Dual Cluster Head Selection Based on LEACH and Differential Search Algorithm to Extend Network Lifetime in Wireless Sensor Network

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***Abstract*—The key component of a wireless sensor network (WSN), the sensor node, has a lot of restrictions. Since sensor nodes must run for a long time, energy is their biggest drawback. Therefore, energy efficiency is a significant highlight in many studies at WSN. A well-known cluster-based technique in the WSN is the Low-Energy Adaptive Clustering Hierarchy (LEACH). However, the selection of cluster heads (CH) in the LEACH does not consider the availability of energy and distance. This article presents a new protocol based on LEACH and Differential Search Algorithm (DSA) to select CHs and Deputy CHs to extend network lifetime. Additionally, the LEACH protocol is used as a comparison to evaluate the functionality of the proposed protocol. The simulation results show that the proposed protocol has a more extended period of stability and network lifetime than LEACH.**

Keywords— Wireless sensor network, Cluster head, LEACH, Differential search algorithm, Energy efficiency, Stability period, Network lifetime.

I. INTRODUCTION

A wireless sensor network (WSN) contains hundreds or thousands of sensor nodes distributed over a large observation area to monitor a specific environment or object. Sensor nodes, the main elements of WSN, are small devices. Therefore, sensor nodes have operational limits such as power limits, processing limits, storage limits, and communication limits.

The main drawback is energy because the sensor nodes can only be powered by batteries [1], [2]. In the meantime, WSN is frequently used for monitoring in harsh and dangerous environments such as volcano monitoring, military, and radiation exposure. Thus, the sensor node battery is difficult to replace or recharge.

Due to the lengthy operation times required by sensor nodes, energy is a significant obstacle in WSN research [3]. In addition to the short operating time, inefficient energy consumption also results in network stability and the quality of data collected by sensor nodes [4], so the results of observations can provide incorrect information about the environment or objects of observation.

In WSN, communication consumes the most energy, especially when a sensor node sends data to another sensor node or sink [5], [6]. The energy used for data transmission is affected by the transmission distance and the amount of data. When the transmission distance gets farther and farther, the sensor node will emit transmission energy that gets bigger and bigger. Therefore, establishing a WSN topology that supports energy efficiency is necessary [7], [8].

Clustering is a method that is considered to be able to build energy-efficient WSN structures [9], [10]. The idea of a clustering strategy is to avoid data redundancy so that the quantum of data transmitted can be minimized. This data redundancy is avoided by exercising data aggregation. So, on the clustering approach, adjacent sensor nodes are grouped in a single clusterFurthermore, each cluster has two groups of sensor nodes, namely cluster members (CM) and cluster head (CH). The cluster members are in charge of collecting data from the observation environment and sending it to the CH. CH has a greater responsibility than CM because CH has to collect data from CM, perform data aggregation, and transmit it to the sink. Since CH has a large load, the optimal CH can produce efficient energy consumption and balanced load distribution [11]. However, the optimal determination of CH is an NP-hard problem [12], [13].

The first and renowned clustering-based protocol in WSN is called Low-Energy Adaptive Clustering Hierarchy (LEACH) [14]. LEACH's operational phases include the setup step and the steady state step. LEACH chooses which sensor node will serve as the CH throughout setup. The only criteria used to choose the CH are the threshold applied to all nodes and the random values produced by sensor nodes. This threshold takes into account the rounds and CH percentage. The sensor nodes that have a random value below the threshold value are given the CH role as a result. The next process is cluster formation and time division multiple access (TDMA) scheduling determination by CHs to CMs.

Once the setup phase is complete, CM and CH perform their duties in the steady state phase. The CM retrieves data regarding the monitored environment and sends it to the CH on schedule. After the CH receives data from the entire CM, it performs the aggregation of the data and sends it to the sink. LEACH offers advantages, including low communication costs between sensor nodes and sinks, reducing data redundancy, and load sharing [15]. However, selections based solely on a percentage of the number of CHs, current rounds, and random numbers can result in CH shutting down suddenly and network instability.

