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CLUSTERING ROUTING PROTOCOL BASED ON GAME THEORY IN WIRELESS SENSOR NETWORKS

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Abstract

A clustering routing algorithm using game theory is presented to extend the lifetime of wireless sensor networks. In the cluster building stage, the cluster head election model is established by the remaining energy of nodes and the energy expenditure of cluster heads. The optimal cluster heads are chosen by Nash equilibrium probability. In the inter-cluster routing stage, cluster heads set their own bidding price according to their remaining energy, energy consumption and distance to sink, and finally form the optimal path to sink through multi-round auction game among neighbour cluster heads. The experiment results show that the routing algorithm can effectively extend the network lifetime, balance the energy expenditure of nodes, and increase the number of packets arriving at sink.

Key Words

Environmental monitoring, wireless sensor networks, auction game, Nash equilibrium, clustering routing

1. Introduction

With the rapid development of economy and society, the ecological environment is deteriorating, which has seriously affected people's lives. The environmental quality needs to be monitored to take targeted protection measures. There are three methods of environmental monitoring. The first method is to use remote sensing technology which is suitable for large-scale macro-environmental quality monitoring, *e.g.*, atmospheric environment monitoring and drought monitoring. The second method of environmental monitoring is to use X-ray, near-infrared, and other methods to accurately measure the content of pollutants in the ecological environment, and obtain the spatial distribution map of pollutants by interpolation method. The third method is to use wireless sensor networks for real-time environmental monitoring. Routing plays a vital role in this application. Clustering routing algorithm has the advantages of saving energy, facilitating data fusion, and expanding easily, which is suitable for large-scale environmental monitoring. However, because cluster heads need to consume more energy, it is easy to cause energy imbalance among nodes, which makes the network die prematurely. Therefore, balancing node energy to prolong the network lifetime is the current research focus in wireless sensor networks (WSNs).

1.1 Related Works

Routing algorithms include plane routing algorithm and clustering routing algorithm. Clustering routing algorithm is more suitable for large-scale environmental monitoring. At present, many clustering algorithms have been presented. The main literatures are as follows:

LEACH protocol [1], as a classical clustering protocol, uses periodic execution process. There are two stages in each round. In the cluster establishment stage, every node generates a random number. If the random number is less than the threshold value, the corresponding node is chosen as the cluster head. In the data transmission stage, every ordinary node sends the collected data to its cluster head in turn, and cluster head sends the fused data to sink. To choose nodes with higher remaining energy as cluster heads, an adaptive clustering model [2] is presented, which chose cluster heads according to the remaining energy of nodes to maintain energy balance among nodes. LEACH-TLCH (LEACH with two-level cluster heads) algorithm was improved in [3]. The authors researched the conditions to deploy two cluster heads to achieve the energy balance, and set secondary cluster heads to lighten the load of main cluster heads. Two algorithms [4] are presented to balance the energy expenditure among sensor nodes. One algorithm was presented for static WSNs, where cluster head is selected by upper bound distance, lower bound distance, and remaining energy of nodes. The other algorithm was presented for mobile WSNs, where cluster head is selected by upper bound distance, lower bound distance and remaining energy of nodes, and least mobility. An improved

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LEACH algorithm using node rank [5] is presented, which calculates the weight of node to choose the cluster head by node location, remaining energy, and connection number to other nodes. Although this algorithm can avoid the randomness of cluster head election in LEACH, it is easy to cause the energy-hole problem.

