

Location-Based Spiral Clustering for Transmission Scheduling in Wireless Sensor Networks

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Abstract— Wireless sensor networks (WSN) consist of a large amount of sensor nodes distributed in a certain region. Due to the limited battery power of a sensor node, lots of energy-efficient schemes have been studied. Clustering is primarily used for energy efficiency purpose. However, clustering in WSNs faces several unattained issues, such as ensuring connectivity and scheduling inter-cluster transmissions. In this paper, we propose a location-based spiral clustering (LBSC) algorithm for improving connectivity and avoiding inter-cluster collisions. It also provides reliable location aware routing paths from all cluster heads to a sink node during cluster formation. Proposed algorithm can simultaneously make clusters in four spiral directions from the center of sensor field by using the location information. Three logical addresses are used for categorizing the clusters into four global groups and scheduling the intra- and inter-cluster transmission time for each cluster. We evaluated the performance with simulations and compared it with LEACH algorithm.

Keywords—Network lifetime, Wireless sensor network, Energy efficiency, Clustering, Inter-cluster collision, Connectivity

I. INTRODUCTION

Recent advances in technology have witnessed an increasing in using wireless sensor networks (WSNs) in many applications, including environmental monitoring and military field surveillance [1]. Unlike general purpose data communication networks, WSNs are typically designed for a specific domain of applications. In these applications, hundreds to thousands of low cost sensors are deployed and periodically report physical information such as temperature, pressure, humidity, light, and chemical activities. Reports from sensors are collected by observers (called sinks). Many WSN applications require only the aggregated value at certain region. In this case, sensors in different positions in a certain region can collaborate to aggregate their data and more efficiently report their information. Moreover, data aggregation reduces the communication overhead in the network, leads to meaningful energy savings.

In order to support such data aggregation or network topology control, nodes can be partitioned into a number of small groups called clusters. Clustering has been considered as an effective approach for organizing the network into a connected hierarchy. Besides achieving energy efficiency, a

well designed clustering mechanism can reduce packet collisions between nodes so that it results in better network throughput under high load conditions. Many localization algorithms [2][3] and clustering approaches [4-9] for WSNs have been proposed.

Each cluster has a coordinator, referred to as a cluster head (CH), and a number of member nodes (MNs). The MNs report sensing data to the respective CHs. The CHs not only perform sensing the environments, but also collect the data from MNs and relay the aggregated data to a sink through gateways (GWs) [4] or other CHs [6][7].

Clustering in WSNs causes several issues, such as ensuring connectivity and scheduling inter-cluster communications [10][11]. In this paper, we propose a location-based spiral clustering (LBSC) algorithm to handle the problems. We iteratively select CHs located along with the four spiral directions. In this paper, we assume that a node knows the location information of its one-hop neighbor nodes (NNs) by exchange hello messages.

The contributions of LBSC are as follows. First, while generating new clusters by LBSC algorithm, the node sets of four different directions can execute LBSC clustering simultaneously without any control packet collisions. Therefore we can reduce the network-wide clustering latency. Second, after completing the cluster formation, each node will be assigned in one of the four global groups and all clusters assigned to the same global group can concurrently transmit data to their respective CHs without inter-cluster collision. Third, each CH is able to select a GW node among one-hop NNs to configure the routing path to the sink node in the process of cluster formation.

The rest of this paper is organized as follows. In Section II, the motivation and approach of our research is introduced. Section III presents our proposed LBSC algorithm in detail. In Section IV, the simulation results are presented. Finally, Section V concludes this paper.

II. MOTIVATION AND APPROACH

Fig. 1 shows general problems in clustering method. First, after cluster formation, if some of nodes are not contained in any cluster because of the limited transmission range, they need a rejoin method for network connectivity. It is unsuitable for energy efficient design.

