

Research Article

A Hybrid Energy- and Time-Driven Cluster Head Rotation Strategy for Distributed Wireless Sensor Networks

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Clustering provides an effective way to extend the lifetime and improve the energy efficiency of wireless sensor networks (WSNs). However, the cluster heads will deplete energy faster than cluster members due to the additional tasks of information collection and transmission. The cluster head rotation among sensors is adopted to solve this problem. Cluster head rotation strategies can be generally divided into two categories: time-driven strategy and energy-driven strategy. The time-driven strategy can balance energy consumption better, but it is not suitable for heterogenous WSNs. The energy-driven cluster head rotation strategy has high energy efficiency, especially in heterogenous networks. However, the rotation will become increasingly frequent with the reduction of the nodes residual energy for this strategy, which causes lots of energy waste. In this paper, we propose a hybrid cluster head rotation strategy which combines the advantages of both energy-driven and time-driven cluster head rotation strategies. In our hybrid rotation strategy, the time-driven strategy or energy-driven strategy will be selected according to the residual energy. Simulations show that the hybrid strategy can enhance the energy efficiency and prolong network lifetime in both homogeneous and heterogeneous networks, compared with either single time-driven or energy-driven cluster head rotation method.

1. Introduction

The advances in MEMS-based sensor technology and wireless communications recently have enabled the development of low-cost, low-power, multifunctional sensor nodes that are in small size and have short communication distance and low computational ability in wireless sensor networks (WSNs). These small sensor nodes are capable of sensing the environment, storing and processing the collected sensor data, and interacting and collaborating with each other within the network [1]. The major challenge in the design of WSNs is the energy management. Due to the strict energy constraint and nonrechargeable energy provision, the energy resource of sensors should be managed wisely to extend the lifetime of networks. Therefore, much attention has been paid to develop low-power hardware design, collaborative signal processing techniques, and energy-efficient algorithms at various WSNs [2, 3].

Neighboring sensor nodes usually have the data of similar events because they collect events within a specific area. If

each node transmits the collected data to the sink individually, lots of energy will be wasted for transmitting similar data. In order to achieve high energy efficiency and extend the network lifetime, sensors are often hierarchically organized into clusters, each of which has its own cluster head (CH). Within each cluster, sensors transmit data to their CH over a relatively short distance, which in turn forwards the data (or it is further aggregated) to the sink via a single-hop or a multihop path through other CHs like the illustration in Figure 1. In hierarchical clustering protocol, network is operated based on rounds. Each round begins with the cluster set-up phase and follows with a steady-state phase. In cluster set-up phase, sensor nodes elect themselves to be CHs at any given time with a certain probability and local cluster network is formed by each CH. In steady-state phase, each noncluster head node, which we call a cluster member, collects events and transmits them to its cluster head. After that, each cluster head aggregates the collected data to prevent duplicated transmissions of similar events and transmits the aggregated data to the sink node.

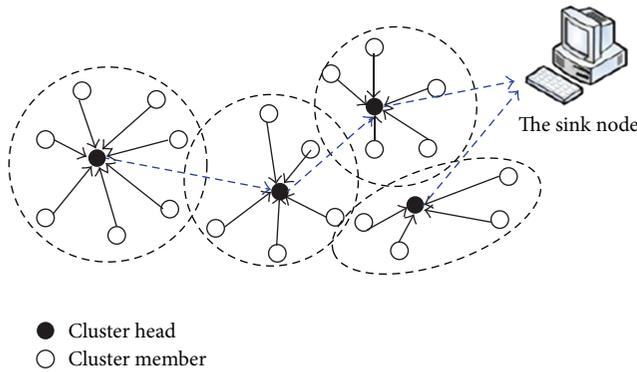


FIGURE 1: Clustering scheme of wireless sensor network.

From the description above, we can see that CHs undertake much heavier responsibilities than cluster members including long distance communication to sink node, intra-cluster data collection, and aggregation. Therefore, CHs consume much more energy than cluster members, and the fast energy depletion problem of them has become a serious issue in the cluster-based sensor networks. In traditional clustering schemes, powerful backbone nodes are proposed to serve as the cluster heads [4], which may increase the system deployment cost and is not suitable for many scenarios, for example, the intrusion detection and large-scale sensor networks which are often automatically deployed by the vehicles or planes. In such cases, the cluster heads are tiny and unattended battery-powered sensors, which require innovative design techniques to ensure high energy efficiency. The only way to prolong the lifetime of CHs lies in organization method. Then, CHs rotation strategy has been exploited to balance the energy consumption among cluster members and heads in hierarchical clustering WSNs.

The CHs rotation strategy is a technology of cluster topology maintenance. It plays a very important role in the reconstruction of the hierarchical cluster structure for avoiding premature death of CH nodes and increasing network lifetime. Many cluster head rotation strategies have been proposed in the recent research literatures. Such strategies can be divided into two categories: time-driven strategy and energy-driven strategy. Heinzelman et al. [5] firstly proposed LEACH cluster protocol in which cluster head is rotated periodically among the sensor nodes to ensure the balanced energy consumption of networks. By such periodical rotation of cluster heads among the sensors, energy is evenly depleted among nodes and the premature exhaustion of battery in any sensor can be avoided. But the time-driven based CH rotation method doesnot consider the residual energy of cluster heads which will cause much unnecessary energy waste and low energy efficiency when the network energy is powerful, especially in heterogeneous WSNs. However, time-driven CH rotation method can maintain fixed energy efficiency at any time.

To better solve this problem, the CH rotation mechanism based on energy driven is proposed in EDAC [6] and EDCR [7, 8], where the cluster head candidacy election phase and rotation phases are triggered only when the residual energy of any cluster head falls below a dynamic threshold. This kind of

energy-driven CH rotation strategy can mitigate the impact of the cluster head rotation on the network and achieve high energy efficiency in heterogeneous WSNs. But under this rotation mechanism, the cluster head rotation will become increasingly frequent along with the reduction of residual energy of the nodes. As a result, more and more energy will be used in rotation rather than data transmission, which will in turn reduce the energy efficiency of the network even to zero.

We notice that the residual energy of nodes will become almost equal in heterogeneous WSNs after a long period of network operation. The heterogeneous WSNs will become nearly the same as the homogeneous WSNs in terms of residual energy. Based on the respective features of time-driven and energy-driven CH rotation strategies above, we can develop new CHs rotation approach to achieve better energy balance and higher energy efficiency. We can use the energy-driven CH rotation strategy to achieve high energy efficiency when the energy of WSNs is abundant and unbalanced. After a long time of network operation, the energy of WSNs nodes is low and almost balanced, therefore; we adopt time-driven CH rotation strategy to ensure stable data transmission efficiency. This is the theoretical basis of our research. In this paper, we build the energy consumption model for contention-based CH selection and data transmission. By analyzing the energy consumption relationship between the cluster set-up phase and the steady-state data transfer phase, we propose a hybrid cluster head rotation strategy for WSNs in which the CH rotation strategy based on time or energy will be selected according to the network energy efficiency. We give the optimal mechanism that when we switch from energy-driven CH rotation to time-driven CH rotation to obtain the maximal energy efficiency for WSNs. Theoretical analysis and simulation results show that hybrid CH rotation strategy can successfully balance the energy consumption of the network and prolong the network lifetime. Moreover, it can obtain better energy efficiency and transfer more useful data to sink than either time-driven or energy-driven CH rotation method in both homogeneous and heterogeneous sensor networks. As a fundamental technology of cluster topology maintenance, our rotation strategy can be used in any cluster protocols.