To solve the energy-hole problem, many scholars have studied non-uniform clustering algorithm. An energy-efficient optimization model [6] is designed to solve the unequal clustering, and the energy hierarchy idea is used to elect cluster heads. The clustering process can achieve faster convergence and less communication overhead. An energy-balanced multi-layer clustering structure [7] is established according to the connectivity density and location of nodes, and a non-uniform clustering algorithm is adopted to choose the cluster head according to the connectivity density of nodes, the remaining energy of nodes, and so on. The proposed algorithm [8] elects cluster heads by the remaining energy of node, the distance from nodes to cluster heads, and the distance from nodes to sink, and divides WSNs into clusters with different sizes. A threshold is calculated according to the size of cluster, the remaining energy of node, the amount of data transmission, and the distance from node to sink. When the weight of cluster is larger than the threshold, the cluster will elect a sub-cluster head to reduce the burden of the main cluster head. The optimal path for data forwarding is constructed by an improved minimal binary tree. A non-uniform clustering algorithm with two cluster heads using particle swarm optimization [9] is presented, in which the primary cluster head collects and fuses data, while the sub-cluster head forwards data among clusters. An average entropy and a data correlation coefficient are designed to improve the efficiency of data aggregation in WSNs [10].

Game theory can effectively solve the cooperation and competition problem among individuals, and has been widely used in WSNs. EECP protocol [11] is presented, which uses game theory to choose node with enough remaining energy as cluster head, and adopts game theory to control multi-hop data transmission among clusters. The routing problem in WSNs is considered as the evolutionary anti-coordination game [12]. The energy balance scheme of the network is given to improve the overload problem of some nodes and effectively prolong the network lifetime. A double cluster head mechanism [13] is designed to decrease energy consumption of cluster head rotation, and the non-cooperative game model is adopted to maintain energy balance among sensor nodes. A distributed clustering algorithm [14] is adapted to build the clusters and elect the cluster heads according to the position and the remaining energy of nodes, and a non-cooperative game model is established to generate the probability of nodes sending data and reduce the energy consumption of sensor nodes.

1.2 Our Contributions

Above algorithms improve the performance of the sensor networks, but there is unbalance load among nodes. When choosing the optimal path among clusters, the remaining energy of cluster head and the distance from cluster head to sink are important factors affecting network lifetime. This paper designs a payoff function that considers the node energy, the energy expenditure of cluster head, the distance between cluster head and sink, and the packet delivery success ratio. An inter-cluster routing algorithm using auction game is presented to optimize inter-cluster data transmission. The major contributions are listed as follows:

1. A cluster head election model is established with game theory. Considering the node energy and the energy expenditure of the cluster heads, Nash equilibrium is used to calculate the equilibrium probability. The nodes with larger equilibrium probability become the cluster heads.
2. The cost function is designed by the distance between the node and the cluster head and the remaining energy of the cluster heads. The common node chooses a cluster head with the shortest distance and the most energy to join.
3. Auction game is used to model the path selection among clusters. By analysing the energy expenditure of cluster head, the bidding function is designed according to the distance between the cluster heads and sink, remaining energy and energy consumption of cluster heads. To maximize benefits, nodes cooperate with each other, and the packet delivery success ratio is introduced to reduce the possibility of selfish nodes betraying. The source node can find the appropriate relay node through auction game. The relay node will initiate a new round of auction game. Until the data is successfully transmitted to sink, the auction game is over.

2. System Model and Assumption

2.1 Energy Consumption Model

In WSNs, nodes consume energy in monitoring, receiving, and transmitting data. Because the communication energy expenditure is much larger than other energy expenditure, the communication energy expenditure of nodes is only considered. The energy expended by nodes to send l-bit data is:

$$E_{Tx}(l,d) = \begin{cases} l \times E + l \times \varepsilon_{fs} \times d^2 \\ l \times E + l \times \varepsilon_{mp} \times d^4 \end{cases} \tag{1}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{2}$$

where E is the circuit expenditure of transmitting data and d is the transmission distance. When $d > d_0$, the free space model is used. Otherwise, the multi-path attenuation model is used. ε_{fs} and ε_{mp} are energy expenditure of sending one-bit data in power amplification. The energy expended by nodes to receive l-bit data is:

$$E_{Rx}(l) = l \times E \tag{3}$$

2.2 Some Assumptions

For convenience, assume that the sensor network has the following characteristics:

1. All sensor nodes have unique *ID* number, which are randomly deployed in the monitoring field.
2. The nodes are static and have limited energy.
3. Sink can communicate with any node in the monitoring area and has the constant location and infinite energy.
4. Network lifetime is measured by the number of rounds of data transmission.
5. The initial energy of all nodes is the same.
6. Every node can get its location information.

