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Energy-efficient mobile cluster-head data collection model for wireless sensor networks

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Abstract: Wireless sensor networks have grown from homogeneous network architecture to heterogeneous networks for the improvement of network efficiency and lifetime. This paper exhibits a mobile cluster-head data collection (MCHDC) model for heterogeneous wireless networks. The MCHDC model illustrates the mobility pattern of mobile cluster-head nodes in a controlled environment with uniform and nonuniform deployment of mobile elements in the area of observation. It focuses on the threshold velocity for movement of mobile elements in the network area. In this paper the effects of data sending rate, network area, sensor node density, and cluster-head node density on energy efficiency of the network with the MCHDC model have been studied through simulations.

Key words: Data sending rate, energy consumption, mobile cluster-head, mobile element, network area, sensor node density

1. Introduction

Wireless sensor networks (WSNs) have become an integral technology that can support the capabilities to monitor and interact with physical parameters, e.g., humidity, temperature, pollution, and pressure. A traditional WSN consists of battery-powered static sensor nodes and a static sink or base station [1]. The static sensors sense the data from the area of observation and send it to the sink node either single-hop or multihop. Because of the limited capabilities of sensor nodes, highly data-intensive applications are difficult to achieve. To enhance the capabilities and performance of a WSN, several techniques have been proposed in the literature, including data clustering [2], data aggregation [3], data fusion [4], heterogeneous architecture [5], and mobility of a few devices [6]. Data clustering, data aggregation, and data fusion help in collecting, compressing, and fusing the correlated data from the sensor nodes before disseminating them to the sink node. Heterogeneous network architecture can be used to reduce the energy consumption of sensor nodes by deploying powerful sensors with more energy capacity and stronger communication ranges [7]. The mobility of a few nodes can be helpful to relay the data sensed by sensor nodes to the sink node with fewer hops. This paper investigates and evaluates the performance of data collection with a mobile cluster-head within a cluster area.

This paper focuses on mobile cluster-head data collection (MCHDC) in WSNs. So far many mobile relay models have been developed and investigated in the literature. These models can be classified according to their objectives and goals as: a) for better connectivity, b) to reduce average packet delay, c) to improve data

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collection, and d) to reduce energy consumption of a WSN. Though all the objectives are equally important, the focus of this paper is on the fourth objective, i.e. energy efficiency of a WSN.

In the remainder of this paper, existing models and the proposed MCHDC model are discussed in Section 2. In Section 3, settings, methodology, and result analysis are discussed for the simulations conducted in this work. Finally, the last section concludes the paper with future works.

2. Data collection models

This section consists of two parts. The first part briefly explains the existing data collection models that are discussed in the literature. The second part explains the proposed MCHDC model in detail with uniform and nonuniform deployment of the cluster-head nodes.

2.1. Existing data collection models

Different types of mobility models have been proposed in the literature. These mobility models have been categorized into three types: mobile sensor nodes [7], mobile sink nodes [8–11], and mobile relay nodes [12–18]. The first category is the mobile sensor node, which is enabled to sense any physical parameter in the area of observation during mobility. The second category is the mobile sink nodes, which are the final destination nodes in the wireless sensor networks. The past literature shows that the mobile sink nodes can cover the area of observation in a better way than static sink nodes [11]. The third and last category of mobility models consists of mobile relay nodes. The relay nodes are the intermediate nodes of a three-tier wireless sensor network, which can collect, store, and forward the collected data from the sensor nodes to the sink node. Many mobile relay node-related models have been proposed and investigated in the past literature. According to the literature, existing mobile relay node models have three aspects: number of mobile relay nodes, mobility pattern of mobile relay nodes, and how the data are being routed [19]. A WSN having a three-tier structure, i.e. sensor nodes, sink nodes, and relay nodes, can be further categorized according to the number of relay nodes in the network. A WSN can have either one relay node or many relay nodes in the network. It was proposed to have only one mobile relay node in a WSN [14–16], but the recent literature favored multiple mobile relay nodes [12–13,17,18]. For efficient data collection by mobile relay nodes, these models can have intermediate cache nodes, which can store the data collected from the static sensor nodes [12–14].

