

An Equiangular Wedge-Based Energy Hole Detection and Prevention Strategy for Wireless Sensor Networks [†]

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Abstract

Clustering is the process in Wireless Sensor Networks (WSNs) used to make the routing process efficient and for selecting the optimized path for sending the data, considering metrics like energy consumption and node distance. Many clustering routing algorithms are addressed for selecting the best path. Among them, Progressive Index Modulation in Intra cluster and Inter cluster routing algorithms uses the index shifting technique for distributing the cluster head role among the sensor nodes. Because of static node deployment, WSN causes the energy hole formation. Hence, this manuscript proposes an Equiangular Wedge Energy Hole Detection (EWED) algorithm for multi-hop WSNs to detect and prevent energy holes. In the hole detection phase, the network region is split into equiangular wedges, where each node serves as a generating point in the geometry to create a Region of Interest (ROI). Finally, the simulation results reveal that the EWED achieves higher network performance compared to the existing clustering routing algorithms.

Keywords: multi-hop WSN; cluster-based routing; progressive index modulation; energy hole; equiangular wedges; node repositioning

1. Introduction

Wireless Sensor Networks (WSNs) have become a fundamental technology in applying Internet of Things (IoT) concepts across diverse sectors such as manufacturing, smart cities, agriculture, and healthcare [1]. These networks consist of numerous independent sensors—such as those measuring temperature or pressure—that collect environmental information and transmit it to a base station (BS) [2]. Although WSNs serve a wide range of purposes, their operational lifespan is often limited by challenges like energy consumption. Designing wide-area WSNs requires attention to three key aspects: partitioning the coverage area, optimizing routing strategies, and managing the energy usage of relay nodes [3]. To achieve this, the network is commonly divided into clusters, with each cluster having a designated cluster head (CH) responsible for gathering data from Cluster Members (CMs) and forwarding it to the sink node or another CH [4].

To extend the operational lifetime of Wireless Sensor Networks (WSNs) and enhance energy efficiency, various clustering strategies are commonly applied, such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and its multi-hop variant (MLEACH) [5]. In flat routing, nodes communicate directly with one another, whereas hierarchical routing



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involves transmitting data first to cluster heads (CHs), which then forward it to the base station (BS) or sink [6]. Selecting efficient routes is critical to prevent early energy depletion and avoid creating dead zones near the sink node [7]. To resolve this issue, multi-hop WSN uses the ICIC energy reduction technique [8]. Another approach, duty cycling, regulates the active and inactive periods of nodes, while Time Division Multiple Access (TDMA) protocols schedule transmission intervals to further conserve energy [9]. However, unreliable data can render nodes ineffective, prompting the use of Index Modulation (IM) methods [10]. Despite their benefits, IM requires complex maximum likelihood estimation, which can burden nodes. To overcome this, a new ICIC-based channel selection method called PIM-ICIC was introduced for multi-hop WSNs [11]. This approach employs an index-shift broadcasting scheme, ensuring a fairer distribution of CH responsibilities among sensor nodes. A new location-free geographic routing strategy called Proactive Approach to Circumvent Holes (PA_tCH) was introduced in [12] to avoid hole areas and provide paths to the target node in WSNs. A novel Unequal Clustering Energy Hole Avoidance (UCEHA) technique helps to tackle hot spot difficulties in cognitive radio WSNs [13]. This method divided the network into clusters and selected CHs according to the node energy, communication channels, neighbours, and sink distance. Neural Network-based Improved LEACH (NN-ILEACH) using the Energy Hole Removing Mechanism (EHORM) helps to avoid energy holes and enhance energy efficiency [14]. However, total energy use remained high compared to LEACH, and the network scalability was low when increasing the network size.

This manuscript proposes the EWED algorithm for multi-hop WSNs to detect and prevent energy holes. Each node acts as a generating point in the geometry to form the ROI during the hole detection phase, which divides the network region into equiangular wedges. The circumcentre and circumradius about the sensing range are then calculated by forming equiangular triangles among nearby nodes. The number of supported mobile nodes with their ideal deployment places is determined to repair the observed energy gaps when the circumradius is larger than the sensing radius. The network topology is changed when the hole region has been identified and is restored using mobile nodes that are compatible.

