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A GRID-BASED CLUSTERING WITH DYNAMIC FORWARDING PATH FOR ENERGY-EFFICIENT DATA GATHERING IN WIRELESS SENSOR NETWORK ENVIRONMENTS

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Abstract. *Wireless sensor networks (WSN) generally consist of a large number of sensor nodes with limited resources and communication links distributed geographically for various purposes. The limitations of WSN nodes have highlighted challenges to minimize energy consumption of the nodes while still maintaining the goal of WSN developments. This paper proposes a new approach of data gathering in WSN environments by integrating grid-based clustering with dynamic forwarding path to minimize overlapping between clusters and balance energy usages. The experiment results have shown the effectiveness of the proposed approach in preserving energy consumption, reducing the number of dead nodes and maintaining the packet delivery ratio in data gathering processes in a WSN simulation environment.*
Keywords: Wireless sensor networks, Data gathering, Grid-based clustering

1. **Introduction.** The proliferation of low-cost sensor nodes with wireless communication capability has generated an increasing interest in research and development in the areas of wireless sensor networks (WSN). Nodes in WSN commonly consist of tiny microcontroller boards equipped with some sensors that are spatially distributed in physical environments. The sensor nodes are programmed to sense data from the environments and forward the captured data to a sink node as the network gateway. Due to the wide ranges of sensor deployment areas, possible damages during the deployments, large population of sensors are expected to be involved [1]. Since sensor nodes are commonly only powered by batteries, there is a critical requirement to minimize energy consumption since any dead of sensor nodes may result in disconnected networks. It has highlighted the network lifetime issue in WSN development. The network lifetime is commonly defined as the number of rounds (can be expressed as time) until the first dead of the sensor node or α% of sensor nodes die [2]. In some cases, a WSN needs to be installed in difficult locations where the sensor nodes may need to be dropped randomly from the air. Accordingly, the dropped sensor nodes must be able to build the wireless networks in ad hoc manner where all the involved sensor nodes must form the collaboration to deliver the sensing data to the sink node [3, 4].

The main aim of WSN deployment is commonly to monitor environment by which each sensor node is programmed to periodically sense data from environments and send the data to a sink node, called as data gathering process [5, 6]. To achieve energy-efficient WSN operations and maintain network performances during the data gathering process in large WSN environments, the cluster-based approach for data gathering process can be applied. In this approach, the WSN can be organized into distributed clusters lead by a set of cluster head (CH) nodes that form hierarchical-based networks. The CH nodes are

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responsible for collecting and aggregating data from the cluster members and send the aggregated data to the sink node. LEACH (low energy adaptive clustering hierarchy protocol) [7, 8, 9] is one of the prominent hierarchical-based clustering approaches for WSN environments. This approach has shown various advantages due to its adaptive characteristic, fully distributed, and self-organizing cluster-based routing protocol [2]. However, in this approach, the CH nodes are randomly selected that may produce unbalance CH nodes distribution in the WSN monitoring field [8, 10]. It may bring related issues of excessive cluster overlapping in some areas while in contrast lack of formed clusters in the other areas. Furthermore, there is also a critical requirement to minimize the number of dead nodes especially in the routes from each CH node to the sink node and avoid network disconnections.

In this paper, we propose a novel grid-based data gathering with dynamic forwarding path (GCDF) technique for WSN environments. The grid-based approach is adopted to minimize overlapping clusters and reduce overhearing and radio collision by balancing the distribution of cluster head (CH) nodes. Furthermore, the dynamic forwarding path technique has been adopted to deliver the aggregated data from each CH node to the sink node to balance energy consumption and to minimize the number of dead sensor nodes during the data gathering process in WSN environments. To get more realistic simulation results, we develop and evaluate the proposed approach using the discrete-event WSN simulation framework that has implemented low-power wireless physical layer and radio models [11]. The rest of the paper is organized as follows. First, we discuss the challenges and related works of data gathering processes in WSN environments in Section 2. Section 3 introduces the proposed grid-based clustering with dynamic forwarding paths for data gathering in WSN environments. Section 4 discusses the experiments and evaluation of the proposed approach using a discrete event simulation framework. Finally, Section 5 concludes this paper.