The mobility of the nodes, i.e. sensors, sink, or relay, can be controlled or uncontrolled. The relay node with controlled mobility moves with a chosen mobility pattern in the area of observation, whereas the relay nodes with uncontrolled mobility may follow any mobility pattern for their movement in the area of observation. Controlled mobility can improve the performance of wireless sensor networks in terms of energy consumption and packet delay [9].

2.2. Proposed MCHDC model

The proposed MCHDC model consists of one static sink that is placed outside the area of observation, a number of static sensor nodes, and a few mobile cluster-head nodes. The sensor nodes are grouped into clusters according to the number of cluster-head nodes in the WSN. The clustering process is carried out by VAS clustering [20] and the data filtering process is carried out by the MTWSW data filtering approach [21] for filtering the redundant and useless data in this WSN.

The proposed MCHDC model is tested for two scenarios, i.e. for uniformly deployed cluster-head nodes and nonuniformly deployed cluster-head nodes, respectively. In this model, one mobile cluster-head node is assigned for each cluster. Each cluster-head is placed at the optimized point, i.e. the head point (HP), which is the centroid of the cluster. Every cluster is further divided into different areas and the data point is the centroid of that area. The uniformly deployed cluster-head nodes are represented in Figures 1 and 2, whereas Figures 3 and 4 represent the nonuniformly deployed cluster-head nodes. Initially cluster-head nodes are placed at HPs. The data dissemination starts with sensor nodes sending data to cluster-head nodes placed at the HP. When a cluster-head node experiences less collection of data, then it starts moving between data points with a constant velocity υ and time τ within the designated cluster.

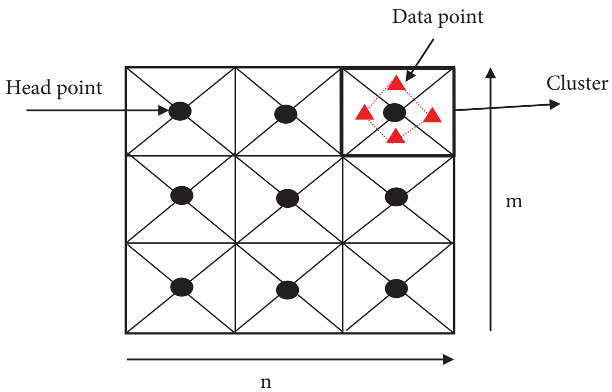

Figure 1. Uniform deployment of $(m \times n)$ cluster-head nodes.

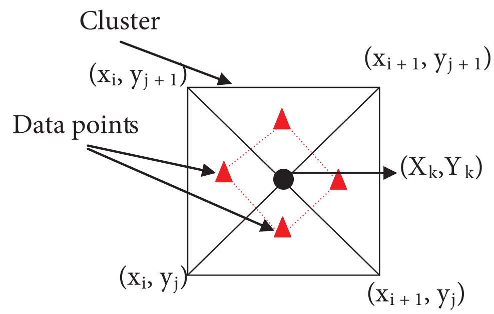

Figure 2. Single cluster in uniformly deployed cluster-head nodes.

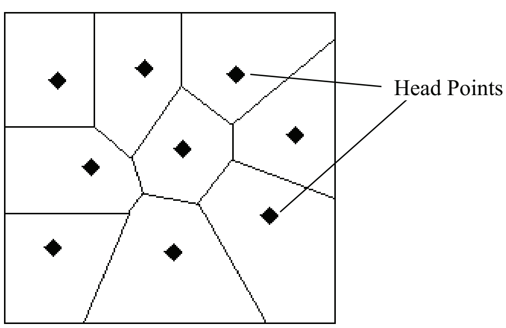

Figure 3. Nonuniform deployment of cluster-head nodes with head points.

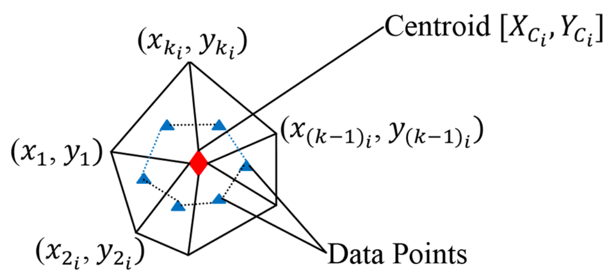

Figure 4. Single cluster in nonuniformly deployed cluster-head node.

