency energy. Energy Harvesting Wireless Sensor Networks (EHWSNs) utilize harvested energy to support continuous network operations and reduce dependence on conventional battery replacement. However, the availability of harvested energy is often intermittent and unpredictable due to environmental variations. Consequently, sensor nodes may experience fluctuations in their available energy, which can affect data transmission, routing decisions, and network connectivity. Energy-neutral operation, in which the energy consumed by a sensor node is balanced by the energy harvested over time, is therefore an important consideration for extending network lifetime and maintaining sustainable communication.

In addition to energy limitations, spectrum scarcity is another significant challenge in wireless communication networks. Cognitive Radio (CR) technology addresses this problem by allowing Secondary Users (SUs) to access temporarily unused licensed spectrum bands without causing harmful interference to Primary Users (PUs). Cognitive Radio Wireless Sensor Networks (CRWSNs) combine wireless sensor network capabilities with dynamic spectrum access to improve spectrum utilization and communication flexibility. When energy harvesting and cognitive radio technologies are integrated, Energy Harvesting Cognitive Radio Wireless Sensor Networks (EHCRWSNs) provide a sustainable communication framework with improved energy availability and efficient spectrum utilization. However, the integration of energy harvesting and cognitive radio introduces additional challenges in routing, as communication decisions must consider both energy availability and spectrum availability.

Routing is a critical network operation that determines the communication path between source sensor nodes and the sink node. Conventional routing protocols generally select routes based on parameters such as hop count, distance, link

quality, or residual energy. However, these parameters may not be sufficient for EHCRWSN environments because the energy availability of sensor nodes changes dynamically, while spectrum availability is influenced by primary user activities. A routing path selected based only on the current residual energy may contain nodes that are expected to experience energy depletion in the near future. Similarly, a route selected without considering spectrum availability may become unavailable when a primary user reoccupies the licensed channel. Such situations can result in repeated route discovery, packet loss, increased communication delay, and inefficient energy utilization.

Another important challenge in EHCRWSNs is sensor node failure. Node failures may occur due to energy depletion, hardware malfunction, communication link degradation, or environmental conditions. The failure of an intermediate node can interrupt the established communication path and affect the delivery of data packets to the sink node. Traditional reactive routing mechanisms generally initiate route recovery after detecting a communication failure. However, repeated route reconstruction can increase control overhead, energy consumption, and end-to-end delay. Therefore, identifying nodes that are approaching energy depletion and establishing alternative communication paths before complete failure can help improve network reliability and communication continuity.

Existing energy-aware routing mechanisms have investigated residual-energy-based route selection, energy harvesting management, spectrum-aware communication, and network reliability. Nevertheless, jointly addressing future energy availability, dynamic spectrum conditions, and proactive node failure recovery within a unified adaptive routing framework remains an important research direction. In particular, routing decisions based only on instantaneous residual energy may not adequately represent the future energy sustainability of sensor nodes. Similarly, the independent consideration of energy management and spectrum availability may lead to routing decisions that are unsuitable under changing network conditions. These challenges motivate the development of a predictive energy-neutrality-aware adaptive routing mechanism for EHCRWSNs.

To address these issues, this paper proposes a Predictive Energy-Neutrality-Aware Adaptive Routing (PENAR) mechanism for Energy Harvesting Cognitive Radio Wireless Sensor Networks. The proposed mechanism considers the predicted energy availability, residual energy, and energy consumption requirements of sensor nodes during route selection. It incorporates spectrum availability and primary user activity to identify suitable communication channels and establish reliable routing paths. Furthermore, a proactive node failure recovery mechanism is designed to identify nodes with a high risk of energy depletion and select alternative routes before communication is interrupted. By jointly considering energy sustainability, spectrum availability, and node failure conditions, the proposed mechanism aims to improve routing efficiency and maintain reliable data transmission in EHCRWSN environments.

The major contributions of this research are summarized as follows:

- Predictive Energy Management: A predictive energy-management mechanism is proposed to estimate the future energy availability of sensor nodes by considering residual energy, harvested energy, and expected energy consumption.
- Energy-Neutrality-Aware Routing: An adaptive routing strategy is developed to select communication paths by considering the energy sustainability of sensor nodes and their ability to maintain energy-neutral operation.
- Spectrum-Aware Route Selection: Spectrum availability and primary user activity are incorporated into routing decisions to improve channel utilization and reduce communication interruptions.
- Proactive Node Failure Recovery: A node failure detection and route recovery mechanism is introduced to identify potentially energy-depleted nodes and establish alternative communication paths.
- Performance Evaluation: The proposed mechanism is evaluated using network performance metrics, including energy consumption, network lifetime, packet delivery ratio, end-to-end delay, residual energy, and primary user collision probability.

