# Efficient Data-replication between Cluster-heads for Solar-powered Wireless Sensor Networks with Mobile Sinks

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## Abstract

In this study, an energy-aware data-replication is proposed to effectively support a mobile sink in a solar-powered wireless sensor network (WSN). By utilizing the redundant energy efficiently, the proposed scheme shares the gathered data among the cluster heads using a backbone network, in order to increase data-reliability. It also maintains a backup cluster head in each cluster to enhance topological resilience. The simulation result showed that, compared to conventional clustering techniques, the proposed scheme decreases the total amount of data loss from the mobile sink as well as saving its energy (by reducing its moving distance), while minimizing the unexpected blackout time of the sensor node.

**Keywords:** Wireless sensor network, Solar energy, Clustering, Mobile sink, Energy sharing

## 1 Introduction

Wireless sensor networks (WSNs) are widely used in ecosystem monitoring, military operations, disaster detection, architecture, and planetary exploration. The wireless sensor node of general WSNs uses a battery and thus has a limited life span. To overcome this problem, there have been increasingly more cases of building WSNs by using sensor nodes that harvest energy from the surrounding environment.

For energy-harvesting sensor nodes, the most commonly used energy source is solar energy. The harvested amount of solar energy varies depending on time of day, weather, and season, but it is generally predictable, and sufficient energy can be harvested to operate all modules of general sensor nodes in an environment that is illuminated at approximately 600lx. Furthermore, because the illumination of an outdoor environment during daytime exceeds 1,200lx on average, the remaining energy after operating the sensor nodes can be stored in batteries. This surplus energy can be not only used to operate the node during nighttime, but also used to achieve a specific network-wide performance, meeting criteria such as throughput and reliability.

It is well known that it is very difficult to achieve full performance with battery-based WSNs due to the energy constraints of the battery. Attempting to do so in battery-based WSNs can seriously shorten the lifetime of a WSN, since enhancing throughput or reliability must be traded against energy. Therefore, the design of battery-based WSNs has been mainly focused on minimizing energy consumption in order to prolong network lifetime. However, in the solar-powered WSN where the energy can be harvested periodically, unused residual energy in a rechargeable battery may stop the harvested energy from being stored there, due to the restrictions on battery capacity. Therefore, it is more important to make the best use of harvested energy than to minimize the energy consumed. To make the best use of harvested energy, the proposed scheme utilizes some of the energy to share the data between head nodes for a WSN with mobile sinks.

The characteristics of solar energy such as periodicity and dynamics necessitate an energy scheduling scheme suitable for solar powered nodes, which is completely different from the scheme used for battery-based nodes. Energy scheduling for a solar-powered sensor should satisfy the following requirements:

- Energy-neutral operation (ENO): Energy input during a harvesting period should not be less than the amount of energy consumed during the same period. Since the energy harvested in one day can vary with environmental conditions, a node should adapt its power consumption rate to this harvested energy.
- Minimizing the waste of harvested energy: Solar energy can only be harvested periodically, and unused residual energy in a battery may stop harvested energy from being stored in the battery.

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DOI: 10.3966/160792642018111906016

Therefore, it is more important to make the best use of harvested energy than to minimize the energy consumed.

Meanwhile, research has been carried out recently to determine schemes of collecting data by using a mobile sink to reduce the energy consumption of the sensor nodes in WSNs. The conventional method of using a fixed sink requires the data to pass through many nodes in order to collect the data of those nodes located far from the sink. Consequently, the energy consumption is large and not balanced. However, if a mobile sink moves around the network to collect the data, the total energy consumption of the network can be reduced since there is no need to transmit the data through so many nodes. On the other hand, when collecting data by having a mobile sink move around the network, data collection would take a long time, and the mobile sink would move very inefficiently. Therefore, recently developed schemes that combine the mobile sink with clustering [1] are being used. These schemes divide the nodes into clusters: a cluster head collects the data of each cluster. Since the mobile sink collects data by visiting to the cluster heads only, delays due to mobile sink operation, as well as the energy consumption of the mobile sink, can be reduced. The energy consumption of mobile sink becomes more critical since the battery-based mobile sinks such as drones are frequently used recently, while the previous mobile sinks were supposed to be unlimited power.

In this paper, a technique called a cluster-based energy-aware data-sharing scheme (CE-DSS) is proposed to decrease the energy consumption of the battery-based mobile sink such as a drone and also to increase the data reliability for solar-powered WSN. For these goals, the CE-DSS adopts the two schemes: the first scheme is to share the data among the cluster heads; the second scheme is to utilize a proxy node for each cluster head. As a result of the former scheme, the amount of missed sensory data gathered at the sink would be reduced due to the duplication. By the same reason, the moving distances of a mobile sink would also be reduced, leading to low data-latency and low energy consumption of the mobile sink. Secondly, for reinforcing data reliability without topology change, CE-DSS utilizes a proxy node which can take over the role of cluster head when the cluster head is blacked out before the topology reconstruction time.

This paper is organized as follows: In Section 2, we introduce the research related to solar-powered WSNs, mobile sinks, and clustering. In Section 3, our proposed clustering scheme is introduced. In Section 4, the performance of our proposed technique is measured through experiments; and in Section 5, we present our conclusions.

