DDCP: The Dynamic Differential Clustering Protocol Considering Mobile Sinks for WSNs

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Abstract

In this paper, we extended a hierarchical clustering technique, which is the most researched in the sensor network field, and studied a dynamic differential clustering technique to minimize energy consumption and ensure equal lifespan of all sensor nodes while considering the mobility of sinks. In a sensor network environment with mobile sinks, clusters close to the sinks tend to consume more forwarding energy. Therefore, clustering that considers forwarding energy consumption is desired. Since all clusters form a hierarchical tree, the number of levels of the tree must be considered based on the size of the cluster so that the cluster size is not growing abnormally, and the energy consumption is not concentrated within specific clusters. To verify that the proposed DDC protocol satisfies these requirements, a simulation using Matlab was performed. The FND (First Node Dead), LND (Last Node Dead), and residual energy characteristics of the proposed DDC protocol were compared with the popular clustering protocols such as LEACH and EEUC. As a result, it was shown that FND appears the latest and the point at which the dead node count increases is delayed in the DDC protocol. The proposed DDC protocol presents 66.3% improvement in FND and 13.8% improvement in LND compared to LEACH protocol. Furthermore, FND improved 79.9%, but LND declined 33.2% when compared to the EEUC. This verifies that the proposed DDC protocol can last for longer time with more number of surviving nodes.

Keywords: WSN, Hierarchical Clustering, Mobile Sink.

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1. Introduction

A wireless sensor network (WSN) refers to integrating various sensors for situational awareness into a widely deployed wired/wireless network infrastructure and linking the sensed data from the sensors with an application service server. What makes WSN different from standard sensors such as temperature sensors is their ability to collectively gather and process data via mutual communication channels between sensor modules.

A sensor network largely consists of sensor nodes, a sink, and a public network such as the Internet. A sensor node refers to a sensor module itself deployed in a targeted area to detect a certain phenomenon, and a sink refers to a gateway that collects information sensed from sensor nodes in a sensor network field and transmits it to a user through a satellite or backbone network. Typically, a wireless transceiver is being used for communications in a sensor network. Due to the limited transmission range of the wireless transceiver, it is almost impossible to directly transmit data to a user far away from the sensor node or it will result in consuming significantly more energy. Therefore, the sensor nodes not only monitor the targeted area but also perform a routing function when they transmit sensed data to a user farther than the transmission range of the sensor nodes. In a sensor network, since sensor nodes are cooperating to transmit sensed data to a sink, the lifespan of each sensor node is a critical factor that determines the lifespan of the entire sensor network. It is worth to note that it is practically impossible to replace or recharge a battery-drained sensor node because a large number of sensor nodes are scattered irregularly in places inaccessible to users. As the lifespan of the sensor node depends on the battery installed on each sensor node, an algorithmic approach is required to increase the lifespan of the entire communication network by reducing the amount of energy consumed by each sensor node as much as possible while ensuring fair energy consumption among sensor nodes so that all sensor nodes can perform their respective roles for an even period of time [1].

In the case of the location of the sink is fixed, an efficient configuration of a sensor network is possible through a relatively simple clustering protocol. However, if the location of the sink is mobile, then additional factors such as cluster reconfiguration according to the relative location of the sink, the optimal time and method for cluster head selection and re-election to reduce energy consumption, etc. should be further considered. When a sink collects, processes, and uses data, it can be configured as a desktop or a server in a fixed location, but it can also be a mobile device that requests data from constantly changing locations [2]. For the sink with mobility, a clustering technique different from the existing methods is required, and various studies have been conducted in the literature [3-10].

Research in the field of sensor networks can be largely categorized into cluster configuration, cluster head selection and replacement, and multi-hop routing. [11] classified 215 clustering protocols based on heterogeneity support, a role of a cluster head, inter-cluster routing, mobility support, and clustering objectives and provided insight into the design of clustering protocols in WSNs.

In this paper, we propose a Dynamic Differential Clustering algorithm that maximizes the lifespan of a cluster-based network by taking the mobility of a sink into account during the phases of the cluster configuration and cluster head selection cycles. The proposed algorithm adjusts the scale of clusters to equalize the lifespan of all sensor nodes depending on the location of a sink. It configures clusters based on how much energy is consumed by a cluster head for data transfer, which depends on the distance or hop counts to a sink, and replaces cluster heads based on the probability-based selection like LEACH [12]. In addition, it differentiates the cluster re-configuration period by adjusting the probability of a cluster head replacement for each cluster as the size of clusters are configured differentially based on the location of the sink. To verify the performance of the proposed algorithm, we evaluated FND, LND, and residual energy through a Matlab-based simulator, and compared its performance with other representative clustering protocols for the same sensor network.