The remainder of the paper is organized as below. Section 2 reviews research work in this area; Section 3 introduces the system assumptions used in this paper; Section 4 establishes and analyzes energy consumption for contention-based CHs selection and data transmission. Section 5 puts forward hybrid energy- and time-driven CH rotation strategy; Section 6 elaborates on our simulation efforts and the analysis results we obtained; Section 7 offers concluding remarks and points out future directions for research work.

2. Literature Review

As an important technology of cluster topology maintenance, cluster head rotation strategy has a great signification for the performance of cluster protocol in WSNs. By restoring the current topology and building a new one, it prolongs the network lifetime and prevents the premature death of sensors. However, it doesnot attract enough attention and extensive

research work is only dedicated to the study of cluster organization and scheduling algorithms. In this section, we briefly describe the most popular research that is most relevant to our approach.

Clustering provides an effective way for extending the lifetime of WSNs. Experiments have proved that the networks based on cluster hierarchy structure protocol are 7~8 times more efficient than traditional dispersed flat nodes protocol in measuring the lifetime of nodes. So, more efficient hierarchical network algorithms based on cluster architecture are designed to extend the network lifetime. Heinzelman et al. [5] proposed the LEACH algorithm, in which the CH is dynamically rotated among all sensors in the cluster for a period of time. Although there are advantages in using this distributed cluster algorithm, it does not consider the residual energy of sensor nodes and creates lots of overhead frames. Heinzelman also proposed the improved LEACH named LEACH-C algorithm [5] that elects cluster head based on the residual energy of sensor nodes.

SEP [9] extends the LEACH by adding a small percentage of higher energy nodes than the normal nodes in the network. HEED [10] elects CHs according to their total residual energy and a secondary parameter such as node degree. It has a much higher overhead compared with other algorithms because of CHs selection and rotation. The energy-efficient clustering method proposed in ANTCLUST [11] assumes that nodes sense their locations either using GPS or some localization techniques. Such an assumption is suitable for location-based information gathering systems but less applicable to low-cost ad hoc sensor networks. ACE [12] is an emergent algorithm to produce uniform clusters. Meanwhile, many other cluster-based hierarchy algorithms are improved based on LEACH [13–20]. All of the above algorithms share a common feature that their CH rotation mechanisms are all time driven. That is, the CH will be changed after a predetermined number of data gathering rounds. EDAC [6] and EDCR [7, 8] algorithms use method based on dynamic energy threshold to initiate a new CH election phase. This energy driven CH rotation strategy can achieve better energy efficiency and produce less overhead, especially in heterogeneous sensor networks.

Both energy-driven and time-driven CH rotations are faced with an urgent issue that how to select the optimum number of data transmission rounds. If a CH election phase is triggered after a smaller number of data transmission rounds, it will result in excessive overhead during the CH election phase. On the other hand, after a large number of data transmission rounds, the CH nodes will not have enough energy to act as ordinary sensor nodes after relinquishing the CH role. In [21], the authors proved that the energy-driven CH rotation strategy is better than the time-driven CH rotation strategy in a single cluster analysis model, and they gave a suboptimal solution for rotation energy threshold in the single cluster model. In [22], authors provided a method to obtain the optimal energy threshold parameter for energy-driven CH rotation strategy. For our hybrid CH rotation strategy, the main challenge lies in the mechanism how to select the best CH rotation strategy, energy driven or time driven, to obtain the maximum energy efficiency and extend the network lifetime. In the latter part, we will

study it theoretically and analyze the simulation result, which constitutes the major part of this paper.

3. Preliminaries

Before describing our proposed algorithm in detail, we will introduce the characteristics of the network model used in our implementations. We consider a WSN consisting of sensors and sink and make the following assumptions.

3.1. Assumptions on Node and Energy of the Network. As Figure 2 shows, we consider a sensor network of N nodes which is randomly dispersed in an $M \times M$ meters square area to continuously monitor the sense area, and all nodes including sink are stationary after disposition. Our assumptions about the sensor nodes and network are as below.

- (1) Nodes are equipped with wireless transmission and reception equipment and they have the capability of data fusion and power adjusting.
- (2) Time Division Multiple Access (TDMA) schedules the data transmission from normal nodes to its cluster head.
- (3) Nodes can estimate the approximate distance to another node based on the received signal strength.
- (4) Links between nodes are symmetric.
- (5) The network runs a periodic data gathering application, in which the sensor generates traffic at an average rate of λ bits/second and sends it to its CH, which in turn delivers it to sink.

3.2. Energy Consumption Model. A typical sensor node includes three basic units: sensing unit, processing unit, and transceivers. For our energy model of communication and transmission scheme, we assume a free space propagation channel model [23]. We ignore the power consumption of node for sensing because it is constant at any time and cannot be reduced with whatever means. Therefore, the energy model of a sensor includes the power for data aggregating, data receiving, and data transmission, in accordance with the radio hardware energy dissipation, both the free space (d^2 Power loss) and the multipath fading (d^4 Power loss) channel models. If the distance is less than the fading threshold d_0 , the free space model is used; otherwise, the multipath model is used. If E_{Tx} denotes the energy consumption of transmitting, E_{Rx} denotes the energy consumption of receiving, and E_{Dx} denotes the energy consumption of aggregating, the energy for transmitting, receiving, and aggregating l bits over distance d is computed as follows:

$$E_{Tx} = \begin{cases} (E_{elec} + \epsilon_{fs} * d^2)l, & d < d_0, \\ (E_{elec} + \epsilon_{amp} * d^4)l, & d \geq d_0, \end{cases} \quad (1)$$

$$\begin{aligned} E_{Rx} &= E_{elec}l, \\ E_{Dx} &= E_{DA}l, \end{aligned} \quad (2)$$

The amplifier energy ϵ_{fs} and ϵ_{amp} are the energy required for power amplification in the two models, respectively.

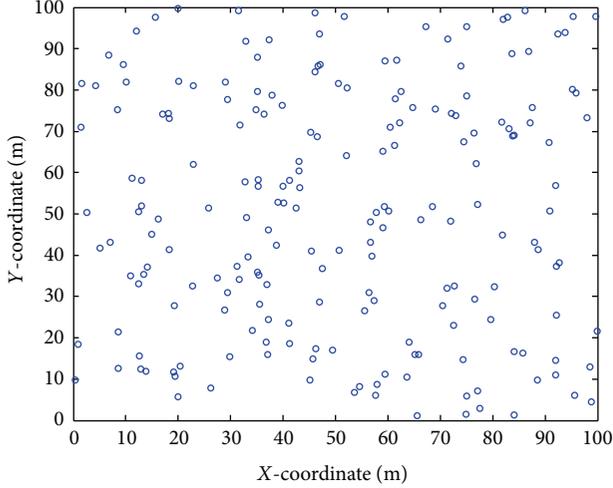


FIGURE 2: Data collection sensor network model.

The electronics energy E_{elec} depends on the factors such as the digital coding and modulation. E_{DA} is the energy used for aggregating unit sensor data. The typical values for the above parameters in current sensor technologies are as follows: $E_{\text{elec}} = 50 \text{ nJ/bit}$, $\epsilon_{\text{fs}} = 10 \text{ pJ/bit/m}^2$, $\epsilon_{\text{amp}} = 0.0013 \text{ pJ/bit/m}^4$, and $E_{\text{DA}} = 5 \text{ nJ/bit/signal}$.