## 2 Related Work

### 2.1 Effects of Topology Control in WSNs

Topology control creates and maintains a list of the immediate neighbors of a node in a network. It is related to both routing and the medium access control (MAC) layer in the protocol stack. Topology control can trigger a route update when it detects that the list of neighbors of the node on which it is running has changed substantially. By doing this, instead of passively waiting for the routing protocol to update each route separately, topology control provides the routing layer with a faster response to topology changes and a reduced packet-loss rate. Conversely, the routing layer will trigger execution of topology control if it detects many broken routes in the network. The presence of broken routes indicates that network topology has changed substantially since the last execution of topology control.

Topology control also determines the transmission range of the node on which it is running. The transmission ranges of all nodes determine the expected contention in the MAC layer. Thus, the efficiency of topology control directly affects that of the MAC layer. Conversely, the MAC layer can trigger execution of topology control if it discovers new neighbors by overhearing network traffic. Since the effectiveness of topology control is closely related to the performance of the routing and MAC layers as described above, it is one of the most important issues in designing efficient WSNs. The use of topology control to enhance the overall performance of WSNs has been studied [2-6], but not for the special case of solar-powered WSNs.

### 2.2 Energy Supply and Demand of Solar-powered Sensor Node

Examples of the power consumption of a selection of commercial sensor network nodes for a range of operating conditions are given in Table 1 [7]. The average values given in Table 1 are based on an operating regime of communication (RX and TX, i.e., receive and transmit) for 1% of the time, processing for 10% of the time and sleeping for the remaining time. We can confirm that the energy demand of sensor node is several $mW$.

Meanwhile, we will now analyze the energy supply in a solar-powered node. PV(Photovoltaic) conversion of visible light to electrical power is well established and PV devices provide relatively high efficiency over a broad range of wavelengths. These devices are typically low cost and provide voltage and current levels that are close to those required for microelectronic circuits. The average solar insulation at the top of the earth's atmosphere is approximately $1370 W{\cdot}m^{-2}$ [11]. The energy available for harvesting at

**Table 1.** Summary of power consumption of commercial sensor network nodes

| | Crossbow MICAz [8] | Intel IMote2 [9] | Jennic JN5139 [10] |
|---|---|---|---|
| Radio standard | IEEE 802.15.4/ZigBee | IEEE 802.15.4 | IEEE 802.15.4/ZigBee |
| Typical range | 100*m* (outdoor), 30*m* (indoor) | 30*m* | 1*km* |
| Data rate (*kbps*) | 250*kbps* | 250*kbps* | 250*kpbs* |
| Sleep mode (deep sleep) | 15$\mu A$ | 390$\mu A$ | 2.8$\mu A$ (1.6$\mu A$) |
| Processor only | 8*mA* active mode | 31~53*mA* | 2.7+0.325*mA*/*MHz* |
| RX | 19.7*mA* | 44*mA* | 34*mA* |
| TX | 17.4*mA* (+0*dbm*) | 44*mA* | 34*mA* (+3*dBm*) |
| Supply voltage (minimum) | 2.7*V* | 3.2*V* | 2.7*V* |
| Average | 2.8*mW* | 12*mW* | 3*mW* |

a particular location on the earth's surface clearly varies with time of day, latitude and atmospheric conditions and the efficiency of conversion depends on the incidence angle to the PV device. Annually averaged surface-received energy varies between around $300W{\cdot}m^{-2}$ near the equator to around $100W{\cdot}m^{-2}$ near the poles. For temperate regions, the daily average available shortwave energy varies from around $25mJ{\cdot}m^{-2}\cdot day^{-1}$ in summer, to around $3mJ{\cdot}m^{-2}\cdot day^{-1}$ in mid-winter [12]. This does however depend on prevailing atmospheric conditions with heavy cloud cover resulting in a drop in available energy of approximately an order of magnitude. Given that commercially available PV cells provide a typical efficiency of around 15%, the minimum average electrical power over a 24-hour period in a temperate location is around $2W{\cdot}m^{-2}$. An important consideration in solar energy harvesting is that the energy is delivered for only part of the day and, assuming the sensor network is required to operate at the same level at all times, the energy gathered during the day must be stored for night time operation. Considering the same temperate location as considered above, a total of 0.15 $mJ{\cdot}m^{-2}$ electrical energy is harvested over an 8-hour period during the day in winter and must be stored to provide for the remaining 16-hour of the day. Commercially available super-capacitors have energy densities of around $5kW{\cdot}h{\cdot}m^{-3}$. Thus, over a 24-hour period, an average power of approximately $200W{\cdot}m^{-3}$ could be stored. This figure would correspond to an average power of $0.2mW/cm^3$. Assuming that the node uses $20cm^3$ (2*cm* x 2*cm* x 5*cm*) PV cell, it can provide an average 4*mW* of power, and this power supply can meet the energy demand of typical sensor nodes described in Table 1.

## 2.3 Routing in Energy-Harvesting WSNs

In the literature, most studies of energy-aware routing focus on residual battery status and do not take into account the environmental energy availability at the nodes. Willig et al. [13] were the first to develop a routing protocol for nodes with a renewable power supply. Although a lot of work has subsequently been put into the design and development of solar-powered sensor nodes, only a few makeshift topologies and routing protocols have been implemented.