The following describes the organization of this paper. After the introduction in Section 1, a brief discussion on related work is presented in Section 2. Section 3 describes our proposed Dynamic Differential Clustering (DDC) Protocol in detail. In Section 4, the simulation results performed using Matlab were compared with LEACH and EEUC for performance evaluation of the proposed DDC protocol. Finally, we conclude the paper in Section 5 with discussions and future work.

2. Backgrounds

The overall operation of the hierarchical cluster-based sensor network can be divided into two phases: the initialization phase and the operation phase. The initialization phase is to configure the cluster and the operation phase is to transmit the collected data. These two phases are repeatedly performed.

The initialization phase is a phase that configures the entire sensor network into a set of clusters. In order to configure an energy-efficient sensor network, it should be carefully decided how many clusters to divide into and which node in each cluster will be the cluster head. There have been numerous studies conducted on the cluster configuration from the early stage of sensor networks to the present, and various algorithms have been proposed. Significant studies for cluster configuration include LEACH, HEED [13], ACE [14], and EEUC [15], etc., and various studies based on these have been conducted up to the present.

The fundamental requirement of a hierarchical clustering algorithm is that every sensor nodes must belong to only one cluster after the cluster configuration initialization. The required messages and time overhead for the cluster configuration initialization should be minimized and the goals of clustering such as maintaining stable cluster configuration, routing, network efficiency, and minimizing energy consumption should be satisfied.

Considering the characteristic that data aggregation is required to reduce energy waste due to redundant transmission of similar information between adjacent sensor nodes in a WSN, a hierarchical cluster-based routing technique has many advantages. That is, each sensor node transmits data to an intra cluster head, and the cluster head aggregates data to reduce the amount of data to transfer and enable more energy-efficient routing. The cluster head is also responsible for performing data transmission for the requested queries so it can prevent inefficient data transmission performed by individual sensor nodes.

2.1. Process of the Hierarchical Clustering Protocols

The operation of the hierarchical cluster-based network (T_{op}) consists of a cluster operation phase for clustering (T_{cp}) and a network operation phase for data communication (T_{no}). In general, the network operation phase has a larger cycle than the cluster operation phase so as to reduce the overhead imposed to network for cluster configuration [2]. The network operation phase consists of the communication within the cluster (T_{intra}) and the communication among the cluster heads (T_{inter}), and data transmission takes place in this phase. The sensor network operation (T_{op}) can be described as a round, and cluster configuration and data collection and transmission are performed in each round.

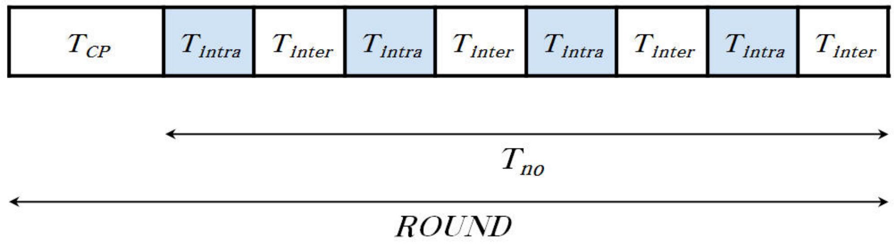


Fig. 1. Round Structure of the Hierarchical Clustering Protocol

2.2. Routing Algorithms for the Hierarchical Clustering Protocols

There have been numerous studies conducted on clustering protocols of WSNs from the early stages of sensor networks to the present, and various algorithms have been proposed. LEACH is the most basic hierarchical cluster network routing algorithm. It forms clusters, processes data locally to reduce global communication (data aggregation), and rotates cluster heads randomly. Every node becomes a cluster head at least once with a certain probability, and the node selected as the cluster head directly transmits data to the sink. However, no guarantee is provided that a sensor node elected as a cluster head will be evenly distributed in the sensor network. This is because the cluster head selection is conducted by a method that randomly forms clusters with local probability. To complement the problem, LEACH-C [16], which forms clusters using a centralized management technique, was proposed.

HEED [13] considers the limited communication range of wireless network and the cost of intra-cluster communication to expand LEACH. The probability to be a tentative cluster head (tentative_CH) will be determined by residual energy possessed by each node and these tentative cluster heads (tentative_CH) compete each other to be a final cluster head (final_CH). The final cluster head (final_CH) is decided by the cost of intra-cluster communication.