Second, a CH can set the time schedule and inform such schedule to its MNs for intra-cluster transmissions. The problem is how to prevent the inter-cluster collisions ($b_2 \rightarrow CH_B$ and $c_2 \rightarrow CH_C$) and how to support the concurrent transmission ($a_1 \rightarrow CH_A$ and $b_1 \rightarrow CH_B$) as shown in Fig. 1. One possible way is to use different code division multiple access (CDMA) code [6]. However, a relatively expensive cost is required for the usage of CDMA.

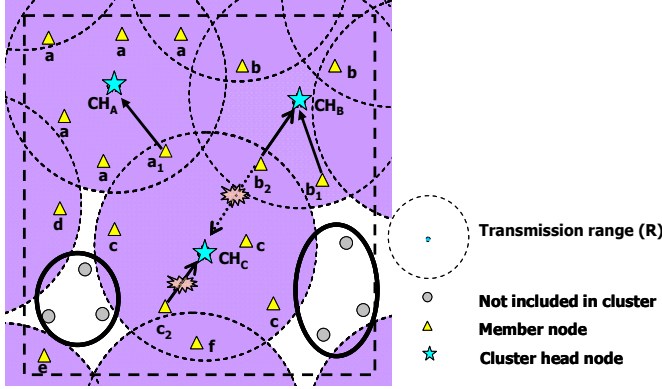


Figure 1. General problem in clustering.

For solving the above-mentioned problems, we propose a LBSC algorithm for improving connectivity and avoiding inter-cluster collisions. The basic idea is to iteratively construct clusters in four spiral directions from the center of the deployed sensor field using the location information as shown in Fig. 2. A_1 denotes direction and A_2 is for the order of clustering tier. Rotating the role of CHs among nodes is essential so as not to lay a burden on a few nodes with more duties than others. The first CH (CH_{FST}) can be replaced by its NNs in every round and we can select different next tier cluster head (CH_{NXT}) by using different degree (θ).

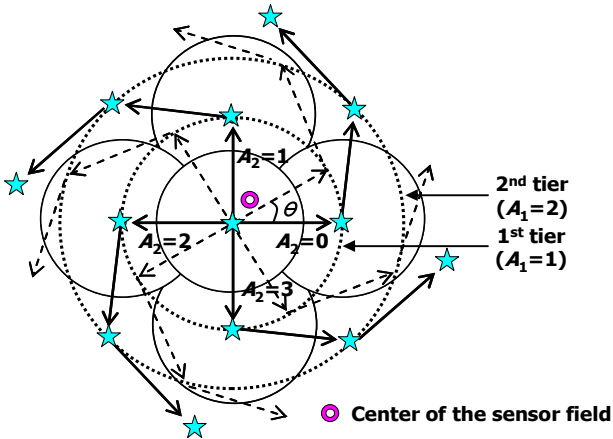


Figure 2. Approach of LBSC algorithm.

When a CH determines the CH_{NXT} , it is not possible that the CH selects CH_{NXT} directly due to the limited transmission range. In order to select CH_{NXT} and perform LBSC algorithm with four directions properly, we define a new type of node so-called decision node (DN) which is one of the neighbor

nodes of the current CH (CH_{CUR}). A DN is selected by its CH, and it will decide a new CH_{NXT} in order to expand the spiral clustering. While the CH_{FST} selects four DNs in order to make four new clusters, every other CH selects only one DN.

After successful cluster formation, each cluster is divided into each global group using proposed address and establish time schedule for concurrent intra-cluster transmission without inter-cluster packet collision. If the number of global groups is less than four, some of nodes are not contained in any cluster. However, if it is more than four, we need not only additional bits to distinguish each global group but also additional inter-cluster time schedule which can lead to packet transmission delay.

As shown in Fig. 3, in order to distinguish four global groups, LBSC algorithm uses three logical addresses as follows. The first address, denoted by A_1 , is initially set as 0 for the CH_{FST} and increases as a new cluster is generated in each spiral direction, in which A_1 represents clustering tier number from the center as shown in Fig. 2. The second address, denoted by A_2 , distinguishes the four different spiral directions. The combination of the A_1 and A_2 distinguishes the four global groups for avoiding the inter-cluster packet collisions. The third address, denoted by A_3 , is used for indexing each MN in a cluster. This address can be changed at every round by clustering procedure.