At a time when energy-harvesting techniques were less effective, there was some research [14-15] on integrating a small number of solar-powered nodes into an otherwise battery-powered sensor network. The well-known routing protocols, LEACH [16] and Directed Diffusion [17] were modified to prolong network activity by placing heavier workloads on these additional energy-harvesting nodes.

The first serious attempt to utilize environmental energy for routing [18] demonstrated that environmentally aware decisions improve performance compared to decisions based only on battery status, although the application scenario was limited. Then, in the Heliomote [19] project, perpetuity of operation was considered in the context of task management, network topology and routing protocol. The UCLA team's implementation of a prototype harvesting node, itself called 'Heliomote', suggested ways to model energy harvesting and consumption numerically, and resulted in the design of a scheme to achieve indefinite operations.

Recently, Noh et al. have studied QoS-aware routing [20] and low-latency routing [21] in solar-powered WSNs. In their WSN, transmission ranges were periodically determined based on estimated energy harvest and predicted energy consumption. Then, the routing program running at each node selected one of the neighbors of that node which was likely to provide a desirable transmission performance, including low latency and high reliability. However, this approach was based on the predictions of variables such as the hop-count to the sink, the energy harvest and the rate of energy consumption, which are inevitably inaccurate, and thus its performance was not always satisfactory.

Lastly, Noh et al. developed efficient energy-aware topology-control and routing schemes which utilize a backbone network consisting of energy-rich nodes in a WSN [22]. This backbone handles most of the traffic with low latency, while reconfiguring itself dynamically in response to changes in the availability of energy at each node.

Many of the studies [18-22] we have explained so far focus on solar-powered WSNs, but assume fixed-position sink and deal with efficient data transmission from sensors to the static sink. On the other hand, this paper focuses on sharing data between clusters for a solar-powered WSN with a mobile sink, so as to enable mobile sink to collect large amount of data with short movement distance.

Finally, Yang et al. [23] study the duplication of data between nodes in a solar energy-based WSN, but this is not for a mobile sink. Additionally, it tries to minimizes data loss due to the sensor failure by distributing data redundantly across multiple sensors. Lastly it targets flat topologies that are not cluster-based.

In this paper, based on our previous research [22-23], we use a dynamic backbone to share the data between cluster heads [22], and also use the energy-threshold value for the best use of the harvested solar energy model [23].

## 3 Cluster-based Energy-aware Data Sharing Scheme

In this paper, we propose a CE-DSS to increase the efficiency of WSNs with a mobile sink, by efficiently using harvested solar energy in a clustering topology.

### 3.1 Energy-aware Node-classification

We will now explore when nodes should become energy-rich nodes (ER-nodes) or energy-saving nodes (ES-nodes), based on a solar-energy model. Formulating an ideal energy model of a solar-powered system requires knowledge of both the energy-harvesting rate of a solar-cell as an energy-input model and the energy- consuming rate of the system as an energy output model. The former is dependent on the location, weather and season where the system is deployed, and the latter is dependent on the data-sensing rate, data-transmitting rate and duty-cycle. The problem we have to challenge is that most of these factors cannot be predicted precisely. We will now introduce a simple but effective energy model [23] that is independent of these elusive factors.

Let the power $P_{\text{solar}}(i)$ be the average charging rate of a solar-powered node $n_i$, and let $P_{\text{sys}}(i)$ be the average power consumption rate of the same node. $P_{\text{sys}}(i)$ and $P_{\text{solar}}(i)$ can be estimated when the network is operational, using moving averages. Knowing the amount of energy currently available at node $n_i$, which we will call $E_{\text{residual}}(i)$, the expected time until the battery becomes full can be expressed as follows:

$$T_{full}(i) = \frac{C(i) - E_{residual}(i)}{P_{solar}(i) - P_{sys}(i)}, \quad \textbf{(1)}$$

where $C(i)$ is the battery capacity of node $n_i$. Note that the battery will only charge if $P_{\text{solar}}(i) > P_{\text{sys}}(i)$, which means that the average energy consumption rate of the node must be less than its average solar energy charging rate, otherwise the node would have to hibernate. Fortunately, even though $P_{\text{solar}}(i)$ cannot be controlled, $P_{\text{sys}}(i)$ can be roughly controlled by adjusting the duty-cycle $DC(i)$ of node $n_i$, since $P_{\text{sys}}(i)$ is a non-decreasing function of $DC(i)$. Therefore, by determining an upper bound on $DC(i)$, we can fulfill the inequality $P_{\text{solar}}(i) > P_{\text{sys}}(i)$.