The remainder of this paper is organized as follows. Section 2 presents the related work and existing energy-management and routing approaches. Section 3 describes the network model and problem formulation. Section 4 explains the proposed PENAR mechanism and its algorithmic design. Section 5 presents the simulation setup and performance evaluation. Section 6 discusses the experimental results and comparative analysis. Finally, Section 7 concludes the paper and identifies possible directions for future research.

2. Energy Management in Energy Harvesting Wireless Sensor Networks

Energy management is one of the major research challenges in Energy Harvesting Wireless Sensor Networks (EHWSNs), where sensor nodes depend on renewable energy sources to maintain continuous network operations. Since harvested energy varies with environmental conditions, efficient energy management is essential for balancing energy consumption and energy availability.

Movva et al. (2022) proposed an energy-aware cluster-based routing protocol with an adaptive semi-synchronized Medium Access Control (MAC) mechanism for energy harvesting wireless sensor networks. Their approach combines cluster-based routing and MAC scheduling to improve energy utilization and extend network lifetime. The study addresses energy management through coordinated communication and scheduling. However, further investigation is needed into predictive energy availability and its integration with spectrum-aware routing in cognitive radio environments.

Sun et al. (2022) investigated Age of Information (AoI) minimization in radio-frequency energy-harvesting cognitive radio networks. Their approach considers energy causality and spectrum constraints and formulates the problem as a partially observable Markov decision process. Dynamic programming is used to optimize sensing and information-

update decisions. Although the study jointly considers energy harvesting and spectrum access, its primary objective is information freshness rather than multi-hop routing and proactive node failure recovery.

Wang et al. (2024) proposed a multi-hop uneven clustering routing protocol using Simultaneous Wireless Information and Power Transfer (SWIPT) for energy harvesting cognitive radio sensor networks. Their approach introduces an energy-state function to represent dynamic energy variations and addresses energy imbalance among sensor nodes. This work is particularly relevant because it jointly considers energy harvesting, clustering, and spectrum availability. However, predictive energy-neutrality-based route selection and proactive node failure recovery provide further aspects to investigate.

2.1 Spectrum-Aware Routing in Cognitive Radio Wireless Sensor Networks

Cognitive Radio Wireless Sensor Networks (CRWSNs) improve spectrum utilization by allowing Secondary Users (SUs) to access available licensed channels without causing harmful interference to Primary Users (PUs). Spectrum availability changes dynamically according to primary user activities, making channel selection an important factor in routing decisions.

Joon and Tomar (2022) proposed an Energy Aware Q-learning AODV (EAQ-AODV) routing protocol for cognitive radio sensor networks. The method uses a Q-learning-based reward mechanism for cluster-head selection and incorporates residual energy, common channel availability, hop count, licensed channels, communication range, and trust factor into routing decisions. Their work demonstrates the importance of combining energy awareness and spectrum-related parameters in cognitive radio routing. However, future energy harvesting prediction and energy-neutrality-based routing require further investigation in EHCRWSN environments.

A study by Wang et al. (2024) investigated multi-hop clustering routing with imperfect spectrum sensing in EH-CRSNs. The authors addressed the limitation of conventional clustering protocols that assume perfect spectrum sensing. Their approach considers SWIPT and imperfect spectrum sensing to improve the practicality of energy harvesting cognitive radio communication. Nevertheless, predictive energy management and proactive recovery from energy-related node failures remain important aspects to investigate.

A recent study by the authors of the Node Grade Factor-based Multi-Path Routing (NGFMR) protocol (2025) proposed a multi-path routing mechanism for cognitive sensor networks. The protocol considers sink distance, spectrum availability, communication cost, and node delay to improve quality of service. Its multi-path approach is relevant to reliable communication. However, the integration of predicted harvested energy and energy-neutrality constraints into route selection is a separate research direction.

2.2 Energy-Aware Routing in Energy Harvesting Cognitive Radio Wireless Sensor Networks

Recent research has focused on integrating energy harvesting and cognitive radio technologies to develop sustainable and reliable routing protocols. The integration requires routing mechanisms to consider energy consumption, harvested energy, spectrum sensing, and communication quality simultaneously.

