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A Low-Energy Clustering Protocol for WSN-based Smart City

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Abstract

In building smart cities, wireless sensor networks have been widely used to sense the basic information of cities. Wireless sensor networks may be deployed in various areas, and they may not be able to replace the sensor batteries in most cases, so it is necessary to adopt energy-saving techniques to prolong the lifetime of the network. Currently, clustering protocols have become the most effective energy-saving technique in WSNs. However in the above protocol, the cluster head takes more responsibilities compared to other nodes, and thus, how to balance the energy consumption among nodes is a tough problem. The popular method is regular global clustering, which consumes too much energy, and also leads to limited energy efficiency of the network. In this paper, we propose a Low-Energy Clustering (LEC) protocol for WSN-based smart city. In the proposed protocol, we first introduce an algorithm that can partition the large-scale wireless sensor network into a number of small-size sub-networks. Moreover, in each sub-network, we propose a node clustering clustering scheme and data collection algorithm based on node heterogeneity. According to the simulation results, the performance of our proposed LEC protocol is greatly superior to other latest representative protocol.

Keywords

Wireless Sensor Network; Smart City; Energy Efficiency; Clustering Protocol.

1. Introduction

With the development of information technology, smart cities have become an important method for city management. As one of the core components of smart city, the wireless sensor network has taken the responsibility to collect and process a variety of basic information about the city so as to improve the city management efficiency [1-2].

The nodes in WSN-based smart cities are huge and need to work as long as possible, thus, how to effectively manage and utilize the energy of the nodes to improve the lifetime of the network is an important direction in the research of WSNs. Among the various energy-saving methods [3-6] that have been proposed, the clustering protocol [7-10] is one of the widely used and effective methods. The clustering protocol divides the nodes in the network into several clusters, and each cluster is responsible for data collection and forwarding by a cluster head. Through clustering protocol, the number of data transmissions and distance can be effectively reduced, thus reducing the energy consumption of nodes.

In clustering protocol, the cluster head takes more responsibilities as compared to other nodes because it has to collect data from all the nodes in the local cluster as well as inter-cluster communication. In order to keep the energy load of all the nodes in the network balanced, researchers proposed periodic global clustering, but each global clustering in the above method generates excessive energy consumption, which results in low energy efficiency of the network.

In this paper, We take advantage of the high density of base stations to propose a Low-Energy Clustering (LEC) protocol. In the proposed protocol, the huge number of nodes in the entire network are firstly divided into different sub-networks. Then, in each sub-network, clusters are formed based on the heterogeneity of nodes. To resolve the unbalanced energy loads among clusters, we raise an inter-cluster node reassignment scheme. The simulation results show that the LEC protocol has superior performance than other latest representative protocol.

2. Related Works

In the clustering protocols, one node is selected as the cluster head to aggregate the data from all the nodes in the local cluster and send them to the base station, and thus, the cluster head is prone to die early. To balance the energy consumption rate of nodes in the network, in LEACH protocol [7], the cluster head role rotates between nodes based on the probability at each round. Considering the blindness of selecting a cluster head, HEED [8] takes the nodes‘ residual energy into consideration when choosing a cluster head.

In LEACH-C protocol [7], each node sends the node’s status information to the base station, and the base station selects the cluster bead according to the residual energy level and position at each round. BCDCP [9] also utilizes a similar scheme to improve the efficiency of reclustering process.

The above node clustering in the whole network at every round generates much network traffic which makes such protocols not scalable. In order to reduce energy consumption and improve protocol scalability, the method of rotating the cluster head among the nodes in the local cluster is proposed. In GAFOR [10] protocol, researchers employ fuzzy logic to obtain the basic information of the network and use a genetic algorithm to decide when to execute the next global node reclustering.

In FSC [11], the nodes in the network are partitioned into several layers, and the cluster heads are first rotated among the nodes in the same cluster, when no node can take the role of cluster head, and then, node reclustering is incurred in the same layer instead of the whole network.