Even though solar energy is not available at night and varies from one day to another, no blackout time would be expected until the next time the battery is full, as long as the amount of energy currently in the battery satisfies the following condition:

$$E_{residual}(i) \geq P_{sys}(i) \cdot T_{full}(i). \quad \textbf{(2)}$$

This is true even in the worst case, in which all solar charging occurs at the very last moment; $T_{\text{full}}(i)$. By solving equations (1) and (2), we can fulfill $E_{\text{residual}}(i) \geq P_{\text{sys}}(i)/P_{\text{solar}}(i) \cdot C(i)$. This means that the system would run without any unexpected blackouts for any pattern of weather or energy consumption, as long as it has at least $P_{\text{sys}}(i)/\underline{P}_{\text{solar}}(i) \cdot C(i)$ energy in the battery. We will call this value the energy threshold $E_{\text{threshold}}(i)$, which is formulated as follows:

$$E_{threshold}(i) = \frac{P_{sys}(i)}{P_{solar}(i)} \cdot C(i). \quad \textbf{(3)}$$

To sum up, if $E_{\text{residual}}(i)$ becomes smaller than $E_{\text{threshold}}(i)$, the system cannot be guaranteed to run without unexpected hibernation. In this case, therefore, the node should operate in ES-mode where it just senses and stores data locally in order to save energy. Otherwise, the node can be determined to have enough energy, so starts operating in ER-mode in order to perform extra tasks such as sharing the data. Figure 1 shows the relation between the system parameters and the system status in our energy model.

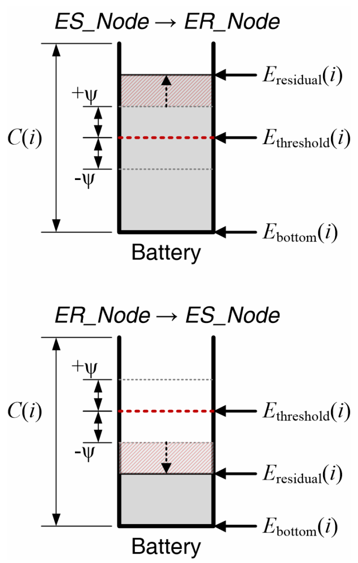


**Figure 1.** Relation between system parameters and system modes in our energy model

Note that it is also necessary to prevent the mode of each node from changing frequently and repeatedly. Let $m_i$ be the mode of node $n_i$, which is 1 if node $n_i$ is an ER-node, otherwise 0. This mode $m_i$ depends on whether $E_{\text{residual}}(i)$ is larger than $E_{\text{threshold}}(i)$. However, comparing $E_{\text{residual}}(i)$ with the exact value of $E_{\text{threshold}}(i)$ may lead to frequent changes of $m_i$. Suppose a node $n_i$ starts to operate as an ER-node as soon as $E_{\text{residual}}(i)$ becomes larger than $E_{\text{threshold}}(i)$. Since node $n_i$ has barely sufficient energy, $E_{\text{residual}}(i)$ is likely to sink below the threshold within a very short period of time. Similar behavior can be observed when the node starts to operate as an ES-node shortly after $E_{\text{residual}}(i)$ becomes smaller than $E_{\text{threshold}}(i)$. Theses repeated mode changes reduce system reliability and performance. Therefore, we use an energy window, $\varphi$ which mitigates the effect of the threshold as shown in Figure 1.

## 3.2 Overview of the Proposed CE-DSS

Figure 2 shows the pseudo-code of the proposed CE-DSS. As shown in Figure 2, the proposed scheme firstly forms a cluster by applying the location-based clustering algorithm [24]. Then, it selects the cluster-head in each cluster by using the probabilistic cluster-head selection scheme which utilizes the weight factor depending on the remaining energy [25]. Note that our scheme classifies all nodes into energy-rich nodes (ER-nodes) or energy-saving nodes (ES-nodes), according to the remaining energy of the node, and only ER-nodes can be a cluster-head. Lastly, the core routine which includes the backbone-constructing and data-sharing is invoked.

**Algorithm 1** CE-DSS($i$)

**Require:** Form cluster with $P_{\text{cluster}}$[22]
**Require:** Select cluster heads with $P_{\text{head}}$[23]
**Require:** Construct ER backbone [20]
**if** $i$ is cluster head **then**
    Share data of $i$
    **if** $E_{\text{residual}}(i) < E_{\text{bottom}}(i)$ **then**
        Find proxy
    **end if**
**else**
    **if** $E_{\text{residual}}(i) > E_{\text{threshold}}(i) + \psi$ **and** $m_i = ES\_NODE$ **then**
        $m_i \leftarrow ER\_NODE$
    **else**
        **if** $E_{\text{residual}}(i) < E_{\text{threshold}}(i) - \psi$ **and** $m_i = ER\_NODE$ **then**
            $m_i \leftarrow ES\_NODE$
        **end if**
    **end if**
**end if**

**Figure 2.** Pseudo-code of the proposed CE-DSS

As dictated in Figure 3, each of the three functions of the proposed CE-DSS scheme (i.e. clustering phase, cluster-head selection phase and the core routine) has its own period. The period of the clustering function is the largest and the period of the core routine is the smallest.

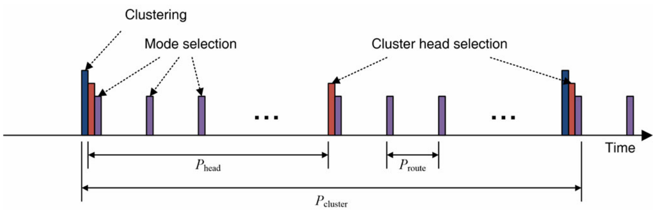


**Figure 3.** Comparison of the invocation period of each function in CE-DSS

The core routine also consists of three steps. The first step in the core routine is to construct a backbone network consisting of only ER-nodes, which is called an ER-backbone [22]. Of course, every cluster head belongs to the ER-backbone. This ER-backbone is used for an inter-cluster communication among cluster heads, while energy-aware location-based multi-hop routing [26] is used for intra-cluster communication. The concept of the ER-backbone is shown in Figure 4. In the second step, the cluster head duplicates its data to one of its neighboring cluster head using the constructed ER-backbone, and then checks its energy level. If its energy level goes down to $E_{\text{bottom}}$, it notifies this situation to the proxy node and makes the proxy node operate as a substitute cluster head. Finally, in the third step of the core routine, each node calculates its level of the remaining energy, and determines its operating type (ES-node or ER-node) for the next round.