This article proposes the selection of CH and deputy CH based on LEACH and DSA. In this proposed protocol, each cluster can have two CHs, namely CH and deputy CH (D-CH). In addition, the threshold value considers the energy factor, the maximum distance of the node to the sink, and the minimum distance of the node to the sink to determine which sensor node is worthy of being a CH. By considering the distance between the sensor nodes in a cluster, the distance between the sensor nodes and the sink, and the potential availability of CH energy in the future, the D-CH selection mechanism makes adopt of DSA. In addition, the role of D-CH is to replace the role of CH if CH dies unexpectedly. Thus, network stability can be maintained for a long time, and the energy consumption is at least.

II. RELATED WORK

Ahlawat and Malik [16] proposed the Vice Low-Energy Adaptive Clustering Hierarchy (V-LEACH) protocol. The purpose of the V-LEACH approach is to mitigate the effects of CH's unexpected death on LEACH. In addition to CH, the V-LEACH protocol selects one sensor node as vice-CH. Vice-CH act to replace CH when the CH energy suddenly runs out and CH dies. Distance and current energy factors are the basis for choosing CH and vice-CH.

Fu, Jiang, Wei, and Wei [17] presented a new protocol, namely the LEACH protocol with two cluster head levels (LEACH-TLCH). In LEACH-TLCH, CH consists of two levels: primary CH and secondary CH. The selection and formation of CH primers still employ the LEACH protocol pattern. However, if the primary CH remaining energy is below the average remaining energy and the primary CH distance to the sink is more than the average distance to the sink. The sensor node with the enormous remaining energy in the same cluster is designated secondary CH. The Secondary CH is responsible for collecting data from cluster members, combining it, and sending it to the CH. Then, the CH forwards the data received from the secondary CH to the sink. So, the selection of secondary CH is only under certain conditions. The LEACH-TLCH protocol works well on high-density networks. However, sensor nodes far from the secondary CH must consume a lot of transmission energy.

Mehmood, Lloret, Noman, and Song [18] proposed an idea to improve the V-LEACH protocol. The protocol proposed by [18] was named LEACH-Vice Head (LEACH-VH). CH selection and cluster formation followed the LEACH protocol. However, the Vice Head (VH) selection is based on the immense residual energy in the same cluster. After VH is selected, VH goes into sleep mode and will replace the role of CH when the residual energy of CH has reached the threshold, which is 10% of the initial energy. However, the LEACH-VH protocol does not consider the distance of the cluster member to the VH and the distance from the VH to the sink, so energy consumption will increase when the node density level is low.

Ding, Ling, Wang, and Song [19] proposed the Dynamic K LEACH (DK-LEACH) protocol. The idea to develop DK-LEACH is since the energy distribution in WSN is uneven. To overcome the uneven distribution of energy, DK-LEACH considers the proportion of the distance between the sensor nodes to the CH and the current residual energy of the CH to form a cluster. Before DK-LEACH builds a cluster, DK-LEACH first selects a sensor node that has remainig energy of more than the average residual energy to be a CH candidate. Then, in the same way as LEACH, DK-LEACH determines CH among CH candidates.

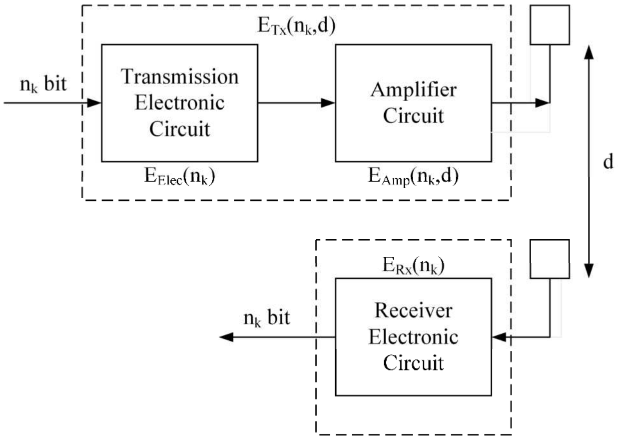

Fig. 1. Radio model [20]

Samara, Hassan, and Zayed [4] presented the intelligent vice cluster LEACH protocol (IVC LEACH). The IVC LEACH protocol divides sensor nodes into five types, namely CH, CH vice (CHv), CH second (CHsec), CH second vice (CHsecv), and regular nodes. The IVC LEACH protocol utilizes fuzzy logic to determine CH, CHv, CHsec, and CHsecv based on residual energy, node-to-sink distance, and distance between nodes.