The cluster-head node in the MCHDC model has three states, the traveling state, waiting state, and data dissemination state. In the traveling state, the mobile cluster-head is traveling from one data point to another data point within a cluster. In waiting state W_t, the mobile cluster-head stops and waits for data collection at one data point. In data dissemination state D_t, the mobile cluster-head disseminates data to the sink node in a single hop or multiple hops.

In the proposed MCHDC model, both schemes, i.e. for uniformly deployed cluster-head nodes and for nonuniformly deployed cluster-head nodes, are discussed as follows.

Uniformly deployed cluster-head nodes

In this scheme, the cluster-head nodes are uniformly distributed in the area of observation. Every cluster-head node is responsible for the same-sized cluster areas as shown in Figure 1. Consider an area of observation having n number of clusters in x direction, each having unit length in the x direction and m number of clusters in the y direction, each having unit length in the y direction as shown in Figure 1. Therefore, the number of clusters in the area of observation is (m *times* n). Now consider the kth cluster having coordinates as shown in Figure 2:

$$(x_i, y_j), (x_{i+1}, y_j), (x_i, y_{j+1}), (x_{i+1}, y_{j+1})$$

where 0 ≤ i ≤ n − 1, 0 ≤ j ≤ m − 1, and 1 ≤ k ≤ n *times* m.

The centroid of the kth cluster is (X_k, Y_k).

$$X_k = \frac{x_i + x_{i+1}}{2} \tag{1}$$

$$Y_k = \frac{y_i + y_{i+1}}{2} \tag{2}$$

Then divide the whole kth cluster into four triangles having coordinates as follows:

$$\text{Triangle 1: } (x_i, y_j), (x_i, y_{j+1}), (X_k, Y_k) \tag{3}$$

$$\text{Triangle 2: } (x_i, y_{j+1}), (X_k, Y_k), (x_{i+1}, y_{j+1}) \tag{4}$$

$$\text{Triangle 3: } (X_k, Y_k), (x_{i+1}, y_{j+1}), (x_{i+1}, y_j) \tag{5}$$

$$\text{Triangle 4: } (x_i, y_j), (X_k, Y_k), (x_{i+1}, y_j) \tag{6}$$

Now find the centroid of each triangle as follows:

Centroid of all the four triangles, i.e. data points:

$$(x_{1_k}, y_{1_k}) = \left[\frac{2x_i + X_k}{3}, Y_k\right] \tag{7}$$

$$(x_{2_k}, y_{2_k}) = \left[X_k, \frac{2y_{i+1} + Y_k}{3}\right] \tag{8}$$

$$(x_{3_k}, y_{3_k}) = \left[\frac{2x_{i+1} + X_k}{3}, Y_k\right] \tag{9}$$

$$(x_{4_k}, y_{4_k}) = \left[X_k, \frac{2y_i + Y_k}{3}\right] \tag{10}$$

Distance moved by mobile cluster-head node D is as follows:

$$D = 2 * \left[\sqrt{[x_{1_k} - x_{2_k}]^2 + [y_{1_k} - y_{2_k}]^2} + \sqrt{[x_{2_k} - x_{3_k}]^2 + [y_{2_k} - y_{3_k}]^2}\right] \tag{11}$$

Nonuniformly deployed cluster-head nodes

In this scheme, the cluster-head nodes are nonuniformly distributed in the area of observation. The area under every cluster-head node may vary and therefore every cluster-head node is responsible for its respective cluster area as shown in the Figure 3. Consider an area of observation having n number of cluster-head nodes 1 $\leq$ i $\leq$ n as shown in Figure 3. Consider the ith cluster having k number of edges as shown in Figure 4 having the following coordinates:

$$[x_{1_i} y_{1_i}],[x_{2_i} y_{2_i}],[x_{3_i} y_{31_i}],\ldots,[x_{k_i} y_{k_i}]$$