3. Routing Algorithm using Game Theory

Game theory studies the optimization strategies by considering the predictive and actual behaviour of individuals in the game [15]. In this section, game model of cluster head election is constructed. Subsequently, inter-cluster routing algorithm using auction game is proposed, which is used to choose the best path for data forwarding.

3.1 Game Model of Cluster Head Election

When using game model to select cluster heads, all nodes in WSNs are game participants. The game is defined as $G = <N, S, U>$. The meanings of each element in this model are as follows:

1. $N = \{1, 2, \ldots, n\}$ is the set of nodes in the game, where n is the number of players in the game, namely the number of sensor nodes.
2. $S = \{s_1, s_2, \ldots, s_n\}$ is the set of the game strategies, where s_i represents the strategy chosen by participants i. The strategy of each participating node corresponds to two choices. One is to declare as the cluster head and the other is to declare as the ordinary node.
3. $U = \{u_1, u_2, \ldots, u_n\}$ is the set of game participants' payoff functions.

There are two strategies for every node, which are CH and CM. CH is to declare as the cluster head, and CM is to declare as the cluster member. The cluster head node processes the data collected by the common node and sends it to sink. In this process, cluster heads need to consume a certain amount of energy, denoted as c. If sink successfully receives the data forwarded by the cluster heads, there must be one common node to collect data. At this time, sink will give the node a payoff, denoted as r, and the payoff of the cluster head node is $(r - c)$. To prevent no node from becoming cluster head, $a = (e_{res}/e_0)$ is introduced to restrain the selfishness of nodes, where e_{res} and e_0 represent the remaining energy of node and the initial energy of node, respectively. If the node is chosen as CH, its payoff is $(a \times r - c)$. If the node is selected as CM, its payoff is $(a \times r)$. The node payoff matrix with only two participants is presented in Table 1.

Assuming that the set of the node hybrid strategy is $P = \{p_1, p_2, \ldots, p_n\}$, the probability of node 1 being elected as CH is p_{i1}, the expected benefits of node 1 choosing a specific hybrid strategy $p_1 = (p_1, 1 - p_{11})$ is:

Table 1
Node Payoff Matrix of Two Participants

	CM	CH
CM	(0,0)	$(a_1 \times r - c_1, a_2 \times r)$
CH	$(a_2 \times r - c_2, a_1 \times r)$	(0,0)

$$\mu_1(p_1, p_2) = p_{11} \times (1 - p_{21}) \times (a_1 \times r - c_1) + (1 - p_{11}) \times p_{21} \times a_2 \times r \quad (4)$$

The expected benefits of node 2 are:

$$\mu_2(p_1, p_2) = p_{21} \times (1 - p_{11}) \times (a_2 \times r - c_2) + (1 - p_{21}) \times p_{11} \times a_1 \times r \quad (5)$$

Next, the optimization problem can be solved and the mixed Nash equilibrium (p_1^*, p_2^*) can be obtained by the following equation:

$$\begin{cases} \max_{p_1 \in P} \mu_1(p_1^*, p_2) = \max_{0 \le p_{11} \le 1} (p_{11} \times (1 - p_{21}^*) \times (a_1 \times r - c_1) \\ \qquad + (1 - p_{11}) \times p_{21}^* \times a_2 \times r) \\ \max_{p_2 \in P} \mu_1(p_1, p_2^*) = \max_{0 \le p_{21} \le 1} (p_{21} \times (1 - p_{11}^*) \times (a_2 \times r - c_2) \\ \qquad + (1 - p_{21}) \times p_{11}^* \times a_1 \times r) \end{cases} \quad (6)$$