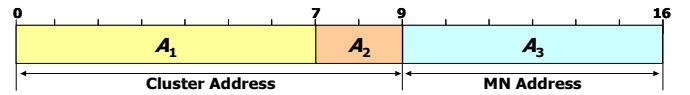


Figure 3. Proposed address distinguishes four global group.

In order to balance the energy consumption between the CHs (including CH_{FST}), the cluster range of the CH which is closer to the center should be smaller than the others. Thus, our proposed algorithm adaptively calculates the proper cluster range (CR) of each CH as follows:

$$CR_{A_1} = \min\{R, \alpha \times R + \beta \times A_1 \times R\} \quad (1)$$

where R represents the predefined maximum transmission range. α and β are scaling parameters. As a CH is departing from the center, its cluster range is increasing up to the maximum value.

In order to select proper CH, DN, and GW, we use NN_k as the set of neighbor nodes (NNs) of the node k and MN_k as the set of MNs of the node k . If a node is located within the CR from CH_{FST} , it becomes a MN of CH_{FST} . Note that $MN_{CH} \subset NN_{CH}$. In the following, the node that is nearest to a basis position BP among the node set S is derived as (2).

$$j^* = \arg \min_{j \in S} (\sqrt{(BP.x - j.x)^2 + (BP.y - j.y)^2}) \quad (2)$$

where j represents a node contained in set S ; $\{j.x, j.y\}$ represents the position of node j .

LBSC also establishes routing paths from all CHs to the sink during clustering. Each CH selects a GW node with the location information of the NN_{CH} , CH_{CUR} , and the sink. Each CH can select a GW node nearest to the sink using (2) where S is NN_{CH} and BP is the sink node position.

III. LOCATION BASED SPIRAL CLUSTERING (LBSC)

LBSC algorithm has the following network conditions. All nodes are fixed and have the same transmission range R . Each node knows the location information of its one hop NNs by using the localization algorithm. In order to prolong the network lifetime, rotating the role of CHs is basically handled by a predefined timer.

A. Time Scheduling

As shown in Fig. 4, in every round, the proposed clustering method is performed at first, and then data transmission and sleep mode are followed repeatedly.



Figure 4. Super frame structure.

As shown in Fig. 5 and Fig. 6, after node deployment, the closest node from the center of the sensor field announced by the sink node becomes the CH_{FST} . Then it selects the four DNs to determine the CH_{NXT} in four different directions. And each CH selects a DN simultaneously. This step will be performed recursively until all nodes are included in clusters.

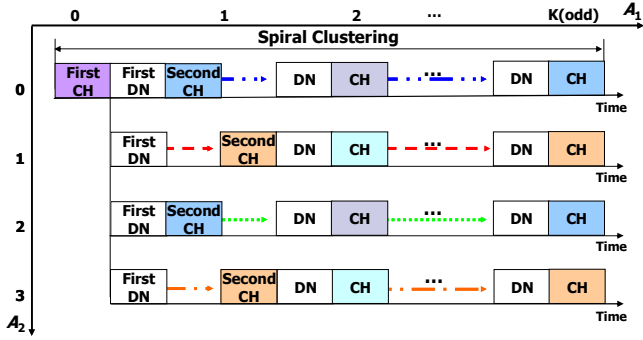


Figure 5. Location based spiral clustering algorithm.

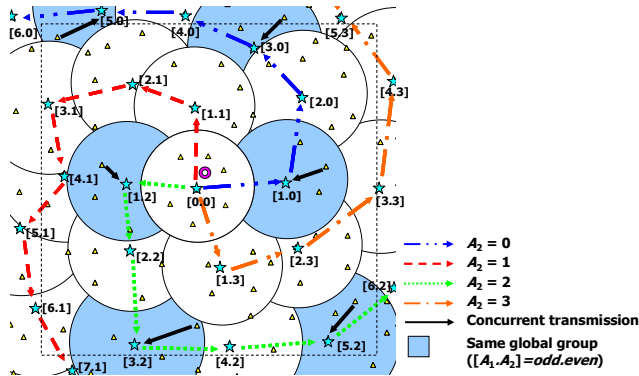


Figure 6. Location based spiral clustering algorithm.

