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Cluster-based Routing Performance Optimization Constraint of Energy, Delay and Connectivity Metrics in Wireless Sensor Network

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Abstract- This paper aims to propose a framework for optimizing performance in cluster-based wireless sensor networks (WSNs) with constrains of energy consumption, delay and connectivity. For the limitation of energy storage being discussed a lot, many researches try to find more solutions to improve it. But, the other index of wireless sensor networks may be deteriorated by many routings which are dedicated to optimizing energy consumption. Thereby, multi-objectives optimization is one of significant issues in WSNs. The model of isolation nodes probability for connectivity in the cluster-based networks is adopted for the issue. Not only will the performance of Leach and existing multi-objectives optimization methods be compared under the proposed framework, but also will the performance of networks in different size of scenarios be analyzed. Simulation results show that the proposed framework combining NSGA can provide an effective sensing in terms of energy consumption, delay and connectivity in the cluster-based networks.

Index terms: Isolation nodes probability, energy consumption, delay, cluster, WSN, optimization framework

I.INTRODUCTION

The optimization problems of the routing protocols in wireless sensor networks can be summarized roughly as follows: network heterogeneity, adaptive for dynamic circumstance, the constraint of Qos. These problems mentioned above, moreover, also may be influenced by energy consumption, delay, and connectivity which are conflicted. Thus, the design of routing in wireless sensor networks should be treated as a multi-objectives optimization problem. However, many existing researches are focused on one single objective. In [1] [2] [3] [4] [5] [6], the optimizations for delay in the wireless sensor networks have been proposed. Yunbo Wang et al. proposed a cross-layer analysis of the end-to-end delay in WSNs; Chi-Tsun Cheng et al. proposed a delay-aware data collection network structure and its formation algorithms; Xiaohua Xu et al. proposed a distributed scheduling method for data aggregation based on multi-hops wireless sensor networks; Chilukuri Shanti et al. proposed a new contention-free TDMA-based integrated MAC and routing protocol, which can provide deterministic delay guarantee; Liu yuan and Wang Yuhao et al. proposed a hybrid MAC mechanism which takes advantages of both TDMA and CSMA mechanism for improving the flexibility and reliability in channel utilization; Cheng Chunling et al. proposed an algorithm based on similar flocking model can detect outliers effectively with less energy consumption.

Comparing the flat-routing network, cluster-based routing protocol show an effective technique in reducing energy consumption and can prolong the lifetime of WSNs [1] [2].Thus, the cluster-based routings can be regarded as the protocols which optimize the energy consumption in WSNs. W.Heinzelman et al. proposed the Leach (Low Energy Adaptive Cluster Hierarchy) [7], when the next round start, the cluster-heads will be re-election and the concept of round which is the procedure of all nodes send their data to sink has been introduced in Leach. The cluster-head of the previous round will not be selected in this round, thus the energy may be allocated to the whole network. In addition, TEEN [8] and APTEEN [9] belong to the cluster-based routings. It is particularly deserve to mentioning that bionics also be applied to research of cluster-based routing. In [10], Chi-Tsun Cheng et al. proposed a clustering algorithm based on social insect colonies, the cluster-heads were regarded as queens and other nodes are workers. The performance of this protocol is much better than that of the Leach, PEGASIS [11] and PEADP [12] .The connectivity of wireless sensor networks has also been regarded as one single objective in many researches. In [13], a unified mathematical model which incorporates the three main factors which cause randomness in the connectivity of WSNs is developed. In [14], the connectivity in 3D wireless sensor network has been investigated.

There are many indicators in WSNs, and the optimization for them may be conflict. Therefore, multi-objective optimization for wireless sensor networks has gradually became one of the current research focuses. In [15], Joohwan Kim et al. developed an anycast packet-forwarding scheme to minimize delay and maximize the lifetime for wireless sensor networks. In [16], Elizabeth F. Wanner et al. proposed a hybrid multi-objective optimization which combines MGoDA（multi-objective global on-demand algorithm）and LoA（local on line algorithm）. In their work, the dynamic coverage and connectivity problem (DCCP) in flat-routing has been addressed and solved efficiently. In [17], the energy minimization and coverage maximization with connectivity are optimized simultaneously. In [18], global probability of error and energy consumption have been optimized, in their work, the optimization is investigated and solved for two types of fusion schemes which contain parallel decision and serial decision fusion. Mingdong Xu and Henry Leung proposed a cross-layer optimization of wireless sensor networks under the constraints of total energy consumption and transmission delay [19]. In [20], L.Liu et al. proposed the problem of achieving energy conservation, coverage and connectivity requirements together without any sensing range or transmission range restrictions for the first time.