3.3. Contention-Based Cluster Head Election Model. We assume that N nodes are divided into κ clusters. Then each cluster includes $n = N/\kappa$ nodes. We can guarantee the connectivity of clusters by adjusting the communication range and the number κ of cluster heads. One continuous cluster set-up phase and steady-state data transfer phase are regarded as a cluster round. Within a round, only one node can be elected as the cluster head in a cluster. For the sake of simplicity, we assume that the frame length of command frame and data frame is l bits. All sensor nodes initially consider themselves as potential candidates CH. We don't require that all sensor nodes are homogeneous in energy. The probability of being a cluster head depends on nodes' residual energy. Meanwhile, we assume that all nodes have data to transmit during each round. To ensure that all nodes die at approximately the same time, the nodes with more energy should be cluster heads rather than those with less energy. It means that a sensor node with more residual energy has more opportunity to be the cluster head than those with less residual energy in a neighboring circle within radius R . This can be achieved by setting the probability of becoming a cluster head as a function of a node's energy and the total energy of the network; thus

$$P_{ri} = \frac{E_{ri}}{E_{\text{rtotal}}}, \quad (3)$$

where E_{ri} is the current energy of node i and

$$E_{\text{rtotal}} = \sum_{i=1}^n E_{ri}. \quad (4)$$

When the cluster set-up phase is triggered, each cluster head will send the residual energy information of all cluster

members to the sink, and the sink node will calculate and broadcast the total energy of the network E_{rtotal} to all nodes. We assume that the CH advertisement phase is limited to a time interval of T time units and the sensor node i announces its candidacy within a radius of R at a time instance T_{ri} :

$$T_{ri} = T(1 - P_{ri}) + k_i. \quad (5)$$

Here, k_i is a random time unit that is introduced to reduce the collision possibility of among sensor node advertisements, and $P_{ri} \in [0, 1]$ represents the probability of being electing the CH for node i among all nodes in its neighboring circle in terms of its residual energy. Each sensor elects itself to be a cluster head at the beginning of the round r (which starts at time t) with a different probability. Hence, from (5), the node with the highest residual energy will have the biggest probability of being elected as a CH in a given neighborhood. Those sensor nodes that receive an advertisement message from any other sensor node will abandon their quest to become a CH and join the corresponding cluster. Obviously, only one node can be chosen as the CH in one cluster for this round. Thus, if there are n nodes in the cluster, we have

$$E(\text{CH}) = \sum_{i=1}^n P_{ri} = 1. \quad (6)$$

We will not elaborate on the cluster head election. For example, in HEED, the cluster heads are elected based on the residual energy of nodes and node connection degree. The major difference of these cluster head selection protocols lies in the information exchange between the cluster head candidate and cluster members. Once the cluster protocol is determined, the energy consumption for cluster head election and data transmission will be fixed regardless whether the energy-driven or time-driven CH rotation strategy is adopted, which only influences the time when we change the CH rotation strategy. Therefore, our proposed hybrid cluster head rotation strategy can be applied to various contention-based clusters protocols so long as the head rotation strategy is adopted.

4. Energy Consumption Analysis for One Cluster Rotation

In this section, we will analyze the energy consumption of in contention-based cluster algorithm. By analyzing the energy consumption ratio between data gathering and cluster head selection in one CH round for both time-driven and energy-driven cluster head rotation strategies, we will study more efficient cluster head rotation methods.

4.1. Energy Consumption for Cluster Set-Up Phase. Once the nodes have elected themselves to be CHs using the probabilities in (3), the CH nodes must let all the other nodes within their communication range know that they have chosen this role for the current round. To achieve this purpose, each CH node broadcasts an advertisement message (ADV) using a nonpersistent carrier-sense multiple access (CSMA) MAC protocol [24]. This message contains the necessary clustering information such as the node's ID, a frame header that distinguishes this message as an announcement message and

so forth. Noncluster head nodes determine their cluster heads in this round in accordance with the priority and strength of the received advertisement signal from cluster heads.

After every node has joined its own cluster, the CH calculates its TDMA schedule and broadcasts it to its cluster members. Then, the cluster set-up phase is finished and the entire network is divided into many clusters. Then the steady-state phase begins, in which the nodes collect data periodically. Noncluster head nodes send their data to their CH in the allotted time slot according to the TDMA schedule. The CH uses a data fusion algorithm to merge the received data and then send it to the sink. Next, we will analyze the energy consumption used for cluster head election in cluster set-up phase and data transmission in steady-state phase.

According to (3), in round r of cluster head set-up phase, the probability of one node being successfully selected as a cluster head within a time slot can be calculated as follows:

$$P_{r,s} = \sum_{i=1}^n P_{ri} \prod_{j=1, j \neq i}^n (1 - P_{rj}). \quad (7)$$

Here, $P_{r,f}$ denotes the probability that no one node has been selected as cluster head within a time slot in round r of the cluster head set-up phase. There is a certain probability that no nodes broadcast any cluster head advertisement frames within a slot, and we call this probability as idle rate of time slot denoted by $P_{r,i}$:

$$\begin{aligned} P_{r,f} &= 1 - P_{r,s}, \\ P_{r,i} &= \prod_{i=1}^n (1 - P_{ri}). \end{aligned} \quad (8)$$

Within one cluster, the cluster head election process will terminate when a node wins the election and becomes the cluster head. The other cluster members will apply to join it. We assume that $P_r(\tau)$ is the probability that the cluster head is elected successfully in τ time slot of round r . Consider

$$P_r(\tau) = P_{r,s} P_{r,f}^{\tau-1}, \quad \tau = 1, 2, 3, \dots \quad (9)$$

From (9), we can calculate the average mathematical expectation for the number of time slots τ when the cluster head is elected successfully. Consider

$$E(\bar{\tau}) = \sum_{\tau=1}^{\infty} \tau P_r(\tau) = \sum_{\tau=1}^{\infty} \tau P_{r,s} P_{r,f}^{\tau-1} = \frac{1}{P_{r,s}}. \quad (10)$$

Because each candidate node in the cluster set-up phase sends a cluster head advertisement frame with probability P_{ri} , if we use \bar{F}_r to indicate the average expected number of advertisement frames in each time slot of round r , it can be given by

$$E(\bar{F}_r) = \sum_{i=1}^n P_{ri} * 1 = 1. \quad (11)$$

According to the formula (10), (11), we can calculate the expected mathematical number of advertisement frames in the whole cluster head election process of round r as follows:

$$C(r) = \frac{1}{\sum_{i=1}^n P_{ri} \prod_{j=1, j \neq i}^n (1 - P_{rj})}. \quad (12)$$

In fact, if $\bar{N}_{r,a}$ sensor nodes send their advertisement frames, we have

$$E(\bar{F}_r) = \bar{N}_{r,a} (1 - P_{r,i}). \quad (13)$$

In the cluster with n nodes, the remaining $n - \bar{N}_{r,a}$ nodes are responsible for receiving advertisement frames. The probability of a time slot in nonidle rate is $1 - P_{r,i}$. Therefore, we can calculate the average number of receiving cluster head announcement frame in the cluster set-up phase of round r as follows:

$$\begin{aligned} H(r) &= (n - \bar{N}_{r,a}) \bar{F}_r \bar{T}_r (1 - P_{r,i}) \\ &= \frac{n - n \prod_{i=1}^n (1 - P_{ri}) - 1}{\sum_{i=1}^n P_{ri} \prod_{j=1, j \neq i}^n (1 - P_{rj})}. \end{aligned} \quad (14)$$

According to (12) and (14), the energy consumption of cluster head election in one round can be given by

$$E_{\text{ch-select}} = C(r) (E_{\text{elec}} l + \varepsilon_{\text{amp}} d_{\text{CH}}^2 l) + H(r) E_{\text{elec}} l. \quad (15)$$

Here, d_{CH} denotes the average distance between the cluster head and other members. The left part of expression (15) represents the energy consumption of sending cluster head frame and the right part is the energy consumption of receiving cluster head circular frame. When cluster head has been elected successfully, all cluster members will send request frames to join it. Then, the CH broadcasts the TDMA schedule among its members. It is obvious that the clusters will consume the least energy if no conflict occurs. Therefore, the lower bound energy consumption of a round in the cluster set-up phase is

$$\begin{aligned} E_{\text{ch-setup}} &= E_{\text{ch-select}} + 2(n-1) (E_{\text{elec}} l + \varepsilon_{\text{amp}} d_{\text{CH}}^2 l) \\ &\quad + 2(n-1) E_{\text{elec}} l. \end{aligned} \quad (16)$$

For the sake of simplicity, we omit the energy consumption for acknowledgement frames in data or commands transmission. This kind of packets is much smaller than the data and commands packets.