In TEEN [17], the sensor nodes transmit data only when the sensed data meets certain thresholds (change in the sensed value) instead of periodically transmitting sensed data. Data transmission will be determined by each sensor node based on the two thresholds, Hard Threshold (H_T) and Soft Threshold (S_T), broadcasted by the cluster head at the cluster decision phase. If the change in sensed value is greater than the stored sensed value (SV) by S_T or more, then the sensed data will be transmitted. LEACH has characteristics that are appropriate for proactive sensor networks, but TEEN is more suitable for reactive sensor networks as it immediately reacts to sudden or drastic changes in the sensed data.

T-LEACH [1] reduces the number of cluster head replacement through the use of the residual energy threshold value on sensor nodes. As a result, it reduces the energy consumption caused by the cluster head replacement in each round and minimizes the gap between FND and LND to prevent a phenomenon in which the energy of a specific node is consumed faster, so that the lifespan of the sensor nodes are balanced and the functional sensor network can last longer. However, T-LEACH doesn't consider cluster reconfiguration and the mobility of the sink.

EEUC [15], which is an energy-efficient unequal clustering protocol, unequally partitions nodes into clusters of different sizes. The small clusters will be formed near the sink and the larger clusters will be placed away from the sink. In addition, the sensor nodes that are closer than a certain threshold distance from the sink directly transmit data to the sink. Therefore, the closer the cluster head is to the sink, the more energy can be conserved in inter-cluster data transmission. This resolves the problem that the existing protocols consumes more energy from the cluster heads close to the sink. EEUC transmits data in multi-hop fashion between elected cluster heads. Recently, C-EEUC [18], a centralized non-uniform clustering routing protocol, has been studied in consideration of the 5G network environment. However, both EEUC and C-EEUC have limitations that an enough number of nodes must be distributed within a radius where direct communication with the sink is possible to form several clusters, and the mobility of the sink is not considered.

2.3. Mobile Sink

The mobile sink distributes energy consumption due to heavy data transmission of a specific node to the entire network by dynamically changing its location. However, the sink location tracking and data routing problems arise in case the sensor network supports the mobility of the sink. In particular, there have been many studies on the routing problem to transmit data to the mobile sink as it deemed to be an important issue that determines the network performance.

TTDD [20] proposed a method of transmitting data to the sink using source-oriented dynamic grid structure, but it has the disadvantage of requiring a lot of energy consumption in the grid setting stage for each source node.

CODE [19] builds grid structure like TTDD, but it searches for the shortest path and transmits data to the sink using grid ID routing by assigning a grid ID to each grid. However, this method also has a disadvantage in that a lot of cost is required to reset the route when the sink moves.

In most WSN environments, a sink is considered as an entity with no resource constraints such as power, processing capability, communication capability, etc. In addition, a sink can be attached to an object such as a mobile device, human, animal, robot, or vehicle and collects data while moving around/inside a sensor field in many WSN applications. If sink mobility is present in the network, it can have advantages in sensor lifetime, coverage, throughput and data fidelity, and security [21].

In [10], the existing protocols that support sink mobility in WSN are classified in detail, and the sink mobility are classified into Random/Unpredictable, Predictable/Fixed-Path, and Controlled Mobile patterns. In case that the cluster configuration is static, the difference in the sink mobility pattern can impact significantly on the performance of the clustering protocol. However, our proposed DDC protocol can flexible in responding to all three mobility patterns since the location of the sink is periodically tracked and dynamic clustering is performed.

3. Dynamic Differential Clustering

3.1. Energy Consumption Model for the Hierarchical Clustering

The sensor network based on the hierarchical clustering protocol is configured as shown in **Fig. 2**, and the process of network configuration can be divided into a process for forming a cluster and a process for operating the formed network.