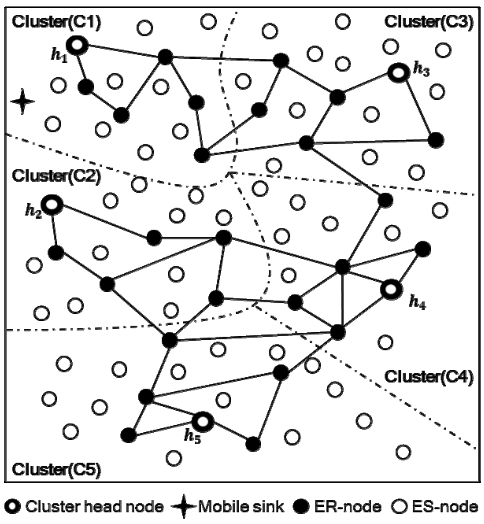


**Figure 4.** ER-backbone overview

## 3.3 Utilization of Harvested Energy

In this section, we explain each step of the CE-DSS algorithm in Figure 2 in more detail.

### 3.3.1 Sharing Data Among Clusters

We applied a method of sharing data between the cluster heads by using the surplus energy to decrease the moving distance of the mobile sink and to improve the data reliability via duplication. When a cluster head that carries data collected in a cluster has extra energy over the threshold value, the cluster head sends its own data to one of its neighboring cluster heads through the ER-backbone by using that extra energy. As shown in Figure 5, each of node $h_2$ and $h_5$, which is the head of cluster $C_2$ and $C_5$ respectively, sends its data to the neighboring cluster head $h_4$. In addition, cluster head node $h_3$ shares its data with neighboring cluster head $h_1$.

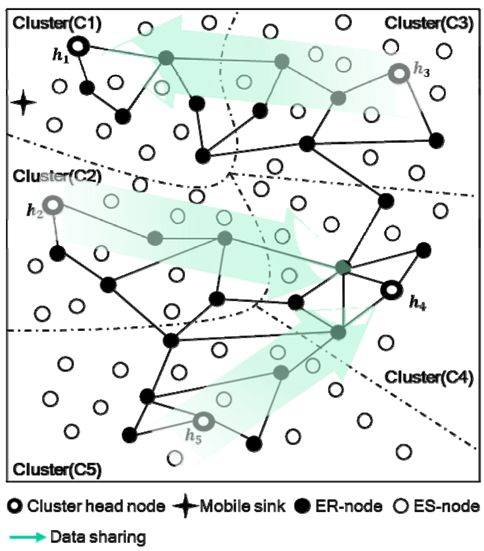


**Figure 5.** Sharing the collected data among clusters heads

When the mobile sink moves to cluster head $h_1$ to collect the data from the WSN, cluster head h1 delivers not only the data of its own cluster $C_1$ but also the data received from the neighboring cluster heads $h_3$. This means that there is no reason for the mobile sink to visit on cluster heads $h_3$. In this way, the mobile sink only needs to visit node $h_1$ and node $h_4$ in order to gather the data, while it should visit every cluster head in the previous approach. Figure 6 shows the comparision on the moving paths of the mobile sink.

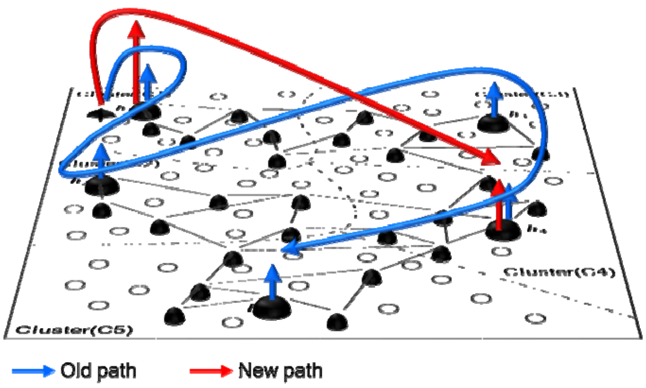


**Figure 6.** Reducing the moving distance of mobile sink node

Consequently, the proposed method substantially reduces the moving paths of the mobile sink. Moreover, if the sink determines that any data from a specific cluster head is missed, the mobile sink visits the other cluster heads which were not visited before to find the missed data. This is possbile because the data is duplicated and stored in neighboring cluster heads. By doing this, network reliability is improved.

### 3.3.2 Substituting an Energy-less Cluster Head

Unlike conventional schemes that reselect the cluster head when its energy goes down under the threshold within a period, our scheme utilize the proxy node for this situation since the re-selection mechanism requires so much energy from every member nodes. In more detail, our scheme selects both a cluster head and a proxy node simultaneously. When the energy of cluster head drops below a certain threshold, it notifies this situation to the pre-selected proxy node and makes the proxy node operate as a substitute cluster head.