4.2. Energy Consumption for Data Transmission Phase. After the completion of set-up phase, the steady-state phase for information collection and transmission begins. For one round data collection, let d_{BS} denote the distance from CH to sink that can be estimated by CH according to signal strength received from sink, the energy consumption for CH is given by

$$E_{\text{ch}} = (E_{\text{elec}} + \varepsilon_{\text{amp}} d_{\text{BS}}^\alpha) l + n E_{\text{DA}} l + (n-1) E_{\text{elec}} l. \quad (17)$$

Here, the value of radio dissipation coefficient $\alpha = 2$ or 4 is determined by the distance between the transmitter and receiver according to (1). Let d_{CH} denote the average distance from cluster members to CH which can be given by $M^2/2\kappa\pi$ [5], the energy consumption for all member nodes in cluster for one round data collection is calculated as follows:

$$E_{\text{non-ch}} = (n-1) (E_{\text{elec}} + \varepsilon_{\text{amp}} d_{\text{CH}}^\alpha) l. \quad (18)$$

The number of data collection rounds depends on the CHs rotation method. In time-driven CH rotation, the number of data transmission rounds is predetermined at the beginning of network operation. It is related to the properties of the network such as nodes density and energy status. We will provide the method to estimate it in the following section. We assume that there are k rounds of data collection and transmission, and then the energy consumption in one steady-state phase based on time-driven CH rotation is

$$E_{\text{Time-}D_r} = k(E_{\text{ch}} + E_{\text{non-ch}}). \quad (19)$$

However, in energy-driven CH rotation strategy, the number of data transmission rounds is a function of the remaining energy of CH node. The CH node i calculates a dynamic energy threshold λ_i based on its residual before it broadcasts its CH Candidacy. The threshold is defined by $\lambda_i = cE_{\text{res}_i}$, where $c \in [0, 1]$ is a predetermined constant and E_{res_i} is the residual energy of cluster head. When the residual energy of cluster head has dropped below this threshold, the steady-state phase will be over and new CHs rotation process is triggered. If we let $\varphi_{r,i}$ denote the number of data transmission rounds that node i severs as a CH, we can calculate the energy consumption in one steady-state phase for energy-driven cluster head rotation method as follows:

$$\begin{aligned} E_{\text{Energy-}D_r} &= \varphi_{r,i} (E_{\text{ch}} + E_{\text{non-ch}}) \\ &= \frac{(1-c)E_{r_i} - E_{\text{choh}}}{E_{\text{ch}}} \\ &\quad \times (E_{\text{ch}} + E_{\text{non-ch}}). \end{aligned} \quad (20)$$

Here, E_{choh} denotes the energy consumption of CH node i in cluster set-up phase. When no conflict occurs, E_{choh} includes the energy consumption for broadcasting CH candidacy, receiving requests for joining from all of its members, and broadcasting TDMA schedule among its members. Therefore, its lower bound can be given by

$$E_{\text{choh}} = 2(n-1)(E_{\text{elec}}l + \varepsilon_{\text{amp}}d_{\text{CH}}^2l) + (n-1)E_{\text{elec}}l. \quad (21)$$

5. Hybrid Energy- and Time-Driven Cluster Head Rotation Strategy

After analyzing the energy consumption in one CH round for both time-driven and energy-driven cluster head rotation strategies, we will deduce the hybrid cluster head rotation strategy which combines the advantages of both energy-driven and time-driven methods in this section. In the cluster-based WSNs, energy consumption can be divided into two categories. The first category is the energy consumption used for topology construction and maintenance. We call it additional energy cost E_a which is mainly consumed in cluster set-up phase. The second category is the energy consumption used for data transmission and reception. We call it efficiency energy cost E_e which is mainly consumed in steady-state phase. The main purpose of the WSNs is to collect as

much useful information as possible in the monitoring area. So, the more energy is used for information collection, the better energy efficiency of cluster hierarchy protocol will be achieved. We define the energy efficiency η as the proportion of the effective energy cost in the total energy cost. Consider

$$\eta = \frac{E_e}{E_e + E_a}. \quad (22)$$

In time-driven CH rotation strategy, we get the energy efficiency according to (15), (16), and (19):

$$\begin{aligned} \eta_{\text{Time-}D_r} &= \frac{E_{\text{Time-}D_r}}{E_{\text{Time-}D_r} + E_{\text{ch-setup}}} \\ &= \frac{k(E_{\text{ch}} + E_{\text{non-ch}})}{k(E_{\text{ch}} + E_{\text{non-ch}}) + E_{\text{ch-setup}}}. \end{aligned} \quad (23)$$

In energy-driven CH rotation strategy, according to (15), (16) and (20), we have the energy efficiency:

$$\begin{aligned} \eta_{\text{Energy-}D_r} &= \frac{E_{\text{Energy-}D_r}}{E_{\text{Energy-}D_r} + E_{\text{ch-setup}}} \\ &= \frac{[(1-c)E_{r_i} - E_{\text{choh}}](E_{\text{ch}} + E_{\text{non-ch}})}{[(1-c)E_{r_i} - E_{\text{choh}}](E_{\text{ch}} + E_{\text{non-ch}}) + E_{\text{ch}}E_{\text{ch-setup}}}. \end{aligned} \quad (24)$$

In (23), E_{ch} , $E_{\text{non-ch}}$, and E_{choh} are only related to the cluster size and node density. $E_{\text{ch-setup}}$ will change little if cluster scale is under good control. That is to say, in a cluster hierarchy WSNs with nodes distribution, the parameters above can be nearly seen as almost constant. Normalizing $\eta_{\text{Time-}D_r}$, we have

$$\eta_{\text{Time-}D_r} = \frac{1}{1 + ((E_{\text{ch-setup}}) / (E_{\text{ch}} + E_{\text{non-ch}})) * (1/k)}. \quad (25)$$

From (25), we can see that the energy efficiency for time-driven CH rotation is only related to the steady-state phase. Once the data transmission rounds k is predetermined, $\eta_{\text{Time-}D_r}$ will be fixed. This is a significant feature of the time-driven CH rotation method, which means that constant energy efficiency can be maintained regardless of how long the network runs. Furthermore, normalizing $\eta_{\text{Energy-}D_r}$, we have

$$\eta_{\text{Energy-}D_r} = 1 \times \left(1 + \frac{E_{\text{ch}}E_{\text{ch-setup}}}{E_{\text{ch}} + E_{\text{non-ch}}} * \frac{1}{(1-c)E_{r_i} - E_{\text{choh}}} \right)^{-1}. \quad (26)$$

In (26), we have that the restriction of $(1-c)E_{r_i} > E_{\text{choh}}$. c is a predetermined constant which depends on the topology of WSNs. The energy efficiency $\eta_{\text{Energy-}D_r}$ for energy-driven CH rotation is only related to the residual energy of cluster head node E_{r_i} . The more residual energy of the cluster head has, the higher energy efficiency we can obtain. The residual energy E_{r_i} will decrease gradually along with the operation of WSNs. It means that more energy will be used for frequent

cluster head election and cluster topology construction when $\eta_{\text{Energy-}D_r}$ becomes lower. Network can achieve good energy efficiency if the remaining energy of CHs is abundant and will get low energy efficiency if the residual energy of CHs is inadequate. This is the major drawback of energy-driven CH rotation strategy.