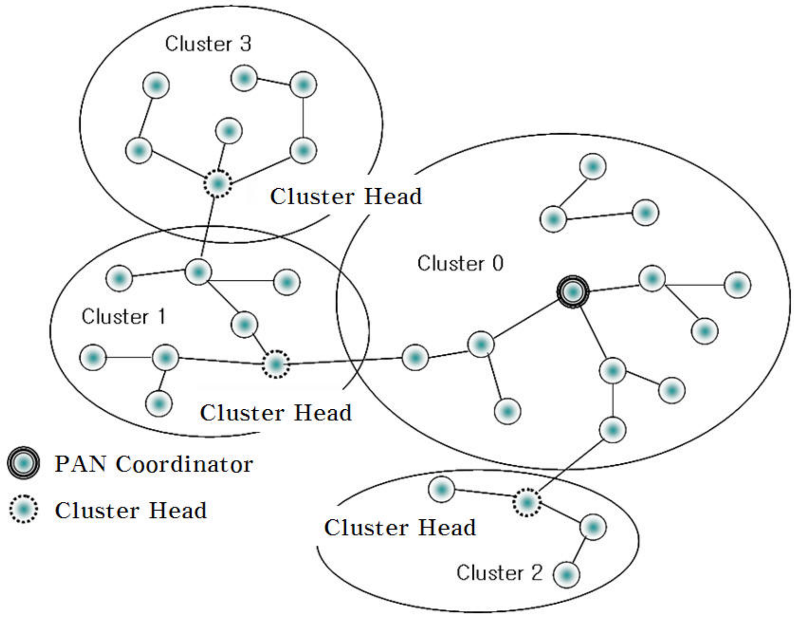


Fig. 2. Network Topology Configured with Hierarchical Clustering Protocol

Energy consumption can also be divided into energy consumed by the initialization process, which is the cluster formation phase, and energy consumed by the operation process, which is the network operation phase. **Table 1** summarizes the research conducted to classify the phases where energy consumption occurs in the clustering process and reduce energy consumption in each phase. With regard to the phase of the cluster formation, studies on cluster formation according to a cluster size, a number of clusters, the location of a cluster head, and the location of a sink have been conducted to reduce energy consumption of the entire network. With regard to the network operation, methods for extending the lifespan of the sensor network by distributing the role of the cluster head responsible for data collection and transmission in the formed unit cluster have been studied.

Table 1. Key features of the clustering protocols and related works

Process	Function	Related Works
Initialization	Clustering	Optimizations for the size of clusters
		Optimizations for the number of clusters
		Selection of the cluster head position
Round	Cluster Head Selection	Probability oriented (LEACH)
	Data Aggregation	Connectivity oriented (ACE)
	Data Transmission	Residual energy oriented (HEED)

3.2. Energy Consumption based on the Position of BS

With delayed selection of a cluster head through an energy threshold value, the lifespan of the entire network can be maximized and the time period from FND to LND can be reduced. However, this will only be effective when the sink node is fixed in the middle of the network field.

In the practical sensor network environment, the sink that collects data can move around actively rather than staying in a fixed location. Due to this mobility of the sink, the cluster reorganization and a new cluster head selection based on the distance from the sink need to be considered.

If the distances between the sink and clusters are not the same, then we need to reorganize clusters differentially based on the distance from the sink node as proposed in EEUC. However, since EEUC assumes that the locations of all nodes including the sink are not changing after the initial arrangement, the cluster organization method of EEUC cannot be applied as is.

In EEUC, the number of clusters around the sink is increased by reducing the size of the clusters as depicted in **Fig. 3 (a)**. This provides the extended lifespan of the entire network by decentralizing energy consumption of forwarding between the sink and nearby clusters.

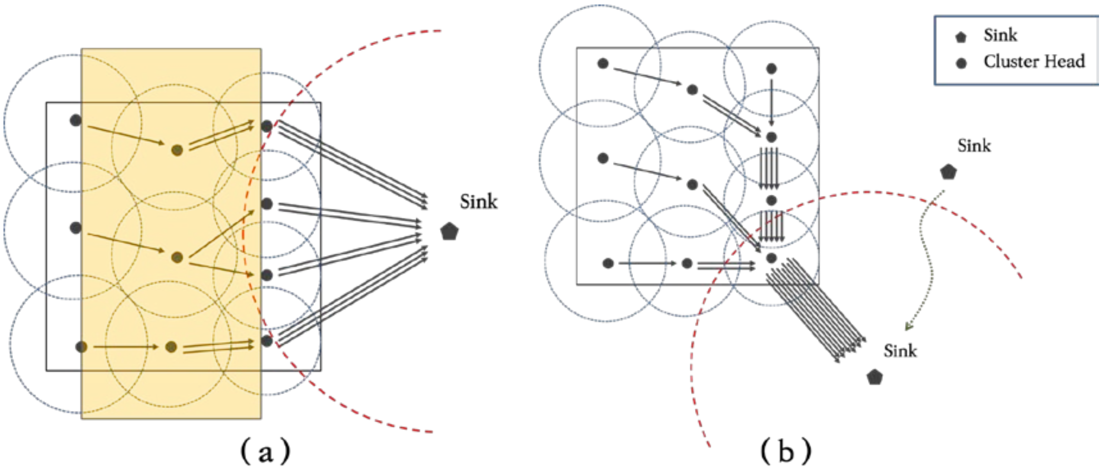


Fig. 3. Clustering method of the EEUC

Fig. 3(a) illustrates the ideal EEUC clustering scenario with evenly distributed sensor nodes near the sink. However, in case that the nodes placed unevenly around the sink node as described in **Fig. 3(b)**, the EEUC clustering method is not suitable due to the increased forwarding energy consumption between the sink and nearby small cluster.