2. **Related Work.** Various approaches have been proposed to deal with data gathering and routing challenges in WSN environments. Based on the network structure, there are two main routing protocols for data gathering in WSN environments, i.e., flat and hierarchical routing techniques [12]. In the flat routing technique, packet data are transferred hop-by-hop, and each sensor node has an equal role in the packet forwarding processes. These flat routing techniques may work effectively in small-scale networks, but may not give good performances in large-scale WSN environments due to the limited nature of sensor nodes, and high volume of data may need to be gathered and forwarded to the sink node. Hierarchical-based routing approaches give more advantages since sensor nodes can play different roles and the entire WSN can be organized into lots of distributed clusters [1, 12]. In this approach cluster head (CH) nodes will collect data from their member nodes in the data gathering processes. To minimize the number of packet data transmission the aggregation process in CH nodes can be applied as shown in [8, 13].

Various works have been proposed to build effective hierarchical-based approaches for data gathering in WSN environments. In [15], a tree-based structure has been introduced. It selects a set of random nodes in the WSN monitoring field as projection nodes which then become the root nodes which are responsible of aggregating data from its member nodes in a minimum spanning tree structure using compressive sensing. In [16], the WSN network area is divided into a few rings surrounding the sink node. One hop communication link between the CHs and the sink node is replaced by multi-hop communication links. The optimal distances between two consequent nodes are then estimated to build optimal multi-hop communication links. A data gathering approach that uses sparse random projection as the candidate of CH nodes by still considering sensor nodes distribution is introduced in [17]. The method that also applies compressive sensing to reducing the volume of data gathered from their members is proposed. The other work deals with the optimal placement of the sink node in WSN environments followed by data gathering from the WSN as described in [19]. By using the central placement of the sink node in WSN environments, the optimal number of clusters is approximated.

The LEACH-based approach [2] is one of the most prominent approaches as the base of hierarchical-based approaches for data gathering in WSN environments. It has adaptive characteristics and is fully distributed to support self-organizing cluster-based formation in WSN environments [2, 7, 9]. Using this approach new CH nodes are selected periodically in a round-based mechanism as shown in (1) wherein every round each sensor node generates a random number $\sigma \in [0, 1]$, if the generated random number is less than the threshold value $T(n)$ for the current round, the sensor nodes become the current available CH nodes. The threshold value for each round is calculated as shown in (1) where p denotes as the probability number for CH nodes appearances, r is the current round, and $\hat{N}$ is a group of sensor nodes which have not been elected as CH until round r as described in [9, 10]. Finally, after $\frac{1}{\sigma}$ round, the threshold value will be 1 to enable the remaining non CH nodes, to become CH. Then all sensor nodes are eligible again to become CHs.

$$T(n) = \begin{cases} \frac{p}{1-p\left(r * \bmod \left(\frac{1}{p}\right)\right)} & \text{if } n \in \hat{N}. \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The basic LEACH protocol is a single-hop clustering technique which may not be appropriate for large WSN areas due to limited wireless ranges of each sensor node [4]. An improvement of the LEACH-based protocol is shown in [9] to avoid consuming more energy in various sizes of clusters by modifying the CH selection method combined with an enhanced schedule of the time-division multiple access (TDMA). However, long-distance data transmission has drawbacks due to collision and overhearing in addition to high energy consumption. These issues may not be addressed if the simulation of the proposed framework is not conducted using realistic wireless channel and radio communication model. A multi-hop LEACH (M-LEACH) has been proposed to address these challenges as shown in [18]. However, one of the drawbacks of the LEACH-based clustering protocol is that the CH nodes are randomly selected [8, 10]. Accordingly, the randomness characteristic of the algorithm may produce unbalance CH nodes appearances in the sensor field as shown in Figure 1.

