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Arranging cluster sizes and transmission ranges for wireless sensor networks

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ABSTRACT

Hierarchical routing is an efficient way to lower energy consumption within a cluster. Due to the characteristics of wireless channels, multi-hop communications between a data source and a data sink are usually more energy efficient than direct transmission. However, because the cluster heads (CHs) closer to the data sink are burdened with heavy relay traffic, they drain much faster than other CHs.

This paper presents a cluster-based routing protocol called "arranging cluster sizes and transmission ranges for wireless sensor networks (ACT)." The aim is to reduce the size of clusters near the base station (BS), as CHs closer to the BS need to relay more data. The proposed method allows every CH to consume approximately the same amount of energy so that the CHs near the BS do not exhaust their power so quickly. Furthermore, we separate the network topology into multiple hierarchical levels to prolong network lifetime. Simulation results show that our clustering mechanism effectively improves the network lifetime over LEACH (Low Energy Adaptive Clustering Hierarchy), BCDCP (Base Station Controlled Dynamic Clustering Protocol) and MR-LEACH (multi-hop routing with low energy adaptive clustering hierarchy).

1. Introduction

A wireless sensor network (WSN) is an ad hoc network composed of small sensor nodes deployed in large numbers to sense the real world. Each node possesses the capacity for wireless communications in order to facilitate data transmissions between nodes. Thanks to the rapid development of wireless communications and integrated circuits, sensor nodes are now smaller and less expensive. A number of factors must be considered before WSNs are implemented, including power consumption, fault tolerance, sensing coverage, coordination and network security. Examples of WSN-based applications include military surveillance, environmental monitoring [19,22] and home automation.

Wireless ad hoc networks' routing protocol cannot be applied to the WSNs, because: (1) sensor nodes are provided with restricted power, computing capability, and memory size; (2) in the WSNs, the depletion of power may be the main cause for topology change, but in wireless ad hoc networks, the mobility of nodes is likely the main reason for the changes; and (3) WSNs utilize broadcasting often, whereas wireless ad hoc networks provide point-to-point communications.

Because of the differences mentioned above, applicable routing protocols have been introduced by many researchers based on the characteristics of WSNs. Al-Karaki and Kamal categorized routing protocols into flat routing protocol, location-based routing protocol and hierarchical routing protocol [3].

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Flat routing protocol (i.e., [16,21]) is a data-centric [32] routing protocol. Initially, the base station (BS) broadcasts query packets; once the query packets reach the sensor nodes, the sensor nodes return data to the BS if the data is available. The advantage of a flat routing protocol is that each sensor node does not need to store much route information; the disadvantage is that if the required data is returned by several sensor nodes simultaneously, it may cause network congestion or a broadcast storm. Consequently, it is not applicable to large-scale networks.

In the location-based routing protocol [30,38,41,43], each sensor node is equipped with a Global Positioning System (GPS) to distinguish its own geographical position from others and figure out the best transmission path for itself. This increase the cost. However, the location-based routing protocol reduces transmitting unnecessary packets (compared to the broadcast type) and is best for network topology that changes frequently.

In the hierarchical routing protocol [13,17,20,25,42], the geographical region of the internet is divided into several clusters, where each cluster selects a cluster head (CH) responsible for collecting the data from cluster members and transferring data to the BS via hierarchical routing. Utilizing clusters in hierarchical routing protocol has its advantages because it allows less power consumption in each node and the CH is capable of processing data aggregation [10,12]. However, it imposes a larger load on the CH, as a CH must manage not only data collection but also data relay.

Because there are limited power resources for WSNs, the power issue should be the top concern when constructing a routing protocol. In a flat routing protocol, a packet is transmitted via broadcasting, which often leads to poor performance, as network congestion easily occurs. The location-based routing protocol equips its sensor nodes with a GPS, which increases the cost of sensor nodes. In contrast to this approach, some believe that the hierarchical routing protocol is more suitable for WSNs. We discuss the hierarchical routing protocol in Section 2. The data detected by adjacent nodes contain higher correlation and thus a significant amount of reduction can be expected if data aggregation is carried out by the CH [14]. Moreover, with limited power supply, utilizing the CH to both collect the data from cluster members and complete data relay through the processing of other CHs not only shortens the transmission distance for sensor nodes but also reduces power consumption. The motivation and main contributions of this paper are listed below.

Although a lot of the literatures on dividing the network into clusters copes with the problem of unbalanced power consumption in WSNs, to the best of our knowledge, none of the existing protocols provide explicit numerical calculations for the cluster radius of each level. Therefore, we propose the arranging cluster sizes and transmission ranges (ACT) for wireless sensor networks, which determines the size of a cluster for each CH according to the distance between the cluster and the BS (the closer the CH and the BS are, the smaller the cluster). Through this approach, the load imposed on the CH around the BS can be alleviated. Furthermore, to avoid cluster reconfiguration in each round, as in the cases of LEACH [13] and HEED [40], we propose cluster maintenance to prolong network lifetime. The main contributions of this paper are summarized as follows:

- Calculating each cluster radius based on the relaying load of CH
  To avoid too many relaying loads on CHs near the BS, cluster radiuses near the BS are smaller, whereas those located away from the BS are larger. We expect the load on each CH to be similar so that the CHs near the BS do not exhaust their power more quickly.
- Utilizing cross-level transmissions to prolong network lifetime
  In ACT, clusters in the 1st level are the smallest in size, and thus fewer cluster members are found in the 1st level. If the sensor nodes within a cluster take turns serving as CHs, the process may end up quickly, as there are not enough sensor nodes. When the BS is aware that each sensor node in the 1st level can no longer serve as a CH, it broadcasts a message to allow the CHs in the 2nd level to transmit data to the BS directly (the same for 3rd level, 4th level, ..., Kth level). In this way, the network lifetime can be prolonged.

The rest of this paper is organized as follows: the details of the hierarchical routing protocol are introduced in Section 2. The proposed method ACT and its analyses are described in detail in Section 3. Section 4 shows ACT's effectiveness via simulations and compares it to LEACH, BCDCP [31] and multi-hop routing with low energy adaptive clustering hierarchy (MR-LEACH) [8]. Section 5 concludes the paper.

2. Related work

In this section, we first introduce five steps in general of the hierarchical routing protocol and related works. We also focus on three typical approaches, which are compared to our proposed ACT scheme.

Hierarchical routing protocol can be divided into CH selection, cluster setup, cluster maintenance, intra-cluster communications and inter-cluster communications.

In CH selection, selecting a CH by looking for a sensor node with the smallest identifier (ID) is not a good approach because sensor nodes with the least remaining power may be selected as the CHs and thus lose power more quickly. Heinzelman et al. [13] selects a CH randomly, while each sensor node serves in turn as a CH to the balance energy dissipation of the nodes. Lotfinezhad et al. [28] select a CH by comparing the remaining power of the nodes. This approach helps to prolong the lifetime of the nodes.