3.3. Dynamic Differential Clustering

The hierarchical cluster has a tree structure, and the cluster located close to the sink becomes the highest-level cluster. Higher-layer clusters require more energy because they have to transmit data from lower-layer clusters to the sink. Assuming that L represents the level of the cluster tree, the cluster head's forwarding energy consumption in the corresponding level can be expressed as Equation (1). In the formula, N represents the total number of nodes, and k represents the number of clusters. Other parameters refer to the values provided in [2].

$$E_{fw} = lE_{elec}\left(\frac{N}{k} - 1\right) + lE_{DA}\frac{N}{k} + lE_{elec} + l\varepsilon_{fs}\left(\frac{d}{L}\right)^2 \quad (1)$$

In addition, the clusters' total forwarding energy consumption in the L level can be represented as follows.

$$E_{totalfw} = E_{fw} \cdot \sum_{i=0}^{L-1}(L-i) \cdot \left(2^{L-i}\right) \quad (2)$$

The extent of forwarding energy consumption according to each level in the cluster tree is shown in **Fig. 5**.

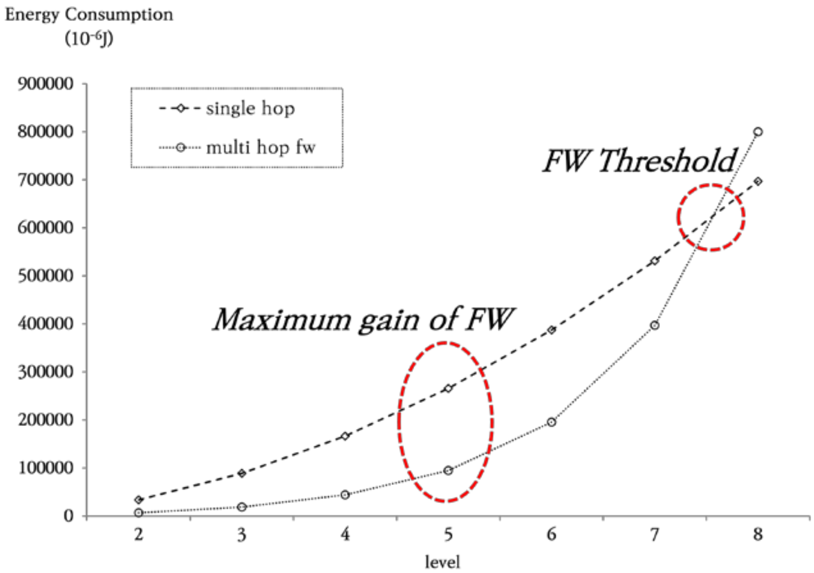


Fig. 5. Forwarding energy consumption by cluster tree level

Fig. 5 also compares the energy consumption of the direct data transmission to the sink with the degree of forwarding energy consumption according to the changes in the total number of tree levels. The largest performance difference is shown when the tree level is 5 to 6, and then the consumption of forwarding energy becomes higher than that of direct data transmission when the tree level is about 7.5 or more. Assuming that all nodes are uniformly deployed in the field and each node has the same initial energy, the size of the cluster must increase so that a cluster can have more energy than other clusters. **Fig. 6** shows the cluster size calculated based on the energy consumption required for forwarding shown in **Fig. 5**.