This paper proposed a framework in cluster-based routing of WSNs for energy consumption, delay and connectivity. As we all know that the energy consumption is one of the issues in the routing design in wireless sensors network, however the optimizations of many factors which influence the performance of WSNs may be conflict. Besides the energy consumption, the delay during the transmission and the connectivity are also the challenges of wireless sensors network. When the cluster-headers increased the energy consumption will be decreased and connectivity will be improved, but the time-slots may be increased. We extend the work reported in [21]，which is the optimization of connectivity in the network has also been taken into consideration. The rest of paper is organized as follows. In Section II, we describe the system model. In Section III, the optimization framework is proposed. The simulation is shown in Section IV. Conclusion is given in Section V.

II.PROPOSED SYSTEM MODEL

In cluster-based routing, each node plays a dual role as data sender and data router. The malfunctioning of some sensor nodes due to power failure can cause significant topological changes, and might require reorganization of the network. In this paper, we research three parameters of cluster-based routing in wireless sensor networks which incorporate energy consumption, delay and connectivity. In this section, we will describe and expound the system model.

a. Energy Consumption

In general, wireless sensor network nodes are divided into three parts as follows: processing module, sensor module and radio module [2] [21]. Environmental information collected by sensing module, the communication between nodes is maintained by radio module. In cluster-based routing, one of the duties in the processing module data fusion is to reduce the number of messages transmitted to the sink. This paper combines and modifies the energy model proposed in [21] [22] [23], and the model is based on architecture of a MICAz [24]. Besides these, the power management schemes can be summarized simply as follows: idle model, the transmitting mode, the receiving mode, the data fusion mode and the sensing mode. In a data collection of cluster-based network, cluster-headers fuse and transmit the messages from sensor nodes to sink node. Thus the energy consumed of cluster-based network in a data collection process can be denoted as follows:

$$\mathrm{E}_{tot} = N_m\left(E_r + E_f\right) + \sum_i^N E_t(d) \qquad (1)$$

In equation 1, N_m is the number of cluster-member nodes, E_r is the energy consumption of cluster-heads in receiver mode, E_f is the energy consumption of fusing two packets together in the data fusion mode and $E_t(d)$ is the energy consumption for a distance of d in transmitting mode of the node i.

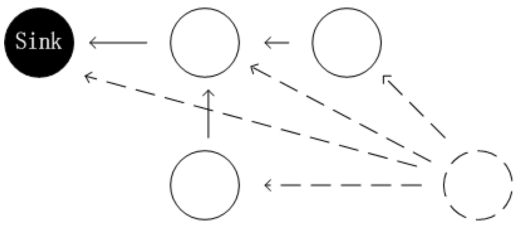
b. Delay

The communication overhead by time division multiple access (TDMA) is relatively low for networks with static topologies in on single channel [25], thus MAC protocol of cluster-based routing in this paper employ TDMA. The data delay can be defined as the duration of messages, which is transferred from sensor nodes to sink. And the data delay by TDMA takes place in three stages: data queuing, data transmission and radio propagation [19]. The delay in queuing depends on how long the message wait for transferring in sensor nodes, the delay of data transmission corresponds to the duration sensor nodes is used to transmit data in the scheduled slots, and radio propagation is the duration for signal disseminates to sink node. In our work, we consider data transmission delay. The typical hierarchical routings are different from flat-routing networks, cluster-head with N cluster-members will last N time-slots to fuse data from its cluster-members, sink node will assign slot-times for cluster-headers to avoid collision. In general, because of the limitations of cost, most of the wireless sensor nodes are half-duplex systems [24], which the sensors can only handle one transmission at a time. The delay D_T in this paper is,