After cluster formation, we can distinguish four global groups and establish time schedule for concurrent data transmissions based on cluster addresses denoted by $A_1.A_2=odd.odd$, $A_1.A_2=odd.even$, $A_1.A_2=even.odd$, and $A_1.A_2=even.even$ as shown in Fig. 6. Then clusters of the

same group can simultaneously transmit the data to the respective CHs without inter-cluster collisions. In Fig. 6 the shadowed clusters represent " $A_1.A_2=odd.even$ " group and they can use the same time interval for data transmission.

For sensing data transmission to the sink node, each node sends its data to the respective CH. Then the CH aggregates the data and sends it to the sink through GWs. Data transmission with inter-cluster coordination can be implemented as two different manners as shown in Fig. 7. First, the cluster time schedule is divided into four different time period for four global groups. Second, each global group uses different frequency channel for simultaneous data transmission. For both cases, the time period for single cluster is also partitioned to the mini slot assigned to each MN with address A_3 category.

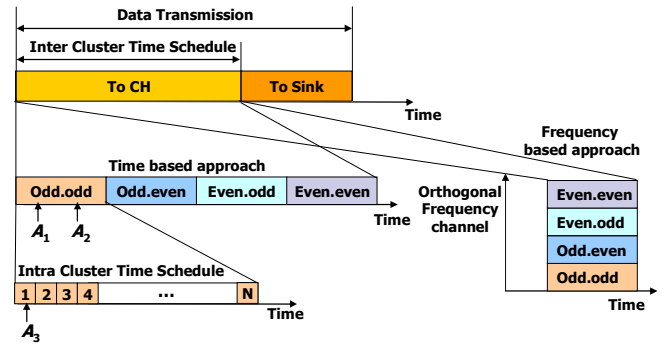


Figure 7. Data transmission with proposed address.

B. Step 1: Selection of the First Cluster Head

The CH_{FST} should be located around the center of the sensor field for successful cluster formation. At the beginning of the proposed clustering algorithm, the sink determines the center position of the sensor field, and then broadcasts a control message, which is carrying the center position and a predetermined range of the possible CH_{FST} from the center. If a node is inside the predetermined range of the center and it does not have any one hop neighbor that is closer to the center, then it will perform the role as the CH_{FST} after random back-off time. CH_{FST} can be replaced by its neighbors in every round for fair energy consumption.

C. Step 2: Selection of the First Tier Decision Nodes

The first work of CH_{FST} is to determine four DNs located in four different directions. CH_{FST} defines four coordinates, P_i ($i = 0, 1, 2, 3$), as the BP of each direction as follows:

$$\begin{aligned} P_i.x &= CH_{FST}.x + R \cos(90^\circ \cdot i + \theta) \\ P_i.y &= CH_{FST}.y + R \sin(90^\circ \cdot i + \theta) \\ \theta &= \omega \times \text{round} / C_{center} \end{aligned} \quad (3)$$

where C_{center} is the number of NNs within predetermined range from center of the sensor field. We can select different CH_{NXT} by using θ . In this paper, we use $\omega = 25^\circ$. Therefore, at each round, cluster selection base point is rotating by θ .

CH_{FST} can select the four DNs nearest to the respective P_i among its NNs as in (2) where S is $NN_{CH_{FST}}$ and BP is P_i . A_2 address of each selected DN follows the index i of each base position P_i as shown in Fig. 8.