We set d_{CH} and d_{BS} as 30 meters and 87 meters, respectively. The distribution density of sensor node is 0.02 and each node is assigned with 0.5 J energy. For the threshold parameter c , without the loss of generality, we adopt the value $c = 0.644$ according to the research results in [22] and let $k = 5$. Advertisement set-up packets and data packets are arranged with 256 bits in length. Then, we can get the change in the energy efficiency with the network operation rounds for energy-driven CH rotation and time-driven CH rotation in clustering WSN as showed in Figure 3. We can see that high energy efficiency can be achieved at the beginning of WSNs if energy-driven CH rotation strategy is adopted. But as the operation time of WSNs increases, the residual energy of the selected CHs will decrease accordingly, which will result in decrease in energy efficiency. When the residual energy of the cluster head declines to a certain level, the energy efficiency of the energy-driven CH rotation strategy will be lower than that of the time-driven CH rotation strategy.

In order to collect as much useful information as possible in the monitoring area and keep as higher energy efficiency as possible, we can make use of the advantages of both the energy-driven strategy and time-driven CH rotation strategy in cluster hierarchy protocol. When the nodes have abundant energy, we can adopt energy-driven CH rotation strategy to achieve good energy efficiency and avoid excessive overhead frames in time-driven CH rotation policy. When WSNs' energy declines to the extent that the energy efficiency of energy-driven CH rotation strategy is lower than that of the time-driven CH rotation strategy, the CH rotation strategy will switch to time-driven method to maintain energy efficiency and data transmission efficiency. This adaptive switch can optimize the energy efficiency of the network. The analysis results above constitute the theoretical foundation of our hybrid energy- and time-driven cluster head rotation strategy in this paper.

According to the results above, when $\eta_{\text{Energy-}D_r} \geq \eta_{\text{Time-}D_r}$, we will adopt the energy-driven CH rotation strategy to obtain better energy efficiency. The time-driven CH rotation strategy is adopted when $\eta_{\text{Energy-}D_r} < \eta_{\text{Time-}D_r}$. Furthermore, we can simplify this criterion. As indicated in Figure 3, when the energy efficiency in energy-driven and time-driven CH rotation is equal to $\eta_{\text{Energy-}D_r} = \eta_{\text{Time-}D_r}$, we have

$$\begin{aligned} & \frac{1}{1 + (E_{\text{ch-setup}}/E_{\text{ch}} + E_{\text{non-ch}}) * (1/k)} \\ &= 1 \times \left(1 + \frac{E_{\text{ch}}E_{\text{ch-setup}}}{E_{\text{ch}} + E_{\text{non-ch}}} * \frac{1}{(1-c)E_{ri} - E_{\text{choh}}} \right)^{-1}. \end{aligned} \quad (27)$$

From (27), we can calculate the energy of the cluster head node when CH rotation strategy needs to switch from

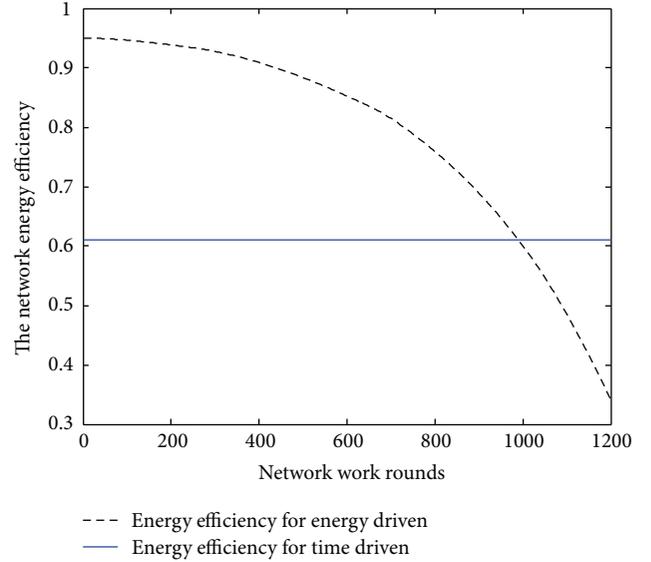


FIGURE 3: Energy efficiency in energy-driven and time-driven strategies.

energy-driven strategy to time-driven strategy. We define this energy of cluster head as critical energy value and it can be given by

$$E_{ri}^* = \frac{kE_{\text{ch}} + E_{\text{choh}}}{1 - c}. \quad (28)$$

From (28), we can see that the critical energy value of CH is only related to the intrinsic parameters of energy-driven and time-driven CH rotation. Moreover, this result proves that the hybrid CH rotation strategy does not depend on homogeneous or heterogeneous characteristics of the network and the exact cluster protocol. What is more is another important issue is to estimate the optimal data transmission rounds k for time-driven CH rotation method in (28). It is an important parameter that determines the timing for switching to the CH rotation strategy. For heterogeneous WSNs, we notice that the energy balance between sensor nodes has been greatly improved after the long time operation of the network using the energy-driven cluster head rotation strategy. It meets the network conditions for time-driven protocol to maintain high energy efficiency, and therefore, it is a good decision to switch to the time-driven cluster head rotation strategy.

In time-driven CH rotation cluster protocol, the steady-state phase should be as long as possible in order to increase energy efficiency. On the other hand, since each node's energy is limited, it will drain the energy of the CH node if the steady-state phase is too long. In [5, 18], authors have proved that if each node can be ensured to act as CH once and noncluster head node in the other rounds during network lifetime, a suboptimal network lifetime for the time-driven CH rotation cluster protocol can be achieved. Generally speaking, the sensor node with the least residual energy will die first. Let E_{min} denote the residual energy of the node with the minimum energy in WSNs when the time-driven rotation strategy is selected. To ensure that each node has enough

energy to be a cluster head for one time and noncluster head sensor node for $(n - 1)$ times, according to (17) and (18), we can get the following equation:

$$kE_{\text{ch}} + (n - 1)k \frac{E_{\text{non-ch}}}{n - 1} = E_{\text{min}}. \quad (29)$$

Therefore, we can obtain the suboptimal number of data transmission rounds k when energy-driven CH rotation method is switched to time-driven method:

$$k = E_{\text{min}} \times \left(\left[(E_{\text{elec}} + \varepsilon_{\text{amp}} d_{\text{BS}}^{\alpha})l + nE_{\text{DA}}l + (n - 1)E_{\text{elec}}l \right] + (n - 1) \left(E_{\text{elec}} + \varepsilon_{\text{amp}} d_{\text{CH}}^{\alpha} \right) l \right)^{-1}. \quad (30)$$

We can see that the parameter k will change along with the gradual decrease of E_{min} . From (28) and (30), we can calculate the corresponding k for each round of CH rotation and then get the critical energy value E_{ri}^* . When the residual energy of each CH $E_{ri} \geq E_{ri}^*$, the energy-driven CH rotation strategy will be adopted; otherwise, the time-driven CH rotation strategy will be selected.