The centroid of a cluster is: $[X_{Ci}, Y_{Ci}]$.

$$X_{Ci} = \frac{x_{1_i}+x_{2_i}+x_{3_i}+\ldots.+x_{k_i}}{k} \tag{12}$$

$$Y_{Ci} = \frac{y_{1_i}+y_{2_i}+y_{3_i}+\ldots.+y_{k_i}}{k} \tag{13}$$

For clusters having k number of edges, k triangles will be formed having one edge as a centroid and two edges as two adjacent edges of the cluster. Then the coordinates of the centroid of any triangle will be:

$$X_{T_{1_i}} = \frac{x_{1_i}+x_{2_i}+X_{C_i}}{3} \tag{14}$$

$$Y_{T_{1_i}} = \frac{y_{1_i}+y_{2_i}+Y_{C_i}}{3} \tag{15}$$

where $T_1 \leq T_i \leq T_k$.

Hence, the coordinates of the last triangle are:

$$X_{T_{k_i}} = \frac{x_{k_i}+x_{1_i}+X_{C_i}}{3} \tag{16}$$

$$Y_{T_{k_i}} = \frac{y_{k_i}+y_{1_i}+Y_{C_i}}{3} \tag{17}$$

Therefore, there are k number of lines joining the centroid of each triangle and the total distance travelled by the cluster-head node between the centroid of k triangles is:

$$D = \left[\sqrt{[x_{T_{1_i}}-x_{T_{2_i}}]^2+[y_{T_{1_i}}-y_{T_{2_i}}]^2}+\sqrt{[x_{T_{2_i}}-x_{T_{3_i}}]^2+[y_{T_{2_i}}-y_{T_{3_i}}]^2}+\ldots.+\sqrt{[x_{T_{k_i}}-x_{T_{1_i}}]^2+[y_{T_{k_i}}-y_{T_{1_i}}]^2}\right] \tag{18}$$

The time period for both the schemes, uniformly deployed cluster-head nodes and nonuniformly deployed cluster-head nodes, is calculated in the same way as shown in Eq. (19).

$$\tau = \frac{TotalDistance(D)}{Velocity(\upsilon)} \tag{19}$$

Therefore, it can be observed from Eq. (19) that the time period varies with varying velocity of the mobile cluster-head node from one data point to another data point within the cluster. Based on the proposed MCHDC model with uniform and nonuniform deployment, the energy efficiency of WSN has been investigated. To verify the proposed model, extensive simulations have been conducted for the result validation.

3. Simulation results

In this section, simulation results of the proposed MCHDC model are discussed. This section consists of three parts. In the first part, simulation settings for the proposed model are stated, the second part explains the methodology used in the proposed model, and the last part explains the results of the simulations conducted by the proposed MCHDC model.

3.1. Settings

QualNet version 6.1 has been used to conduct the network simulations. In these simulations, 100 homogeneous sensor nodes and 9 cluster-head nodes with unlimited battery energy [14] are placed in an area of 100 *times* 100) m^2. A stationary sink node (BSN) is placed outside the area of observation with unlimited energy. The power parameters used for the simulations are MicaZ, ZigBee application with 127 bytes packet size, IEEE 802.15.4 standard at the MAC and physical layer, linear battery model (1200 mAh) for sensor nodes, and two-ray signal propagation model. The values of both W_t and D_t were set as 30 s and the traveling state is varied with the varying velocity as shown in Eq. (19).

3.2. Methodology

The proposed MCHDC model with controlled mobility in uniformly or nonuniformly deployed cluster-head nodes follows three steps. In the first step, the VAS algorithm was used for clustering and routing data from static sensor nodes to mobile cluster-head nodes. In the second step, the MTWSW data filtering approach has been used so that redundant data can be discarded at the source nodes. In the last step, the proposed MCHDC model has been applied for mobility of cluster-head nodes within the designated cluster area with uniform velocity. The cluster-head node moves with velocity υ in time period τ within the designated cluster from one data point to another data point.