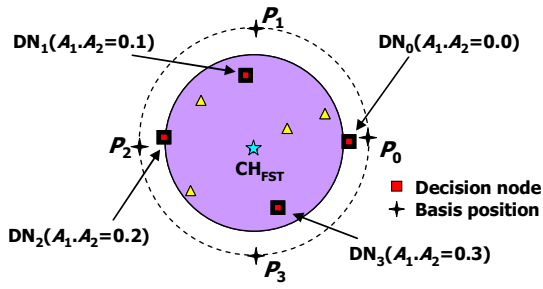


Figure 8. Method for selecting the first decision node.

D. Step 3: Selection of the Second Tier Cluster Heads

As shown in Fig. 9, in order to select the second tier cluster heads, CH_{SND} , in four directions, Each DN defines new coordinate, P_i ($i=0,1,2,3$), as the basis position for selecting second clusters.

$$\begin{aligned} P_i.x &= CH_{FST}.x + \frac{4}{3} CR_{A_1} \cos(90^\circ \cdot i + \theta) \\ P_i.y &= CH_{FST}.y + \frac{4}{3} CR_{A_1} \cos(90^\circ \cdot i + \theta) \end{aligned} \quad (4)$$

The reason of calculating P_i is to avoid a hole which includes certain nodes that are not contained in any cluster. Then DN can select the CH_{SND} nearest to the respective P_i among the set $S = NN_{DN} - MN_{CH_{FST}}$ as in (2). In order to avoid control packet collision, DNs with $A_2=0$ or 2 select CH_{SND} at first and then DNs with $A_2=1$ or 3 select CH_{SND} next as shown in Fig. 9.

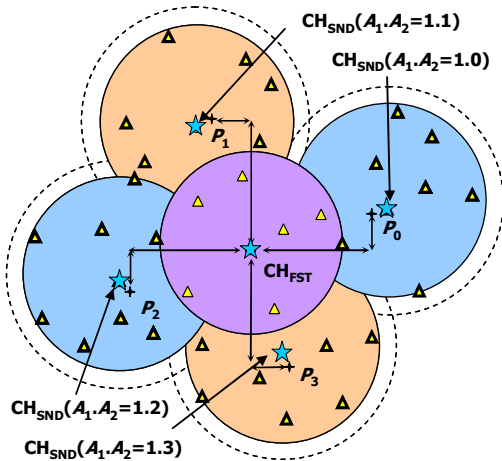


Figure 9. Method for selecting the first decision node.

E. Step 4: Selection of Decision Nodes for $A_1 > 0$

After selecting four CH_{SND} s, each CH_{SND} node concurrently repeats selecting DNs and CHs until no more nodes will be found in four direction. Method for selecting the DN is divided into two procedures as follow.

1) Calculating Intersection Points: As shown in Fig. 10, each CH_{CUR} can find two intersection points of the line that crosses the line between CH_{CUR} and CH_{FST} at a right angle and the transmission range circle from CH_{CUR} . Each CH can calculate two intersection points $\{(x_1, y_1), (x_2, y_2)\}$ by using a quadratic formula. Then select one point P from two

intersection points as in (5). The reason of calculating P is to select proper DN.

$$\begin{aligned} & \text{if } (CH_{CUR}.x > CH_{FST}.y) \\ & \quad \text{if } (y_1 - \text{slope}(x_1 - CH_{FST}.x) - CH_{FST}.y > 0) \\ & \quad \quad P.x = x_1, P.y = y_1 \\ & \quad \text{else } P.x = x_2, P.y = y_2 \\ & \text{else } \text{if } (y_1 - \text{slope}(x_1 - CH_{FST}.x) - CH_{FST}.y < 0) \\ & \quad \quad P.x = x_1, P.y = y_1 \\ & \quad \text{else } P.x = x_2, P.y = y_2 \end{aligned} \quad (5)$$

where slope is $(CH_{FST}.x - CH_{CUR}.x) / (CH_{FST}.y - CH_{CUR}.y)$.