Mortada et al. (2025) proposed a Location Information-Based Routing Protocol (LIBRO) for Energy Harvesting Cognitive Radio Wireless Sensor Networks. The proposed approach adapts LIBRO to cognitive radio operations by incorporating spectrum sensing and energy harvesting capabilities. A multi-objective optimization technique is employed to balance primary user collision probability, energy consumption, packet delivery latency, and network throughput. The study demonstrates the potential of location-based routing for achieving sustainable network operation. However, investigating predictive energy availability and proactive node failure recovery alongside adaptive spectrum-aware routing remains a possible research direction.

Wang et al. (2024) developed a multi-hop uneven clustering routing protocol based on SWIPT and energy harvesting for EH-CRSNs. Their method uses an energy-state function to monitor variations in node energy and considers dynamic spectrum availability, neighbouring nodes, and energy conditions during cluster-head and relay selection. The protocol also introduces intra-cluster and inter-cluster energy transfer mechanisms to reduce transmission failures caused by energy depletion. However, the authors identify limitations associated with perfect spectrum-sensing assumptions and finite battery capacity. They also identify predictive maintenance, including fault diagnosis and early warning, as future research directions. These observations provide motivation for investigating predictive energy management and proactive failure recovery in EHCRWSNs.

2.3 Node Failure Detection and Fault-Tolerant Routing

Node failure is a significant challenge in wireless sensor networks because the failure of an intermediate node can interrupt communication between source nodes and the sink. Energy depletion, hardware malfunction, and environmental conditions are among the factors that contribute to node failures. Therefore, fault-tolerant routing mechanisms are required to maintain network connectivity and reliable data transmission.

Swathi et al. (2024) proposed an energy-efficient and fault-tolerant routing mechanism using an optimizer-based deep learning model for wireless sensor networks. Their proposed FT-RR protocol uses Bernoulli's rule to identify reliable nodes and establish routing paths towards the base station. The mechanism focuses on preventing network failures and improving reliability through energy-aware route establishment. Simulation results demonstrate improvements in packet loss rate, end-to-end latency, and network lifetime. However, the study focuses on conventional WSN environments, leaving the integration of energy harvesting

prediction and dynamic spectrum availability in EHCRWSNs as an area for further investigation.

Prasad et al. (2025) proposed a Node Grade Factor-based Multi-Path Routing (NGFMR) protocol for cognitive wireless sensor networks. Their approach considers node distance, residual energy, spectrum availability, communication cost, and node delay to establish multiple node-disjoint communication paths. The use of alternative paths helps improve data delivery reliability and distribute network traffic. However, the integration of future harvested-energy prediction and energy-neutrality constraints into the multi-path routing process requires further investigation

3. System Model and Problem Formulation

The proposed Predictive Energy-Neutrality-Aware Adaptive Routing (PENAR) mechanism is designed for Energy Harvesting Cognitive Radio Wireless Sensor Networks (EHCRWSNs). The system considers dynamic energy availability, energy consumption, spectrum availability, and node failure conditions during routing decisions. The objective is to establish reliable and energy-efficient communication paths while maintaining sustainable network operation.

The proposed system integrates five major components: network modelling, energy harvesting, energy consumption, spectrum availability, and node failure prediction. These components are jointly considered to formulate an adaptive routing optimization problem.

3.1 Network Model

The proposed EHCRWSN is represented by a directed graph (G=(V,E)), where (V={v_1,v_2,\ldots,v_N}) represents a set of (N) wireless sensor nodes and (E) represents the available communication links between neighbouring nodes. The network consists of energy harvesting secondary user (SU) sensor nodes, primary users (PUs), and a sink node.

Each sensor node is equipped with a rechargeable energy storage unit, a wireless communication module, and cognitive radio capabilities. The sensor nodes collect environmental information and transmit the collected data to the sink node through single-hop or multi-hop communication paths. The sensor nodes harvest energy from renewable sources such as solar, thermal, or radio frequency energy to support their communication and sensing operations.

The following assumptions are considered in the proposed network model:

The network consists of a fixed number of sensor nodes deployed within a predefined monitoring area.

Each sensor node has a limited battery capacity and an energy harvesting capability.

Sensor nodes communicate through wireless links using available licensed spectrum bands.

Primary users have priority over licensed spectrum channels, while secondary users utilize the channels when they are available.

Each sensor node maintains information about its residual energy, harvested energy, energy consumption, and neighbouring nodes.

Sensor nodes periodically exchange control information to support routing and node condition monitoring.