During cluster setup, CHs broadcast signals, and non-CH nodes determine which CH to join according to the signal strength received. They tend to join the CH closest to them; as a result, clusters come in various sizes. The larger the cluster is, the larger the load of its CH. Some studies attempt to take measures to control the size of each cluster so as to reduce the load-difference between each CH [5,11,23,35].

The power of a CH may be exhausted after going through cluster setup and several data transmissions. At this time, cluster maintenance, such as picking out a new CH [18] and merging clusters, should be performed to continue data transmissions from sensor nodes to the BS. Cluster maintenance is also required when a CH is away from its original cluster due to the mobility of sensor nodes.

Some works suggest that sensor nodes featuring sleep mode should be adopted in intra-cluster communications so that only one node in a cluster is active (e.g., cluster members take turns collecting data), while the other nodes enter sleep mode to save energy. Accordingly, scheduling sleep time is a major issue worthy of discussion [7].

As for inter-cluster communications, energy dissipation increases if the message to be transmitted is far away from the BS. Accordingly, Chang et al. [6] apply multi-hop communications to make a CH find out the appropriate one to relay data (e.g., data is transmitted to a CH that is closest to the BS). However, using a CH close to the BS for relaying data might impose too much load on the CH; therefore, searching for different transmission paths around the BS to alleviate the loads of the CHs is also studied.

Furthermore, many methods deal with energy efficiency issues [29] and prolonging the lifetime [34] of the WSNs. Bandyopadhyay and Coyle [4] compute the number of aggregators in each level for energy conservation. They also demonstrate that the use of a hierarchical structure can help conserve energy. In [36], Wang et al. proposed several energy-efficient communication protocols based on power control and load balancing. Alippi et al. [2] propose a k-level hierarchical extension of the low-energy localized clustering (LLC) algorithm, which estimates the residual energy of nodes and the aggregation degree. In the following, several representative protocols, which are compared with our proposed scheme, are briefly introduced.

2.1. Low energy adaptive clustering hierarchy (LEACH)

LEACH [13] is organized in rounds, each of which consists of a setup phase and a steady state phase. In the setup phase, each sensor node randomly chooses a number between 0 and 1. If the chosen number is less than the value of the threshold denoted by $T(n)$, the node n declares itself a CH.

$$T(n) = \frac{p}{1 - p \times \left(r \bmod \frac{1}{p}\right)}, \quad \text{if} \quad n \in G \tag{1}$$

where p is the desired percentage of CHs (e.g. 0.05); r represents the number of current round; and G refers to the set of nodes that have not served as the CH in the last $1/p$ rounds. Sensor nodes join the CHs that are closest to them based on the signal strength of the CHs, and thus, several clusters may be formed. The CH arranges a TDMA (Time Division Multiple Access) schedule for its cluster members and assigns different time slots to cluster members accordingly. In steady state phase, cluster members transmit the collected data in the allocated time slot, while the CH processes data aggregation before passing the obtained data to the BS via single-hop.

The advantages of LEACH include the following: (1) because CHs collect data forwarded by cluster members before passing the data to the BS, power consumption decreases; (2) any node that served as a CH in certain round cannot be selected as the CH again, so each node can equally share the load imposed upon CHs; (3) utilizing a TDMA schedule prevents CHs from unnecessary collisions; and (4) cluster members can open or close communication interfaces in compliance with their allocated time slots to avoid excessive energy dissipation.

2.2. LEACH variant

Farooq et al. [8] present a multi-hop routing with low energy adaptive clustering hierarchy (MR-LEACH) protocol. The aim is to reduce the energy dissipation of sensor nodes by adaptively increasing the clustering hierarchy. In MR-LEACH, CHs are responsible for collecting the data from cluster members and acting as relaying nodes for CHs at lower-layers to transmit data to the BS. This protocol prolongs network lifetime because transmission is based on multi-hop routing from lower-layers toward higher-layers.

A centralized version of LEACH, LEACH-C [14], improves LEACH by using the BS central control and building optimal clusters. During the set-up phase, each sensor node sends information about its current location and remaining energy to the BS. The BS computes the average node energy, the nodes whose energy level is above this average may be selected as CHs. For minimizing the total sum of squared distances between all the non-CHs and the closest CH, LEACH-C uses the simulated annealing algorithm to find the optimal clusters.

Abdulsalam and Kamel [1] present weighted low energy adaptive clustering hierarchy aggregation (called W-LEACH). Weights are based on a sensor's density and its remaining energy. The weights are then used to decide which sensor nodes are good candidates to be CHs and which nodes are good candidates to send data to CHs in each cluster. W-LEACH is able to handle both uniform and non-uniform WSNs.

Hong et al. [15] present T-LEACH, which is a threshold-based CH replacement method for WSNs. T-LEACH minimizes the number of CH selections by using the threshold of residual energy. By reducing CH selection and replacement cost, the network lifetime can be prolonged.

Lin et al. [24] introduce the forwarding station that forwards the integrated messages from all CHs back to the BS. Simulation results show that the network lifetime can be extended.

Deterministic cluster-head selection (LEACH-DCHS) [26] takes the residual energy of the sensor node into the threshold function. Each sensor node randomly chooses a number between 0 and 1; if the number is less than the threshold $T(n)$, the node becomes a CH for the current round.

$$T(n) = \frac{p}{1 - p \times \left(r \bmod \frac{1}{p}\right)} \left[\frac{E_{n\_current}}{E_{n\_\max}} + \left(r_s div \frac{1}{p}\right)\left(1 - \frac{E_{n\_current}}{E_{n\_\max}}\right)\right], \quad \text{if} \quad n \in G \tag{2}$$

where p is the desired percentage of CHs; r represents the number of the current round; r_s refers to the number of consecutive rounds during which a sensor node has not been CH and is reset to 0 when the sensor node becomes a CH; and $E_{n\_current}$ and $E_{n\max}$ are the current energy and initial energy of the node, respectively. This method ensures that the sensor node with more energy has a greater opportunity to be the CH.

Loscri et al. [27] build a two-level hierarchy for LEACH (called TL-LEACH). TL-LEACH uses one of the CHs that lie between the CH and the BS as a relay station. This allows CHs to better distribute the energy load among sensor nodes when the network density is higher.

Xiangning and Yulin [37] introduce the energy-LEACH protocol (called E-LEACH), choosing CHs based on remaining energy so that sensor nodes with more remaining energy are good candidates as CHs in each round.

Yassein et al. [39] propose the concept of vice-CH (called V-LEACH), a sensor node that becomes a CH if the current CH uses up its energy. This ensures that data is always delivered to the BS.