2) Selecting Decision Nodes: As shown in Fig. 10, in order to select the DN, first CH_{CUR} constructs the S_{DN} (set of DN candidate nodes), in which to be a DN candidate node, any node N of $NN_{CH_{CUR}}$ should satisfy the following two conditions as in (6).

$$\begin{aligned} & \sqrt{(CH_{CUR}.x - N.x)^2 + (CH_{CUR}.y - N.y)^2} > \frac{1}{2} R \\ & \sqrt{(P.x - N.x)^2 + (P.y - N.y)^2} < R \end{aligned} \quad (6)$$

Then CH_{CUR} can select the DN nearest to the respective P among the set as in (2) where S is S_{DN} and BP is P . If selected DN does not find CH_{NXT} appropriately, it sends a message to the CH_{CUR} to select another DN except it.

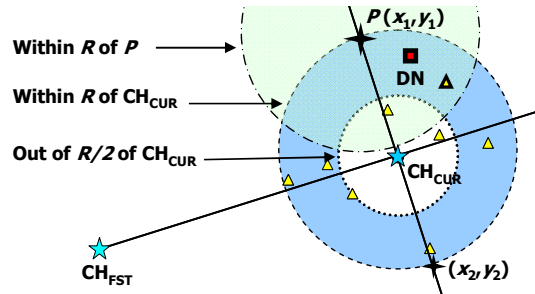


Figure 10. Method for selecting the first decision node.

F. Step 5: Selection of Cluster Heads for $A_1 > 1$

As shown in Fig. 11, the DN selects the CH_{NXT} with the location information of the NNs, CH_{CUR} , and CH_{FST} . In order to select the CH_{NXT} , DN constructs the set $S_{CH} = NN_{DN} - MN_{CH_{CUR}}$. Then DN can select the CH_{NXT} , which is the nearest node to the CH_{FST} among the nodes of S_{CH} using (2), in which S is S_{CH} and BP is CH_{FST} .

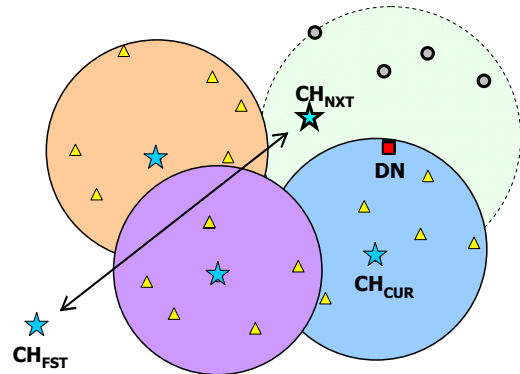


Figure 11. Method for selecting the decision node ($A_1 > 0$).

IV. SIMULATION RESULTS

In this section, we compare the performance of LBSC and LEACH throughout computer simulation. The specific parameters are summarized Table 1.

Table 1. Simulation Parameters

Parameter	Value
Field size	900m × 900m
Node type	Static node
Number of nodes	200
Transmission range of node (R)	150m
α, β	0.8, 0.05
ω	25°

Fig. 12 shows that every node in the sensor network is included in one of the clusters generated by LBSC algorithm. We can also see that all the clusters are successfully categorized into one of four global groups. Moreover, we can see that the LBSC algorithm is well formed in spiral directions by following the four colored arrows in Fig. 12. However, in case of LEACH, we can observe that a number of nodes were not able to join any cluster after clustering procedure as shown in Fig. 13.

The result of successful cluster formation using LBSC, each set of clusters are engaged in one of the four global groups as shown in Fig. 14. Thus each set of clusters engaged in a global group can concurrently perform the

packet transmission without inter-cluster packet collision using the inter-cluster time schedule.

