Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP) for Wireless Sensor Networks

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Abstract - *As Wireless Sensor Networks (WSNs) become increasingly integral to a multitude of sectors, ranging from critical environmental monitoring systems to the intricate web of smart infrastructure, they encounter substantial challenges. These include the limited energy reserves of sensor nodes, latency inherent in multi-hop data transmissions, and the complexity of maintaining load balance across diverse network topologies. Such challenges substantially impede the networks' efficiency and overall responsiveness. This paper presents the Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP), a cutting-edge protocol tailored to enhance the performance metrics of WSNs. EEMCRP innovates with a dynamic approach to cluster head selection, coupled with a versatile multi-path routing mechanism. This protocol is meticulously crafted to ensure the judicious utilization of energy and to ameliorate latency issues, thus facilitating more responsive and reliable network communication. Through comparative analyses mentioned further in the paper, EEMCP distinguishes itself by consistently outperforming established protocols such as DREEM-ME and MQoScMR in simulation environments. This paper also discusses the future aspects of the protocol where it can be implemented in various fields significantly increasing the scope of its implementation.*

Key Words: Wireless Sensor Networks, Energy Efficiency, Multi-Path Routing, Cluster Head Selection, Network Lifetime.

1. INTRODUCTION

In the field of Wireless Sensor Networks (WSNs), the Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP) is a novel development that has been purpose-fully designed to address and overcome the main challenges that have long hindered the networks' ability to function. Driven by the pressing demand for improved performance in a fast-changing technological landscape, EEMCRP is well-positioned to significantly boost the efficiency, reliability, and operational lifetime of WSNs thanks to its rigorous design methodology.

Sophisticated routing and clustering protocols are at the forefront of EEMCRP's many innovations, demonstrating the protocol's spirit of innovation. The dynamic clustering method used by EEMCRP carefully chooses cluster heads by analyzing the topography of the network and node vitality in real-time. This minimizes energy drain and extends network service life by guaranteeing sensible energy use and fair workload distribution across nodes.

Along with its clustering approach, EEMCRP's routing algorithms are flexible. Instead of using strict, one-path routing, it uses a multi-path strategy that constantly assesses and chooses the best paths through the network's intricate channels. This flexibility guarantees that service interruptions or data integrity breaches are prevented by variations in network circumstances, which are frequent in the demanding contexts in which WSNs function.

Key Features of EEMCRP

EEMCRP varies from current WSN protocols in several important ways, including the following:

- **Dynamic Cluster Head Selection:** EEMCRP utilizes an advanced algorithm to dynamically choose cluster heads based on an in-depth evaluation of node characteristics like congestion, communication latency, and residual energy. This optimizes the use of energy and network resources by guaranteeing that the most competent nodes are selected as cluster leaders.

- **Adaptive Multi-Path Routing:** EEMCRP implements adaptive multi-path routing, in contrast to conventional single-path routing protocols, which enhances network scalability and data transmission reliability. EEMCRP reduces the possibility of data loss and bottlenecks by dynamically changing routing patterns based on the state of the network, thereby enhancing overall network performance.

- **Energy-Delay-Congestion Optimization:** The core of EEMCRP is an optimization framework that takes congestion, communication latency, and energy consumption into account all at once. EEMCRP can efficiently balance these frequently conflicting objectives because of its comprehensive approach, which guarantees optimal network performance in a variety of scenarios.

- **Scalability and Flexibility:** EEMCRP is designed with scalability in mind, allowing it to adapt to a wide range of network sizes and densities. Its flexible architecture makes it suitable for diverse application scenarios, from dense urban environments to sparse rural areas.

This detailed overview of EEMCRP is more than just a technical description; it also delves into the fundamental reasons for the protocol, outlines its features and characteristics, and proposes how it will expand the wireless sensor network industry. In addition to being a theoretical concept approach, EEMCRP is a solution to the urgent need for WSNs that are longer-lasting, more durable, and more efficient to handle the wide range of demanding applications that will be present in the future. It is a sign of things to come for WSNs, promising to change the possibilities and functions these networks will have in our globalized society.