2.3. Base Station Controlled Dynamic Clustering Protocol (BCDCP)

As mentioned above, LEACH relies on probability to determine whether a sensor node is to be a CH or not. Clusters are formed based on the control signals, yet it may become a load to sensor nodes with limited power. In view of this, BCDCP [31] relies on the BS to process CH selection and cluster setup; therefore, the sensor nodes are responsible for sensing and relaying data only. BCDCP works with two phases: setup phase and data communication phase.

The main activities in setup phase are cluster setup, CH selection, CH-to-CH routing path formation, and schedule creation for each cluster. The BCDCP uses a balanced clustering technique [9] to ensure that all clusters have approximately the same number of sensor nodes.

In data communication phase, sensor nodes inside the cluster sense and pass the data during their designated time slot to the CHs. The CHs run data aggregation and pass the obtained data to the next CH through the calculated transmission path.

The advantages of BCDCP include the following: (1) clusters and transmission paths are constructed by the BS to reduce energy dissipation of sensor nodes, and (2) TDMA is employed to schedule the time slots of cluster members; this allows sensor nodes to open communication interfaces only if data transmissions are required, which means energy can be saved at the same time.

3. ACT

This paper presents a cluster-based routing protocol called "arranging cluster sizes and transmission ranges for wireless sensor networks (ACT)." The design methodology is as follows:

(1) Utilizing multi-hop communications to relay data via multiple CHs.
It can shorten transmission distances so that the power of those CHs far from the BS is not depleted as quickly.
(2) Separating the network topology into multiple levels of different cluster sizes.
To avoid too many relaying loads on CHs near the BS, clusters near the BS are smaller, whereas those located far from the BS are larger. It is expected that the given load on each CH is similar so that the power of the CHs near the BS is not exhausted earlier.
(3) Utilizing cluster maintenance to prolong network lifetime.
To avoid frequent topology reconfiguration, cluster maintenance, which includes CH rotations and cross-level transmissions, is suggested.

ACT consists of the cluster formation phase, data forwarding phase and cluster maintenance phase. The following conditions are assumed.

- The positions of BS and sensor nodes are fixed.
- The power of all sensor nodes is the same in the beginning.
- Each sensor node transmits one unit of data to the CH in each round.
- A CH aggregates data and then forwards them to BS.

- Sensor nodes are uniformly distributed in the sensor field with density d_n.
- Sensor nodes can adjust power levels. The maximum power level can be used in transmitting data to BS directly.
- Sensor nodes can recognize their geographical position and the BS's position via exchanging information.
- The covered area is a $W \times L$ rectangle, where W is the width and L is the length. Note that the area considered in LEACH and BCDCP are also rectangular.

3.1. Cluster formation phase

The cluster formation phase consists of the determination of the hierarchical level of network topology, the calculation of cluster radius, cluster setup and CH-to-CH routing path formation:

3.1.1. The determination of the hierarchical level of network topology

First of all, the BS divides the network topology into K levels. The sizes of each cluster within each level are the same, with clusters closest to the BS grouped in the 1st level and so on. The clusters located farthest from the BS are put in the Kth level (as shown in Fig. 1).

3.1.2. The calculation of cluster radius

According to the radio energy dissipation model [14], the energy consumed by sensor nodes for transmitting k bits of data at a distance d is:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$

That is,

$$E_{Tx}(k,d) = E_{elec} \times k + \varepsilon_{amp} \times k \times d^2 \tag{3}$$

where E_{elec} is the energy used in a sensor node (not including the transceiver) for transmitting one bit of message. ε_{amp} is the energy consumed by the transceiver during its transmission of one-bit data through the amplifier.

Eq. (3) is simplified into Eq. (4):

$$E_{Tx}(k,d) = k \times (E_{elec} + \varepsilon_{amp} \times d^2) \tag{4}$$

In ACT, we hope to balance the energy consumption of each CH, and this can be achieved by applying Eq. (4) to calculate the radius of each cluster. Let us suppose a network consists of clusters with K different sizes, and cluster members pass one bit of data to CHs. The transmission range is measured from the distance between the centers of two clusters for simplicity in calculations, except in the 1st level (i.e., $(r_k + r_{k-1})$ in Kth level, $(r_{k-1} + r_{k-2})$ in $(K-1)$th level and so forth).

Each CH in the Kth level (with node density d_n) only takes care of the data transmitted by its own cluster members; its transmission range is $(r_k + r_{k-1})$, and thus the total energy dissipation of CH in Kth level is

$$E_k = (r_k^2 \times \pi \times dn) \times [E_{elec} + \varepsilon_{amp} \times (r_k + r_{k-1})^2] \tag{5}$$

CHs in the $(K-1)$th level not only process data given by their cluster members (i.e., $r_{k-1}^2 \times \pi \times d_n$), but they also perform data relaying for Kth level. Because its transmission range is $(r_{k-1} + r_{k-2})$, the total energy dissipation of CH in $(K-1)$th level is

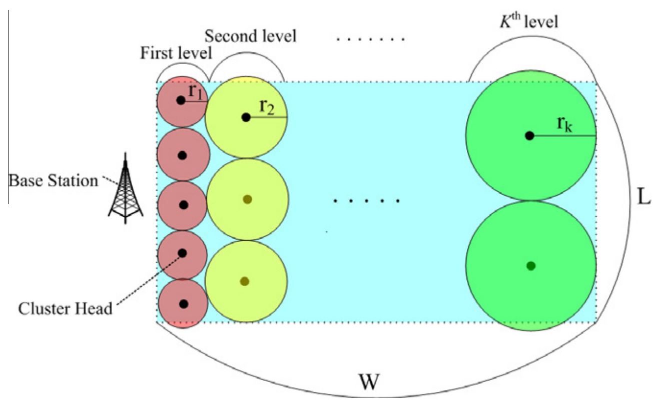

Fig. 1. Level structure of network topology.

$$E_{k-1} = \left\{ (r_{k-1}^2 \times \pi \times d_n) + \left[r_k^2 \times \pi \times d_n \times \left(\frac{L}{2 \times r_k} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{k-1}} \right)} \right] \right\} \times [E_{elec} + \varepsilon_{amp} \times (r_{k-1} + r_{k-2})^2] \tag{6}$$

Here, $\frac{L}{2 \times r_k}$ and $\frac{L}{2 \times r_{k-1}}$ represent the number of clusters in Kth level and $(K-1)$th level. These can be denoted as a_k and a_{k-1}, respectively (they reappear in Eq. (11)). Therefore, we rewrite Eq. (6) as

$$E_{k-1} = \left\{ (r_{k-1}^2 \times \pi \times dn) + \left[r_k^2 \times \pi \times dn \times (a_k) \times \frac{1}{(a_{k-1})} \right] \right\} \times \left[E_{elec} + \varepsilon_{amp} \times (r_{k-1} + r_{k-2})^2 \right] \tag{7}$$