In Fig. 15, we simulated relatively long time (100 rounds) to evaluate performance. In case of LEACH, we vary the expected number of clusters from 10 to 50. Note that in LEACH, the expected number of clusters should be set before sensor node deployment. Unlike LEACH, in LBSC appropriate numbers of clusters are automatically generated in accordance with node's transmission range. In Fig. 15-(a), the generated number of clusters in LBSC is about 30 for every round. However in LEACH, even though the expected number of clusters was set to 30, the actually generated clusters are about 40 because LEACH algorithm requires the cluster re-forming procedure for the nodes that fail to participate in any cluster as shown in Fig. 15-(b). It represents that LEACH requires additional packet exchanges, and thus may have the lengthy network-wide clustering latency. Fig. 15-(c) shows the required inter-cluster time slot separations (or the required frequency channels) to avoid inter cluster collisions. LBSC always needs four inter-cluster time slots whereas LEACH needs much more time slots. Moreover, in LEACH to avoid inter cluster collisions, neighboring CHs need to negotiate their time slots. LEACH requires complex computation work to guarantee that in the entire sensor network there is no inter cluster collision. LBSC generally has the stable number of nodes in a cluster than that of LEACH as shown in Fig. 15-(d).

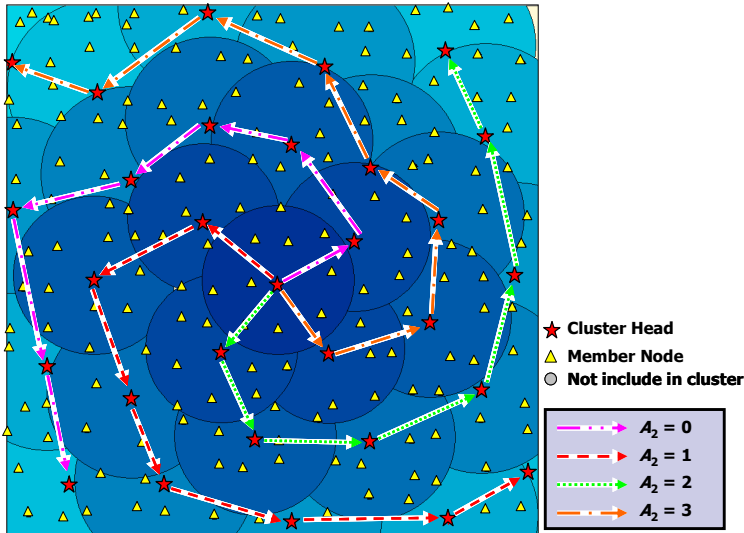


Figure 12. After cluster formation using LBSC.

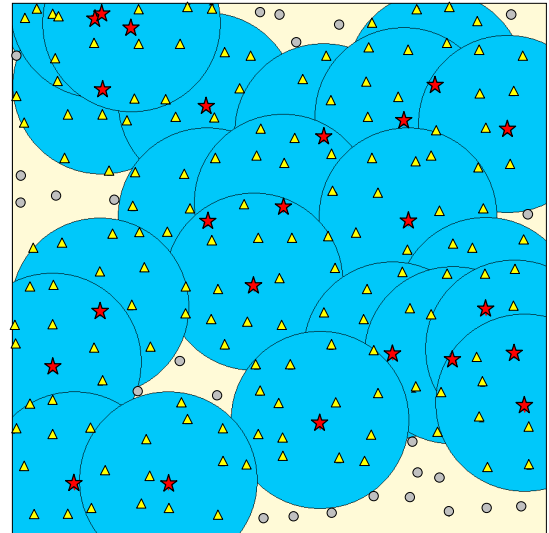


Figure 13. After cluster formation using LEACH.