The sink node has sufficient computational and energy resources to collect network information and coordinate routing decisions.

Sensor nodes may experience energy depletion, communication link degradation, or hardware-related failures.

The routing path from a source node to the sink node is represented as:
P=(v_s,v_1,v_2,\ldots,v_d)

where (v_s) represents the source node and (v_d) represents the destination sink node.

The proposed PENAR mechanism selects an appropriate routing path by considering the predicted energy availability, spectrum availability, communication delay, and node failure probability of the intermediate sensor nodes.

4. System Model and Problem Formulation

The proposed Predictive Energy-Neutrality-Aware Adaptive Routing (PENAR) mechanism is designed for Energy Harvesting Cognitive Radio Wireless Sensor Networks (EHCRWSNs). The system considers energy harvesting, energy consumption, spectrum availability, and node failure conditions during routing decisions. The main objective is to establish reliable communication paths while improving energy efficiency and network lifetime.

4.1 Network Model

The proposed network consists of multiple wireless sensor nodes, primary users (PUs), secondary users (SUs), and a sink node. Each sensor node is equipped with energy harvesting capabilities, a rechargeable battery, and a cognitive radio communication module. Sensor nodes collect environmental information and transmit the collected data to the sink through single-hop or multi-hop communication paths.

The network considers dynamic energy availability, wireless communication links, and licensed spectrum channels. Each sensor node maintains information about its residual energy, harvested energy, neighbouring nodes, and communication link quality. The proposed PENAR mechanism uses this information to select suitable routing paths.

4.2 Energy Harvesting Model

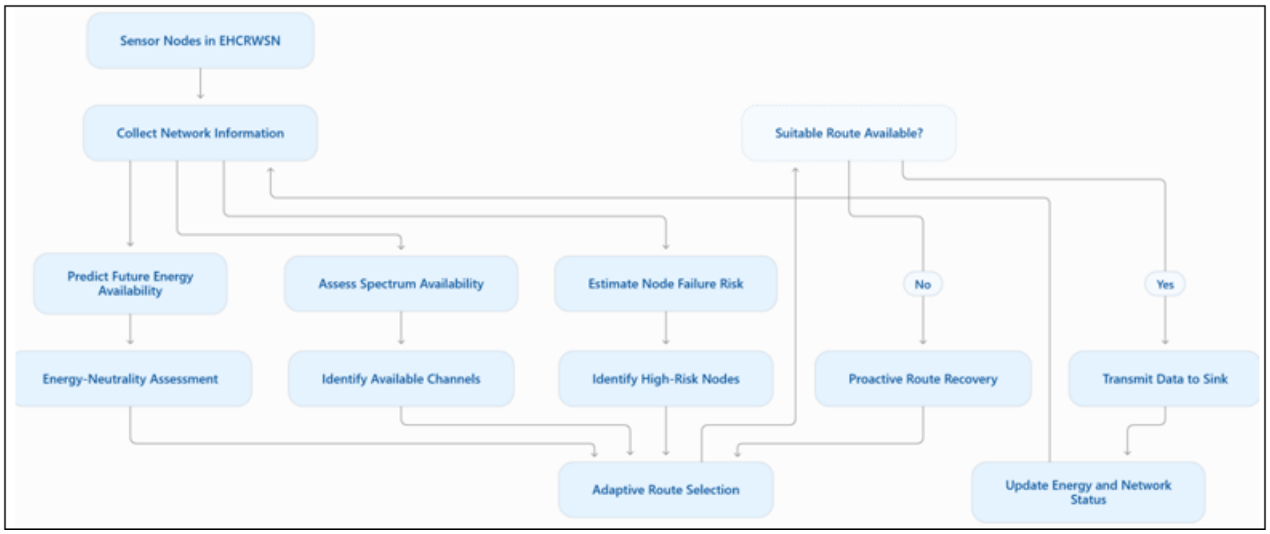
Energy harvesting enables sensor nodes to obtain renewable energy from environmental sources such as solar, thermal,

wind, and radio frequency energy. However, harvested energy varies depending on environmental conditions and source availability.

The proposed PENAR mechanism considers both the current residual energy and future harvested energy of sensor nodes. Historical energy harvesting information is used to estimate future energy availability. This predictive approach helps identify nodes that may experience energy shortages and supports sustainable routing decisions.

The energy-neutrality principle is also considered to ensure that energy consumption is balanced with available harvested energy over an observation period.