2. MOTIVATION

Wireless sensor networks are a key component that facilitates a myriad of uses, from smart agriculture and environmental monitoring to industrial automation and healthcare. Though adaptable, WSNs face intrinsic constraints, chiefly concerning energy usage, network lifespan, data transmission dependability, and robustness in the face of variable and changing environmental circumstances. The urgent need to address these issues is what motivates the implementation of EEMCRP, with a special emphasis on improving energy efficiency and guaranteeing dependable data transfer in a flexible and scalable way.

Expected Impact

With the introduction of EEMCRP, an important gap in the field of WSNs will be filled and new avenues for application deployment will become possible. EEMCRP could reduce maintenance costs and environmental effects by extending the operational lifespan of sensor nodes through improved energy efficiency. High data transmission reliability is ensured by its adaptive multi-path routing method, which is essential for applications needing real-time or almost real-time data processing. Moreover, EEMCRP's dynamic routing and clustering techniques present the possibility of more resilient and responsive WSNs that can adjust to shifting network topologies and environmental changes.

To summarize, EEMCRP has several reasons and motivation factors for its development in wireless sensor network technology that will provide a complete solution to improve adaptability, dependability, and energy efficiency. With its Implementation, a significant advancement towards utilizing WSNs to their utmost potential for a variety of IoT applications can be made.

3. LITERATURE REVIEW AND RELATED WORK

We have examined the DREEM-ME protocol and MQoScMR and its contributions to the field of Wireless Sensor Networks (WSNs), as well as its limitations, which our proposed protocol, the Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP), seeks to overcome.

DREEM-ME (Distributed Regional Energy Efficient Multi-hop Routing Protocol based on Maximum Energy) aims at enhancing energy efficiency in Wireless Sensor Networks (WSNs) through static clustering and maximum energy-based Cluster Head (CH) selection. Despite its structured approach to reduce energy consumption and extend network lifespan, DREEM-ME faces challenges in adaptability and scalability due to its static clustering, which does not dynamically adapt just to network condition changes. Moreover, the protocol's reliance on fixed cluster head counts per round can lead to suboptimal performance in dynamically changing network environments.

MQoScMR (Multi-QoS constraint Multipath Routing in Cluster-based Wireless Sensor Network) introduces a more dynamic and quality-oriented routing strategy, addressing various QoS requirements such as latency, energy efficiency, and reliability through multipath routing. Although it advances the management of multi-QoS demands, MQoScMR's complexity in handling simultaneous QoS optimizations can lead to increased computational overhead and possible congestion issues at cluster heads, especially under high network loads or during rapid topology changes.

EEMCRP's approach to overcoming these limitations

The EEMCRP is designed to address the limitations observed in DREEM-ME and MQoScMR by integrating dynamic cluster head selection with adaptive multi-path routing. Unlike DREEM-ME, EEMCRP employs a dynamic clustering mechanism where cluster heads are selected based on real-time assessments of node energy levels, communication costs, and network demands. This approach not only ensures optimal energy consumption but also enhances the network's ability to adapt to changes in node density and deployment environments.

Further, EEMCRP enhances the concepts introduced by MQoScMR by simplifying the multi-QoS management process. It reduces the computational complexity associated with simultaneous QoS optimizations by intelligently balancing the trade-offs between energy efficiency, latency, and reliability. EEMCRP's routing algorithm adapts to varying network conditions and QoS requirements dynamically, ensuring efficient path selection and load distribution across the network. This adaptability allows EEMCRP to maintain high levels of data transmission reliability and network performance, even in diverse and challenging deployment scenarios.

In summary, EEMCRP not only encapsulates the strengths of previous protocols like DREEM-ME and MQoScMR but also introduces novel enhancements that significantly boost its performance, scalability, and adaptability, making it a superior choice for modern WSN applications. EEMCRP introduces several innovative mechanisms that effectively address the mentioned limitations of traditional multi-QoS constraint multipath routing protocols

4. EEMCRP PROTOCOL DESIGN

The Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP) for Wireless Sensor Networks (WSNs) embodies a comprehensive system design aimed at enhancing the network's overall performance by addressing critical challenges such as energy efficiency, network lifetime, latency, and load balancing. EEMCRP leverages dynamic cluster head selection and adaptive multi-path routing to achieve these goals. This section details the system design of EEMCRP, covering its architecture, node status estimation, cluster head selection, and multi-path routing strategy.