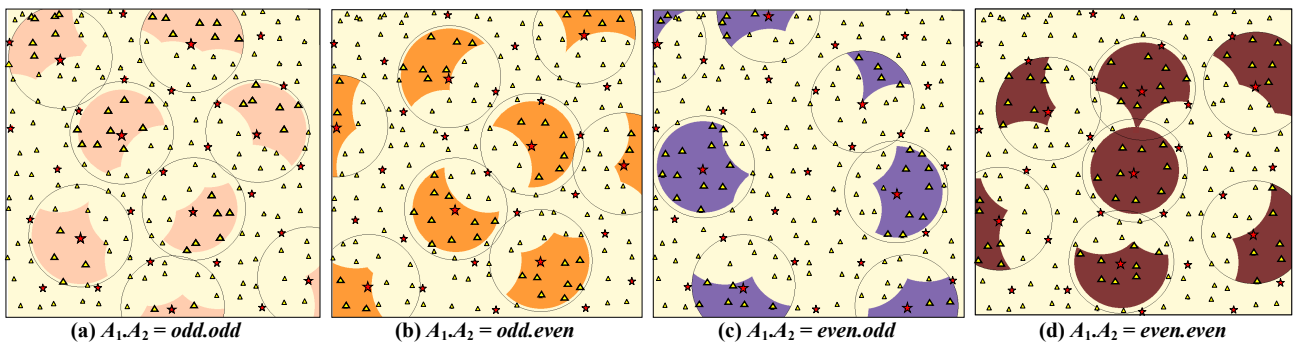


Figure 14. Concurrently perform the packet transmission without inter-cluster packet collision.

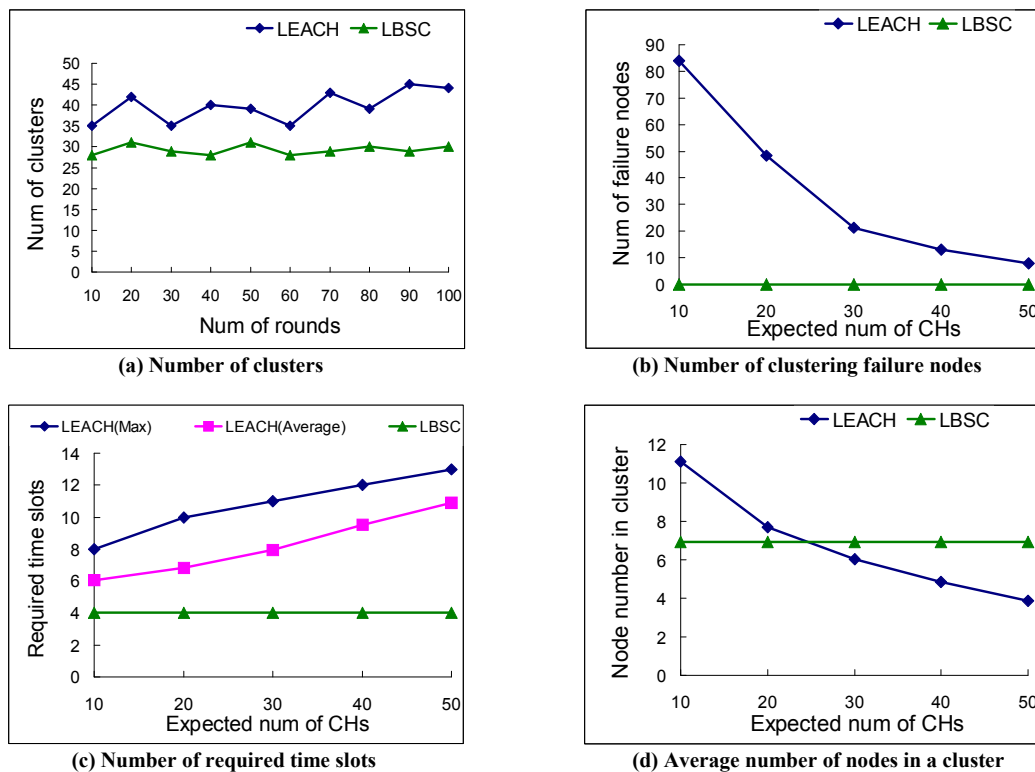


Figure 15. Performance comparison with LEACH.

V. CONCLUSIONS

In this paper, we proposed a location-based spiral clustering algorithm which assures that all nodes are included in clusters without control packet collisions during the cluster formation period. It also provides the routing path from CHs to the sink. We categorize all generated clusters into the four global groups and establish time schedule by using three logical addresses. Clusters belonging to the same global groups can share the same time schedule so that we can increase network throughput and avoid data packet collisions. Simulation results show that each global group concurrently transmits data from MN to respective CH without inter-cluster collisions using four inter-cluster time schedule.

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