4.3 Energy Consumption Model



Sensor nodes consume energy during data transmission, data reception, spectrum sensing, processing, and control communication. Energy consumption also depends on packet size, transmission distance, and communication conditions.

The proposed mechanism considers these energy-consuming activities while evaluating the suitability of sensor nodes for routing. By estimating the energy requirements of each node, PENAR aims to avoid unnecessary energy consumption and improve overall network energy utilization.

4.4 Spectrum Availability Model

Cognitive radio technology enables secondary users to access temporarily available licensed spectrum channels without causing harmful interference to primary users.

The proposed PENAR mechanism performs spectrum availability assessment before selecting communication paths. It considers the availability of common channels between neighbouring sensor nodes and the activity of primary users.

When a primary user occupies the selected channel, the secondary user must stop transmission and switch to another available channel. This mechanism aims to reduce communication interruptions and improve spectrum utilization.

4.5 Node Failure Model

Sensor node failures may occur due to energy depletion, hardware malfunction, and communication link degradation. Such failures can interrupt established routing paths and affect successful data transmission.

The proposed PENAR mechanism estimates node failure risk by considering predicted energy availability, energy requirements, and communication link quality. Nodes identified as having a high risk of failure are avoided during route selection whenever suitable alternatives are available.

4.5.1 Proactive Route Recovery

When an intermediate node is identified as having a high failure risk, the mechanism searches for an alternative neighbouring node with sufficient energy and available spectrum. An alternative routing path is established to maintain communication between the source node and the sink.

This proactive recovery approach aims to reduce packet loss, communication interruptions, and repeated route discovery.

4.6 Problem Formulation

The main objective of the proposed PENAR mechanism is to select an energy-efficient, spectrum-aware, and reliable communication path between source sensor nodes and the sink node.

Conventional routing approaches may select paths based on current residual energy, distance, or hop count. However, these parameters may not adequately address future energy availability, dynamic spectrum conditions, and potential node failures.

Therefore, the proposed routing problem considers four major optimization objectives:

- **Minimization of energy consumption:** Reduce the total energy required for data transmission, reception, and spectrum sensing.

- **Minimization of end-to-end delay:** Reduce the time required for successful data delivery from source nodes to the sink.
- **Minimization of node failure risk:** Avoid nodes that are likely to experience energy depletion or communication failures.
- **Maximization of spectrum availability:** Select communication paths with suitable available spectrum channels while protecting primary users.

The proposed mechanism considers energy availability, predicted energy requirements, energy neutrality, spectrum availability, network connectivity, and node failure risk as routing constraints.

By jointly considering these factors, PENAR aims to improve energy sustainability, communication reliability, and network lifetime in EHCRWSN environments.

5. Conclusion

Energy harvesting cognitive radio wireless sensor networks (EHCRWSNs) face several challenges, including fluctuating energy availability, dynamic spectrum conditions, and unexpected node failures. These challenges can affect network lifetime, routing efficiency, and reliable data transmission.

To address these issues, this paper proposes Predictive Energy-Neutrality-Aware Adaptive Routing (PENAR), an approach that considers predicted energy availability, spectrum conditions, and node failure risk during route selection. The proposed mechanism aims to improve routing reliability by selecting suitable forwarding nodes and supporting proactive route recovery when network conditions change.

The proposed approach provides a framework for energy-aware and spectrum-aware routing in EHCRWSNs. Its effectiveness will be evaluated through simulation by comparing it with existing routing protocols using metrics such as energy consumption, network lifetime, packet delivery ratio, end-to-end delay, and node failure rate. The results will help determine its suitability for reliable and sustainable EHCRWSN communication.

6. Future Enhancement

The proposed PENAR approach can be extended in several directions to improve its adaptability and performance. Machine learning techniques can be incorporated to improve energy harvesting prediction and identify potential node failures under changing network conditions. Advanced spectrum prediction methods can also be explored to improve channel selection and reduce interruptions caused by primary user activity.

Furthermore, the approach can be extended to large-scale and heterogeneous sensor networks with different energy harvesting capabilities and communication requirements. Real-world implementation using energy harvesting sensor hardware can help evaluate its performance under practical environmental conditions. Future work may also investigate multi-objective optimization techniques to achieve a better balance among energy efficiency, routing reliability, spectrum utilization, and end-to-end delay.

Important for publication: Since PENAR is currently a proposed method and you have not yet completed implementation and simulation, these sections avoid claiming that it has already improved network performance. Once your experiments are complete, we can revise the conclusion to include your actual results and numerical comparisons.

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