It is important to find out the optimum velocity with which cluster-head nodes can move in their respective clusters, which is called the threshold velocity. If the speed of the cluster-head node is lower than the threshold velocity, it may lead to loss of data packets at the source nodes because of packet time out. If the speed of the cluster-head nodes increases from the threshold velocity, it may also lead to loss of data packets because high-speed cluster-head nodes may ignore many data packets during mobility [14].

Hence, to find out the threshold velocity for this scenario, simulations were conducted with the settings above. The velocity of the cluster-head nodes was varied from 0.5 m/s to 3 m/s with an increment of 0.5 m/s. The proposed MCHDC model has been evaluated with different velocities on the basis of energy consumption. The effects of data sending rate, network size, and sensor node density have been analyzed on energy consumption of the WSN having cluster-head nodes with different velocities. Figures 5, 6, and 7 illustrate the effect of data sending rate, network size, and sensor node density on energy consumption, respectively.

As observed in Figures 5, 6, and 7, the velocity of the cluster-head node at 2 m/s proved to be more energy-efficient in terms of number of data packets sent per second, network area, and number of sensor nodes in the field of observation. Therefore, the velocity of the mobile cluster-head was set to be 2 m/s for the rest of the simulations.

3.3. Result analysis

For given WSN settings with specified W_t, D_t, and υ, 20 randomly generated topologies were simulated. To achieve the minimum energy consumption of the WSN, velocity υ was set to be 2 m/s. Figure 8 shows the

MCHDC model with both the uniformly placed and nonuniformly placed cluster-head nodes. The proposed data collection model has been compared with a random mobility model (random way-point) and horizontal mobility model (line) on the basis of energy consumption. The effect of data sending rate, network size, number of sensor nodes, and number of cluster-head nodes has been shown in Figure 8.

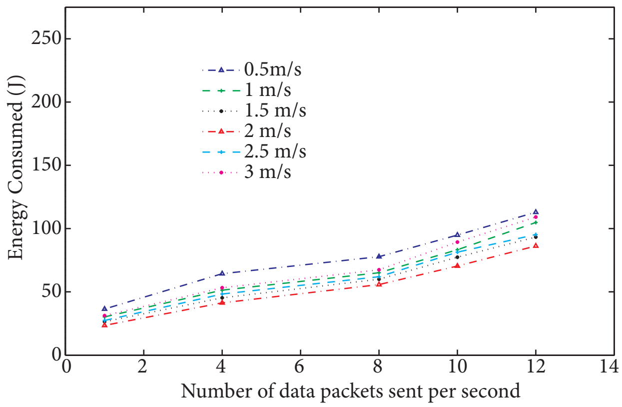

Figure 5. Effect of data sending rate on energy consumption with varying velocities.

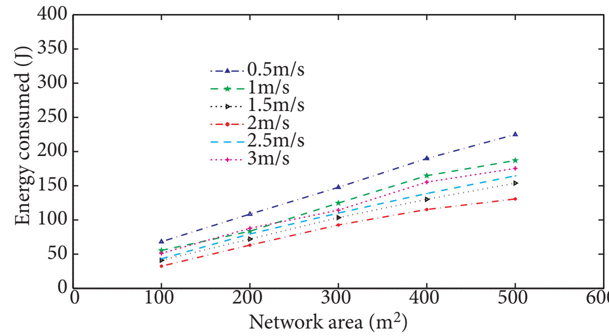

Figure 6. Effect of network size on energy consumption with varying velocities.

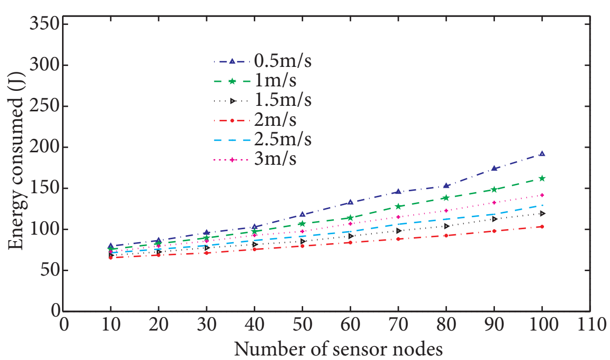

Figure 7. Effect of sensor node density on energy consumption with varying velocities.