The pseudo code of hybrid energy- and time-driven cluster head rotation strategy is presented in Algorithm 1. First, in cluster set-up phase, each node computes its P_{ri} using immediate neighbor information to run for cluster head. At the same time, the sink node computes and broadcasts parameter k to the whole network according to the *Res_Energy_List* that is collected and sent back by all CHs. After successful election, each CH calculates E_{ri}^* and compares it with its own residual energy. If CHs' residual energy is larger than E_{ri}^* or even equal, energy-driven CH rotation strategy is adopted; otherwise, time-driven CH rotation strategy will be used. When the network is worked based energy-driven CH rotation strategy, if the cluster head rotation is triggered, CHs will send the residual energy list *Res_Energy_List* of all cluster members back to the sink node. Once WSNs switch to time-driven CH rotation strategy, there is no longer any need to calculate the parameter k , and the network will operate based on time-driven CH rotation strategy until the network dies.

From Algorithm 1, we can see that the hybrid CH rotation strategy increases the message exchange of cluster protocol in cluster set-up phase. Since the cluster head selection process is message driven, we will discuss the message complexity of algorithm. We will validate that our hybrid rotation strategy does not add the complexity for all clustering protocol through the complexity analysis. When energy-driven rotation strategy is selected, at the beginning of the cluster head election phase, the sink node will broadcast system frame with parameter k included. Then κ tentative cluster heads are elected and each of them broadcasts election header frame *COMPETE_HEAD_MSG*. Later on, they make a decision to act as a final cluster head by broadcasting election frame *FINAL_HEAD_MSG*, or an ordinary node by broadcasting a quit election frame *QUIT_ELECTION_MSG*. They send out κ cluster heads to confirm acknowledgement *CH_ADV_MSGs*, and then $(N - \kappa)$ ordinary nodes transmit $(N - \kappa)$ join cluster frames *JOIN_CLUSTER_MSGs*. Thus, the messages add up to $N + \kappa + \kappa + \kappa + N - \kappa = 2(N + \kappa)$ in the cluster

formation stage per round, that is, $O(N)$. When time-driven rotation strategy is selected, the network will not select cluster head rotation strategy any longer and the message complexity is the same as that of time-driven CH rotation strategy cluster protocol. Analysis above shows that the hybrid CH rotation strategy will not increase the complexity of cluster protocol compared with single energy-driven or time-driven CH rotation strategy.

6. Simulation Results

In this section, both the numerical results and the simulation results will be presented to evaluate the performance of the hybrid energy- and time-driven cluster head rotation strategy. The simulations are performed in Matlab 7.0, and two scenarios are chosen. We will firstly discuss the influence of the threshold parameter c on network and find a suitable value for our sensor networks model. Then, we will apply our hybrid CH rotation strategy, time-driven and energy-driven CH rotation methods, respectively, to reform LEACH, which is a famous and successful cluster hierarchy protocol recently. By comparing the lifetime and valid data transmission efficiency for the three CH rotation strategies, we will prove that our hybrid CH rotation strategy truly improves the energy efficiency as well as prolongs the network lifetime in both homogeneous and heterogeneous networks. In order to conduct the experiments, proper parameters for both the sensor nodes and the network should be defined. The simulation parameters for our proposed mechanism are given in Table 1.

In the following simulation, we evaluate the three CH rotation strategies in both homogeneous and heterogeneous network. In homogeneous WSNs, 200 nodes each with 0.5 J energy are randomly dispersed in a 100×100 region with BS located at (50, 50). In heterogeneous WSNs, 200 nodes each with 0.3 J to 0.8 J energy (randomly assigned) are randomly dispersed in a 100×100 region with BS located at (50, 50).

6.1. The Analysis of Energy Threshold. As we have explained in the previous section, the energy efficiency is the standard to judge whether energy-driven and time-driven CH rotation mechanism should be selected in our hybrid CH rotation strategy. When energy-driven CH rotation is selected, the residual energy of each existing CH will determine when a network calls for a new CH selection phase. The selection phase will be triggered once the residual energy of any of CHs falls below a predetermined threshold value. This energy threshold influences the energy efficiency of energy-driven rotation method and decides when the cluster head selection policy should turn from energy-driven to time-driven mechanism. Therefore, it is vital to find out the suitable energy threshold parameter c for energy-driven CH rotation strategy based on the above network model and parameters before performance evaluation.

Figure 4 illustrates the network lifetime of LEACH based on our hybrid energy- and time-driven CH rotation strategy in homogeneous WSNs with the energy threshold parameter c increasing from 0.4 to 0.8. Figure 5 shows these results in heterogeneous WSNs. From these two figures, we can see that network lifetime will change with different threshold

Algorithm: Hybrid cluster head rotation mechanism

```

1: Setup ()
2: if Initial round then
3:   Compute  $P_{ri}$  using immediate neighbor information
4: end if
5: Sink computer  $k$  and broadcast CH Selection Command
6: CHs Selection (COMPETE_HEAD_MSG, FINAL_HEAD_MSG,
   QUIT_ELECTION_MSG)
7: CHs Construction (CH_ADV_MSGS, JOIN_CLUSTER_MSGS)
8: CHs compute  $E_{ri}^*$ 
9: if  $E_{ri} \geq E_{ri}^*$ 
10:  {while ( $E_{res_i} \geq cE_{ri}$ )
11:   {data_collection ()}
12:   data_transmission ()}
13:   CH Request BS for a CH Change
14:   CHs Sent Res_Energy_List to Sink
15:   goto 2
16:  }
17: else goto 18
18: Sink broadcast Switch to Time-driven CH Rotation
19: if Initial round then
20:   Compute  $P_{ri}$  using immediate neighbor information
21: end if
22: CHs Selection () and Construction ()
23: Data_Round =  $k$ 
24: while (Data_Round > 0)
25:  {data_collection () and data_transmission ()}
26:  Data_Round = Data_Round-1}
27: else goto 19

```

ALGORITHM 1: Hybrid energy- and time-driven cluster head rotation strategy.

TABLE 1: Parameters and characteristics of the network.

Parameter	Value
Network size (square)	100 × 100 meter
Sink location	(50, 50)
Command frame and data packet size	256 bits
Number of nodes	200
Cluster head probability	0.05
Aggregation ratio	0.1

parameters. When energy threshold is small, nodes die evenly as time passes by. When energy threshold is larger, we can see that the lifetime curve trends to right angle. Most of nodes will have a longer life and die almost simultaneously within a short time interval. When c is small, the elected cluster head node will consume most of its energy on cluster head position. After rotation, it has little residual energy and will die quickly. When c is larger, the cluster heads can still reserve some energy to act as regular nodes after fulfilling their role as cluster heads. Since noncluster head nodes consume less energy than cluster head nodes, the reserved energy can help it to last for a longer time. Nodes die almost simultaneously because all the nodes have little energy left after rotating for several times. Meanwhile, if c is larger, the CH will rotate frequently and waste lots of energy compared with sleep-listen model in steady-state phase. This result can be seen

from Figures 4 and 5. It shows that network lifetime is longer when $c = 0.6$ rather than $c = 0.7$.