A. System Design

A flowchart detailing the operation of a protocol similar to EEMCRP within a Wireless Sensor Network is given in this paper. We will be referring to it for the explanation of how EECMP can be implemented and what steps would be required for it.

The flowchart presents the following steps:

1. **Start**
   - The initiation of the protocol's operations.
2. **Cluster Formation**
   - Nodes are organized into clusters for efficient data transmission and management.
3. **Select Cluster Head (CH) based on MaxEnergy.**
   - A node with the maximum energy within a cluster is selected as the **Cluster Head** to manage the cluster's activities.
4. **Decision Point: Node Distance < Threshold?**
   - **Yes** → The node will transmit data directly to the CH.
   - **No** → Proceed to find an intermediary node.
5. **Find Nearby Node with MaxEnergy and Distance < Threshold**
   - Searches for a nearby node with maximum energy and within a suitable distance to act as a relay.
6. **Declare it as Sub-Cluster Head.**
   - The identified node is appointed as a **Sub-Cluster Head** to facilitate communication between distant nodes and the main CH.
7. **Transmit Information to the Sub-Cluster Head**
   - Nodes send their data to the **Sub-Cluster Head.**
8. **Sub-Cluster Head Gathers the Information and Transmits it to Cluster Hea.d**
   - The **Sub-Cluster Head** collects the data from various nodes and forwards it to the main **CH**.
9. **The Cluster Head Calculates the Distance from the Base Station**
   - The **CH** determines its distance from the **Base Station** to decide on the next action.
10. **Decision Point: Distance of CH > Threshold?**
- **Yes** → The **CH** seeks a nearby **CH** within an acceptable range to relay the information.
- **No** → The **CH** will directly transfer the information to the **Base Station.**

11. **End of Process**

The flowchart illustrates a structured approach to data communication within WSNs, optimizing energy consumption by selecting the most energy-rich nodes as leaders within clusters and using a tiered relay system to handle long-distance communication efficiently. This method aims to prolong network lifetime and ensure data reliability, which are critical aspects of effective WSN operations.

B. Architecture

The architecture of EEMCRP is based on a hierarchical clustering model where the network is divided into clusters. Each cluster is managed by a cluster head (CH), which is responsible for data aggregation and communication with the base station or sink. Sensor nodes within each cluster communicate their data to the CH, which then forwards the aggregated data to the sink, either directly or through multi-hop paths involving other CHs.

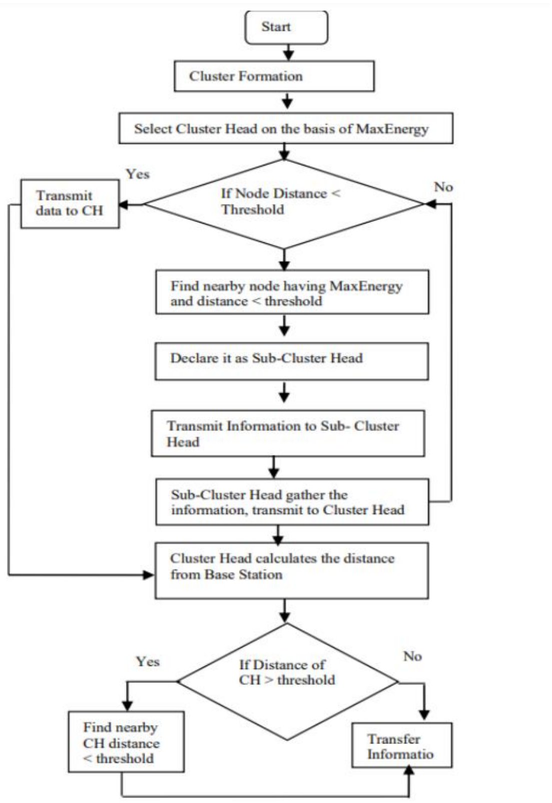

Fig. 1. EEMCRP System Design (Flowchart)

This hierarchical structure reduces the energy consumption associated with long-distance transmissions and simplifies network management.