For the same reason, each CH in $(K-2)$th level not only forwards data generated by its own cluster members (i.e.,$r_{k-2}^2 \times \pi \times d_n$), but it also performs data relaying for $(K-1)$th level and Kth level. Because its transmission range is $(r_{k-2} + r_{k-3})$, the total energy dissipation of CH in $(K-2)$th level is

$$E_{k-2} = \left\{ (r_{k-2}^2 \times \pi \times d_n) + \left[r_{k-1}^2 \times \pi \times d_n \times \left(\frac{L}{2 \times r_{k-1}} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{k-2}} \right)} \right] + \left[r_k^2 \times \pi \times d_n \times \left(\frac{L}{2 \times r_k} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{k-1}} \right)} \right] \right\} \times [E_{elec} + \varepsilon_{amp} \times (r_{k-2} + r_{k-3})^2] \tag{8}$$

In this way, the total energy dissipation of a CH in each level (for one generated message bit) is calculated as follows:

$$\begin{cases} K\text{th level} : E_k = (r_k^2 \times \pi \times dn) \times [E_{elec} + \varepsilon_{amp} \times (r_k + r_{k-1})^2] \\ (K-1)\text{th level} : E_{k-1} = \left\{ (r_{k-1}^2 \times \pi \times dn) + \left[r_k^2 \times \pi \times dn \times \left(\frac{L}{2 \times r_k} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{k-1}} \right)} \right] \right\} \times [E_{elec} + \varepsilon_{amp} \times (r_{k-1} + r_{k-2})^2] \\ \vdots \\ 1\text{st level} : E_1 = \left\{ (r_1^2 \times \pi \times dn) + \left[\sum_{i=2}^{k} r_i^2 \times \pi \times dn \times \left(\frac{L}{2 \times r_i} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{i-1}} \right)} \right] \right\} \times \left[E_{elec} + \varepsilon_{amp} \times (r_i')^2 \right] \end{cases} \tag{9a}$$

where $r_1, r_2, \ldots, r_k$ are the cluster radiuses (in K different sizes), respectively. Because the transmission distance for the 1st level is very different from r_1, r_i' is used instead to calculate the transmission range in the 1st level, which we explain below (in Eqs. (13)–(15)). Here, d_n is the density of sensor nodes and E_i is the energy consumed on each CH in ith level.

Because we hope the energy consumption of CHs in each level is similar, Eq. (9b) is applied to calculate cluster radius in each level:

$$\begin{cases} E_1 \cong E_2 \cong \ldots \cong E_k \\ r_1 + r_2 + \cdots + r_k = \frac{W}{2} \end{cases} \tag{9b}$$

where W is the width of sensing area.

3.1.3. A numerical example

If a BS wants to construct three clusters of different sizes, it lets $K = 3$. The ratio of r_1, r_2 and r_3 can be obtained by Eq. (10a). The obtained ratio can therefore be put in Eq. (10b) to calculate the actual cluster radius.

$$\begin{cases} 3^{\text{rd}}\ \text{level} : E_3 = (r_3^2 \times \pi \times d_n) \times [E_{elec} + \varepsilon_{amp} \times (r_2 + r_3)^2] \\ 2^{\text{nd}}\ \text{level} : E_2 = \left[(r_2^2 \times \pi \times d_n) + \left(r_3^2 \times \pi \times d_n \times \left(\frac{L}{2 \times r_3} \right) \times \frac{1}{\left(\frac{L}{2 \times r_2} \right)} \right) \right] \times [E_{elec} + \varepsilon_{amp} \times (r_1 + r_2)^2] \\ 1^{\text{st}}\ \text{level} : E_1 = \left[(r_1^2 \times \pi \times d_n) + \sum_{i=2}^{3} \left(r_i^2 \times \pi \times d_n \times \left(\frac{L}{2 \times r_i} \right) \times \frac{1}{\left(\frac{L}{2 \times r_{i-1}} \right)} \right) \right] \times [E_{elec} + \varepsilon_{amp} \times (r_1')^2] \end{cases} \tag{10a}$$

$$\begin{cases} E_1 \cong E_2 \cong E_3 \\ r_1 + r_2 + r_3 = \frac{W}{2} \end{cases} \tag{10b}$$

3.1.4. Cluster setup

The information (including the number of levels in the network topology and the value of cluster radius as counted in each level) can be obtained by Eq. (9b). The sensor nodes exchange their geographical positions with each other, seeking a sensor node most suitable to serve as a CH, with its location closest to the ideal.

The elected CH broadcasts a Head_Msg that contains information regarding current energy level, the distance between the CH and BS, and the sensor node's ID, which is be used as cluster's ID as well. If multiple Head_Msgs are broadcasted to a sensor node from several CHs, the sensor node chooses and joins the closest CH before sending a member_Msg to inform the CH of its condition. If some sensor nodes are not CHs and do not receive a Head_Msg, they may send a find_Msg to look for the closet clusters to join them (as shown in Fig. 2).

3.1.5. CH-to-CH routing path formation

After a cluster is setup, assigning numbers to each CH is required. The transmission path of each CH can be assigned a two-dimensional array [X][Y], with the first index representing the level in which the CH is, and the second indicating the order of the cluster in that level. The BS then calculates the number of clusters in each level according to the radius of the clusters (for simplicity, we assume L is dividable by $2 \times r_i$):

Given that r_i is the cluster radius as counted in ith level, suppose a_i is the number of clusters in ith level. Thus,

$$a_i = \frac{L}{2 \times ri} \qquad (11)$$
$$a_1 > a_2 > a_3 > \cdots > a_i$$

If the number of clusters in each level is obtained, we have the number of clusters in ith level divided by the number of clusters in $(i-1)$th level.

$$S = \left\lceil \frac{a_{i-1}}{a_i} \right\rceil \qquad (12)$$

where S means the number of CHs in $(i-1)$th level with which it must communicate for each CH in ith level.

For example, three clusters are in 2nd level and six are in 1st level. The value of S is 2 if we have 6 divided by 3. We know the CH in 2nd level looks for two CHs closest to it in the 1st level for data transmission.