p_{11}^* and p_{21}^* can be obtained by calculating extreme value:

$$p_{11}^* = \frac{a_2 \times r - c_2}{(a_2 + a_1) \times r - c_2} \quad (7)$$

$$p_{21}^* = \frac{a_1 \times r - c_1}{(a_2 + a_1) \times r - c_1} \quad (8)$$

When $(a_2 \times r - c_2) > 0$ and $(a_1 \times r - c_1) < 0$, the strategy $s = \{CM, CH\}$, node 2 is selected as the cluster head.

When $(a_2 \times r - c_2) < 0$ and $(a_1 \times r - c_1) > 0$, the strategy $s = \{CH, CM\}$, node 1 is selected as the cluster head.

When $(a_2 \times r - c_2) > 0$ and $(a_1 \times r - c_1) > 0$, the strategy $s = \{CH, CH\}$, if $p_{11}^* > p_{21}^*$, select node 1 as the cluster head, otherwise, node 2 is selected as the cluster head.

When $(a_1 \times r - c_1) < 0$ and $(a_2 \times r - c_2) < 0$, the strategy $s = \{CM, CM\}$, there is no node to be the cluster head.

From the above analysis, nodes with more remaining energy are more likely to be selected as the cluster head. Energy consumption function of node i is given as:

$$c(i) = E_{Tx}(i) + E_{Rx}(i) \quad (9)$$

where $E_{Tx}(i)$ is calculated by (1) and $E_{Rx}(i)$ is calculated by (3).

Using the cluster head game model proposed above, the cluster head election process includes three stages: node initialization stage, cluster head election stage, and cluster formation stage.

In node initialization stage, every node sends an initial message to sink. The initial message includes: ID number of the node, remaining energy of the node, and location of the node. In addition, the node broadcasts the Hello packet in the transmission radius R. Every node can get the number of its neighbour nodes within its transmission radius R.

In cluster head election stage, each node plays game as a player with its own neighbours, calculates p_{11}^*, p_{21}^* by (7) and (8). The node with high-equilibrium probability is chosen as the cluster head.

In cluster formation stage, ordinary nodes will choose to join the cluster head which is short distance from it and has the most remaining energy.

3.2 Inter-cluster Routing Algorithm using Auction Game

This part mainly introduces the whole process of auction game. When the auction game starts, many sellers (neighbour nodes) compete each other for payoff. The source node (buyer) chooses the best neighbour node to forward data. After the packet forwarding is successful, the source node quits from this round of game and the selected node initiates the next round of game as bidder. When the data is transmitted to sink, the game is over.

This paper regards source node and neighbour nodes as buyer and sellers of auction game. Source node as buyer finds a reliable forwarding node through bidding, and neighbour nodes as seller auction their own data forwarding service. In the process of auction, the buyer and the sellers first estimate their own prices, and quote each other.

The energy consumption function of head node j is:

$$ec(j) = \sum_{i \in Nb_j} c(i) \tag{10}$$

where $ec(j)$ is the energy consumption of the node j, Nb_j is the neighbour node set of the node j, and $c(i)$ is energy consumption of the node i, which is computed by (9). The bidding price function of the neighbour node j (seller) of node i (buyer) is defined as:

$$\alpha_j(i) = \omega \times \log_{10}\left(\frac{d_j}{e_j}\right) + (1-\omega) \times ec(j) \tag{11}$$

where ω is the weight coefficient (variable parameter), d_j is the distance from the cluster head j to sink, and e_j is the remaining energy of the cluster head j. Equation (11) shows that the cluster head node with high remaining energy, low energy consumption, and close to sink will have the lower price. The node with lower price participates in packet forwarding, which is beneficial to balance the energy expenditure of the network. The buyer's price function of the node i is:

$$\beta(i) = \sum_{j \in HNi} \frac{\alpha_j(i)}{HNb(i)} \tag{12}$$

where HNi denotes the neighbour cluster heads set of the cluster head i, and $HNb(i)$ is the number of neighbour cluster heads of the cluster head i. $\alpha_j(i)$ is the price of node j which is neighbour of node i.