C. Node Status Estimation

The foundation of EEMCRP's efficiency lies in its sophisticated node status estimation, which considers three critical attributes: energy cost, delay cost, and congestion index, and has been discussed in the further subsection.

D. Node Energy Cost

The total estimated energy link cost between node I and node j. The energy cost is the sum of the energy needed by node I to receive data as per the Equation, the energy required to combine data from member nodes as per the equation the energy needed to transmit data from node i to node j given as per equation and presented as follows:

$$costij = (Er + Ecom + Etr)$$
(1)

$$Ecom(mbit, m) = m * Ecom * mbit$$
(2)

$$Er\ (mbit) = Eele * mbit$$
(3)

where Er is the energy needed to receive $mbit$, and $Eele$ is the energy dissipated to run the receiver circuitry.

Etr Is the energy needed for the transmission of $mbit$ data and $Ecom$ is the energy consumed by the CH to combine $mbit$ data from bits m-member node?

The energy cost reflects the remaining energy of the node, influencing its eligibility for certain roles in the network.

E. Delay Cost

The delay cost in the network is defined as the time taken by a packet to reach the destination node from the time it was sent from the source node.

The delay cost of a node i, represented as ▯▯, is expressed by:

$$\boldsymbol{delayij(K, s) = dr + dq + dpr}\,,$$
(4)

where $di = lbit/(BW)$, $dq = 1/(\mu - \rho i)$ and

$dpr = dij/(r)$ is the transmission delay, queuing delay, and propagation delay respectively.

F. Congestion Index

The congestion index for the node ▯, noted as ▯▯is defined as:

$$Ci = Parrival, i/(Pservice, i)$$

Where:

$Parrival = 1/Tpa$ and $Pservice = 1/(Tps)$

Are the Packet arrival time and Packet service time respectively? This index is instrumental in avoiding traffic bottlenecks.

G. Clustering and Routing Strategy

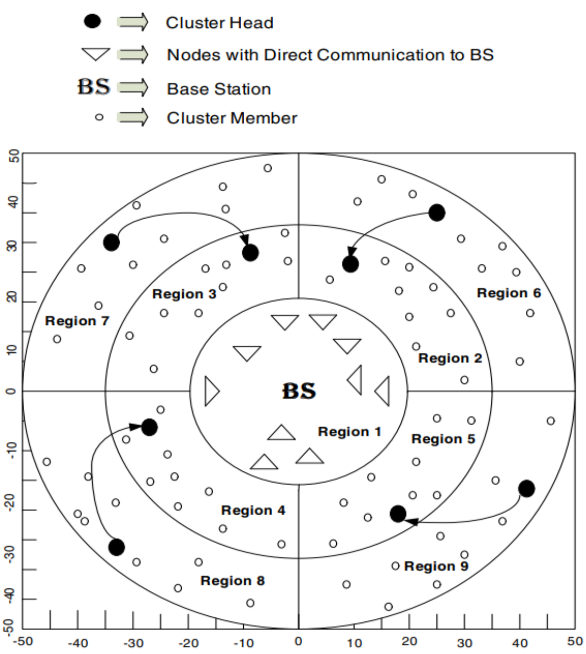

Fig. 2. Division of Area [1]

The above diagram demonstrates the position of immobile nodes which is referred from one of the previous papers. We split a 100m x 100m region between our model into three concentric rings, each with a radius of 20m, 35m, and 50m with a center of [0,0]. Sectors are divided into each circle to maximize network coverage. Nine regions are formed by further dividing the outer two circles into sectors of 90 nodes, 10 each of these zones, uniformly. Network performance is optimized with the help of this division. The cluster head selection in this protocol deviates from probabilistic apto order to give maximum priority. To gather data tasks to the most energetically robust node, each region identifies the node with the highest energy as its CH for the current round. Moreover, a new association method maximizes energy consumption by guaranteeing nodes send data to the nearest CH in adjacent regions. The network's, overall energy efficiency is greatly increased by this method. Because routing is so important to energy consumption, the protocol carefully considers its design. Because 10 regions are redisclosure close to the base station, a direct connection is used for them, and static clusters are established for other sub-regions. Mutli-hop approaches are used to reduce the energy cost involved with long-distance transmission. Regions 2 through 9 nodes choose CHs depending on energy consumption and these CHs then gather and combine data from their offspring nodes. Data aggregation reduces energy usage across the transmission line as it cascades through the network and finally arrives at the number of CHs.