Based on the above analysis, we find that the existing research tries to reduce the frequency of global reclustering with various methods so as to improve the energy efficiency of the network. Since the global reclustering is not removed, the improvement of energy efficiency is limited. In this paper, we first divide nodes in the WSN-based smart city into each sub-network in order to avoid designing complex protocols for large-scale networks, and then, we introduce an effective node reassignment scheme to balance the residual energy among clusters in each sub-network, and the energy consumption is greatly reduced compared with global clustering.

3. The Proposed LEC Protocol

We have made some reasonable assumptions about the nodes the base stations in the network, which are as follows: (1) the nodes are stationary after they have been deployed, and each node can obtain its location information by GPS or other positioning modules; (2) the base stations have unlimited energy resources, and also have high computing resources.

The operation of LEC protocol can be divided into two phases: sub-network formation phase, sub-cluster formation phase, and sensor data retrieval phase. In the sub-network formation phase, the nodes and the base stations in the WSN-based smart city are assigned to different sub-networks according to the distances between them. Then, in the sub-cluster formation phase, the nodes are divided into a number of sub-clusters based on the distances between nodes and the node heterogeneity. In the sensor data retrieval phase, each sub-cluster head collects the data from the local sub-cluster and then sends them to the nearby base station directly. When the total energy difference of the remaining nodes between clusters exceeds the specified threshold, the inter-cluster node reassignment is launched to balance the remaining energy of nodes among clusters.

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3.1 Sub-network Formation Algorithm

It is very difficult to design complex and efficient protocols for large-scale networks, and thus, we first partition the entire network into several small-size sub-networks. Along with the popularity of 5G technology, 5G base stations have been gradually deployed in smart cities. In 5G network, the distance between base stations is about 300-1000 m in urban and suburban areas. In contrast, the transmission distance of the node can reach 2000 m, and this means that each node can easily communicate with the neighboring base stations directly.

Based on the high density of base stations in 5G networks in smart cities, we propose a Low-Cost Sub-network Formation (LCSF) algorithm, and its procedure is as follows:

(1) In the proposed algorithm, the number of sub-networks matches that of base stations, and also, the base station is the first node of the corresponding sub-network.

(2) Each base station broadcasts its Join_Sub_Network message to the nodes in the nearby areas, and the above message contains its location and the local sub-cluster ID information.

(3) After every node receives the Join_Sub_Network messages from the nearby base stations, it will choose the sub-cluster that includes the nearest base station so as to reduce the inter-cluster communication overheads. Then, the node sends the RES_Join message, which contains its node ID and the joined sub-cluster ID to the above base station.

(4) Each base station collects the nodes‘ RES_Join message, and then, it obtains the information on which nodes are the members of the local sub-cluster. All the base stations broadcast the information about its sub-cluster members.

3.2 Cluster Formation Algorithm

In our previous work [12], we introduced a centralized nodes‘ residual energy information maintenance algorithm, which is based on the nodes‘ energy prediction scheme, for the base station in the network, and we employ the above method to help the base station to maintain the remaining energy of nodes with little overhead in each sub-network, and then it can utilize the analytical model proposed in LEACH protocol to get the optimal number of clusters Kopt in the local sub-network. K-Means algorithms to partition each node in the sub-network into various clusters. In each cluster, considering the different characters of nodes, the nodes with high computing power and higher or even unlimited energy resources have more chances to become cluster heads.

In each sub-network, the detailed procedure of the cluster formation algorithm is as follows:

(1) The base station maintains nodes' residual energy information by utilizing a prediction scheme in [12].

(2) Base station employs the analytical model which is given by formula (1) to produce the optimal number of clusters with using the nodes' status information as input.

$$\mathrm{K}_{opt} = \frac{\sqrt{N}}{2\pi}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}\frac{M}{d^2{}_{toBS}}}, \quad (1)$$

(3) Where N is the number of nodes in the local cluster, and M is the side length of the square-shaped monitoring area. dtoBS is the average distance from all the nodes to the sub-cluster head in each sub-network.