When we calculated the cluster radius, we found that the transmission range of CHs (not for 1st level) can be approximated by the sum of two clusters' radiuses. However, the distance between the CH and the BS in the 1st level is different than the sum of two cluster radiuses. The following explains the allocation of transmission capacity in CHs in 1st and other levels:

We now consider the 1st level (as shown in Fig. 3). Assume r'_1 is the transmission range of CH_i in the 1st level and N is the total number of clusters in the 1st level. In this case, N is either an odd or even number. N_i is the vertical distance of node i, which is the vertical distance between the center of node i and the BS. Therefore, N_i can be derived as follows:

Case 1: N is an odd number.

$$N_i = \begin{cases} [N-(2i-1)] \times r_1, & i = 1 \sim \lfloor \frac{N}{2} + 1 \rfloor \\ 2\left[i - \lfloor \frac{N}{2} + 1 \rfloor\right] \times r_1, & i = \lfloor \frac{N}{2} + 2 \rfloor \sim N \end{cases} \qquad (13)$$

Case 2: N is an even number.

$$N_i = \begin{cases} [N-(2i-1)] \times r_1, & i = 1 \sim \frac{N}{2} \\ \left[2(i - \frac{N}{2}) - 1\right] \times r_1, & i = \frac{N}{2} + 1 \sim N \end{cases} \qquad (14)$$

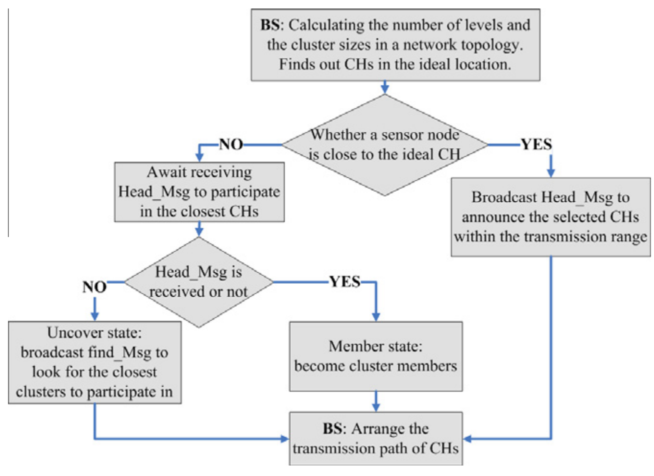

Fig. 2. Flow chart of the cluster setup phase.

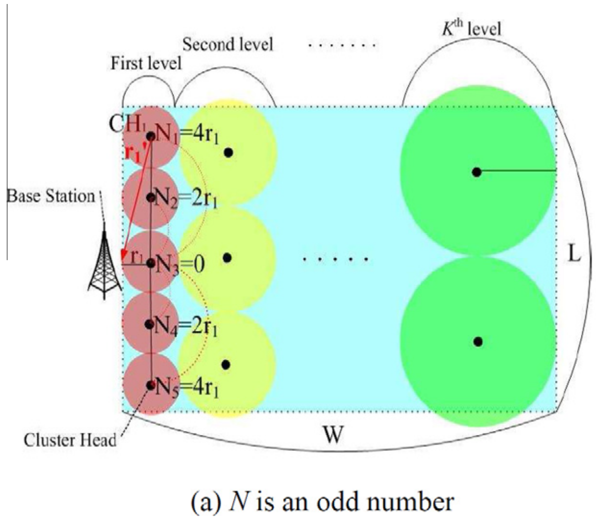

Fig. 3. Transmission range between CHi in the first level and BS.

Finally, the transmission range between CH_i in the 1st level and BS can be obtained:

$$r'_i = \sqrt{(r_1)^2 + (N_i)^2} \tag{15}$$

We then consider other levels. If the obtained value S is an integer, it means that the transmission capacity delivered from CHs in the ith level is equally shared by CHs in the $(i-1)$th level. If this is not the case, the transmission capacity of CHs may be allocated unequally (as shown in Fig. 4a, the transmission capacity given to the first cluster in $(K-1)$th level is $M/2$; the second cluster has a transmission capacity of M and the third has a capacity of $M/2$. This shows how the transmission capacity is unevenly distributed). For this reason, an adjustment is required to even the shares of each CH (as shown in Fig. 4b, after an adjustment is made via ACT's algorithm, each cluster in $(K-1)$th level has an equal amount of transmission capacity of $\frac{2M}{3}$). Here the Kth level and the $(K-1)$th level are used as an example. Fig. 5 presents the algorithm of transmission capacity on CHs.

3.2. Data forwarding phase

The data forwarding phase consists of intra-cluster data forwarding and inter-cluster data forwarding.

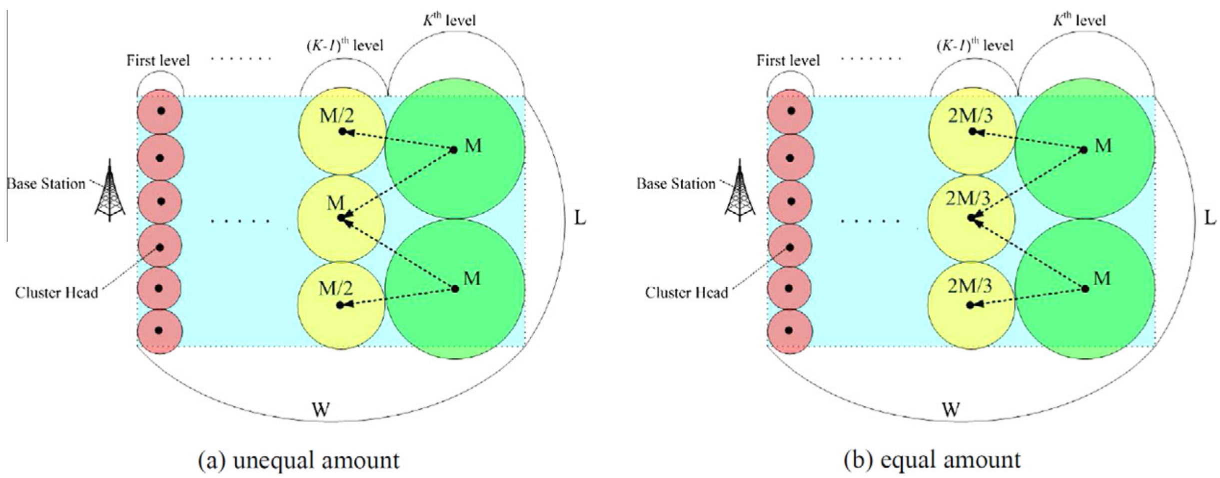

Fig. 4. Allocating transmission capacity between CHs in two level.

Algorithm: Allocation of transmission capacity on CHs

Input: M_i is the message size in a cluster and a_i is the number of clusters in i^{th} level

Output: An equal amount of transmission capacity on CHs

Begin

$i = K$ // From K^{th} level

Repeat

For Each CH in i^{th} level,

Allocate equal amount of transmission capacity on CHs in $(i-1)^{th}$ level

// Equal amount of transmission capacity $= \frac{a_i}{a_{i-1}} \times M_i$

$i = i - 1$ // From K^{th}, $(K-1)^{th}$, …, 1^{st} level

Until $(i = 2)$ // 2^{nd} level transmit data to 1^{st} level

CHs in the 1^{st} level pass data to BS directly

End

Fig. 5. The algorithm of allocating transmission capacity on CHs.