III. NETWORK ARCHITECTURE AND ENERGY DISSIPATION MODEL

A. Network Architecture

This study considers the WSN structure consisting of W sensor nodes, which are expressed in the set $NS = \{ns_1, ns_2, ns_3, \cdots, ns_w\}$. These sensor nodes deployed randomly to the observation environment measuring R x R. After being distributed, the position of the sensor nodes is fixed, and each sensor node knows the coordinates of its position. The technical specifications of all sensor nodes are the same, as well as in terms of battery capacity. Furthermore, the communication channel is symmetrical, i.e., the energy consumed to transmit data between the two sensor nodes is the same. Each round, each sensor node generates one piece of data and sends it to the sink. The sink position is fixed. In addition, the energy capacity of the sink is tremendous because the sink receives energy from external sources.

B. Energy Dissipation Model

The sensor node has four components: radio as a communication component, battery as an energy supply component, microcontroller component, and sensor. The radio comprises a transmitting unit, a receiver unit, and an amplifier unit. This radio model is based on research from [20]. Fig. 1 featured a radio model in the study. Individual unit in a radio consumes a certain amount of energy. Unit of the transmitter and receiver unit consumes as much energy as E_{Elec} for one bit. While the propagation model influences the energy consumption of the reinforcing unit, namely E_{Amp}. This study considers two propagation models, namely the multipath fading model and the free space model. When the sensor node uses the free space model, the amplifier unit on the sensor node will consume as much energy as E_{Fs} in every bit data. However, if the sensor node chooses a multi-path fading model, then the amplifier unit will consume as much energy as E_{Mp} for one bit of data. The selection of this propagation mode depends on the transmission distance d, this transmission distance is compared to the distance threshold d_{th}. If the transmission distance is less than the distance threshold, then a free space model is adopted; instead, multi-path fading is selected as the propagation model. Here is the formula for calculating the distance threshold:

$$d_{th} = \sqrt{\frac{E_{Fs}}{E_{Mp}}}. \tag{1}$$

Assume that if a sensor node ns_i transfers n_k bit data to another sensor node ns_j within d distance, hence the transmission energy E_{Tx} sensor node ns_i can be calculated by the following formula:

$$\begin{gathered} E_{Tx}(n_k, d) = \left(E_{Elec} + E_{Amp} \times d^{\varepsilon}\right) \times n_k \\ E_{Tx}(n_k, d) = \begin{cases} (E_{Elec} + E_{Fs} \times d^2) \times n_k, & d < d_{th} \\ \left(E_{Elec} + E_{Mp} \times d^4\right) \times n_k, & d \geq d_{th}. \end{cases} \end{gathered} \tag{2}$$

On the sensor node ns_j as a data recipient, ns_j consumes energy E_{Rx} as follow:

$$E_{Rx}(n_k) = E_{Elec} \times n_k. \tag{3}$$

If the sensor node ns_j has role as CH, then a sensor node ns_j will perform data aggregation. This data aggregation process requires the energy of E_{Agg} for every bit data. So, the formula to calculate the energy spent by the sensor node ns_j to aggregate n_k bit is:

$$E_{Da}(n_k) = E_{Agg} \times n_k. \tag{4}$$

The dissipation energy model in this study adopts the research in [21], as this energy model has been utilized in many studies at WSN to test or evaluate the performance of proposed protocols [9].