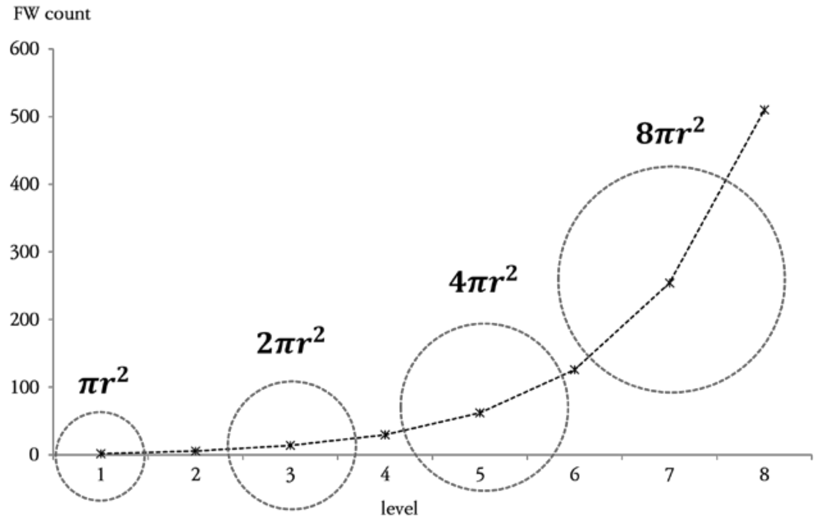
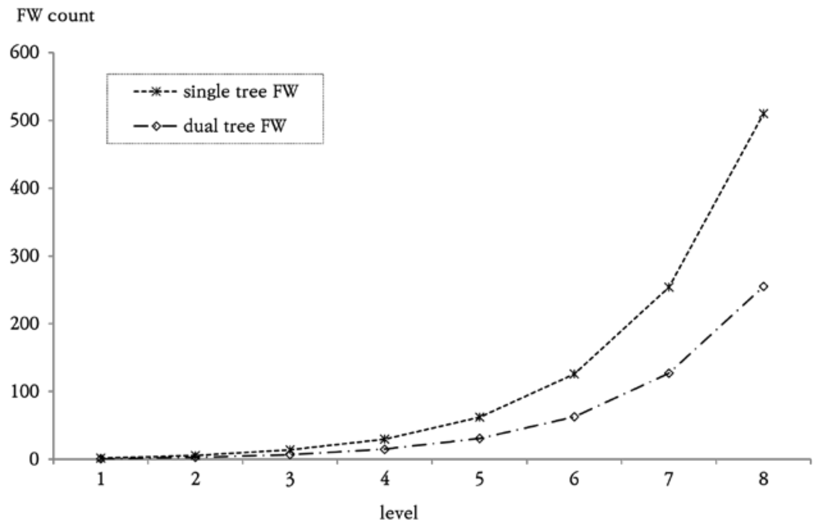


Fig. 6. Scale of the clusters related to each tree level

As shown in **Fig. 6**, the size of the cluster at each stage increases by about 1.4 times. In this case, the size difference between the highest and lowest clusters rapidly increases, and it is difficult to form an appropriate cluster because the size of the highest-level cluster tends to be abnormally large. Therefore, the size of the highest-level cluster needs to be limited by dividing the tree into two or more sub-trees if the cluster tree’ level increases beyond a certain threshold.



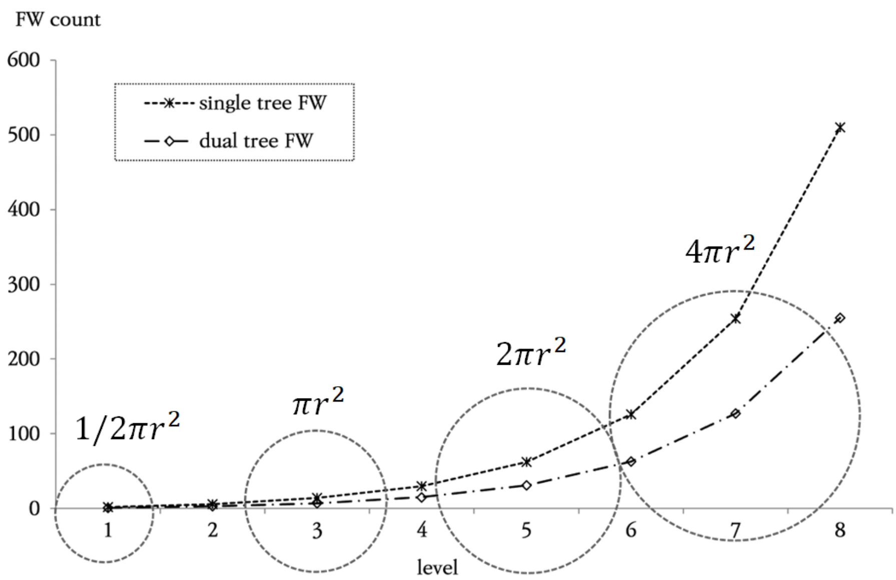


Fig. 7. Division of the cluster tree

Fig. 7 shows the changes in the cluster size when the cluster tree is bifurcated to limit the size of the highest-level cluster.
In [4], Equation (3) is used to satisfy the requirements for the calculated optimal number of clusters, but it is not suitable for symmetric clustering using multi-hop forwarding as this is based on the distance from each cluster to the sink.
In symmetrical clustering, the optimal number of clusters must be obtained according to the number of hops required by each cluster for data transmission to the sink.

$$E_{total} = k \cdot E_{cluster} + E_{fw} \cdot \sum_{i=0}^{L-1}(L-i) \cdot \left(2^{L-i}\right) \tag{3}$$

In Equation (3), the optimal number of clusters can be obtained by finding the number of clusters, k, such that the total energy E_{total} becomes 0.

$$k_{opt} = \frac{N(E_{elec}+E_{DA})}{\varepsilon_{fs}\left(\frac{d}{L}\right)^2 \cdot \sum_{i=0}^{L-1}(L-i)\cdot\left(2^{L-i}\right)} \tag{4}$$

When the level of the cluster tree is 3 and 4, energy consumption becomes the lowest if the number of clusters is 7 and 15, respectively. If the number of clusters exceeds 2^{L-1}, then the cluster tree level increases and the energy consumption of forwarding rapidly increases accordingly.