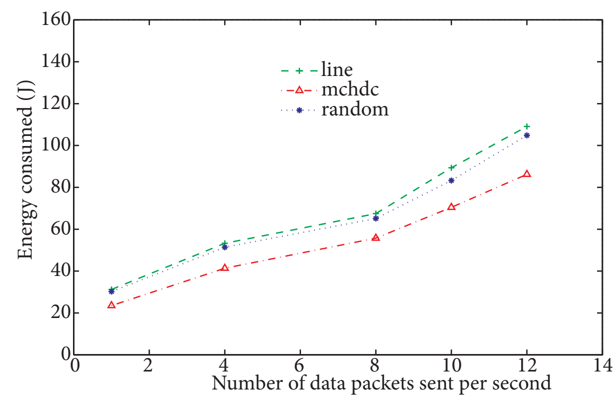

Figure 8. Effect of data sending rate on energy consumption in uniform deployment.

3.3.1. Effect of number of data packets sent per second on energy consumption

The data sending rate, i.e. number of data packets sent per second, has been varied from 1 packet to 12 packets per second. With an increase in number of packets sent per second, the network load and congestion increase. This section shows the effect of data sending rate on the energy consumption of the WSN.

It is observed from Figures 8 and 9 that the MCHDC model shows better performance in both the scenarios, i.e. with uniform and nonuniform deployment of cluster-head nodes. However, the MCHDC model with uniformly placed cluster-head nodes has more advantages because of better coverage in terms of load sharing by every cluster-head node. The MCHDC model saves approximately 18% to 26% of the energy with uniformly deployed cluster-head nodes and saves 22% to 39% of the energy with nonuniformly deployed cluster-head nodes as compared to the horizontal line model and random mobility model, respectively. Hence, the MCHDC model proves to be an energy-efficient mobility model for wireless sensor networks.

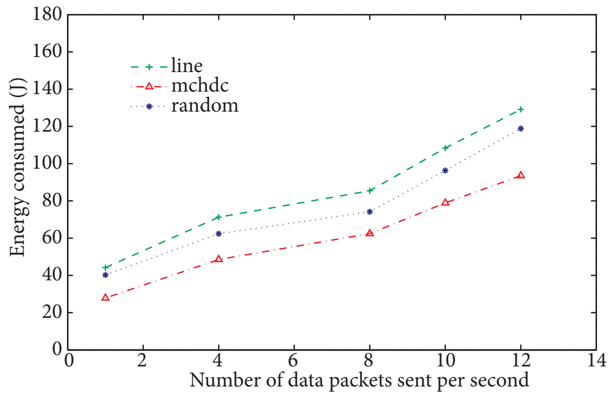

Figure 9. Effect of data sending rate on energy consumption in nonuniform deployment.

3.3.2. Effect of network size on energy consumption

The network area for the basic scenario has been kept at 100 *times* 100 m^2. The network size has been varied from 100 *times* 100 m^2 to 500 *times* 500 m^2. Variation in size has much impact on the network performance because by increasing the area under observation, node density becomes low. The effect of network size on energy consumption is shown in Figures 10 and 11. In the MCHDC model, each cluster has many data points, i.e. centroids of subparts of a cluster. The cluster-head nodes move from one centroid to another centroid in every cluster and are hence capable of covering the whole cluster area in an efficient way.

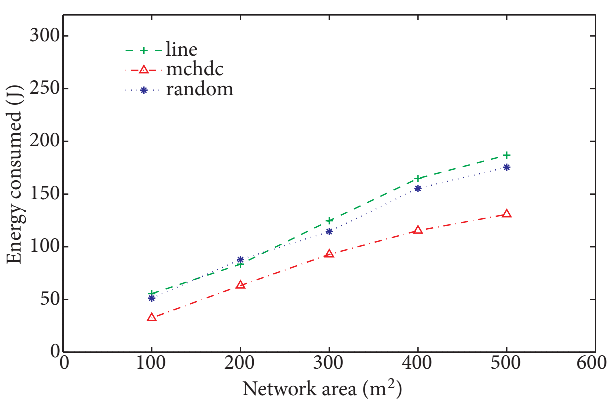

Figure 10. Effect of network size on energy consumption in uniform deployment.