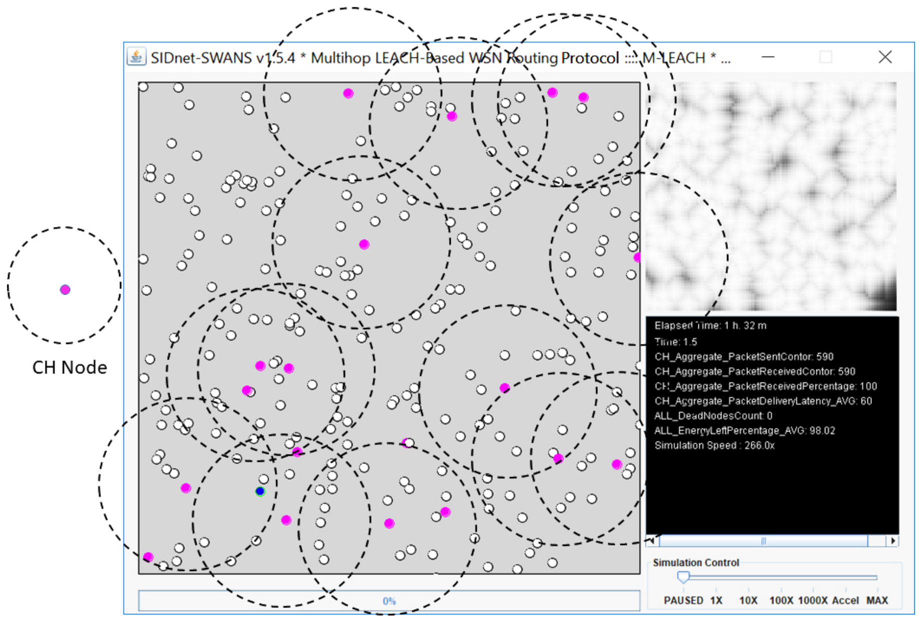

Figure 1. Unbalanced CH nodes produced using LEACH approach

This paper proposes a novel approach to performing data gathering processes in WSN environments. It divides the WSN monitoring field into grids and uses geographical location of sensor nodes to form clusters. The cluster head (CH) nodes will be selected among sensor nodes located closest to the grid center with largest neighbors. Nevertheless congestion occurring in node closer to sink may affect the performances of the proposed WSN [3, 14]. To deal with this issue, data aggregation processes are performed in all of the selected CH nodes to reduce traffic volume. The dynamic data forwarding path scheme is then proposed to balance energy consumption among sensor nodes in the forwarding paths from CH nodes to the sink node. The details of the proposed approach are described in the following sections.

3. **Grid-Based Cluster for Data Gathering Process in WSN.** In this paper, a grid-based cluster mechanism for energy-efficient data gathering processes in WSN environment is proposed. By using this approach, the entire area of sensor monitoring fields is divided into many grids where the sensor nodes are distributed randomly on the field. Each sensor node is assumed to know its position coordinate. Let $S = \{s_1, s_2, s_3, \ldots, s_n\}$ be a set of sensor nodes placed randomly in two-dimensional spaces of a sensor monitoring field which is divided into a number of grid areas $G = \{G_1, G_2, G_3, \ldots, G_n\}$.

As illustrated in a flowchart in Figure 2, after an initial nodes random placement, each sensor node s_i is programmed to broadcast *heartbeat* message to other sensor nodes in its wireless radio range R_i. The purpose of this broadcast is to report their location as well as the remaining energy to all of the neighboring nodes N_i located within the wireless range R_i. Suppose that, a sink node $s_n \in S$ is assigned among the available sensor nodes by