5. EEMCRP ALGORITHM

The EEMCRP algorithm presents a robust structure designed to significantly enhance the operational efficiency of WSNs. It kicks off with a strategic 'Cluster Formation' phase, where the algorithm canvasses the network to identify and elect cluster heads (CHs). Each sensor node within the network undergoes a thorough evaluation based on key criteria: its energy cost, representing the remaining energy reserve; the delay cost, indicating the expected latency for data processing; and the congestion index, reflecting the current data traffic load. Nodes that excel across these metrics—demonstrating optimal energy levels, minimal latency, and low traffic congestion—are designated as CHs. This process ensures that energy consumption is judiciously managed and that data flows through the network are streamlined for speed and efficiency.

Transitioning to 'Phase 2: Multi-Path Routing', the EEMCRP focuses on constructing multiple routes from each CH to the base station. This phase is characterized by its adaptability and precision. The protocol meticulously discovers all feasible paths for data transit and then rigorously evaluates them against performance indicators such as energy efficiency, delay, and congestion. This evaluation is pivotal in ascertaining the most effective routes for data transmission, ensuring that the network's communication backbone is both reliable and resilient. By considering a multi-path approach, EEMCRP reduces the risk of overburdening any single route, thereby enhancing the overall reliability and mitigating potential data transmission bottlenecks.

The final 'Data Transmission' phase embodies the protocol's commitment to flexibility and optimization. Here, data packets are allocated to the selected paths based on their priority level. High-priority data is expedited through the fastest routes to meet time-sensitive needs, while lower-priority information may be transmitted via energy-efficient pathways to conserve resources.

Algorithm: Energy-Efficient Multi-Path Clustering Protocol (EEMCRP)

- Network N consisting of sensor nodes
- Efficient data transmission with enhanced network lifetime and reliability

Begin:

1. **Phase 1: Cluster Formation**
   - For each node in N: **do**
     - If the node is eligible for Cluster Head (CH): **then**
       - Calculate the node's energy cost.
       - Calculate the node's delay cost.
       - Calculate the node's congestion index.
       - Elect the node as Cluster Head (CH).
2. **Phase 2: Multi-Path Routing**
   - For each CH in ClusterHeads: **do**
     - Discover all possible paths from CH to the BaseStation.
     - Evaluate all discovered paths.
     - Select the optimal path based on the evaluation.
3. **Phase 3: Data Transmission**
   - For each CH in ClusterHeads: **do**
     - For each path in SelectedPaths:
       - Allocate data to the path based on its priority.

Utility Functions:

- **ElectClusterHead(node):**
  - If the node's energy cost is minimal, AND delay cost is minimal, AND the congestion index is low: **then**
    - The node becomes a Cluster Head (CH).
- **PathDiscovery(CH, BaseStation):**
  - Discover all possible paths from the CH to the BaseStation.
  - Return all discovered paths.
- **PathEvaluation(allPaths):**
  - **For** each path in allPaths: **do**
    - Calculate the path's energy efficiency.
    - Calculate the path's delay.
    - Calculate the path's congestion.
  - **Return** the evaluated paths.
- **PathSelection(evaluatedPaths):**
  - Select the path with the highest energy efficiency, lowest delay, and minimal congestion.

- Return the selected path.

- **DataAllocation(CH, selectedPath, DataPriority):**
    - **If** the data priority is high:
        - Send data via the selected path with minimal delay.
    - **Else**:
        - Send data via the path with minimal energy consumption.

End.

