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Improving the Energy Efficiency of LEACH Protocol in WSNs

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ABSTRACT
Currently, Wireless Sensor Networks (WSNs) have been applied in various domains to collect and monitor comprehensive information about environments or objects. To extend the operational duration of WSNs, a multitude of energy-saving techniques have emerged, with clustering protocols being the most effective. The earliest clustering protocol to appear was the LEACH protocol, which, despite its significant enhancement of network performance, had notable drawbacks. This paper summarizes various methods for optimizing the LEACH protocol, including: techniques for optimizing cluster head selection, advancements in inter-cluster routing, and improvements in clustering strategies.
Keywords: *WSNs, clustering protocol, LEACH, energy efficiency*

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I. INTRODUCTION

In the evolution of Wireless Sensor Networks (WSNs), we have witnessed a transformation from simple data collection systems to sophisticated intelligent monitoring platforms. With advancements in microelectronics, communication technology, and computing power, WSNs are playing an increasingly important role in various fields such as environmental monitoring, industrial automation, healthcare, and military applications. The vast number of nodes in WSNs, spread widely, enable comprehensive coverage and meticulous monitoring of target areas. Their capabilities in data collection and processing are crucial for understanding and controlling complex systems.

Within WSNs, clustering protocols, exemplified by LEACH [1], play a pivotal role. The LEACH protocol organizes sensor nodes into clusters and elects cluster heads within each cluster to be responsible for data collection and transmission. This approach effectively reduces communication overhead among nodes, thereby significantly enhancing the network's energy efficiency and lifespan. This hierarchical management not only reduces the latency of data transmission but also strengthens the network's scalability and flexibility, which is of great importance for the long-term stable operation of WSNs.

However, the LEACH protocol has also revealed some drawbacks in practical applications. For instance, its cluster head election mechanism may lead to certain nodes frequently becoming cluster heads, which accelerates the energy consumption of these nodes and shortens the overall lifespan of the network. Additionally, the strategies of the LEACH protocol in inter-cluster routing and data transmission are relatively simple and may not be adaptable to complex network environments and diverse communication requirements.

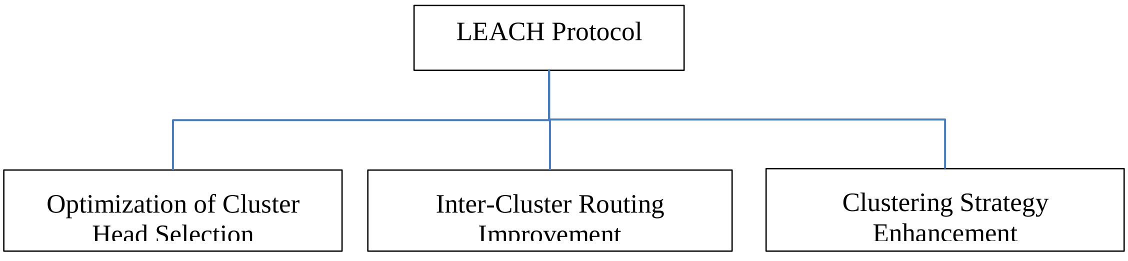

Figure 1: Optimization schemes for LEACH protocol

Addressing these limitations of the LEACH protocol, this paper will delve into optimization techniques in aspects such as cluster head selection, inter-cluster routing, and clustering strategies. We will analyze the working principles, advantages, and challenges faced by existing optimization schemes and discuss how to further enhance the performance of the LEACH protocol to meet the growing demands of WSN applications, as shown in Figure 1. Through in-depth research and improvement of the LEACH protocol, we aim to provide more efficient and reliable solutions for the design and deployment of WSNs.

II. OPTIMIZATION OF CLUSTER HEAD

The principle behind cluster head selection in the LEACH protocol is based on a probabilistic method to randomly select cluster head nodes, with the aim of evenly distributing the entire network's energy load among each sensor node to reduce network energy consumption and enhance the overall network lifetime. In the LEACH protocol, each sensor node generates a random number between 0 and 1, and compares it with a preset threshold T(n). If the random number is less than T(n), the node is elected as a cluster head for that round.