- Intra-cluster data forwarding:
  After cluster setup, CHs collect data transmitted from cluster members and perform data aggregation. If a CH adopts single-hop for intra-cluster data forwarding, the sensor nodes farthest from the CH consume much more energy in larger clusters. To avoid this, we employ the concept of the MST [33] to reduce the distance between the sensor nodes and CHs for data transmission.
  In a network with a high density of sensor nodes, the transmitted information may go far before reaching the targeted CHs if the MST is applied. Therefore, we assign a hop count H. At the time the data transmission begins, the data forwarding from one sensor node to another causes the value of H to be decreased by one. When the value H is equal to zero but the data fails to reach the targeted CH, the sensor node that holds the data at the moment passes the data to the CH directly to avoid time-consuming routing.
- Inter-cluster data forwarding:
  The inter-cluster data forwarding refers to transmissions of CHs' collected data from cluster members in the ith level to the next CH in the $(i-1)$th level closest to the BS until the transmitted data reach the BS.

3.3. Cluster maintenance phase

In the traditional cluster-based routing protocol, the cluster maintenance phase is very important because the loads imposed on the CHs are much larger than those imposed on the sensor nodes; as a result, the power of CHs may be exhausted quickly. In case the power of the CH approaches depletion, a new CH is elected. In ACT, the cluster maintenance phase consists of CH rotations within a cluster and cross-level data transmission to the BS.

- CH rotations in a cluster:
  Define the threshold of CH power as T (15% of initial energy). When the remaining power of a CH is under T, a new CH is selected from among the sensor nodes, usually the one closest to the CH within its cluster group, while a change_msg is broadcast to inform cluster members of the change of CH.
- Cross-level data transmission to BS:
  In ACT, clusters in the 1st level are the smallest in size, and thus, fewer cluster members are found in the 1st level. If the sensor nodes within a cluster take turns serving as CHs, the process may finish quickly as there are not enough sensor nodes. When the BS is aware that each sensor node in the 1st level can no longer serve as a CH, it broadcasts a message to allow the CHs in the 2nd level to transmit data to BS directly (as shown in Figs. 6 and 7). Let the network topology be

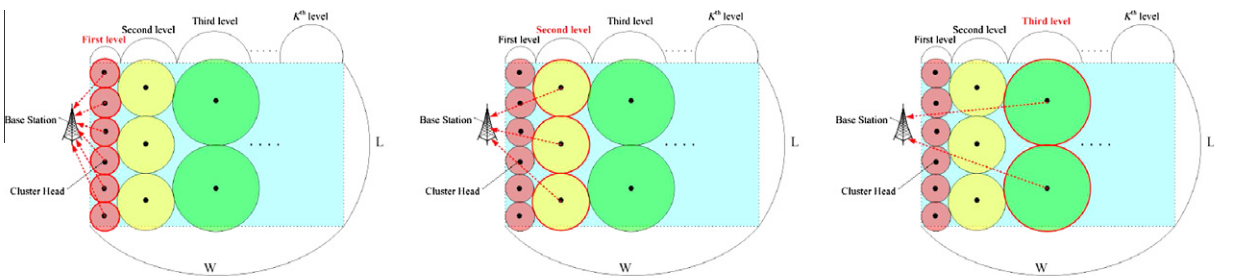

Fig. 6. The architecture of cross-level data transmission.

```
Algorithm: Cross-level data transmission
  Input: Two-dimensional array [X][Y]
         X representing the level in which the CH is
         Y indicating the order of the cluster in that level
  Output: All sensor nodes use up their power

    Begin
      X = 1                  //From 1st level
      Repeat
        For Each cluster Y in Xth level, pass data to BS directly
        if the residual energy of CH is under T
                             //T: the threshold of CH power
          pick out a new CH
                             //Closest to the original CH within its cluster group
        if the power of each cluster in Xth level is exhausted (under T)
          X = X + 1   //Cross-level data transmission
      Until (the residual energy of all sensor nodes are depleted)
    End
```

Fig. 7. The algorithm of cross-level data transmission.

divided into K levels with the CHs in the 1st level transmitting data to BS. When the power of each sensor node in the 1st level is exhausted after a while, the CHs in the 2nd level assume the process of data transmission (the same for 3rd level, 4th level, ..., Kth level). In this way, the network lifetime can be prolonged.

A classification and comparison of the WSNs discussed below is shown in Table 1. Cluster head selection, cluster setup and intra-cluster communications are the fundamental methods of forming a cluster. LEACH, BCDCP, MR-LEACH and ACT are also compared under the same basis. LEACH utilizes single-hop communications to transmit the aggregate data to a BS. BCDCP, MR-LEACH and ACT adopt multi-hop communications for energy saving purposes. Moreover, while ACT does consider "cross-level data transmission to BS" and "communication load balance for each cluster," LEACH, BCDCP and MR-LEACH do not.

4. Performance evaluation

We conduct simulations to study the performance of the proposed ACT and the other three schemes, LEACH, BCDCP and MR-LEACH. First of all, we describe the simulation settings. Secondly, we present the simulation results, which show the performance results under different performance metrics. Finally, we discuss and analyze the simulation results.

4.1. Simulation setup

We use a combination of the NS-2 [44] and the Mannasim [45] in simulations. We apply the first order radio model [14] to evaluate the energy dissipation in sensor nodes. We average the results based on 300 runs for each scenario.

In addition, we are interested in the following performance metrics: (1) average energy dissipation; (2) standard deviation of energy consumption of CHs (utilizing standard deviation to observe the scattering of values); (3) the number of sensors alive; and (4) network lifetime [13] (which is defined as the number of rounds in which the first sensor node uses up its energy). The definition of a round is when one packet is transferred from the sensor node via the CH to the BS.

In Figs. 8–10, 96 sensor nodes are uniformly distributed in an $80 \times 120\ m^2$ rectangle. Note that the areas considered in LEACH, BCDCP and MR-LEACH are also rectangular. The positions of the BS and sensor nodes are fixed. The initial energy of each sensor node is the same (0.5 J). Each sensor node transmits one unit-data to the CH in each round. Each CH aggregates

Table 1
Classification and comparison of WSNs.