In the process of auction, sink should pay the corresponding remuneration to the source node when it receives the data, and the source node should also pay certain remuneration to the forwarding node as the fund for purchasing the data forwarding service. The source node only can select one of the nodes for transaction. Some nodes do not forward data to gain more benefits after obtaining the data forwarding qualification. This phenomenon is called selfish behaviour of nodes, which results in many data packet losses. The packet delivery success ratio is used to reduce the possibility of betrayal caused by selfishness of nodes. At t time, the packet delivery success ratio of cluster heads node i is defined as:

$$a_i(t) = \frac{S_p(t)}{R_p(t)} \tag{13}$$

where $a_i(t)$ is the packet delivery success ratio of cluster heads node i, $S_p(t)$ is the number of packets sent and forwarded by node i, and $R_p(t)$ is the number of packets received by node i.

The payoff function of node i is defined as:

$$\mu_i(t) = a_i(t) \times (\gamma - \alpha_j(i) - \theta) \tag{14}$$

where $\mu_i(t)$ denotes the benefit of node i at t time, $a_i(t)$ denotes the packet delivery success ratio of cluster heads node i, γ is the payoff for each source node from sink, $\alpha_j(i)$ is the transaction price, and θ is the cost of data transmission.

Equation (14) shows that the source node needs to improve its packet delivery success ratio and choose the lowest transaction price to obtain the maximum revenue. That is to say, the source node will choose the lowest bidding node among its neighbours as the next hop.

When the first round of auction is over, the source cluster head quits the game. The next hop cluster head launches a new round of auction game. The auction process is the same as that of the source cluster head. Using the auction game model established above, cluster head node can find an optimal path for forwarding data. The specific process of auction game is as follows. Firstly, the cluster head node broadcasts Hello packets within the transmission radius CR. Each cluster head keeps its neighbour cluster head information table, including the node ID, the remaining energy, the distance from the cluster head to sink, and the cluster size. When there is data to be forwarded, the source node and the neighbour node get their bidding price through information exchange. The source node chooses the neighbour node with the greatest profit as the forwarding node. After data forwarding is successful, the forwarding node launches a new round of auction game. When the data is successfully transmitted to sink, the game is terminated.

4. Experiments and Result Analysis

4.1 Setting of Experiments Parameters

The nodes are randomly deployed in a 100 m × 100 m monitoring field. The experiment parameters are listed in Table 2. GEEC [16] and LEACH [1] algorithms are chosen to make comparisons. GEEC and LEACH belong to clustering routing algorithm, and GEEC uses the evolutionary game. These characteristics are the same as the proposed algorithm [clustering routing algorithm using game theory (CRA-GT)].

Table 2
Setting of Simulation Parameters

Size of monitoring area	100 m × 100 m
Sink position	(50 m, 50 m)
Number of nodes	100
Initial energy of nodes	1 J
E	50 nJ/bit
ε_{fs}	0.0013 pJ/(bit/m^4)
ε_{mp}	10 pJ/(bit/m^2)
Packet length	4,000 bit
Advertising packet length	200 bit