IV. DUAL CLUSTER HEAD SELECTION BASED ON LEACH AND DIFFERENTIAL SEARCH ALGORITHM PROTOCOL

The CH election process is an imperative stage in any cluster-based protocol because CH can affect the level of energy consumption and the operating length of the WSN. This study introduced the selection of LEACH and DSA-based dual cluster heads, abbreviated as LEACH-DSA. The LEACH-DSA protocol divides sensor nodes into three types, namely CH, deputy CH (D-CH), and regular nodes. The operation time is expressed in rounds. In each round, the LEACH-DSA performs operations in two stages: the setup stage and the data collection stage.

A. Setup Stage

At this stage, the LEACH-DSA protocol builds a cluster-based WSN structure. Cluster formation begins with the CH selection process. CH selection procedure in LEACH adopted LEACH-DSA. The sink will then set a threshold value for each of the network's sensor nodes. After that, the sensor nodes that have never been selected as CH in a certain number of rounds generate random values in susceptible 0 and 1. This random value is further compared to the threshold value. The threshold value setting in the LEACH protocol considers the current round and the percentage of CH so that the sensor node away from the sink can become a CH.

Similarly, a sensor node with low remaining energy can be chosen as CH. Long transmission distance impacts large energy consumption and the limitation of CH to operate thoroughly. The LEACH-DSA protocol proposes the search for threshold values by considering the factor of the average residual energy ratio of all sensor nodes ($\overline{E}_{Res}$) with initial energy (E_0), the farthest distance of the sensor node to the sink (d_{Max}) and the sensor node's shortest distance from the sink (d_{Min}). Here is the formula for finding the threshold value:

$$Th(n) = \begin{cases} \frac{p}{1-p\times(r mod\left(\frac{1}{p}\right))} \times \left(\frac{\overline{E}_{Res}}{E_0} + \frac{d_{Max}-d_{Min}}{d_{Max}}\right), & n \in B \\ 0 & , otherwise \end{cases}. \tag{5}$$

In this formula, p is the percentage of the number of CHs set in the network, r is the current round, and B is the set of sensor nodes that have never been a CH in $1/p$ rounds.

After the CH selection is completed, the sensor nodes not selected as the CH look for the CH closest to him. When the sensor node has found the nearest CH, the sensor node will join that CH in a cluster. Following the formation of this cluster, a deputy CH (D-CH) was elected. The D-CH selection process is carried out in each cluster to avoid overhead. The D-CH is responsible for taking over the duties of the CH if the CH dies suddenly. As a substitute role, D-CH selection needs to produce optimal D-CH so that the process of collecting data from all members of the cluster can be sent to the sink efficiently. Therefore, the LEACH-DSA protocol proposes a Differential Search Algorithm (DSA) to evaluate the feasibility of sensor nodes becoming D-CH.

Pinar Civicioglu put forth the DSA in [22]. This algorithm is an adaptation of the migration pattern of living organisms. Many living things have demonstrated the ability to survive in harsh natural environments and solve problems such as reproduction, foraging for food, and defending against predators. Most of the time, the individuals within a group of organisms work closely together to produce this ability. Numerous computational intelligence methods, such as Shuffled Frog Leaping Algorithm [23], Artificial Bee Colony Algorithm, Cuckoo-search, Particle Swarm Optimization [24], and Ant Colony [25], then emulate this social pattern created by actual species. Numerous research also demonstrates the power of herd-based computational intelligence to find solutions to issues, including WSN [9].

In this D-CH selection process, DSA evaluates the feasibility of a sensor node becoming a D-CH with reference to three parameters. The distance among the D-CH candidate and every other member of the cluster is the first parameter.