The cluster head selection mechanism of the LEACH protocol, while ensuring that each node in the network has an equal probability of becoming a cluster head and thus enabling a relatively balanced energy consumption among nodes, also has several drawbacks:

(1) Uneven energy consumption: The LEACH protocol does not take into account the residual energy of nodes during the cluster head election process. This can lead to the selection of nodes with lower energy as cluster heads, accelerating their depletion and affecting the overall network performance.

(2) Cluster head node lifespan issue: Cluster head nodes, due to their frequent communication requirements, typically consume energy at a faster rate than other nodes, resulting in a shorter lifespan for these nodes.

(3) Communication distance limitation: LEACH assumes that all nodes can communicate directly with the sink node, which may be unrealistic in large-scale wireless sensor networks, as cluster heads that are far from the base station consume excessive energy.

(4) Protocol assumption limitations: The LEACH protocol assumes that all nodes start with the same amount of energy during the initial cluster head selection round and that each node elected as a cluster head consumes approximately the same amount of energy. This assumption may not hold true in practical applications, especially in networks with uneven energy distribution among nodes.

(5) Cluster head count distribution: The LEACH protocol does not specify how the number of cluster heads should be distributed to achieve optimal network performance, which may result in an uneven concentration of cluster heads in certain areas of the network, leaving other areas with ineffective communication.

In LEACH-C, the performance is enhanced by incorporating a central controller to improve the process of cluster head selection and management, thereby enhancing network performance and energy efficiency. In LEACH-C, the selection of cluster heads is no longer independently and randomly determined by individual nodes but is centrally managed by the central controller. The criteria for cluster head selection may include the residual energy of nodes, geographical location (aiming for even distribution within the network to reduce communication distances), and historical records of serving as a cluster head, with the aim of balancing energy consumption across the network and prolonging the network's lifespan.

The DEEC protocol [2] is another enhancement of the LEACH protocol. It optimizes energy efficiency by considering not only the residual energy of nodes but also the density of nodes within the network when selecting cluster heads. The primary objective of DEEC is to extend the network's lifetime while maintaining its connectivity. During the operation of the network, the runtime is divided into multiple rounds, and at the beginning of each round, all nodes have the opportunity to become a cluster head. A threshold T(n) is set to dynamically adjust the probability of becoming a cluster head based on the node's number n. T(n) increases with the node number, indicating that nodes closer to the base station have a higher probability of becoming cluster heads due to their lower energy consumption in transmitting data to the base station. Regarding the selection of cluster heads, each node independently calculates its probability of becoming a cluster head based on its residual energy Eremn and a function related to the node's number, typically an adjustment factor based on T(n). Specifically, the probability P(n) of becoming a cluster head is directly proportional to the node's residual energy Eremn and is adjusted according to the node's location (or number). Nodes closer to the base station, with a larger T(n), may have a higher probability of becoming a cluster head even if their energy is lower. Nodes decide whether to become a cluster head using a random number generator; if the generated random number is less than P(n), the node becomes the cluster head for that round.

The WCA protocol [3] aims to optimize the energy efficiency and network performance of wireless sensor networks through the judicious selection of cluster heads. During the operation of the protocol, each sensor node evaluates its own parameters, which typically include residual energy, location information, and the number of neighboring nodes. These parameters reflect the suitability of the node to serve as a cluster head. Based on the evaluated parameters, a weight value is calculated for each node. The weight is usually a weighted combination of the aforementioned parameters, designed to balance energy consumption, coverage, and communication efficiency within the network. For instance, nodes with higher residual energy are assigned greater weights to ensure a more even distribution of energy consumption; nodes with a higher number of neighboring nodes may be assigned lower weights to prevent the concentration of cluster heads in certain areas. Each node participates in the cluster head election based on the calculated weight value. The WCA may employ a distributed approach, allowing nodes to compare their weights with neighboring nodes and decide whether to declare themselves as cluster heads. This typically involves a threshold or ranking mechanism, where only those nodes with weights above a preset threshold or ranking among the top few in their vicinity can become cluster heads.

III. INTER-CLUSTER ROUTING INPROVEMENT

In the LEACH protocol, once the cluster head has collected data from other nodes within its cluster, it directly transmits the data to the base station without any data transmission between cluster heads. Regarding the data transmission technology, multiple access techniques such as TDMA (Time Division Multiple Access) or FDMA (Frequency Division Multiple Access) are employed to prevent communication conflicts among cluster heads. Given the limited communication range of the nodes, the LEACH protocol is only applicable to small-scale networks.