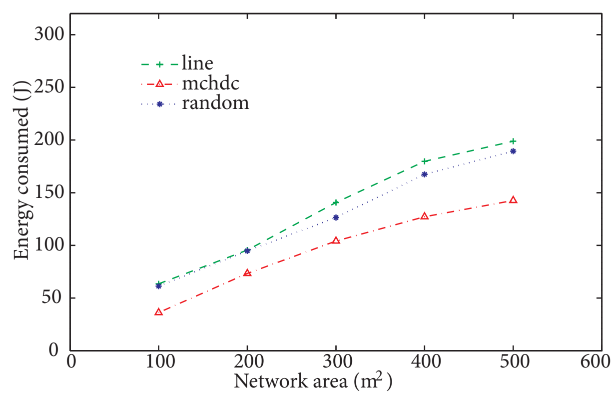

Figure 11. Effect of network size on energy consumption in nonuniform deployment.

The rate of energy consumption with the MCHDC model in both the scenarios is almost the same but the MCHDC model with uniformly deployed cluster-head nodes consumed less energy as compared to the MCHDC model with nonuniformly deployed cluster-head nodes. To support our argument, it can be observed from Figures 10 and 11 that the MCHDC model saves approximately 26% to 42% of the energy with uniformly deployed cluster-head nodes and saves 25% to 43% of the energy with nonuniformly deployed cluster-head nodes as compared to the random mobility and horizontal line mobility model. Hence, the MCHDC model proves to be an energy-efficient mobility model with varying network area.

3.3.3. Effect of sensor node density on energy consumption

The number of sensor nodes is kept as 100 for the basic scenario. In this section, the number of sensor nodes is varied from 10 to 100 with an increase of 10 sensor nodes every time. The size of the network increases by increasing the number of sensor nodes and hence it impacts the network performance. The MCHDC model works well even in sparse networks because of the well-distributed cluster area into data points. The data collection at the data points is more likely as compared to other mobility models because of adequate division of the cluster area.

The effect of sensor node density on energy consumption can be seen in Figures 12 and 13. It can be seen from Figures 12 and 13 that the MCHDC model is able to save approximately 10% to 37% of the energy with uniformly deployed cluster-head nodes and 10% to 22% of the energy with nonuniformly deployed cluster-head nodes as compared to the random mobility model and horizontal line mobility model, respectively. Hence, the MCHDC model is an energy-efficient mobility model as compared to the random mobility model and horizontal line mobility model.

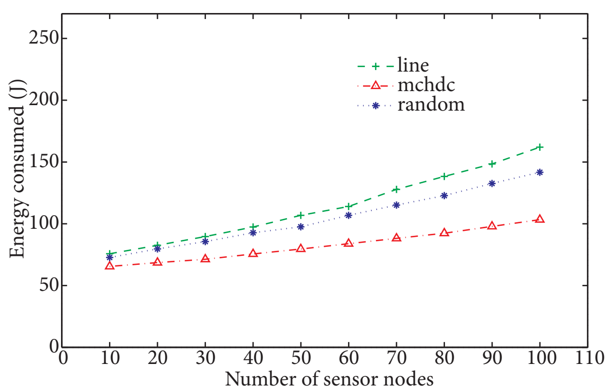

Figure 12. Effect of sensor node density on energy consumption in uniform deployment.

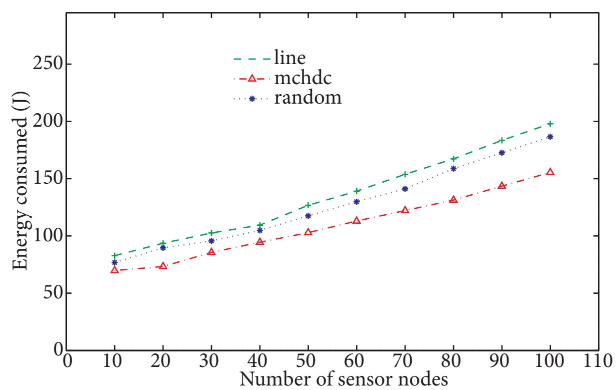

Figure 13. Effect of sensor node density on energy consumption in nonuniform deployment.