In order to save cluster members energy when transmitting their data to D-CH, the distance among each cluster member and D-CH candidate must be as small as feasible. If the number of cluster members is $W_{alive-c}$, L_{CDCH} is the candidate position of D-CH, and L_{CM_i} is the position of the i-th, cluster member, then this first parameter can be expressed as:

$$cF_{CDCH-CM} = \sum_{i=1}^{W_{alive-c}-1} dist(L_{CDCH}, L_{CM_i}). \tag{6}$$

The distance here between sink and the D-CH candidate should be taken into account as the second parameter. The D-CH will be compelled to use a lot of energy because of the transmission distance to the far sink. As a result, there must be a short distance between the sink and the D-CH applicant. Thus, the distance from the sink to the D-CH applicant must be close. Let L_{Sink} be the sink position, then this factor can be expressed in:

$$cF_{CDCH-Sink} = dist(L_{CDCH}, L_{Sink}). \tag{7}$$

The next factor that needs to be considered is energy availability in the next round. This factor is vital because D-CH continues the unfinished CH task. Let $E_{CDCH-Av}$ be the currently available D-CH candidate energy and $E_{cluster}$ be the energy consumed by D-CH to receive data, aggregate data, and send data to the sink.

$$cF_{CDCH-AVNR} = E_{CDCH-Av} - E_{cluster}. \tag{8}$$

Based on these three factors, the fitness function used to define the sensor node as D-CH is as follows:

$$Minimize\ cF = cF_{CDCH-CM} + cF_{CDCH-Sink} - cF_{CDCH-AVNR} \tag{9}$$

Once LEACH-DSA decides a sensor node is qualified to be a D-CH, that sensor node broadcasts an advertising message to the cluster members regarding its status as a D-CH. Then the cluster member responds to the message by storing information about the D-CH in the current round.

B. Data Collection Stage

The data collection phase comes after the setup phase has been finished in its entirety. Each cluster member scans the area or object of observation at this stage. At this stage, all CHs and D-CHs are always active because each cluster member will transmit data retrieval results from the environment or observations to the CH. If the CH shuts down unexpectedly, the sensor node timeout to participate in the following D-CH selection is set, and the sensor node sends data to the D-CH. This data transmission process follows the TDMA schedule determined by the CH in the setup stage.

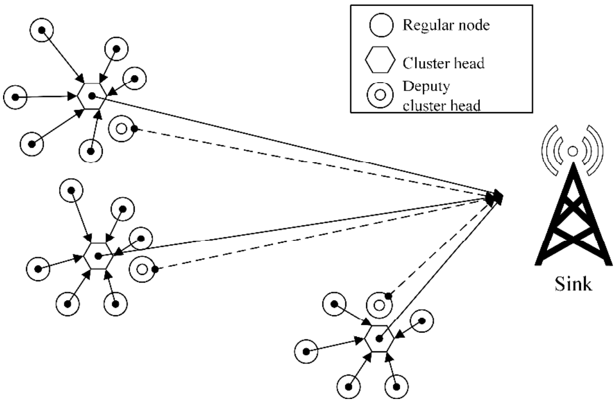

Fig. 2. WSN structure in LEACH-DSA

Further, the cluster member will update the remaining energy information to the sink and go into sleep mode. The entire CH or D-CH then aggregates the data received from all members of the cluster. Next, the CH or D-CH transmits the aggregation data to the sink. This process keeps repeating until the entire sensor node dies because the sensor node runs out of power.

V. PERFORMANCE EVALUATION AND RESULTS

A. Performance Evaluation

The capability of the LEAC-DSA protocol was tested in a simulated environment using MATLAB. In this simulated environment, the network area is 100 m × 100 m. The network region is then randomly spread with 100 sensor nodes. Next, the sink is placed in the center of the network area. The position of the sensor and sink nodes did not change during the simulation. The simulation continues until all sensor nodes in the network die.

Furthermore, the initial energy of each sensor node is the same, i.e., 0.5 J. All sensor nodes transmit 2000 bits of data in each round. The percentage of the expected amount of CH (p) is 0.05. This research adopted energy and p values from studies in [20]. Table 1 shows the detailed simulation parameters.

This study compares the performance of the LEACH-DSA protocol with the well-known cluster-based protocol, LEACH. Many studies use LEACH as a comparison, as in [26]–[28]. First Node Dies (FND), Half of the Nodes Dies (HND), Last Node Dies (LND), Total Energy Consumption per round, and Average Remaining Energy per node per round are the parameters used to evaluate the effectivity of LEACH-DSA. Following are the definitions for the FND, HND, and LND parameters:

- FND is round, which indicates a node dies for the first time.