(4) The base station runs the K-Means algorithm to partition the nodes in the sub-network to the sub-clusters by utilizing Kopt as input.

(5) The node that has high computing power and higher or even unlimited energy resources is selected as the cluster head.

(6) The base station broadcasts the sub-cluster formation results to all the nodes in the local sub-network.

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(7) When all nodes receive the broadcast message, they will know which clusters they belong to.

The data collection process can be divided into two phases. In intra-cluster communication, each cluster head collects the sensor data from the nodes in the same cluster with one hop mode, and in inter-cluster communication, the cluster head checks whether its own energy supply is unlimited, and if so, it transmits these data to the base station in the local sub-network directly, and otherwise, it sends the data to one nearby cluster head whose energy supply is unlimited, and this node will transmit data for it.

During the network runtime, the current cluster head in each cluster checks its status at the end of each round, if its energy supply is unlimited, it will take the cluster head role all the time, and otherwise, it will transfer its cluster head role to another node which has higher remaining energy level.

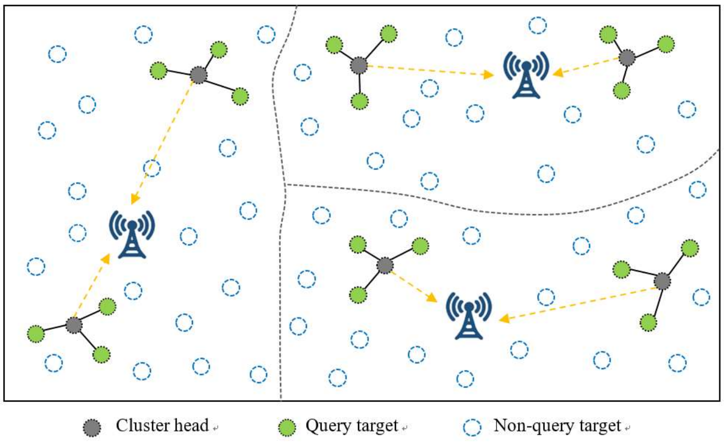

Figure 1. A sample cluster formation results in the LEC protocol

3.3 Inter-cluster Energy Balancing Scheme

During the operation of the network, each cluster head communicates with the base station in the same sub-network with low frequency so that the base station can maintain the remaining energy information of all the clusters in the local sub-network. If the difference in the total energy of the nodes among clusters exceeds the given threshold, the base station performs an inter-cluster energy balancing process to reduce the differences of residual energy among clusters.

Unlike the traditional employment of energy-excessive global reclustering algorithms, we adopt an Energy-efficient Node Reassignment (ENR) algorithm which is executed by the base station, and the main procedure is as follows:

(1) Add all the clusters in the local sub-network to the set Q;

(2) Select the cluster in set Q with the lowest remaining energy level as C[0];

(3) Selext out the cluster in set Q with the highest residual energy level as C[max];

(4) Set i=1;

(5) Choose a cluster C[i] from Q, and C[i] is a neighboring cluster of C[i-1], and it is nearer than the cluster C[i-1];

(6) Set i=i+1, and then, repeat step (5) until C[i] is one of neighboring cluster of C[max];

(7) Reassign the cluster members of each cluster in set C to make sure that all the clusters have around the same remaining energy as follows:

a) Set j=0, and the average remaining energy of cluster in set C is denoted as Eavg;

b) If the remaining energy of cluster C[i] is lower than Eavg, obtain the nearest several nodes from the neighboring clusters in the set C which has not been adjusted so as to make its residual energy up to the Eavg;

c) If the remaining energy of cluster C[i] is higher than Eavg, select several nodes from this cluster to neighboring cluster in the set C that have not yet been adjusted so that its residual energy is around Eavg;

d) If the remaining energy of cluster C[i] is equal to Eavg, do nothing;

e) Check whether j is equal to i, if it is, set j=j+1 and then perform step b);

f) The energy balancing process among clusters is at its end.