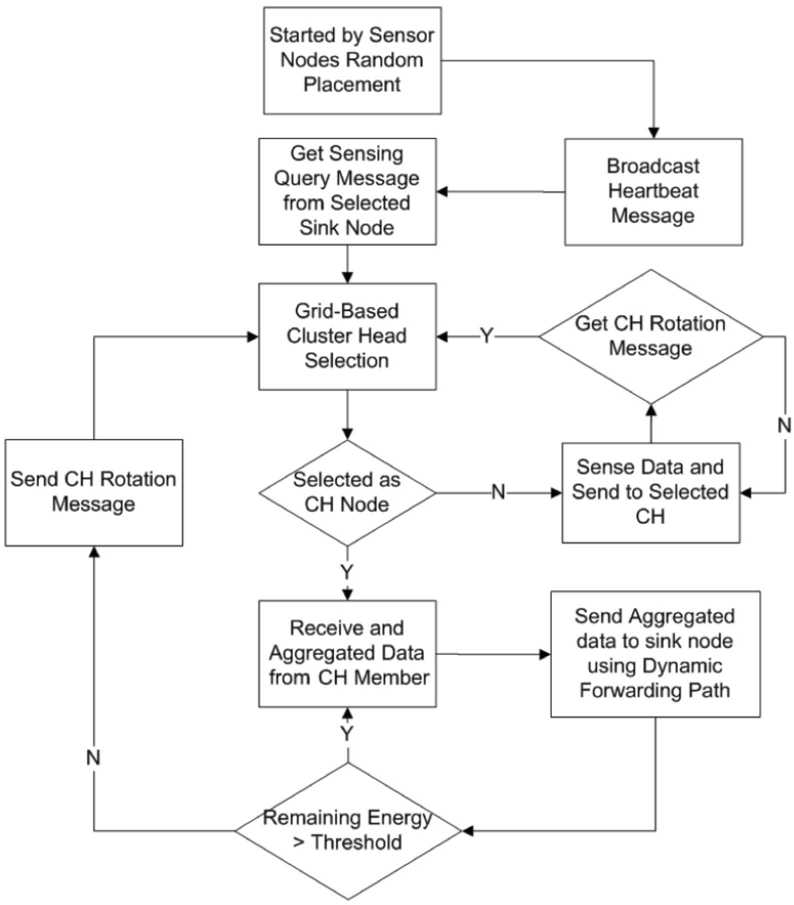

FIGURE 2. Flowchart for energy-efficient data gathering processes in WSN environments

the user. The sink node starts the data gathering process by broadcasting *sensing query* message to the entire WSN. The query packet consists of information about the necessary sensor data to be collected, the interval of each sensor sampling and the duration of the data gathering process. The query packet also consists of location and IP address of the sink node.

3.1. **Cluster head selection.** In the CH selection processes, upon receiving *sensing query* message from the sink node, all sensor nodes will try to find the best node within its radio range (including itself) to be a cluster head in their grid. Let x_j be the location of the grid center $G_j \in G$. Sensor nodes $s \in S$, placed inside the grid G_j, are denoted as located within the CH candidate zone Z_j, if their distances $d(s, x_j)$ from the grid center are less than a distance threshold t_d. These sensor nodes are then selected as CH candidates for the corresponding grid. The reason behind this approach is based on their positions, and they may be able to reach larger number of sensor nodes in the grid and to minimize overlapping cluster formed in other grids.

The other sensor nodes in the grid G_j then become the cluster member nodes. Depending on the dimension of the grid and radio coverage of each cluster member node, they will select a CH node among reachable CH candidates in the same grid that has the largest neighbors among the others. The selected cluster heads will then aggregate data arrived from their cluster members and forward the aggregated data to the sink using dynamic forwarding paths once their buffers are full. If their remaining energy is less than threshold they will broadcast the information to their surroundings, and the cluster members will then find another cluster head through the CH selection process.

3.2. **Dynamic forwarding path scheme.** The forwarding processes from CH nodes will involve a number of sensor nodes located in the packet flow paths to the sink node. To minimize and distribute energy consumption we proposed dynamic data forwarding from CH to the sink node since radio transmitting and listening consume a considerable amount of energy in addition to sensing operations. Figure 3 illustrates a scenario where a CH node c_i in Grid 4 forwards the aggregated data to the sink node in Grid 0. This process will involve sensor nodes in the direction to the sink node.

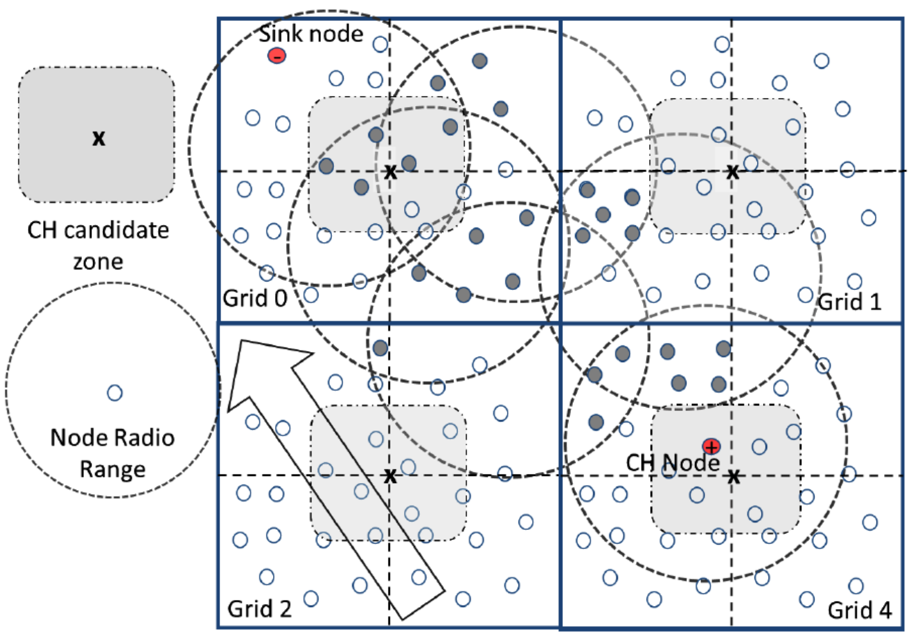

FIGURE 3. Dynamic forwarding areas from a CH node in Grid 4 to the sink node in Grid 0