TABLE I. DETAILS OF SIMULATION PARAMETERS

Parameters	Value
Network area size (R x R)	100 m × 100 m
Number of sensor nodes (W)	100
p	0.05
E_{Elec}	50 nJ/bit
E_{Fs}	10 pJ/bit/m^2
E_{Mp}	0.0013 pJ/bit/m^4
E_{Agg}	5 nJ/bit
E_0	0.5 J
Data size	2000 bit

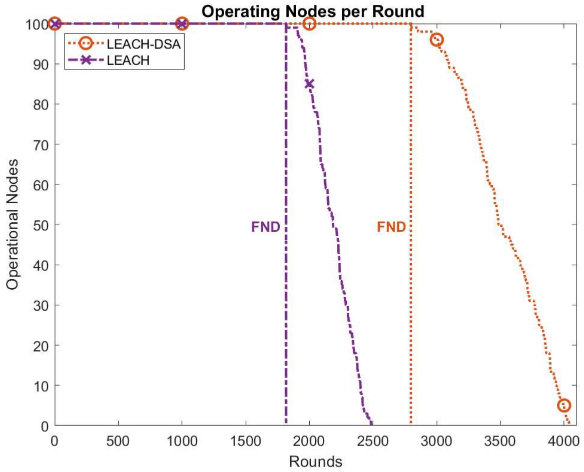

Fig. 3. LEACH-DSA v.s LEACH: operating nodes per round

- HND is round, indicating when half of the total sensor nodes are off.
- LND is round, which indicates that none of the network's sensor nodes are active.

B. Results

Network lifetime and energy efficiency are critical parameters in evaluating protocol performance at WSN. In the discussion of network lifetime, the FND and LND parameters are the benchmark for the durability of the protocol in the period of stability and after the period of stability [1], [13], [28]. The stability period is measured from when the sensor nodes start operating until an FND occursThe protocol moves from the stability phase to the instability phase since one sensor node is down. The effectiveness of the protocol diminishes and vulnerable sensor nodes die rapidly during this time.

Figure 3 shows the evaluation results for the LEACH-DSA and LEACH protocols during operating time. Figure 3 denotes the FND generated by the LEACH-DSA protocol, which is longer than the FND achieved by the LEACH protocol. Similarly, in the case of LND, the LEACH-DSA protocol can achieve an LND value that is longer than the LND value that the LEACH protocol generates. The LEACH-DSA protocol can overcome performance declines during unstable periods. In contrast to the LEACH protocol, the LEACH protocol experiences a rapid decline in performance after passing a period of stability.

The data in Table II also redound the LEAC-DSA protocol's network lifetime strong point. Based on the data in Table II, the LEACH-DSA protocol obtained an FND value, which is 2803. In contrast, the FND value of the LEACH protocol is 1820. These results show that the LEACH-DSA protocol can increase the period of stability by 54.01%. Moreover, in the HND parameter, the protocol returns a value of 3485, while the LEACH protocol only reaches 2186. So, the HND value of the LEACH-DSA protocol is higher than the LEACH by 59.42%.

TABLE II. NETWORK LIFETIME PARAMETERS

Protocol	**Network Lifetime**		
	FND	***HND***	***LND***
LEACH-DSA	2803	3485	4040
LEACH	1820	2186	2485

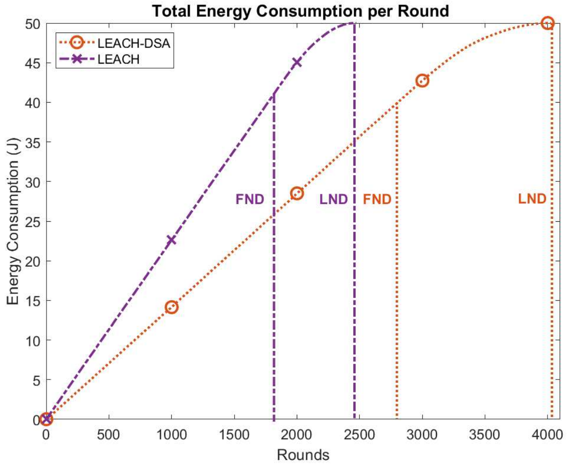

Fig. 4. LEACH-DSA v.s LEACH: Total energy consumption per round.