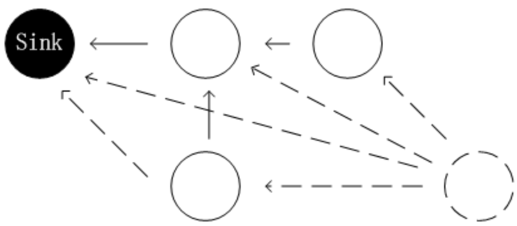
$$D_t = \begin{cases} C_{min} + C_N - 1 & C_D \leq C_N \\ C_{max} & C_D \geq C_N \end{cases} \quad (2)$$

c. Connectivity

In [13] , Ramesh Rajagopalan et al. proposed an index which includes probability of isolation nodes, end-to-end connectivity and network connectivity for evaluating connectivity in wireless sensor networks. In their work, probabilistic connectivity of WSNs under different channel fading models is analyzed. Figure 1 shows the definitions of connectivity in the form of graphics. The isolation node is the one which cannot connect to others, end-to-end connectivity is defined as path between all sensor nodes with sink node and network connectivity is that path between every each pair of nodes in the WSN.



(a)



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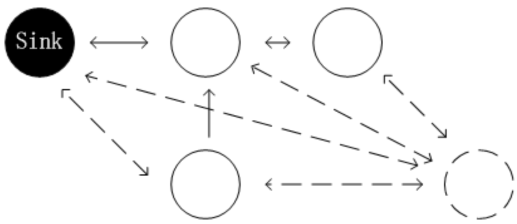


(c)

Figure 1. The description of connectivity in form of graphics: (a) Isolation nodes. (b) End-to-end connectivity. (c) Network connectivity.

In the hierarchical networks, cluster-heads are hubs of network. And the mode of connectivity may be different from the one in [13].The isolation node can be defined as the nodes which cannot communicate with their cluster-heads. The end-to-end connectivity and network connectivity, however, had better to be used to describe flat-network or multi-hops networks, thus we mainly research the isolation nodes probability in this paper. There also exits multi-hops mode in wireless sensor networks [3], however, the single-hop clusters have several advantages over multi-hop clusters, such as simple medium access control (MAC) and synchronization protocol designs [26], thus we only consider single-hop clusters. Figure 2 illustrates the description of isolation nodes in the cluster-based network.

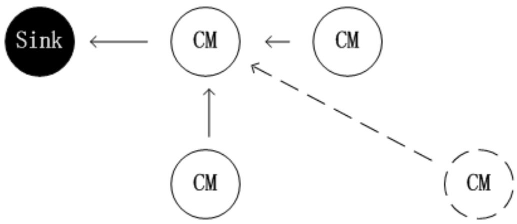


Figure 2. An example of isolation nodes in the cluster-based network

We exploit two-ray ground reflection model for the communication mode in this paper, so the distance of communication can be described as follows:

$$\mathrm{d} = \left(\frac{P_t G_t G_r h_t^2 h_r^2}{P_r L}\right)^{\frac{1}{4}} \qquad (3)$$

In equation 3, P_t is power of the transmitter, P_r is power of the receiver, h_t and h_r are the height of transmit and receive antennas respectively, G_t and G_r represent the gain of transmit and receive antennas, respectively, and L is path loss. According to this model, we can calculate the max communication distance of each pair of nodes. Because of the energy restriction, we research the relationship between residual energy and maximum communication distance, which the situation that unable to communicate each other result from lack of energy has been considerate. The probability of isolated nodes can be denoted as follows:

$$\mathrm{P}_{iso} = 1 - P(E_i < E_\tau | D_L < D_{max}) \qquad (4)$$

where E_i is the residual energy of nodes, E_τ is overhead energy consumption during one transmission, D_L is the distance between sensor node and its cluster-head and D_{max} is the maximum communication distance.

IV.THE OPITIMZATION FRAMEWORK

In this paper, we research the way to optimize energy consumption, delay and connectivity in the cluster-based network simultaneously. And it can be regarded as the MOO (multi-objective optimization) problem. To compare with the performance of MOO for wireless sensor networks, two methods of MOO are selected and employed. The connectivity of wireless sensor networks has also been regarded as one single objective in many researchers.