The LEACH-F protocol [4] is an enhancement based on the LEACH protocol, which optimizes inter-cluster communication by introducing Forwarding Nodes (FN) to reduce the energy consumption for data transmission from cluster heads to the base station. After the election of cluster heads, the LEACH-F protocol proceeds to select some non-cluster-head nodes as Forwarding Nodes (FN). The selection of Forwarding Nodes can be based on various strategies, such as the remaining energy of the nodes, their relative positions to the cluster heads and the base station, with the aim of establishing one or more efficient energy paths from the cluster heads to the base station. The Forwarding Nodes form one or multiple paths to the base station, which can be either directly connected to the base station or indirectly connected through a relay of multiple Forwarding Nodes. The selection of these paths is intended to minimize energy consumption and enhance transmission reliability.

The LEACH-G protocol [5], building upon the standard LEACH protocol, incorporates geographical information to optimize the formation of clusters and the routing process between clusters, thereby enhancing the energy efficiency and data transmission reliability of the network. Initially, each node within the network must ascertain or be pre-aware of its geographical location information, which can be achieved through GPS modules, triangulation positioning, or other location technologies. During inter-cluster communication, LEACH-G utilizes geographical location information to plan multi-hop routing paths. Data, originating from the cluster head, passes through meticulously selected intermediate nodes (which could be other cluster heads or dedicated forwarding nodes) to reach the base station with minimal energy consumption. The path selection can be based on criteria such as the shortest path, minimum accumulated energy consumption, or other optimization metrics. Considering the dynamic nature of the network (such as node failure or energy depletion), LEACH-G allows for the dynamic adjustment of routing paths according to the current network conditions. Geographical information plays a pivotal role in this process, assisting the system in quickly identifying and activating alternative paths.

IV. CLUSTERING STRATEGY ENHANCEMENT

In the LEACH protocol, the node that becomes a cluster head broadcasts its identity and the corresponding Cluster Identifier (CID). Other non-cluster-head nodes, based on the received signal strength and other potential optimization parameters such as distance and predicted energy consumption, select the nearest cluster head to join, thereby forming a cluster. In this manner, the network is divided into multiple independent clusters, each consisting of one cluster head and several cluster member nodes.

The LEDC protocol [6] proposed by researchers is a centralized clustering protocol aimed at enhancing the energy efficiency of query-based Wireless Sensor Networks (WSNs). In the LEDC protocol, the process of node clustering primarily consists of the following two steps: Firstly, the Base Station (BS) employs a prediction-based mechanism to maintain the positional and residual energy information of nodes within the network. After the initialization of the network, nodes transmit their location and initial energy information to the BS using a multi-hop routing protocol, such as the Greedy Perimeter Stateless Routing (GPSR). Secondly, the BS collects query requests over a certain period and regularly calculates the optimal number of clusters,. Thereafter, the BS generates optimal dynamic clusters based on the spatial distribution of query targets, utilizing the K-Means++ algorithm.

CEEC [7] is a centralized energy-efficient clustering protocol designed to extend the network lifetime in WSNs by minimizing and balancing energy consumption. In this protocol, the process of node clustering involves two phases: initial cluster formation and inter-cluster size balancing. During the initial cluster formation phase, the network field is divided into square-shaped clusters, each with an identical width denoted as a. In this process, each node utilizes its positional information and the width of the cluster to calculate which cluster it belongs to. After the initial cluster formation, the number of nodes in each cluster may vary. In the inter-cluster size balancing phase, to balance the node count among different clusters, the Base Station collects information from all clusters and calculates the average number of nodes per cluster, denoted as N_{avg}. Subsequently, the BS adjusts the node allocation between clusters based on the discrepancy between each cluster's node count Nc and the average N_{avg}.

V. CONCLUSION

The LEACH protocol, as one of the earliest protocols to emerge in clustering protocols, plays a very important role in optimizing the performance of wireless sensor networks. However, it also has its own shortcomings in various aspects. Based on these deficiencies, this paper summarizes the optimization methods for cluster head selection, inter-cluster routing selection, and clustering strategies, and analyzes and summarizes the representative protocols in each category of optimization methods. This is conducive to providing guidance for research and development personnel in future research in this field.

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