Furthermore, the LEACH-DSA protocol also outperforms LEACH in terms of LND. LEACH-DSA produces an LND value of 4040, while the LEACH protocol only generates an LND of 2485. This data means the LEACH-DSA protocol has a network lifetime of 62.58% longer than LEACH. Also, the difference between FND and LND in the LEACH-DSA approach is 1237 rounds. In the LEACH protocol, the difference between FND and LND is up to 665 rounds. These data indicate that the LEACH-DSA protocol has a more extended period of instability than LEACH.

The benefits of the LEACH-DSA protocol go beyond simply having a longer network lifetime than LEACH. The energy using up level of the sensor nodes that employ the LEACH-DSA protocol in every round is lower than that of the sensor nodes that use LEACH, as shown in Fig. 4. The total energy consumption of the LEACH-DSA protocol at the time of FND was only 39.96 J. LEACH's total energy consumption at the FND moment was 41.14 J. After passing the FND, LEACH's total energy consumption increased.

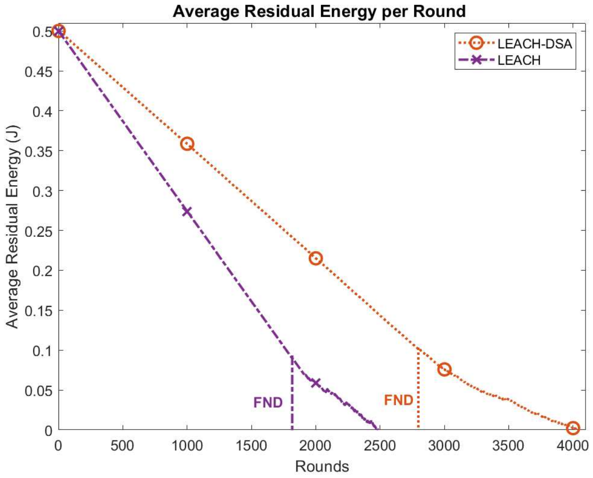

Fig. 5. LEACH-DSA v.s LEACH: Average residual energy per round.

The average remaining energy of the sensor nodes per round is shown in Fig. 5. The average residual energy per round in the LEACH-DSA protocol is higher than in LEACH. The average residual energy in LEACH-DSA is 0.1 J when one sensor node is turned off for the first moment. Meanwhile, the average residual energy in LEACH is 0.09 J and continues to decline rapidly. The ability of LEACH-DSA that can diminish the level of energy consumption is influenced by CH and D-CH selection strategies. Considering the distance communication, remaining energy, and remaining energy availability in the future, LEACH-DSA can determine the optimal CH and D-CH. The optimal selection procedure has an impact on energy efficiency. We should consider mobile sink and dual CH strategies to improve energy efficiency in LEACH because these strategies can shorten communication distances and extend longer network lifetime.

VI. CONCLUSION

This study proposes the LEACH-DSA protocol to increase the period of stability and network lifetime. The CH selection mechanism in LEACH-DSA improves the LEACH protocol. In addition, the LEACH-DSA protocol leverages the DSA to determine the optimal D-CH by considering the D-CH energy availability in the next round, the distance between the D-CH applicant to another member of the cluster, and the distance of the D-CH applicant to the sink.

The results of experiments in the simulation environment showed that the LEACH-DSA protocol had better performance than LEACH. LEACH-DSA produces a more extended stability period than LEACH, which is 54.01%. The LEACH-DSA protocol also prolonged network lifetime by 62.58% compared to LEACH. The increase in the period of stability and network lifetime shows that LEACH-DSA is operating efficiently. Subsequent research leveraged strategies with mobile sinks and dual CH to extend operating times and periods of stability in WSN.

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