The simplest way to achieve multi-objective optimization is to regard multi-objectives as one goal and multiply the constraints with different weightings and linearly add the products together into a single objective function. The function for MOO problem of clustering in wireless sensor networks can be denoted as follows:

$$\min\{\omega_1 \frac{f_1}{f_{1\_max}} + \omega_2 \frac{f_2}{f_{2\_max}} + \omega_3 \frac{f_3}{f_{3\_max}}\} \qquad (5)$$

In equation 5 $f_1 = E, f_2 = D_T$, $f_3 = P_{iso}$ and the sum of weights (ω_1 , ω_2 and ω_3) is one. The f_{1_max}, f_{2_max} and f_{3_max} are the maximum values of objectivesf_1 , $f_2$and f_3, respectively. Each set of weights determine a single point on Pareto frontier and optimization results. In 1992, Hajela and Lin proposed Hajela's and Lin's Genetic Algorithm (HLGA)[27], this algorithm was based on the vector evaluated genetic algorithm (VEGA) proposed by Schaffer in 1984. The key of their ideas is to divide the population into sub-populations by different weight combinations. Thus, it is important to elect appropriate weights for the objective function. In[28], Srinivas and Deb proposed Non-dominated Sorting Genetic Algorithm (NSGA) which was improved by Deb in 2002[29]. The advantage of NSGA is that it does not been considered the selection of weights. The function for MOO problem of NSGA in this paper can be denoted as equation 6 and their simulation results will been given in Section IV.

$$\min\{f_1, f_2, f_3\} \quad f_1 = E, f_2 = D_T , f_3 = P_{iso} \quad (6)$$

IV. SIMULATION RESULTS AND ANALYSIS

In this section of the paper, firstly, we research the relation of objectives which contain energy consumption, delay and connectivity; secondly, we analyze the performance of cluster-based network with different algorithms; lastly, the effect of different size of areas has also been discussed. The simulation is executed by matlab. Note that the sensors are regarded as synchronous which are achieved by the pairwise broadcast synchronization technique [28] [29].This paper focus on the influence of performance in wireless sensor networks which is impacted by clustering, so the synchronization techniques have not been discussed in detail.

Since it is powered by the attached battery, high efficient energy utilization is necessary [30] [31]. Once some nodes run out of their energy, the performance and connectivity of network may be influenced by fail nodes. In some real-time applications, the sensor information should be sent to sink node promptly otherwise the messages will lose its value. Such QoS requirements usually depend on two common parameters: timing and reliability [1]. Therefore, the delay of network has also become one of major indicators in WSNs. We know that the delay may be influenced by time-slots which are assigned in cluster-based networks. The energy consumption should be decreased when the number of cluster-heads increased, but the delay in the network may be extended due to the increase in the time-slots. In Figure 3 shows that Leach can reduce energy consumption effectively by increasing the number of cluster-headers, however, delay of the network is elevated.

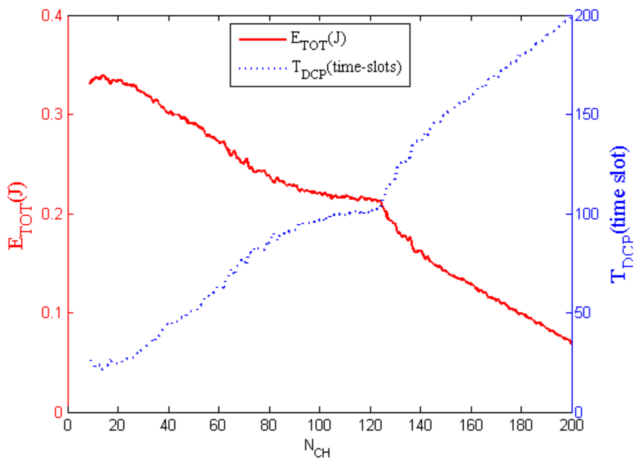
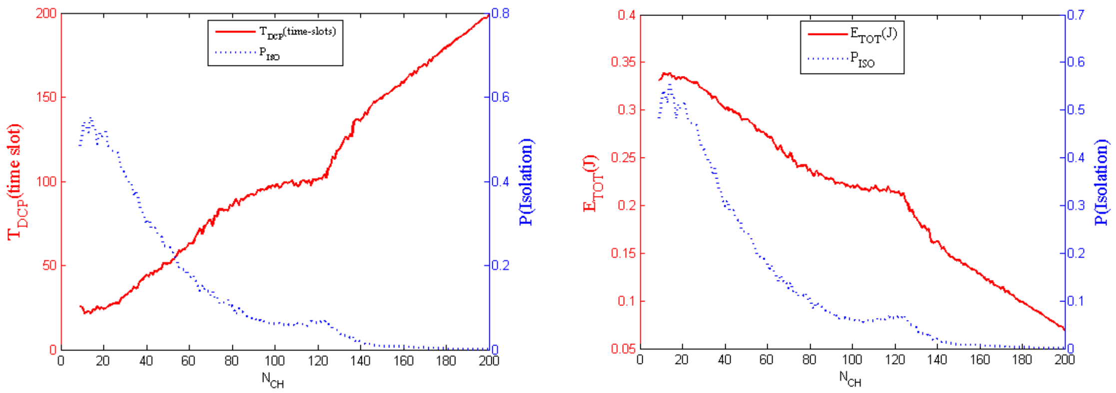