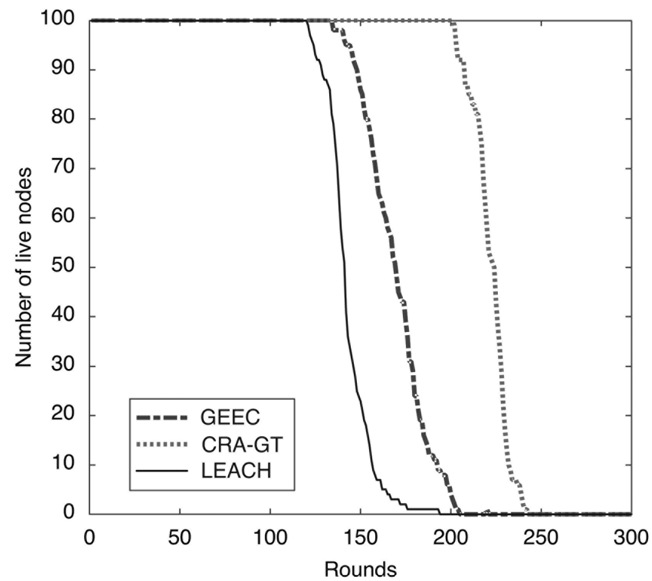

Figure 1. Number of live nodes.

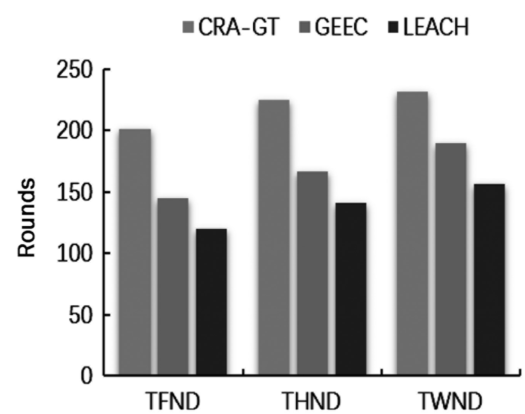

Figure 2. TFND, THND, and TWND.

4.2 Network Lifetime

First, define the following units of measurement to represent the network lifetime:

TFND represents the time of the first node death.

THND represents the time of half of nodes death.

TWND represents the time of 90% of nodes death.

The number of live nodes in each round is shown in Fig. 1. CRA-GT has more live nodes per round than GEEC and LEACH because nodes expend less energy in CRA-GT. The network lifetime is shown in Fig. 2. TFND, THND, and TWND of CRA-GT are 38.6%, 34.5%, and 22.1% longer than those of GEEC, respectively, and 67.5%, 59.5% and 48.7% longer than those of LEACH, respectively. LEACH uses a random cluster head selection method. GEEC selects the optimal cluster heads by the evolutionary game. GEEC and LEACH use the single-hop communication between cluster heads and sink, which result in great energy expenditure and shortens the network lifetime. CRA-GT chooses the optimal cluster heads by game model and uses the multi-hop communication between cluster heads and sink, which decreases the energy expenditure of nodes and makes the remaining energy of nodes more balanced. So, CRA-GT can effectively extend the network lifetime.

4.3 Energy Expenditure of Network

Figure 3 shows the energy expenditure of network in every round. CRA-GT expends the smallest energy in all algorithms. Figure 4 shows the standard deviation of remaining energy of nodes in different rounds. It shows that the maximum value of standard deviation of remaining energy in CRA-GT is less than that in GEEC and LEACH. So, the energy consumption among nodes is the most balanced in CRA-GT.

4.4 Number of Packets Arriving at Sink

Figure 5 shows the number of packets arriving at sink. In CRA-GT, 59.7% and 91.5% more packets arrive at sink than those in GEEC and LEACH, respectively. Because CRA-GT can make more efficient use of network energy, sink can receive more data packets.