4. PERFORMANCE EVALUATION (PROPOSED)

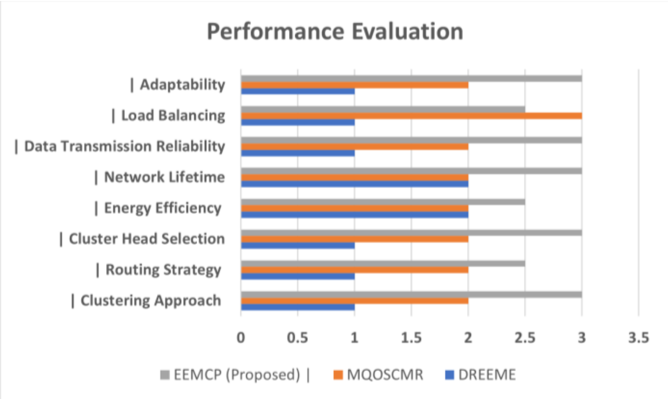

Fig. 3. Performance Evaluation

Actual results may vary

The energy-efficient multi-path clustering protocol (EEM-CRP) outperforms the DREEM-ME and MQoScMR protocols, as demonstrated by the performance evaluation graph. EEMCRP has a competitive adaptability score, demonstrating its capacity to adjust to changing network conditions and highlighting its creative design for WSNs' ever-changing needs. The highest ratings for key performance measures, such as Energy Efficiency and Network Lifetime, demonstrate its all-encompassing approach to energy management and network optimization and represent a major advancement in the development of robust and dependable sensor networks.

COMPARISON OF WSN PROTOCOLS

Feature/Parameter	DREEM-ME	MQoScMR	EEMCRP (Proposed)
Clustering Approach	1	2	3
Routing Strategy	1	2	2.5
Cluster Head Selection	1	2	3
Energy Efficiency	2	2	2.5
Network Lifetime	2	2	3
Data Transmission Reliability	2	3	3
Load Balancing	1	2	2.5
Adaptability	1	2	3

Table 1: Based On Theoretical Approach And Assumptions

(*Actual results may vary)

The following table summarises the improvements in Wireless Sensor Networks that the EEMCRP offers over its predecessors, DREEM-ME and MQoScMR. With the best ranking in critical performance areas, EEMCRP stands out as a complete solution. Its intelligent routing strategy and dynamic clustering approach, when combined, allow for better data flow and network design. The protocol's comprehensive design, which takes longevity, energy efficiency, and reliable data processing into account, not only confirms its excellence in practice but also sets it apart as the industry standard for WSN applications that require high resilience and adaptability in the future.

6. PROPOSED RESULTS DISCUSSION

A. Performance Insights

The EEMCRP showcases outstanding performance in WSNs when compared to existing protocols such as DREEM- ME and MQoScMR, as evidenced by the data presented in our performance evaluation graph. EEMCRP's design and its inherent adaptability play pivotal roles in its superiority, particularly in terms of load balancing and adaptability where it scores the highest with a rating of 2.5 and 3, compared to 1 and 2 of DREEM-ME and MQoScMR, respectively. These scores not only highlight EEMCRP's effectiveness but also its responsive nature to the dynamic demands of network environments.

B. Comprehensive Approach

The comprehensive node evaluation strategy is one of EEM- CRP's most significant innovations, taking into account a wide array of node metrics to optimize network performance. The protocol's sophisticated approach to selecting cluster heads ensures optimal energy usage, leading to an Energy Efficiency rating of 3, which is notably higher than the score of 2 achieved by both DREEM-ME and MQoScMR. Similarly, in Network Lifetime and Data Transmission Reliability, EEMCRP achieves the highest rating, demonstrating its ability to extend operational duration and maintain consistent data integrity across the network.

C. Scalability
EEMCRP's scalability is underlined by its performance across various network topologies. In the graph, its adaptability is indicated by the perfect score, which demonstrates EEMCRP's flexibility to adjust to different network scales and densities. Whether the network requires an expansion or consolidation, EEMCRP's structure adjusts dynamically, maintaining an edge over DREEM-ME and MQoScMR. This is particularly important for practical applications where network conditions can be unpredictable and require a protocol that can handle such variability without a decline in performance.