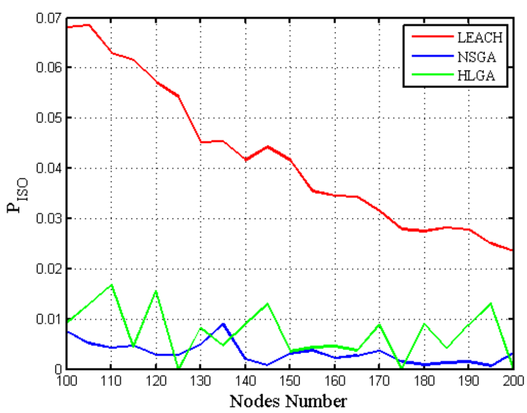
Figure 3, the simulation result of energy consumption and delay by leach in the area of 2000x2000(m^2) and sink node is located at (1000, 1000).

In general, there are a large number of nodes in the network, so choosing the right path is an important part of routing. The main goal of routing protocol for wireless sensor networks is to find the optimal path of source nodes to sink. And in the cluster-based routing, connectivity is also related to the number of the cluster-heads, the increase of cluster-headers can shorten the communication distance, that is to say the connectivity may be improved. The performance of delay, however, will be deteriorated by the increase of time-slots. Figure 2 shows that the trends of delay and isolation nodes probability are mutual restraint, but the one of the isolation nodes probability and energy consumption are the same. The simulation results in Figure 3 and Figure 4 both observer that the optimization of a single aspect may bring negative effects to other aspects.



(a) (b)

Figure 4. The simulation results by leach in the area of 2000x2000(m^2) and sink node is located at (1000, 1000): (a) delay and isolation nodes probability; (b) energy consumption and isolation nodes probability.



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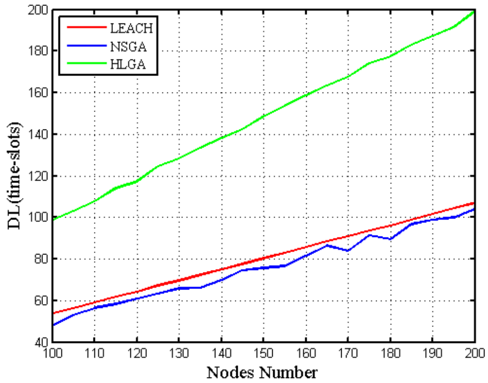

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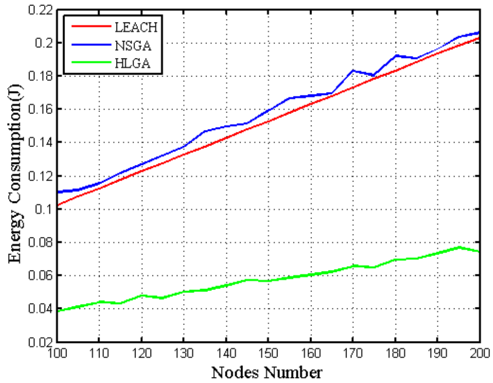
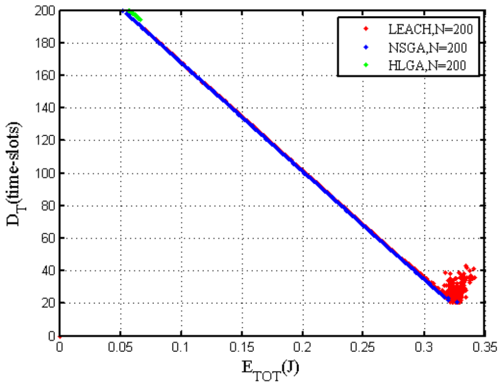


(c)

Figure 5. The simulation results of different algorithms with nodes number: (a)Isolation nodes probability;(b)Delay(time-slots);(c)Energy consumption(J).