In [7], the authors have proved that the optimal value c mainly varies with the distance from nodes to their CHs and with the distance from CH to sink node in a single energy-driven CH rotation. In other words, it is mainly determined by network topology structure. The network will switch to time-driven CH rotation model in the late stage of network in accordance with our hybrid rotation method. It can be seen in Figures 4 and 5 that the energy threshold parameter acquires almost the same value when the network gains the optimal lifetime no matter whether in homogeneous or heterogeneous WSNs, so long as they have the same network topology. From the simulation and analysis results above, we find that the network will achieve better lifetime when $c = 0.6$. We will adopt this threshold value in the following part. For single energy-driven CH rotation, we use the optimal value $c = 0.644$ according to the research results in [22].

6.2. Performance Comparison in Network Lifetime and Energy Efficiency. In this part, we verify the network lifetime and energy efficiency of our hybrid CH rotation strategy by LEACH cluster protocol. To estimate the lifetime of the WSNs, the metrics of First Node Dies (FNDs), Percent of the Nodes Alive (PNA), and Last Node Dies (LNDs) are always used [9, 20]. FND is useful in sparsely deployed WSNs. However, PNA is more suitable to measure the network

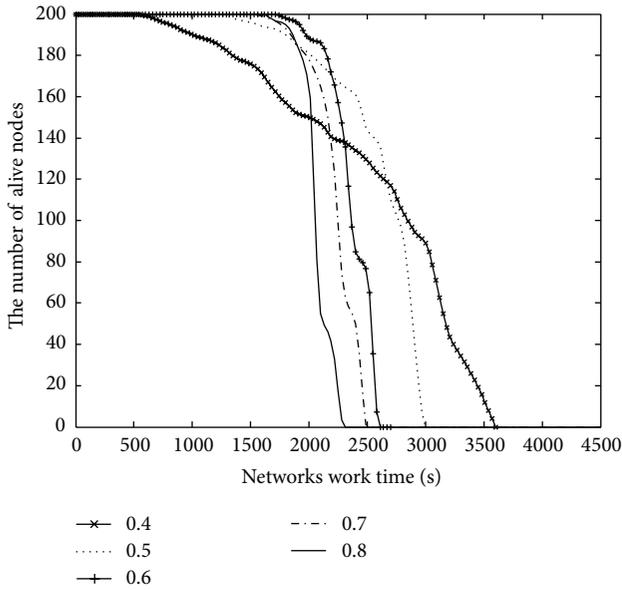


FIGURE 4: Comparison of lifetime for threshold parameter c in homogeneous WSNs.

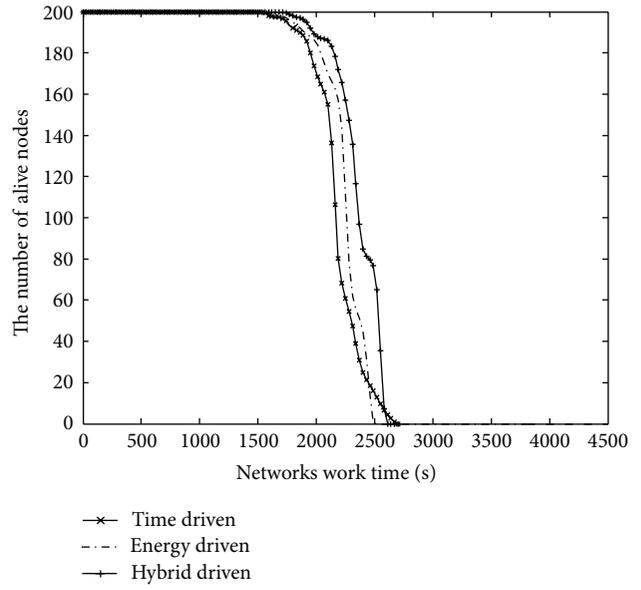


FIGURE 6: Lifetime in homogeneous WSNs for LEACH based on three rotation strategies.

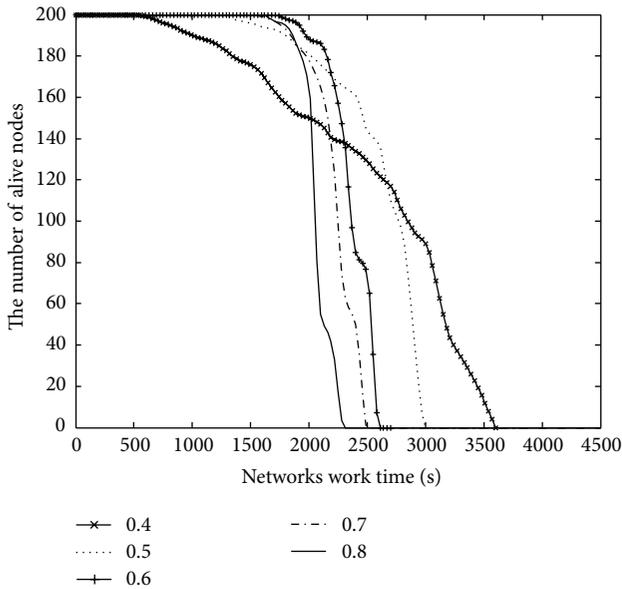


FIGURE 5: Comparison of lifetime for threshold parameter c in heterogeneous WSNs.

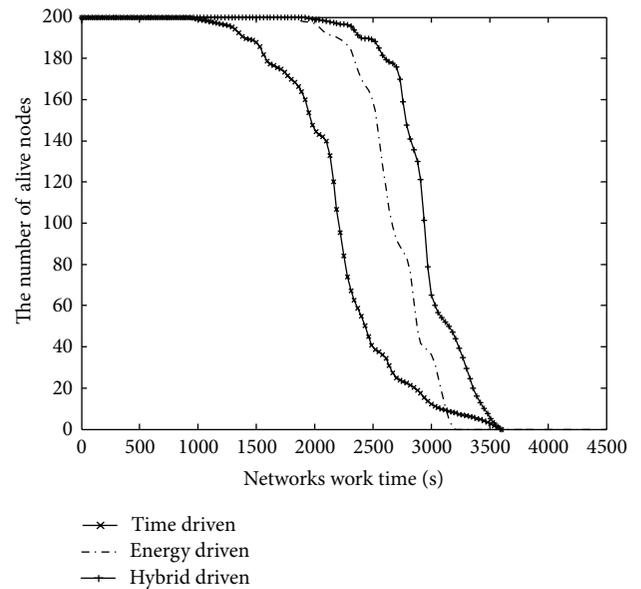


FIGURE 7: Lifetime in heterogeneous WSNs for LEACH based on three rotation strategies.

lifetime in densely deployed WSNs. LND is not suitable for practical application. Hence, in this paper, we use the FND and PNA metrics to measure performance of our CHs rotation strategy. In the case of PNA, we have assumed 95% of nodes alive in the network.

Figures 6 and 7 present the comparison of network lifetime for LEACH based on three CH rotation strategies both in homogeneous and heterogeneous WSNs. We can see that our hybrid energy- and time-driven CH rotation strategy is better than either the single energy-driven or time-driven CH rotation method both in FND and PNA. In homogeneous

network, the initial energy of each node is equal, so the time-driven cluster head rotation strategy can also achieve a better balance on energy consumption among nodes. The advantage for hybrid CH rotation strategy in the network lifetime is not obvious in FND, but there is still a lot of improvement in PNA. However, in heterogeneous network, our hybrid CH rotation approach is remarkably better than both the time-driven CH rotation strategy and the energy-driven CH rotation strategy in terms of FND and PNA. For the time-driven CH rotation strategy, the initial energy is not equal in heterogeneous WSNs and it cannot achieve the energy consumption balance

among sensor nodes. On the other hand, for the energy-driven CH rotation strategy, the frequent rotation of cluster head may make all nodes always in active stage and lead to premature death in the final stage of WSNs, thus reducing the network lifetime.