4. Experiments and Results

4.1. Experimental Environment

In order to verify that DDC can improve the efficient energy consumption and network lifespan in a sensor network environment with a mobile sink node, a simulation was performed using Matlab. In the simulation, the same network field was configured with the same number of sensor nodes deployed in the network field randomly, and the sink was moving at a constant speed around the network field. The results of FND, LND, and Residual Energy are compared each other for LEACH, EEUC, and DDC protocols.
The energy consumption model of the sensor node required in the process of data transmission/reception is shown in **Fig. 8**. The parameters for the experiment are shown in **Table 2**.

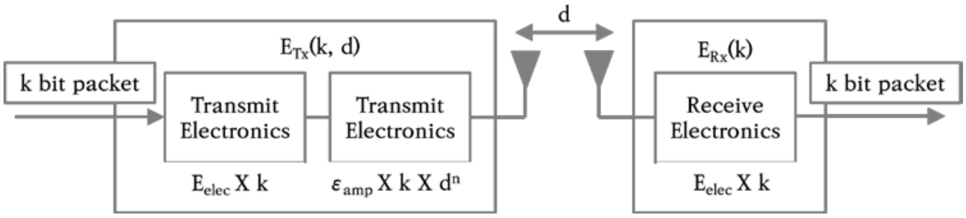


Fig. 8. Energy consumption models for Tx and Rx

Table 2. Parameters

Class	Applications	Descriptions
Network coverage	(0,0)~(200,200)m	-
Base station location	Clockwise rotation with radius 100 m	-
N	100	the number of nodes
Initial energy	0.5 J	-
E_{elec}	50 nJ/bit	the energy consumption in electronics for sending or receiving a bit
E_{fs}	10 pJ/bit/m^2	free space factor
E_{mp}	0.0013 pJ/bit/m^4	multipath factor
E_{DA}	5 nJ/bit/signal	the energy for aggregating data
Data packet size	4000 bits	-

Using the parameters shown in **Table 2**, the energy required for data transmission from one cluster to the sink can be calculated as shown in Equation (5).

$$E_{CH_n} = lE_{elec}(\frac{N}{k} - 1) + lE_{DA}\frac{N}{k} + lE_{elec} + l\varepsilon_{mp}d^4{}_{toBS} \quad (5)$$

In addition, the energy required for data transmission to the sink through n-hop forwarding between clusters is shown in Equation (1) and (2).

4.2. Simulation Results

A sensor network is formed based on the parameters in **Table 2**, and *N* sensor nodes are distributed randomly in the network field. The sink rotates around the field at a constant speed in clockwise from the 12 o'clock position of the network field. In the proposed DDC protocol, four levels are set as shown in **Fig. 9**, and different p values are set for each cluster level as shown in **Table 3** to adjust the frequency of the cluster head replacement process based on the size of the cluster.

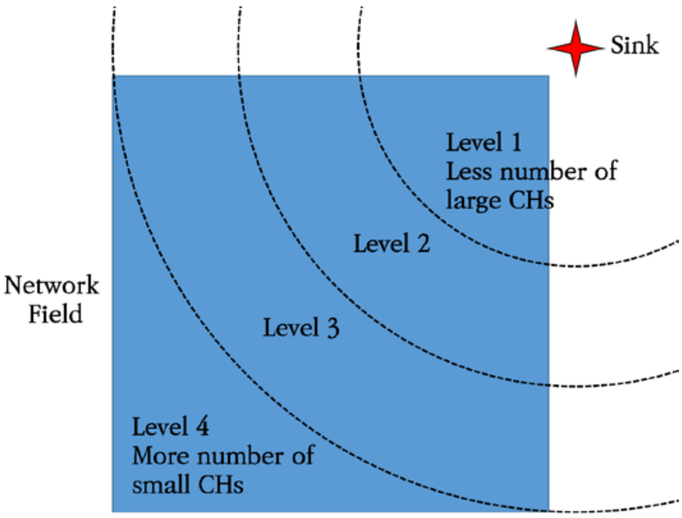


Fig. 9. Energy consumption models for Tx and Rx

Table 3. p value for cluster level

Cluster Level	***p* Value**
1	The probability to be a CH is low so that we can keep less number of CHs in Level 1 (p = 0.05). The rotation period of CHs is fast as each CH consumes more energy than other CHs in the lower levels.
2	p = 0.1
3	p = 0.2
4	The probability to be a CH is higher than other levels. Each sensor node has higher probability to be a CH so we can keep more number of CHs in Level 4 (p = 0.4).