Figure 5 shows the average of simulation results about isolation nodes probability, delay and energy consumption of all clustering solutions in the network. In each network, the number of nodes which were distributed randomly into a sensing field of 1000x1000m^2 (Sink is located at 500,500) are 100 to 200. As expected, with the nodes number increasing, energy consumption and delay improve, but isolation nodes probability decrease. In the simulation of isolation nodes probability, leach has highest isolation nodes probability, because of the difficult of choosing weights in HLGA the results seem to unstable, and NSGA always be lowest of three algorithms. Comparing Figure 5(b) with Figure5(c), HLGA has the lowest energy consumption and the highest delay. The result of Leach is nearly linearly with nodes number. And the performance of NSGA is approximate to Leach.



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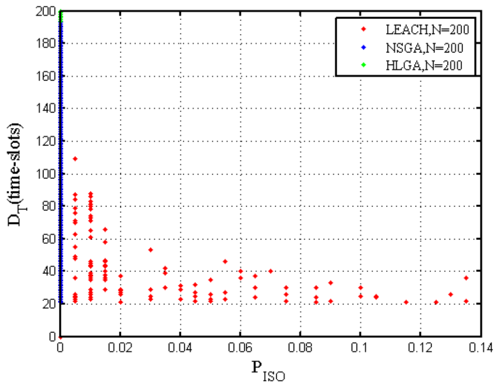


(b)

Figure 6. The simulation of different algorithms which contain Leach, NSGA and HLGA with 200x200(m^2): (a)The performance of energy consumption and delay; (b)The performance of delay and the probability of isolation nodes.

In Leach algorithm, the cluster-headers are elected by comparing random numbers which are assigned in each round and threshold. Moreover, the cluster-headers would not be reelected in next round, thus energy consumption is distributed into all nodes in the network. There is no doubt that leach can optimize the performance of network for energy consumption. However leach cannot control clusters size in the network, thus the delay and connectivity of leach may not be optimized. Figure 6 scatters all solutions of clustering (many solutions are overlapped at y-axis, especially NSGA and HLGA) and show that delay is higher than NSGA when the indexes of energy consumption are identical. The isolation nodes probability is also higher than NSGA and the number of isolation nodes even reaches up to 26 in some parts of solutions by leach. It proved that the performance of NSGA for cluster-based network is better than that in leach under constraints energy consumption, delay and connectivity.

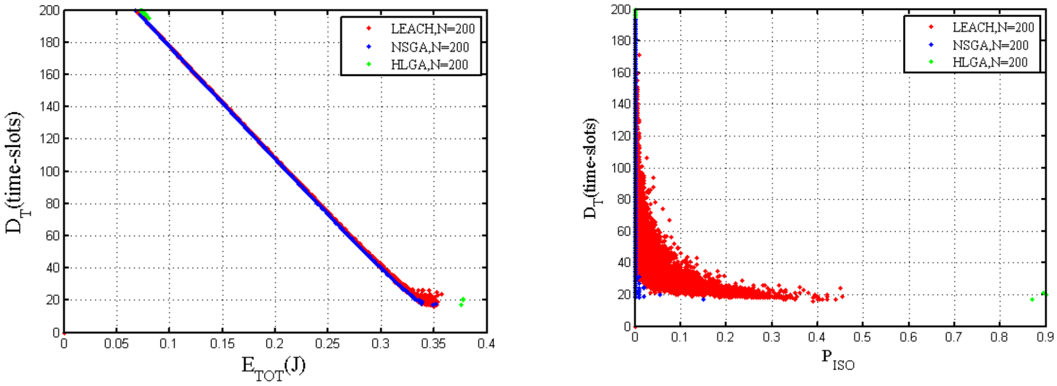
In HLGA algorithm, the selection of weights is important. It is difficult to find right combination of weights to optimize objectives, especially when objectives are constraints. In this case, objective function is extremely sensitive for alter of weights. Although weights change slightly, the results may still fluctuate strictly as well. Figure6 shows that some parts of solutions in HLGA for clustering are worse than NSGA even leach. As expected, HLGA failed to get most of the pareto frontier. In contrast, NSGA is good at maintaining population diversity and can find non-dominated solutions.