Figure 7 shows the actions of the proxy node. Instead of energy-lacking cluster head $h_1$, the proxy node $p_1$ collects the data inside cluster $C_1$ and shares the data between neighboring cluster heads. When the mobile sink arrives at cluster $C_1$ to collect data, cluster head $h_1$ notifies the existence of proxy node $p_1$ to the sink. Then, the sink gathers the data (which is collected before and after selecting the proxy node) from cluster head $h_1$ and proxy node $p_1$ respectively. To sum up, using the proxy node can reduce the risk of data loss due to energy depletion of the cluster head with low overhead.

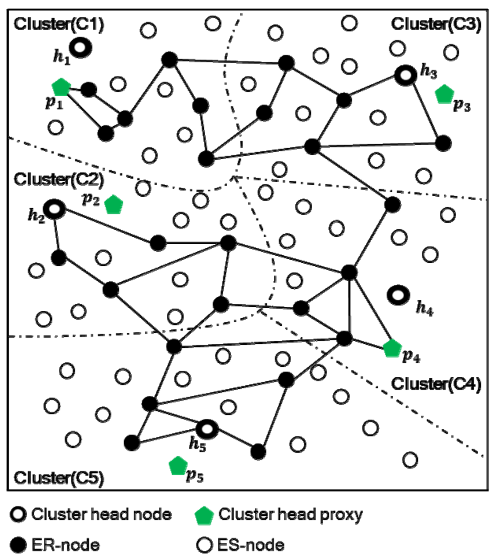


**Figure 7.** Substituting an energyless cluster head using a proxy node

### 3.3.3 Making the Resilient Connectivity of ER-backbone

The backbone network can be dynamically changed, so it is possible to have a lacking stability. For example, when there is not enough sunlight during a day, most nodes enter ES-mode and then transit to sleep mode during the night, when the backbone network may be disconnected. To solve this problem, we try to control the number of ER-nodes. In more detail, our scheme makes some of the ER-nodes, which are not critical for the connectivity of the backbone network, to operate in ES-mode so that they can construct an ER-backbone during an energy-deficient period when most nodes are operating in ES-mode.

A node is critical if its removal will disconnect the ER-backbone into two or more separate components. In Figure 8, for example, the square-shaped blue nodes are critical, since removal of any of them will partition the backbone. Therefore, each of critical ER-node must consist of backbone network, since its existence is crucial for the connectivity of the backbone network. Otherwise, an ER-node can be chosen to operate in ER-mode or in ES- mode with a given probability for the later use. For example, the triangle-shaped red nodes in Figure 8 operate in ES-mode although it is actually an ER-node. This kind of node is usually called the reserved node. By preparing the reserved nodes, the backbone network becomes more stable regardless of the environmental factor.

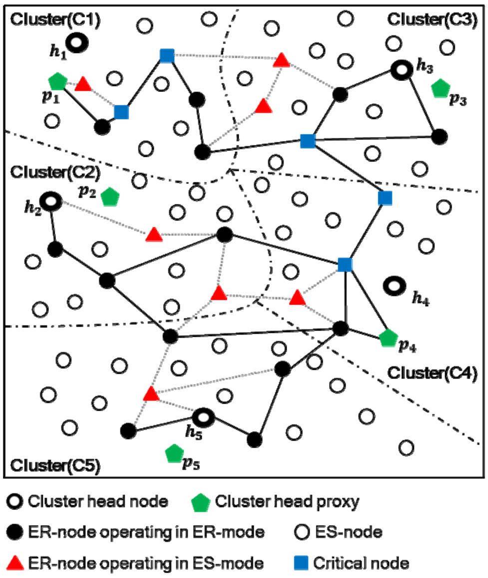


**Figure 8.** Making the resilient connectivity of ER-backbone using critical nodes

## 4 Experimental Results

This section presents the results of measuring the performance of the proposed clustering scheme. In the simulation, we compared our scheme with two other schemes. One is the very popular cluster-based scheme named HEED (Hybrid Energy-efficient Distributed Clustering) [23]. HEED is a hierarchical and distributed clustering scheme in which a single-hop communication pattern is retained within each cluster, whereas multi-hop communication is allowed among cluster heads, but does not consider any idea of data-sharing or proxy node. The other one is called ER-Scheme which works in the same way of CE-DSS except that every node operates in an ER-mode without considering its energy status.

### 4.1 Simulation Environment

We measured the performance of each scheme by using the improved SolarCastalia [27] simulator. The simulation was performed with 50, 75, 100, 125 and 150 nodes, during 10 days (500 rounds). A round means the period when the sensory data was gathered by the mobile sink. The number of clusters changed from 3 to 7. The major parameters used in the simulation are shown in Table 2. When performing simulation, we reflected the real experimental value of EZ2430-RF2500-SEH mote made by Texas Instruments (e.g. solar energy harvesting rates and system energy consuming rates), and present the average value as a result.