We compared the performance of LEACH, EEUC, and the proposed DDC protocol based on the same network settings while the sink is moving around the network. The performance of the protocols was measured in terms of FND, LND, and residual energy. The average results of 100 rounds of simulation for each protocol illustrated in **Table 4** and **Fig. 10**.
In the simulation results, we found that the proposed DDC protocol presents 66.3% improvement in FND and 13.8% improvement in LND compared to LEACH protocol. Furthermore, FND improved 79.9%, but LND declined 33.2% when compared to the EEUC.

Table 4. p value for cluster level

	LEACH	EEUC	DDC
FND	335	112	557
HND	869	885	925
LND	1053	1596	1198

Fig. 10 compares the number of dead nodes and residual energy as the three protocols run through the number of rounds. As shown in **Fig. 10 (a)**, the first node dead was most effectively delayed and the total number of dead nodes were relatively reduced by the proposed DDC protocol. This verifies that the proposed DDC protocol shows the best performance for a longevity of the network in which a meaningful number of sensor nodes participate (more than 30% of the sensor nodes). Furthermore, we evaluated the performance of the three protocols by varying the number of nodes in the network field and examined how the density of nodes impacts their effectiveness. The results of the simulations consistently indicated that the DDC protocol demonstrated most effective performance (first node dead) with a similar level of improvement.

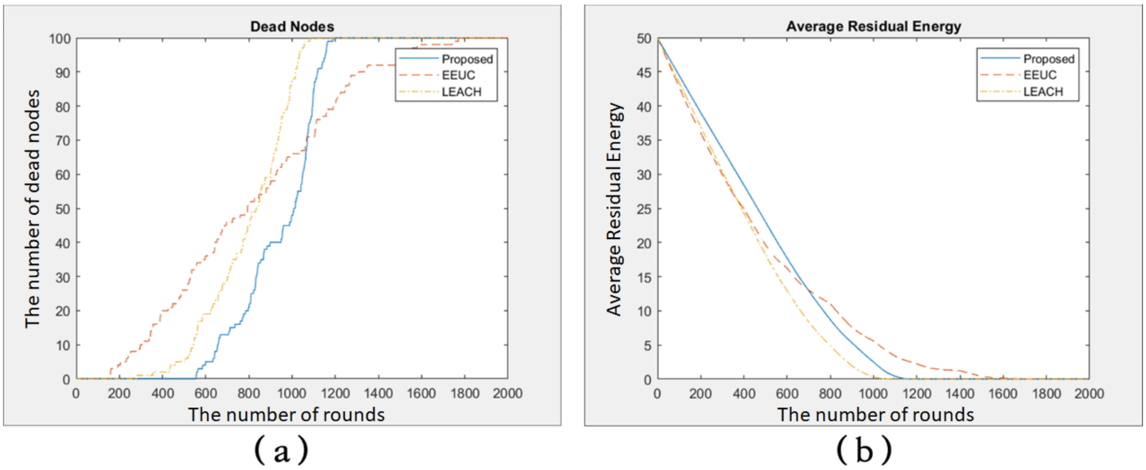


Fig. 10. Comparison of Dead Node Count and Residual Energy for LEACH, EEUC, DDC

6. Conclusions

In this paper, we studied Dynamic Differential Clustering technique in order to ensure the same lifespan of all sensor nodes while minimizing the energy consumption. The proposed DDC protocol considers the mobility of the sink in a hierarchical clustering technique, which is well-researched in the field of sensor networks. If the sink has mobility in sensor networks, the cluster that is the closest to the sink uses the most energy for forwarding data. Due to this large energy consumption, the clustering process needs to consider the amount of the forwarding energy consumption. In addition, the size of the cluster must be considered to prevent the excessive growth of the cluster and uneven energy utilization among them since clusters themselves build a hierarchical tree structure.

The Matlab simulation results prove that satisfaction of the requirements of the proposed DDC protocol. In the simulation, we compared FND, LND, and residual energy of LEACH, EEUC, and the proposed DDC protocol. The result shows that FDN appears that the last and the point

that increases Dead node count has been postponed. Therefore, we prove that the network, which has most active nodes can last longer with the proposed DDC protocol.
As a future work, additional research will be conducted on the reset period of clusters depending on the time interval for tracking the location of the sink and the degree of energy consumption required to reconstruct clusters.

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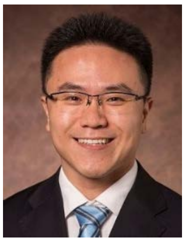

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