The mechanism for prolonging the network lifetime by hybrid CH rotation strategy can be explained as follows. After clusters have been built successfully, the cluster head creates a TDMA schedule and tells each member node the exact time for transmission data. This allows sensor nodes to remain in the sleep model in other nodes' time slot in steady-state phase. If the node is in the sleep state, the radio and processor modules are turned off which can save considerable energy. But in cluster set-up phase, all nodes must keep active with all modules which will consume much energy especially for the radio communication module. If the energy-driven CH rotation strategy is adopted, when the nodes have abundant energy, the steady-state phase for data transmission is longer than that of time-driven CH rotation strategy, which means less cluster head frames and longer sleeps state. When the energy of nodes is scarce, if we continue to use energy-driven CH rotation method, frequent cluster head selection will happen, which will result in lots of energy waste. However, if we switch to the time-driven CH rotation strategy, frequent cluster head selection can be avoided and the network lifetime can be prolonged.

When the energy level of network is low and energy of nodes is balanced, time-driven CH rotation method can achieve higher energy efficiency than energy-driven CH rotation method. Table 2 shows the energy distribution between sensors when we switch from energy-driven CH rotation to time-driven CH rotation in heterogeneous network for LEACH. It shows that the energy of sensor nodes is quite evenly distributed among them. So, switching to time-driven CH rotation is a good choice when $\eta_{\text{Energy-}D_r} < \eta_{\text{Time-}D_r}$, and it also proves the rationality of the hybrid energy- and time-driven CH rotation strategy indirectly.

In addition to network lifetime, energy efficiency is another important performance indicator of WSNs. As replacing or recharging batteries is difficult or even impossible for sensor nodes in many cases, the cluster protocol needs to maintain high energy efficiency of networks in order to collect as much useful information as possible. According to the algorithmic details of our hybrid energy-time driven CH rotation, energy efficiency of the network is used as the criterion to select CH rotation strategy. In the next simulation test, we use the data transmission rounds that 95% of nodes are alive in the sensor network to measure and compare the energy efficiency.

Figures 8 and 9 illustrate the energy efficiency comparison among the three CH rotation strategies in both homogeneous and heterogeneous networks for LEACH. It can be seen that even though there is no big difference in network lifetime in homogeneous sensor network, our hybrid energy- and time-driven CH rotation strategy is about 1.3 times and 1.1 times more efficient in data transmission than time-driven CH rotation and energy-driven CH rotation, respectively. But in heterogeneous WSNs, the hybrid energy- and time-driven CH rotation strategy can achieve 2 times and 1.2 times

TABLE 2: Node energy distribution between sensors in heterogeneous network.

Nodes Energy Distribution (J)	When energy-driven CH rotation begins	When time-driven CH rotation begins
0-0.1	0	8
0.1-0.2	0	147
0.2-0.3	0	41
0.3-0.4	42	4
0.4-0.5	40	0
0.5-0.6	43	0
0.6-0.7	39	0
0.7-0.8	36	0

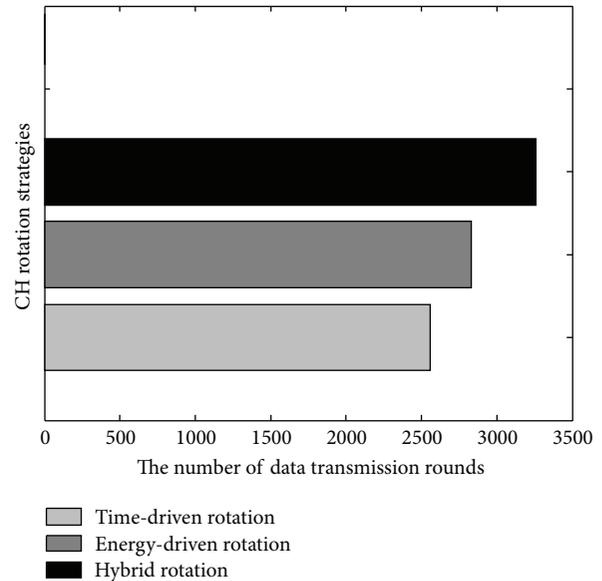


FIGURE 8: Data transmission rounds with PND for LEACH in homogeneous networks.

more efficient in data transmission than time-driven CH rotation strategy- and energy-driven CH rotation strategy, respectively. Such results are mainly attributable to the fact that time-driven CH rotation strategy does not consider the energy imbalance of nodes. Under such a circumstance, cluster head selection is triggered after a constant number of data transmission rounds no matter whether the node's energy is abundant or not, thus resulting in unnecessary energy waste. At the same time, for energy-driven CH rotation strategy, the energy efficiency will decrease sharply when the energy of network reduce to some degree. The hybrid CH rotation strategy takes full account of such a situation and can achieve good energy efficiency by selecting either energy-driven or time-driven CH rotation according to the residual energy of network in real time.

7. Conclusion

In this paper, we have proposed a hybrid energy- and time-driven CH rotation strategy for distributed wireless sensor

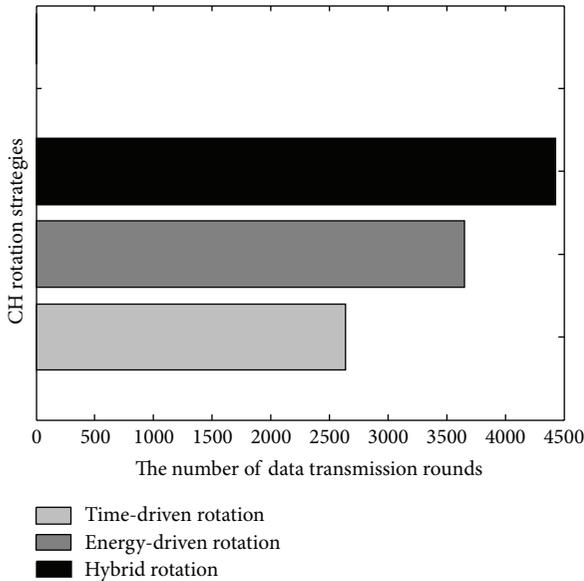


FIGURE 9: Data transmission rounds with PND for LEACH in heterogeneous networks.

networks. The main objective of our algorithm is to improve the energy efficiency and prolong the lifetime of WSNs by optimizing the CH rotation strategy in cluster hierarchy protocol. By analyzing energy consumption ratio between data gathering and cluster head selection for the time-driven cluster head rotation and energy-driven cluster head rotation, we propose the hybrid cluster head rotation strategy for WSNs, in which the CHs rotation mechanism based on time or energy will be selected according to the change of energy efficiency.

By comparing the simulation results, we find that our rotation strategy integrates the advantages of both the energy-driven CH rotation strategy and the time-driven CH rotation strategy in cluster hierarchy protocol and can enhance the energy efficiency and prolong network lifetime in both homogeneous and heterogeneous networks. As an important technology of cluster topology maintenance, our rotation strategy can be used in any cluster protocol for the topology reconstruction of the hierarchical cluster network.

The energy threshold parameter c plays an important role in our hybrid CH rotation strategy and it is mainly decided by network topology structure. In this paper, we only obtain a suitable value by simulation analysis. How to find out its optimal value in a different network topology structure for WSNs is an issue of great importance for our hybrid CH rotation strategy. We will try to find a solution that could determine the optimal value of these parameters according to different cluster topology structures in our future work.

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