**Table 2.** Simulation parameters

| Parameter | Value |
|---|---|
| Simulation Time | 10 *days* (500 *rounds*) |
| Field Size | 100 by 100(*m*) |
| Topology | Random |
| Transmitter power | -5*dBm* |
| Routing | Energy-adaptive location based routing |
| MAC | T-MAC |
| Weather | Randomly chosen among sunny, cloudy and rainy |
| Cell Size | 7.5 by 7.5(*cm*) |
| Rechargeable Battery | NiMH |
| Battery Capacity | 200(*mAh*) |
| Data rate | 100 packets/round/node |
| Duty cycle | 15% |

### 4.2 Simulation Results

#### 4.2.1 Moving Distance of the Mobile Sink

Firstly, we checked the cumulative moving distances of the mobile sink over the rounds. A mobile sink should visit an appropriate number of head nodes to gather all data stored in WSN during a round. As shown in Figure 9, CE-DSS and ER-Scheme made the mobile sink move much shorter distance to gather all data stored in cluster heads than the HEED. This was du e to the fact that the cluster heads, in the proposed CE-DSS and ER-Scheme, shared their data with the neighboring header nodes using the ER-backbone, thus there was no need for the mobile node to visit every cluster-head.

#### 4.2.2 Amount of Data Gathered by the Sink

Secondly, we measured the total amount of data gathered by the mobile sink over the rounds. As shown in Figure 10, the proposed CE-DSS showed similar amount data with HEED, and both of them can gather

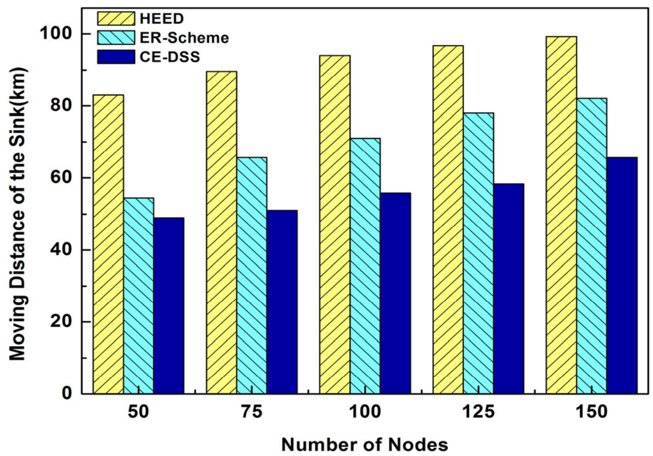


**Figure 9.** Comparison of the moving distance of the mobile sink

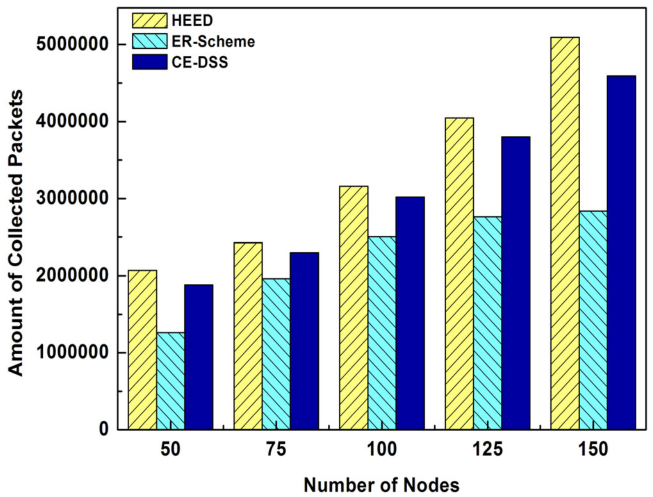


**Figure 10.** Comparison of the number of collected packets

much greater amount of data than ER-Scheme. Morever, the difference became larger over the rounds. This is beacuse the blackout times of each node between the CE-DSS and the HEED are almost the same but those of ER-Scheme is much larger. Remind that the functions of sharing data and working as a proxy node of the cluster-head did not demand the rise of blackout time on each node. Figure 11 shows the number of dead nodes as the number of nodes grows. As described in Figure 11, the CE-DSS showed the lower number of dead nodes than the ER-Scheme. The reason of superiority of CE-DSS over ER-Scheme is the energy awareness, which means that the number of dead node became much higher when ER-Scheme was applied since every node in ER-Scheme worked as an ER-node. We also confirms that the number of dead nodes is similar between CE-DSS and HEED. This is because the proposed scheme only utilizes the excess energy (which means the extra energy that does not affect the basic operation of the node such as sensing, computation and storing) to share the data. Therefore, the data sharing has no influence on the number of blackouts of nodes.

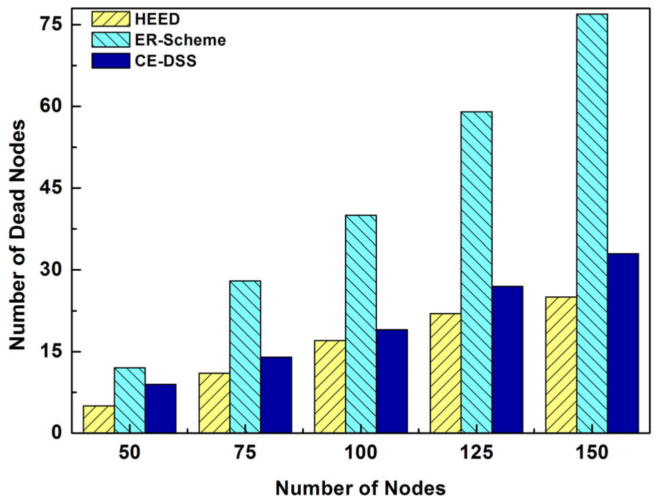


**Figure 11.** Comparison of the number of dead nodes

The other reason is that, in CE-DSS, when the energy of the cluster head became exhausted during a certain time within the period of core routine, the proxy node performed its role instead. Therefore, when the mobile sink arrived, the collected data could be safely delivered.