2. Materials and Methods

2.1. Problem Statement

Since sensor nodes are deployed randomly across the Region of Interest (ROI), Wireless Sensor Networks (WSNs) often operate in a dynamic and uncertain environment. Excessive energy consumption leads to gaps in coverage and isolated nodes. The central aim of this research is to accurately measure the extent of these coverage gaps within the ROI, which is crucial for assessing damaged areas during natural disasters. Such insights enable routing protocols to adapt paths and reposition relay nodes effectively to repair the network.

2.2. Energy Hole Detection and Prevention Algorithm

This section describes the energy hole detection and prevention algorithm to identify and determine the holes region in the ROI. It consists of ROI creation using a polar coordinate system, energy hole detection, and energy hole healing.

2.2.1. ROI Creation Using Polar Coordinate System and Wedge Pairing

This work uses a polar coordinate system to generate a local equiangular wedge. First, the network region for each static node is divided into equiangular wedges, with the assumption that all nodes know the coordinates of their neighbouring nodes, as illustrated in Figure 1. These wedges are split into sectors using concentric rings or coronas centred on

their respective regions. Each wedge and corona intersection forms a distinct sector, with its own wedge and corona identifiers. The ROI construction ensures that each node in the coordinate system belongs to exactly one sector and is aware of its sector's identification.

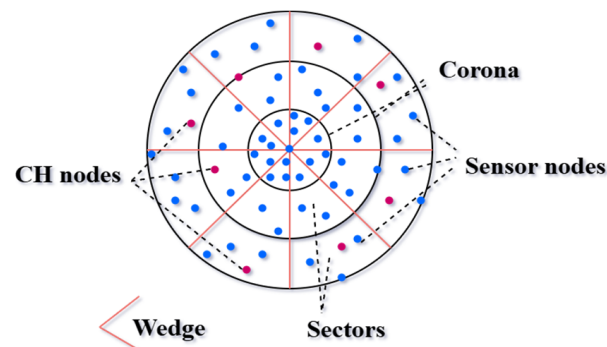


Figure 1. Example of equiangular wedge-based ROI creation.

The energy holes in the network can deteriorate its performance. Consequently, the energy hole issue must be resolved to optimize network longevity. Subsequent to the data transmission phase of each round, the proposed hole detection and healing approach evaluates the average energy of each sector. This occurs because a decrease in the average energy of any sector results in an energy deficit in that segment of the network. As a result, the wedge containing the low-energy sector merges with an adjacent wedge.

2.2.2. Energy Hole Detection

This study estimates the energy holes by creating equiangular triangles with the circumcentre and circumradius. Consider C_0 as the circumcenter of the three nodes, $S_{(i,j,k)}$, and the distance $d(S_i, C_0)$ as the circumradius R , as portrayed in Figure 2. Also, assume that all sensor nodes' sensing range is a circle with a radius of R_s , and R_c is the communication range. If $R_s > R$, then there does not exist an energy hole between the three nodes; otherwise, there must exist energy holes between the three nodes. When C_0 is not covered by node S , there must exist energy holes and the hole region needs to be estimated.

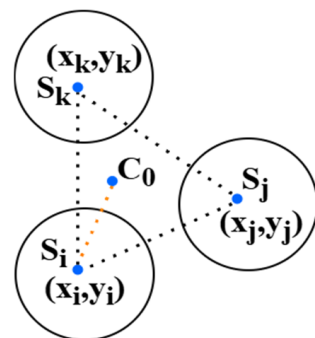


Figure 2. Formation of equiangular triangle by nodes.

2.2.3. Energy Hole Healing

To heal the energy holes in the network, the healing process is described in Algorithm 1.

Thus, this repositioning approach ensures that relay nodes are optimally placed to reduce energy holes, enhance the network lifespan, and maintain efficient communication.

Algorithm 1: Energy Hole Healing Process by Deploying Supported Nodes

Input: Node's positions

Output: Coordinates of supported mobile nodes to heal energy hole

1. Start the process.
2. Divide the region into equiangular triangles and estimate how many supported sensor nodes are needed in each triangle.
3. If only one supported node is required:
 - 3.1 Place it at the centre of the triangle.
4. If more than one supported node is required:
 - 4.1 Place the first node at the centre of the triangle.
 - 4.2 Measure and rank the distances from the centre to each triangle vertex.
 - 4.3 For the second node:
 - 4.3.1 If the shortest distance is within a defined range, place the node halfway between the centre and the nearest vertex.
 - 4.3.2 Otherwise, place it at a fixed distance from the centre.
 - 4.4 Continue assigning additional nodes using the same logic.
5. If four or more supported nodes are needed:
 - 5.1 Place one node at the midpoint of the line connecting the centre to one of the triangle's sides.
 - 5.2 Continue assigning the remaining nodes using the same method.
6. End the process.