Initially, the CH node c_i will collect a number of candidate forwarding nodes within its radio range, where their locations are closer to the sink node than the location of c_i. These forwarding nodes must have distance gaps greater than a threshold δ toward the CH node c_i. In Figure 3 these sensor nodes are marked with dark grey colors. Then, at each hop of data forwarding step toward the sink node, the selected forwarding node for each step will be randomly rotated to balance the energy. In addition, the available forwarding node with the low remaining for the current round compared to an energy threshold will be excluded from the list. The affected sensor nodes in each packet forwarding hop apply these forwarding schemes until the packet arrives at the sink node.

4. **Simulation Setting and Results Evaluation.** We have developed and evaluated the proposed GCDF approach using SIDnet-SWANS [11], a discrete-event WSN simulator framework with the implementation of 802.15.4 MAC layer, energy consumption and radio models. The proposed GCDF framework extends the underlying network layer of SIDNet-SWANS with grid-based cluster management and dynamic packet forwarding protocol in addition to neighbor and energy monitoring.

In the simulation experiments, we randomly placed 200 sensor nodes in a 500m×500m sensor monitoring field. Each sensor node is equipped with 802.15.4 wireless module with −12dBm transmission power, −91dBm radio sensitivity and 5000bps bandwidth. The battery of each sensor node is assigned at 75mAh. We then compare the performances of the proposed GCDF approach with multi-hop LEACH (M-LEACH) [18] with the parameters $p = 0.07$ and 10 minutes CH rotation duration in each round. We also compared the performances of the proposed GCDF approach with non-grid CH selection scheme that only consider sensor node within radio range with the largest reachable neighbors (LRN). During the simulation, we use the default SIDnet-SWANS energy consumption model as also used in [18].

The results of the experiments are shown in Table 1. It shows that the proposed GCDF gives better performance in preserving battery during the simulation time compared to the other approaches with the average of the remaining battery end of the simulation being 9.6% compared to 5.36% (LRN) and 8.13% (M-LEACH). The table also shows the number of sensor nodes that lost their energy (dead nodes). In 60 hours no dead nodes for GCDF and M-LEACH while one dead node occurrence for the LRN approach. After 70 hours of simulation, ten dead nodes occur for GCDF compared to 15 dead nodes (LRN) and 13 dead nodes for M-LEACH. Finally, after 72 hours, the total number of dead nodes for GCDF is 22 compared to 38 and 29 dead nodes for LRN and M-LEACH approaches. The dead node increments for the last 2 hours of simulation times (70-72 hours) where the average remaining battery is less than 10% are 12 (GCDF), 23 (LRN) and 16 (M-LEACH). These results show the effectiveness of the GCDF approach for data gathering in WSN environments. Figures 4 and 5 illustrate the results in figures.

TABLE 1. Average remaining battery power and number of dead nodes

Simulation Hours	**Average Remaining Battery Power (%)**			**Number of Dead Nodes**		
	LRN	**M-LEACH**	**GCDF**	**LRN**	**M-LEACH**	**GCDF**
20	98.28	98.2	98.92	0	0	0
24	91.25	91.21	92.05	0	0	0
40	63.2	63.32	64.51	0	0	0
60	27.99	28.49	30.11	1	0	0
65	19.25	19.83	21.52	1	0	0
70	10.55	11.32	12.97	15	13	10
72	5.36	8.13	9.6	38	29	22