### 4.2.3 Network Reliability

To demonstrate another advantage of data sharing, we impose malfunction on one cluster head (assuming a H/W or S/W error occurs) at random time during the experiment, and compare the ratio of the amount of sensory data and that of data gathered by the sink. As shown in Figure 12, our scheme showed higher performance than other schemes. This occurred because CE-DSS maintained the duplicated data among the neighboring cluster head. Therefore, when the data could not be gathered from a certain cluster head due to its H/W or S/W faults, the sink can gather it from its neighboring cluster head. The ER-Scheme performed better than the HEED, but it has little meaning because the blackout time is so large as the absolute amount of data collected is quiet small.

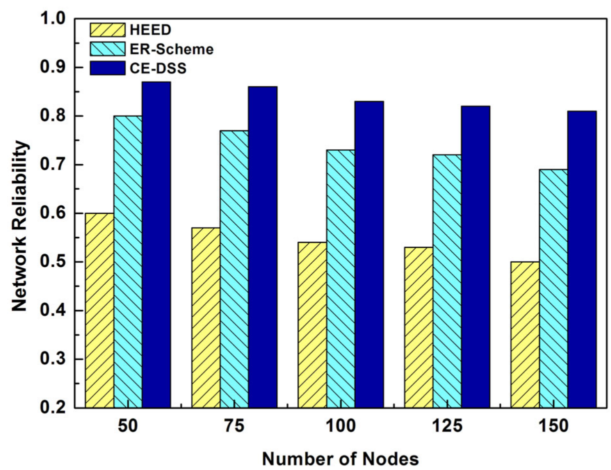


**Figure 12.** Comparison of the network reliability when one of the cluster head malfunctions

The proxy node (which operates as a cluster-head in an emergency) and the reserved node (which operates in ES-mode although it is actually an ER-node for the later use) are engaged to increase the stability of the network in our scheme. In order to verify the effectiveness of the proxy node and the reserved node, we measured the ratio of the amount of data gathered by the sink to the amount of data generated from 150 nodes of the WSN for the proposed scheme. Then, we compare it with the scheme which does not use of proxy nodes and reserved nodes respectively or both. As can be seen in Figure 13, both of these kinds of nodes are significant in terms of network reliablility.

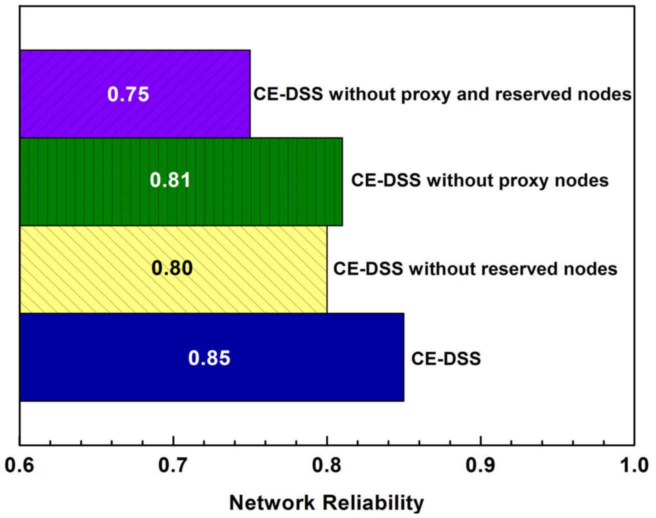


**Figure 13.** Comparison of the network reliability with and without proxy nodes and reserved nodes

## 5 Conclusion

Unlike a battery-powered WSN, which has a limited life span, a solar-powered WSN harvests energy from the surrounding environment. Accordingly, an energy optimization technique specialized for this situation is required. In this study, we proposed a technique to improve the reliability of the network and to reduce the moving distance of the mobile sink in a solar-powered WSN by using clustering. In this technique, clusters were created by using the k-means clustering algorithm. Each cluster head exchanged its data with other cluster heads through an ER-backbone when there was surplus energy, after collecting the data from in-cluster nodes. Here, the moving distance of the mobile sink was reduced by visiting a minimal number of cluster heads to collect the data of the entire network. Network reliability was enhanced by storing the duplicate data in other cluster heads. Furthermore, by using a proxy node to replace a cluster head that had insufficient energy, packet loss due to blackout of the cluster head was prevented, and the re-clustering overhead was decreased.

In this work, we dealt with the data-sharing and cluster-head substitution problem only from the energy aspect, assuming that the cluster nodes have enough space to store the duplicated data of the neighbor cluster heads. In the future, we will consider not only the energy limitation, but also the constraints of the storage space.

## Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (No. NRF-2016R1C1B1015937).

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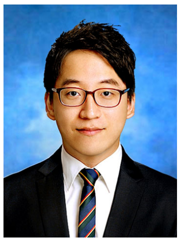

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