4. Network Performance Evaluation

We check the performance of our proposed LEC protocol with MATLAB software, and the comparative protocol is MH-LEACH [13], which utilizes the global reclustering method to balance the energy among nodes. The parameters of the simulation are illustrated in Table 1.

Table 1. Simulation Parameters

Parameters	Values
Monitoring area	400m×400m
Locations of four base stations	(100m,100m), (300m,100m), (100m,300m), (300m, 300m)
Number of nodes powered by batteries	500
Number of nodes whose energy is unlimited	100
Node's transmission radius	300m
Data packet length	2500bytes
Control packet length	500bytes
The initial energy of nodes powered by batteries	0.8J

Three criteria, including network lifetime and network throughput, are employed to validate the net work performance. Network lifetime is the percentage of alive nodes powered by batteries during th e network runtime, and the network throughput refers to the total amount of data that is received by the base station.

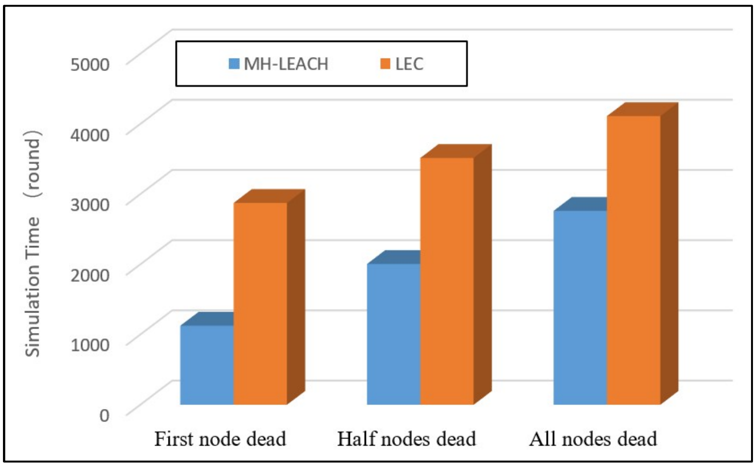

Figure 2. Network lifetime comparison

The network lifetime comparison is shown in Figure 2, and it can be found that the last node of LEC protocol depletes the energy at around 4100 rounds. By contrast, the last node of MH-LEACH becomes dead at 2700 rounds. Similarly, LEC also has a much longer time than that of MH-LEACH before the first node dies. Based on the above simulation results, our proposed LEC protocol is greatly superior to the baseline protocol.

Table 2 illustrates the network throughput results, and we can find that when the first node becomes dead, the total network throughput in LEC is 2.75×108bytes which is two times that of MH-LEACH protocol. After the last node dies in the network, the network throughput of LEC is 1.35 times that of MH-LEACH protocol. The above analysis indicates that our LEC protocol also has better performance in network throughput.

Table 2. Network Throughput Comparison

Simulation Time	MH-LEACH	LEC
First node dead	1.18×10^8	2.75×10^8
Half nodes dead	2.12×10^8	3.51×10^8
All nodes dead	3.15×10^8	4.26×10^8

5. Conclusion

In this paper, we have proposed an energy-efficient clustering protocol, called LEC, to improve the performance of WSN-based smart cities by avoiding the periodical global reclustering process which is energy-excessive. The LEC protocol includes three aspects: firstly, we utilized the LCSF algorithm to partition the whole WSN network into numerous small-size sub-networks; secondly, in each sub-network, nodes are assigned into different clusters to reduce energy consumption in data transmission processes; in the end, we raised node reassignment scheme to balance the remaining energy of clusters in each sub-network. The simulation results illustrate that our LEC has great superiority in network lifetime and network throughput, compared with other clustering protocols.

Acknowledgments

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