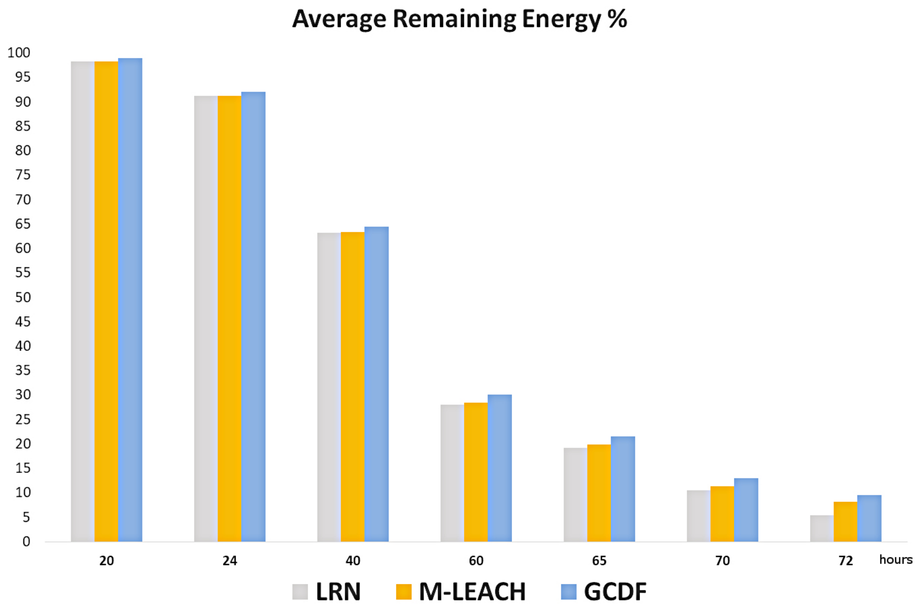

Figure 4. Percentage of remaining energy during 72 hours of simulation time

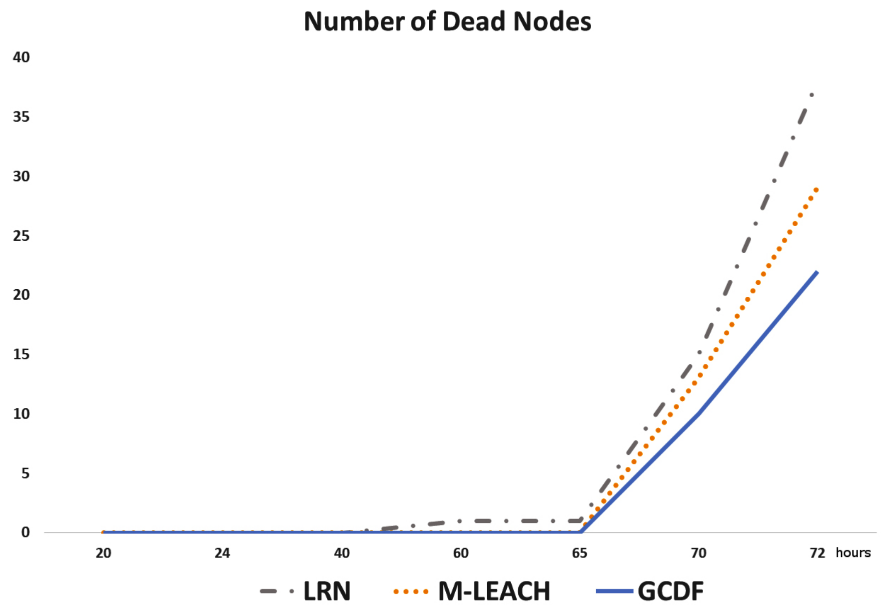

Figure 5. Number of dead nodes during 72 hours of simulation time

The packet delivery ratio and latency during data transmission from CH nodes to the sink node were also evaluated. From the experiments, we obtain that during 72 hours of simulation times, the proposed GCDF approach produces the highest PDR ratios (93.7576%) compared to the other approaches M-LEACH (93.38541%) and LRN (92.6959%). However, the proposed GCDF approach has data latency at 73ms, higher than the data latency for M-LEACH approach (61ms) and LRN approach (63ms). M-LEACH [18] gives the lowest latency in the simulation since in this approach if multiple CH announcements are received the cluster node members will select the one located closest to the sink node. The LRN approach picks available CH with largest neighbors and ignoring their grid location. On the other hand, the GCDF approach will select CH candidates within the same cluster grid and their places close to the grid centers. In the case for cluster members with the positions closer to the sink than the CH node, this approach will increase the packet latency due to backward routing direction.

5. **Conclusions.** In this paper, a grid-based routing protocol with dynamic forwarding (GCDF) to support data gathering in WSN environments was proposed. The main idea of the proposed approach is to distribute clusters location that will minimize overlapping between cluster heads their formed cluster which then also reduce radio collisions and overhearing. Furthermore, dynamic routing paths between CH nodes to the sink node are also integrated to distribute energy usage and to reduce the number of dead nodes. The experiment results show that the proposed approach gives better performances in preserving energy consumption and reducing the number of dead nodes. The proposed approach is also capable of maintaining the packet delivery ratio with a higher value than the other approaches with an acceptable latency. Future work will focus on dynamic grid allocations by considering density and priority of sensing information in various application scenarios.

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