	LEACH [13]	BCDCP [31]	MR-LEACH [8]	ACT
CH selection and cluster setup	Yes	Yes	Yes	Yes
Intra-cluster communications	Yes	Yes	Yes	Yes
Each CH transmits the aggregate data to BS via single-hop/multi-hop communications (Inter-cluster communications)	Single-hop	Multi-hop	Multi-hop	Multi-hop
Cross-level data transmission to BS	No	No	No	Yes
Communication load balance for each cluster	No	No	No	Yes

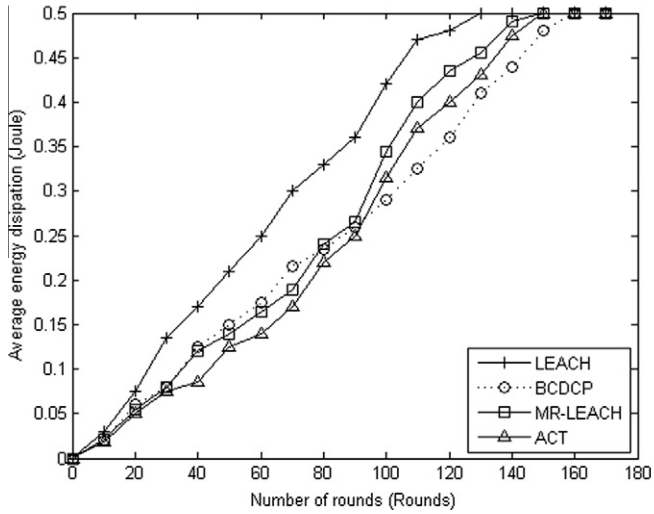

Fig. 8. A comparison of ACT's average energy dissipation with LEACH, BCDCP and MR-LEACH.

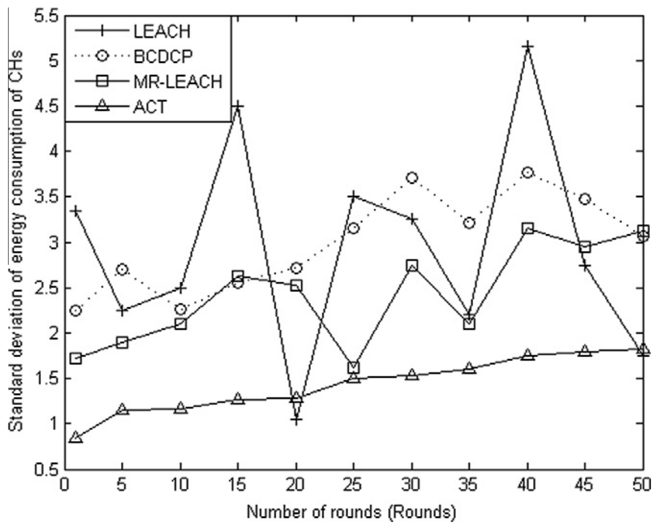

Fig. 9. The standard deviation of energy consumption of CHs.

data and forwards them to the BS. Sensor nodes can adjust power levels. The maximum power level can be used in transmitting data to the BS directly. The simulation parameters are given in Table 2.

4.2. Simulation results

Fig. 8 shows the average energy dissipation in sensor nodes in four types of routing protocols, namely LEACH, BCDCP, MR-LEACH and ACT, within a range of $80 \times 120\ \mathrm{m}^2$. The energy dissipation found in LEACH is greater than that in BCDCP, MR-LEACH and ACT as a whole. This is because LEACH adopts single-hop communications with the CH sending its data directly to the BS; BCDCP, MR-LEACH and ACT utilize multi-hop communications that require less energy consumption from each sensor node. In addition, ACT utilizes network topology and applies an energy consumption equation to locate the ideal CH. ACT balances the load on each CH by considering cluster sizes and CH locations. In this way, energy spent by sensor nodes close to the BS is less than in BCDCP and MR-LEACH, so the average energy dissipation in ACT is a lower than in BCDCP and MR-LEACH. The selection of a new CH in ACT occurs when the energy of the current CH is below a given threshold, but the locations of CHs deviate from the original ones; the average energy dissipation in ACT increases and consumes more than BCDCP after running for approximately 96 rounds.

Fig. 9 shows the standard deviation of energy consumption of CHs in LEACH, BCDCP, MR-LEACH and ACT. The CHs in LEACH, BCDCP and MR-LEACH are picked out randomly. The CHs in LEACH are selected from sensor nodes by chance,

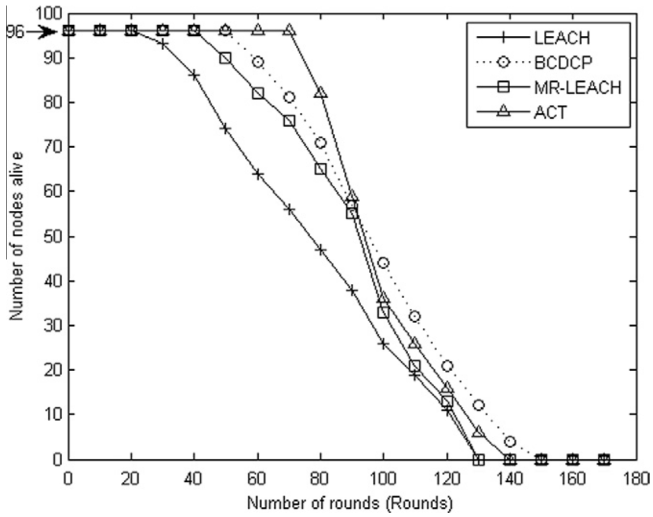

Fig. 10. The number of alive sensor nodes over time.

Table 2
The simulation parameters.

Parameter	Value
Network size	80×120 m^2
Base station location	(0,40) m
Number of sensor nodes	96 nodes (for Figs. 8–10)
Density	1 node/ 100 m^2 (for Figs. 8–10)
Initial energy of each sensor node	0.5 J
Data packet size	500 bytes
E_{elec}	50 nJ/bit
ε_{amp}	100 pJ/bit/m^2
K	3 for ACT, 4 for MR-LEACH

providing each sensor node a chance to serve as a CH; the CH in BCDCP is chosen randomly from the sensor nodes with higher than average remaining power; and the CH in MR-LEACH is selected in each round based on the available energy of sensor nodes. Accordingly, the standard deviations of energy consumption of CHs in LEACH, BCDCP and MR-LEACH show substantial variations, with the scatterings of energy consumption oscillating in each round. The loads on CHs, the ideal locations for CHs, and cluster sizes are calculated in ACT to balance the given loads on each CH; as a result, the standard deviation of energy consumption of CHs in ACT is better than in LEACH, BCDCP and MR-LEACH.

Fig. 10 shows the number of sensor nodes still alive over the simulation time. LEACH uses single-hop communications to send its data directly to the BS; therefore, sensor nodes with less remaining power are frequently far from the BS (i.e., the first sensor node exhausts its power in 20 rounds). CHs in BCDCP and MR-LEACH are selected from sensor nodes with sufficient power, so their energy is not used up as quickly as it is in LEACH. However, BCDCP and MR-LEACH utilize multi-hop communications, which cause higher energy dissipation rates for sensor nodes close to the BS; on the contrary, ACT computes the ideal locations for CHs to balance the energy dissipation of each CH. For this reason, the first sensor node exhausts its power (i.e., after 70 rounds) later than in both BDCDP (i.e., 50 rounds) and MR-LEACH (i.e., 40 rounds). Moreover, the slope of the curve in ACT is sharper than in LEACH, BCDCP and MR-LEACH; this phenomenon explains that ACT causes many sensor nodes to use up their energy.