3.3.4. Effect of cluster-head node density on energy consumption

The number of cluster-head nodes is kept as 9 for the basic scenario. In this section, numbers of cluster-head nodes are varied to 1, 2, 4, 6, 8, and 9. Increase in number of cluster-head nodes increases the number of clusters in the network and hence decreases the cluster size. Small-sized clusters can do better clustering and improve the network performance. The MCHDC model works well with more clusters because the area under each cluster can be managed and monitored in a better way. For this scenario, the MCHDC model's performance is constant after 6 cluster-head nodes. Hence, the optimum number of cluster-head nodes in this scenario is 6 for uniformly and nonuniformly deployed cluster-head nodes.

It can be seen from Figures 14 and 15 that the performance of the MCHDC model has increased until the threshold value, i.e. 6 cluster-head nodes. If the numbers of cluster-head nodes are increased more than the threshold value, the performance is constant. It can be further observed from Figures 14 and 15 that the MCHDC model is able to save approximately 9% to 17% of the energy with uniformly deployed cluster-head nodes and 10% to 18% of the energy with nonuniformly deployed cluster-head nodes as compared to the random mobility model as well as the horizontal line mobility model. Hence, the MCHDC model turns out to be better mobility model as compared to the random and horizontal line mobility models.

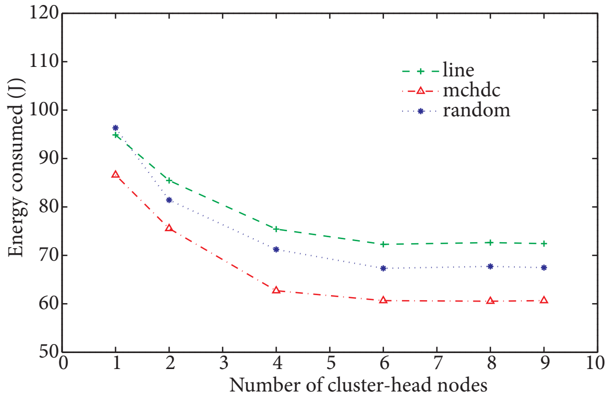

Figure 14. Effect of cluster-head node density on energy consumption in uniform deployment.

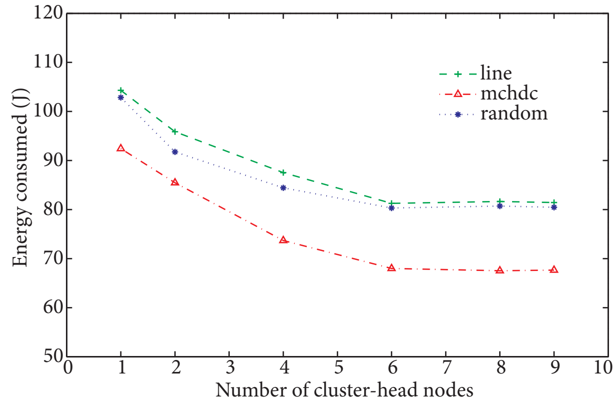

Figure 15. Effect of cluster-head node density on energy consumption in nonuniform deployment.

4. Conclusions

In this paper, a novel mobile cluster-head data collection model has been proposed to investigate the effect of mobility within the clustered area of observation. Multiple clusters with cluster-head nodes have been considered, which can move within the cluster with controlled mobility. This model has been extensively compared with the random mobility model and horizontal line mobility model. The simulation results have been shown by varying various parameters like data sending rate, network size, sensor node density, and cluster-head node density. The effects of these parameters have been analyzed on energy consumption of the WSN. Based on the simulation results, it is verified that the proposed mobility model, the MCHDC model, performs better than the random mobility model and horizontal line mobility model for uniform as well as nonuniform deployment of cluster-head nodes. Further research in this area can offer promising results. It can be compared with other mobility models, as well. The security aspects can also be worked on in the future research.

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