3. Results and Discussion

This section assesses the efficiency of the EWED and compares it to other algorithms, such as PIM-ICIC [11], PA_tCH [12], UCEHA [13], and NN-ILEACH [14]. The simulation is performed using the MATLAB 2019b. A comparison is made using the Packet Delivery Ratio (PDR), energy consumption and utilization, number of dead nodes, and end-to-end delay (E2D).

3.1. Packet Delivery Ratio

It defines the number of packets delivered to the sink node per round. Using several CRAs with varying node counts, Figure 3 compares the total number of packets transmitted to the sink node across 1000 cycles. Figure 4 depicts the total number of packets transmitted to the sink node, utilizing various CRAs across a varying number of rounds with 400 nodes.

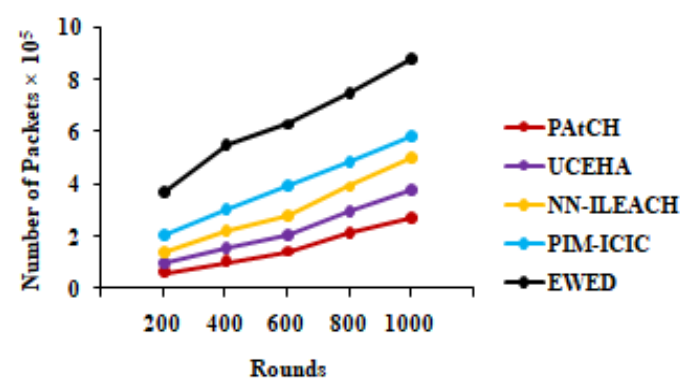


Figure 3. Total packets delivered to the sink node vs. no of rounds for 400 nodes.

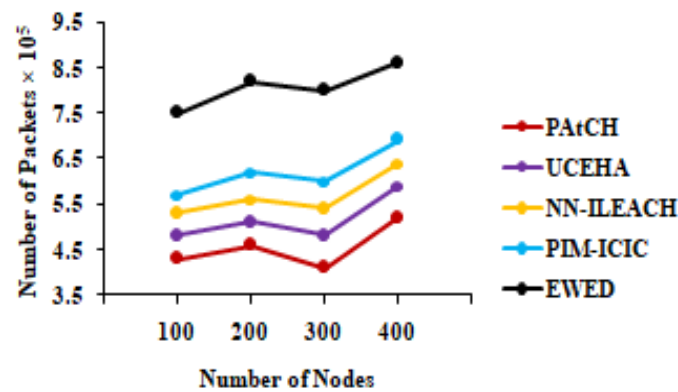


Figure 4. Total packets delivered to sink node vs. no of nodes for 1000 rounds.

3.2. Network Energy Consumption and Utilization

Network Energy Consumption is the ratio of the energy utilized by the nodes to the total starting energy available for node deployment. Figure 5 compares the network energy use of various CRAs using different rounds for 400 nodes. Figure 6 compares the network energy usage of several CRAs for data transmission during node deployment, with varying numbers of nodes across 1000 rounds.

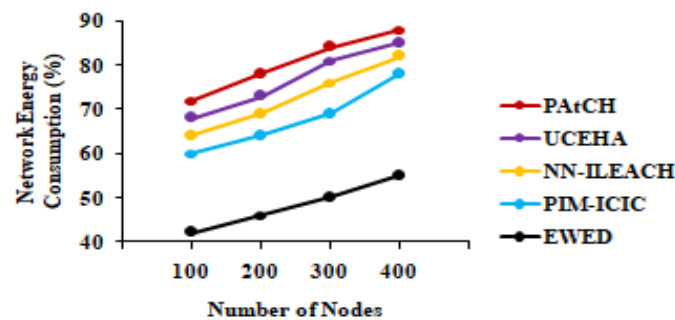


Figure 5. Network energy utilization in data transmission vs. no of nodes for 1000 rounds.