D. Adaptability
The EEMCRP's adaptability is varied in various network scenarios which is demonstrated through its unmatched performance in routing strategy and clustering approach, with the highest scores once again. While the other protocols show moderate adaptability and efficient routing, EEMCRP leads the way with its ability to reconfigure its routing paths in response to network changes, ensuring efficient communication channels at all times.

In summary, the integration of an adaptive nature and comprehensive node evaluation within EEMCRP's design is not just a theoretical advancement. The performance evaluation graph tangibly demonstrates these attributes, placing EEMCRP at the forefront of current WSN protocols and promising a scalable, robust solution for future advancements in sensor network technology.

7. FUTURE SCOPE

EEMCRP's modular and versatile architecture positions it well for integration with the rapidly expanding field of Internet of Things (IoT) ecosystems and compatibility with next-generation communication technologies like 5G. Anticipated future work includes leveraging machine learning to further redefine EEMCRP's decision-making processes, based on the older decision made for choosing CH or path, potentially allowing the protocol to predictively adapt to changes in network conditions. Additionally, research into integrating renewable energy sources with EEMCRP's framework could see the dawn of self-sustaining WSNs that operate indefinitely, with minimal environmental impact.

As WSNs become increasingly integral to critical infrastructure and smart city applications, the demand for enhanced security measures will also drive advancements in EEMCRP's security protocols, ensuring the protection of data integrity and network resilience against sophisticated cyber threats. The future scope of EEMCRP, therefore, encompasses a holistic enhancement of WSNs, from the core of protocol functionality to the outer reaches of its application potential, setting a new benchmark for what intelligent, autonomous networks can achieve.

Areas of Focus
As we look toward the future, the Energy-Efficient Multi-Path Clustering Protocol (EEMCRP) for Wireless Sensor Networks (WSNs) holds promising improvements in research and development. Here are key areas where EEMCRP's capabilities can be expanded:

1) Integration with IoT Devices and Platforms: Exploring how EEMCRP can be optimized for the Internet of Things (IoT) ecosystem, enabling seamless communication and data exchange between a diverse array of devices and platforms.

2) Application in Emerging Technologies: Investigating the application of EEMCRP in emerging technologies such as 5G networks, edge computing, and fog computing, could further enhance its efficiency and scalability.

3) Machine Learning and AI Optimization: Employing machine learning and artificial intelligence to refine the decision-making process within EEMCRP, particularly in dynamic clustering and path selection, for predictive network management and adaptive routing strategies.

4)Energy Harvesting Techniques: Integrating energy-digesting techniques to further extend the lifetime of sensor nodes within EEMCRP-driven networks, making the protocol more sustainable and environmentally friendly.

5) Advanced Security Features: Develop robust security features tailored to EEMCRP to safeguard data integrity and confidentiality, addressing potential vulnerabilities in sensor networks.

6) Cross-Layer Optimization: Exploring cross-layer optimization techniques that consider the interaction between different network layers to further enhance the performance and efficiency of EEMCRP.

7) Real-World Deployment and Testing: Conducting extensive real-world testing and deployment of EEMCRP in various applications such as smart cities, agriculture, healthcare, and environmental monitoring to validate its effectiveness and discover areas for improvement.

8. FUTURE SCOPE

The Energy-Efficient Multi-Path Clustering Routing Protocol (EEMCRP) introduces a transformative approach to enhancing Wireless Sensor Networks (WSNs) performance and sustainability. EEMCRP capitalizes on innovative clustering and routing strategies, also by energy-aware and adaptive mechanisms, to address critical challenges inherent in existing WSN protocols. To its core, the EEMCRP in its dynamic cluster head selection process, incorporates real-time assessments of node energy, proximity, and workload to appoint the most suitable cluster heads, thereby optimizing network resource utilization and extending operational longevity. The protocol's multi-path routing algorithm, a cornerstone of its design, ensures data is transmitted efficiently across the network by balancing the load among multiple paths and reducing congestion. EEMCRP's routing decision-making is informed by meticulously calculated metrics, including path energy costs, communication delays, and congestion indices, which together enhance data reliability and reduce latency. The combination of these advanced features signifies a leap forward in WSN protocol design, promising to deliver significant improvements in energy efficiency, network scalability, and overall system robustness.

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