In Fig. 11, we measure the network lifetime for different node densities of 40, 60, 80, 100 and 120 nodes. We define network lifetime as the number of rounds before the first sensor node uses up its energy in the network [13]. Because CHs are selected randomly in LEACH, the CHs have insufficient power, which makes LEACH have a shorter network lifetime than BCDCP, MR-LEACH and ACT. Even though the CHs in BCDCP and MR-LEACH are selected randomly from sensor nodes with sufficient power, their use of multi-hop communications increases the energy consumption of the sensor nodes around the BS, as the CHs close to the BS share higher relaying loads. When the CHs relay data, the cluster sizes are adjusted appropriately and the energy dissipation of each CH is equally allocated in ACT; as a result, ACT achieves the longest network lifetime.

Table 3 shows the relationship between the level of K and cluster radius (r_k) within the same scenario (80×120 m^2). The trends are all consistent with the concepts of cluster radius as proposed within ACT (to avoid too many relaying loads on CHs near the BS, cluster sizes near the BS are smaller, whereas those located away from the BS are larger).

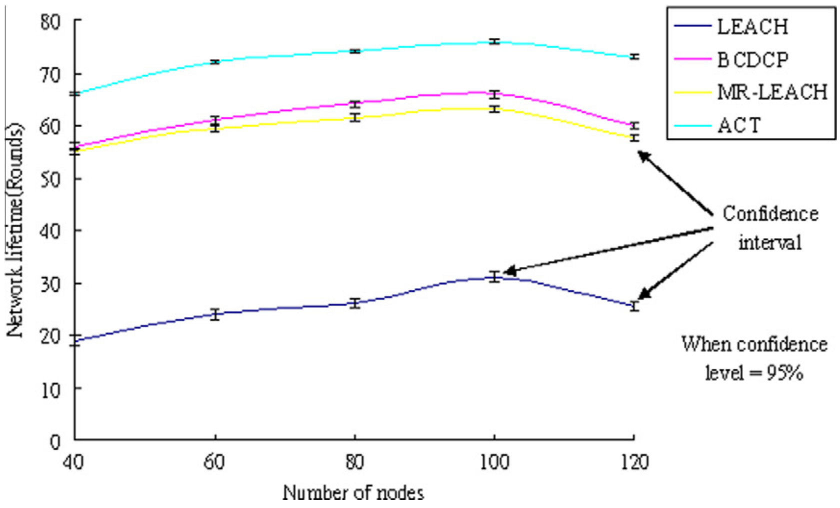

Fig. 11. The network lifetime of different node densities.

Table 3
The relationship between the level of K and cluster radius.

	r_k				
Level K	r_1	r_2	r_3	r_4	r_5
$K = 3$	11.84 m	18.62 m	29.54 m	×	×
$K = 4$	6.59 m	10.42 m	16.58 m	26.41 m	×
$K = 5$	3.85 m	6.10 m	9.74 m	15.53 m	24.78 m

5. Conclusion and future work

In the cluster-based WSNs, single-hop communications increase the energy dissipation of CHs farthest from the BS because the CHs send data directly to the BS. Utilizing multi-hop communications facilitates data relays by CHs. However, the CHs around the BS undertake larger relaying loads and exhaust their energy more quickly.

This paper proposes an approach that slows the energy consumption of CHs. Considering the relaying load undertaken by each CH, the network topology and energy consumption are used to calculate a cluster radius to balance the energy dissipation of each CH while prolonging network lifetime. Simulation results show that ACT can efficiently reduce the energy consumption of CHs around the BS and have similar energy dissipation in each CH. In addition, ACT has a longer network lifetime than LEACH, BCDCP and MR-LEACH.

As to future work, we present the guideline for formulating coverage problem as an integer linear programming problem (ILP). We will implement the optimization problem, with the objective function given in Eq. (16) and several constraints (17)–(23). This problem can be solved to optimality by using CPLEX solver [46].

To maximize network lifetime, we need a trade-off between total energy consumption and energy balancing among sensors. We first define the following notations.

Let $|S|$ is the total number of sensor nodes, $|C|$ is the total number of clusters and $|K|$ is the total number of levels. Let r_i is the cluster radius in the ith level, d_n is the density of sensor nodes, E_i is the energy consumed on each CH in the ith level, a_i is the number of clusters in the ith level, E is the total energy and NL is the network lifetime. Then, we define binary decision variables:

$$\forall i = 1 \dots |K|, \quad \forall m = 1 \dots |S|, \quad \forall n = 1 \dots |S|, \quad \forall c = 1 \dots |C|$$

$$X_m = \begin{cases} 1, & \text{if sensor} \quad m \quad \text{is} \quad a\ CH \\ 0, & \text{else} \end{cases}$$

$$Y_{m0} = \begin{cases} 1, & \text{if sensor} \quad m \quad \text{can communicate with the BS} \\ 0, & \text{else} \end{cases}$$

$$Z^i_{mn} = \begin{cases} 1, & \text{if sensor} \quad n \quad \text{is connected to} \quad CH \quad m \quad \text{in level } i \\ 0, & \text{else} \end{cases}$$

Therefore, the problem of maximize network lifetime (NL) is formulated as follows:

$$\text{Maximize} \quad NL \tag{16}$$

$$\text{Subject to}: \quad \sum_{m=1}^{|S|} X_m \times Y_{m0} = \sum_{i=1}^{|K|} a_i \tag{17}$$

$$\sum_{m=1}^{|S|} X_m = |C| \tag{18}$$

$$\forall m = 1 \ldots |S|, \quad \forall i = 1 \ldots |K|, \quad \sum_{\substack{n=1 \\ m \neq n}}^{|S|} Z_{mn}^i \leqslant \pi \times r_i^2 \times d_n \tag{19}$$

$$\sum_{i=1}^{|K|} a_i \times E_i \leqslant E \tag{20}$$

$$\sum_{i=1}^{|K|} \sum_{\substack{n=1 \\ m \neq n}}^{|S|} Z_{mn}^i + \sum_{m=1}^{|S|} X_m \times Y_{m0} = |S| \tag{21}$$

$$r_1 < r_2 < r_3 < \ldots < r_k < \frac{W}{2} \tag{22}$$

$$X_m, Y_{m0}, Z_{mn}^i \in \{0, 1\} \tag{23}$$

Constraint (17) ensures that each CH can communicate with the BS. Constraint (18) means the number of the selected CHs equals to the number of clusters. Constraint (19) presents an upper bound on the clusters' sizes. Constraint (20) ensures the energy consumed in all levels is less than or equal to the total energy. Constraint (21) ensures that all sensor nodes can communicate with the BS via CHs. Constraint (22) is the constraint for the variables. Eq. (23) is the binary constraints.

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