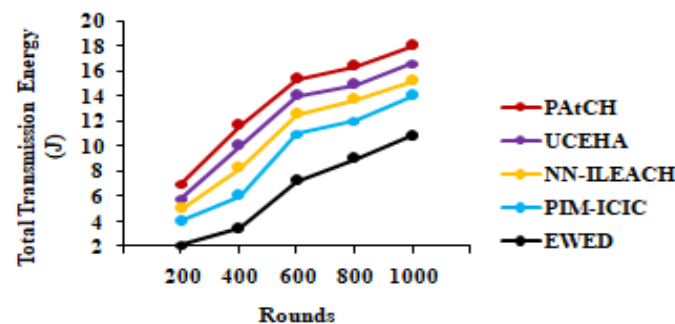


Figure 6. Network energy consumption vs. no of rounds for 400 nodes.

3.3. Number of Dead Nodes

It refers to the total number of nodes that have exhausted their energy and cannot continue to work. Figure 7 compares dead nodes in the network using various CRAs with variable node counts over 1000 rounds. Figure 8 depicts the comparison of dead nodes in various CRAs throughout many rounds of 400 nodes.

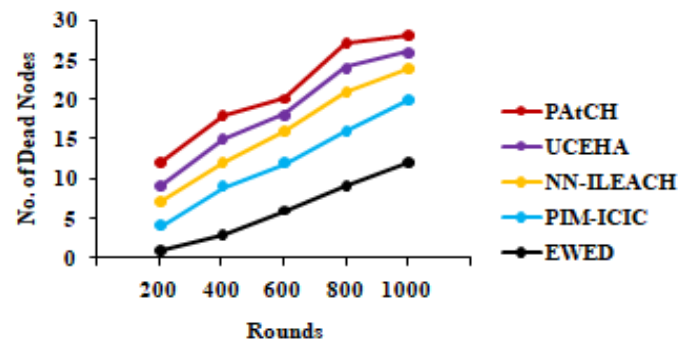


Figure 7. No. of dead nodes vs. no of rounds for 400 nodes.

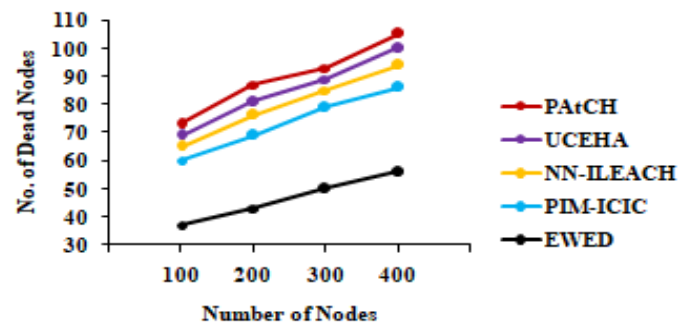


Figure 8. No. of dead nodes vs. no of nodes for 1000 rounds.

3.4. E2D

It is the duration taken for forwarding information between the source and the destination nodes within the network. The E2D values of many CRAs for various numbers of rounds are shown in Figure 9.

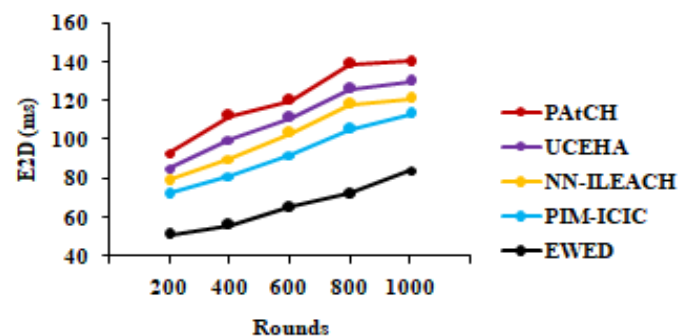


Figure 9. End-to-end delay vs. no of rounds for 400 nodes.

4. Conclusions

In this paper, the EWED algorithm was proposed for multi-hop WSNs to detect and prevent energy holes. It leveraged the equiangular wedge-based coordinate system for hole detection and relay positioning-based hole healing approaches. During the hole identification phase, the network area was segmented into equiangular wedges, and equiangular triangles were constructed between surrounding nodes. After locating and recovering the hole region with these nodes, the network topology was updated. Finally, simulation results proved that the EWED achieved a PDR of 8.8×10^5 packets, consumed 10.8 J of energy, had an E2E delay of 84 ms, and had 12 dead nodes over 1000 rounds. With 400 nodes in the network, the EWED achieved a PDR of 8.6×10^5 packets, consumed 55% of the energy, and had 56 dead nodes.

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