The network is also simulated under different sizes of area. Table I shows the configuration of scenarios. Figure6 and Figure7 show the results in size of scenarios are 1000x1000m^2 and 2000x2000m^2 respectively, and the results of Scenario I have been given.

Table I the configuration of simulation scenarios

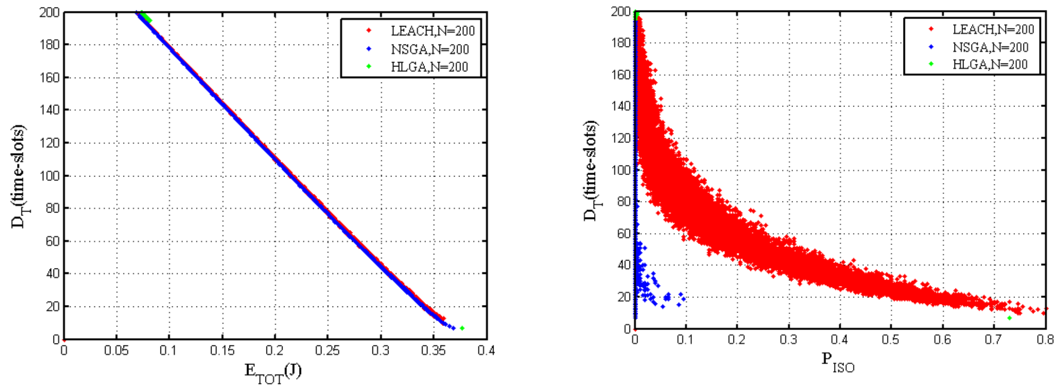
	The Size of Scenario(m^2)	The Location of Sink	The Numbers of Nodes
Scenario I	200x200	(100,100)	200
Scenario II	1000x1000	(500,500)	200

Scenario III	2000x2000	(1000,1000)	200



(a) **(b)**

Figure 6. The simulation of different algorithms which contain Leach, NSGA and HLGA with 1000x1000(m^2): (a)the performance of energy consumption and delay; (b)The performance of delay and the probability of isolation nodes.



(a) **(b)**

Figure 7. The simulation of different algorithms which contain Leach, NSGA and HLGA with 2000x2000(m2): (a)the performance of energy consumption and delay;(b)the performance of delay and the probability of isolation nodes.

We observed that the performance of optimization is also affected by size of scenarios. Wireless sensor nodes are battery-powered devices, therefore the power in the network has to be limited. Thus, in our work, the maximum power of nodes is fixed. The connectivity may depend on the random distribution of nodes and high node density in sensor networks may solve the connectivity problem in the network effectively. This, however, may not relieve the disconnection in the large scene but lack of sensors. When the communication distance of nodes is limited and the maximum power of nodes is stationary, the isolation nodes in the network will be surged while the distance getting larger, energy consumption of each node tends to the same and simulation results proved it. In Figure 6 and Figure 7, the isolation nodes probability of leach lift obviously and the energy consumption is increased linearly by the decrease of time-slots. Results also indicate that the optimization effect under constraint of delay and energy consumption getting smaller with enlarge of simulation scenario, but the one under constraint of delay and the probability of isolation nodes getting lager.

V. CONCLUSION

In this paper, we developed a model for cluster-based wireless sensor networks to optimize three objectives which contain energy consumption, delay and connectivity. We modify the existing model of connectivity and energy for hierarchical routing. The probability of isolation nodes is employed as one of the evaluating indicator for the performance of WSNs. Our analysis shows that Leach may not decrease the delay and isolation nodes simultaneously in the network, and HLGA is limited by weight in objective function. Simulation results show that NSGA own better performance than HLGA and Leach with constraint of delay, energy consumption and connectivity. We also compare three simulation scenarios, our results show that NSGA can achieve a better effect of optimization for energy and delay in small scenarios. However, for isolation nodes probability and delay, we observed that the larger scenarios achieve the better performance.

ACKNOWLEDGMENT

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