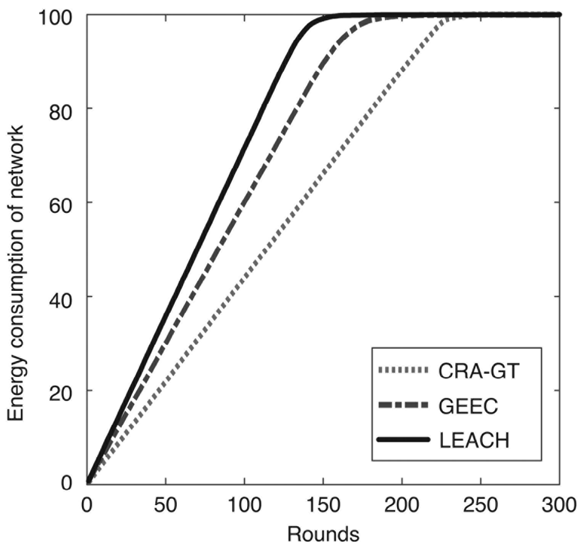

Figure 3. Energy consumption of network.

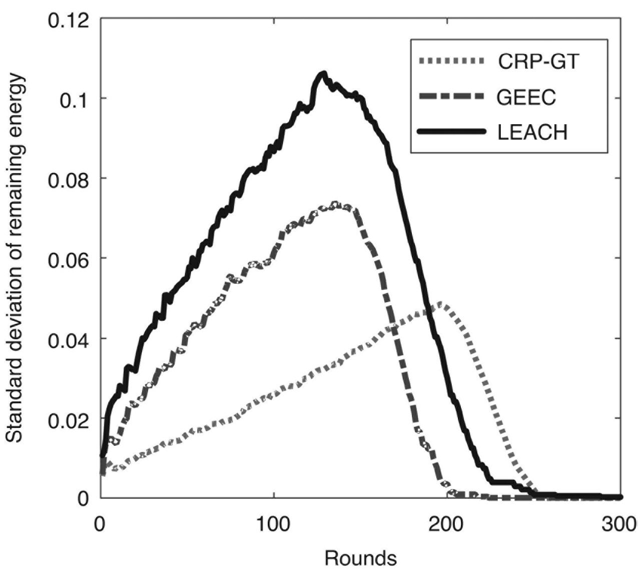

Figure 4. Standard deviation of remaining energy.

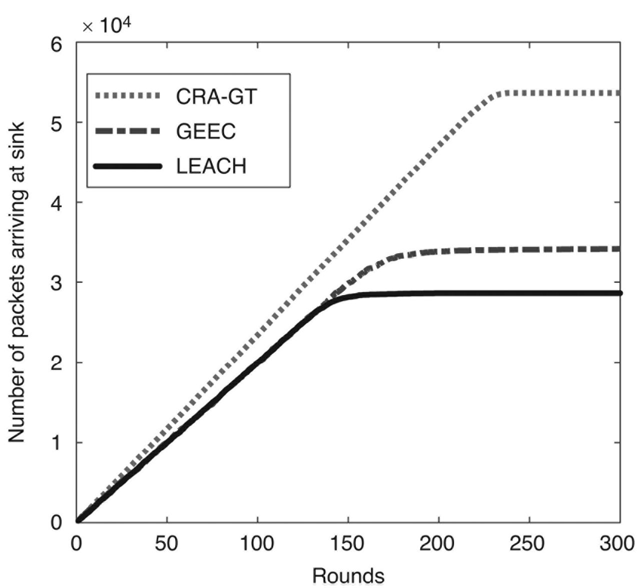

Figure 5. Number of packets arriving at sink.

5. Conclusion

Firstly, this paper analyses the problems of existing clustering protocols, which are mainly manifested in that the unbalanced energy expenditure of nodes shortens the network lifetime. Then, by analysing the energy expenditure of cluster heads in different stages, this paper presents a CRA-GT. In the cluster building stage, the cluster head election model is established by considering the remaining energy of the nodes and the energy consumption of cluster heads. The appropriate cluster heads are selected by calculating the equilibrium probability. In the data transmission stage, the optimal data transmission path among cluster heads is constructed by established auction game model. The experimental results show that CRA-GT has better performance than GEEC and LEACH in prolonging the network lifetime, balancing the energy expenditure of nodes, and increasing the number of packets arriving at sink.

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