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A Lifetime Maximization Algorithm Based on Heuristic Strategy for Wireless Sensor Network

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Abstract. *Wireless sensor network (WSN) is an important branch of modern communication system, which plays a significant role in human life and production. With being deployed in wide area and complex environment, the battery-powered sensor nodes are difficult to be charged or replaced. Thus it will seriously affect the network lifetime so as to limit the application. For network lifetime issues, a mathematical model is established based on node deployment, activity scheduling, data routing and sink mobility in this paper. Moreover, two heuristic algorithms are proposed to maximize the lifetime and accelerate the process of solving the mathematical model as well. Simulation results show that the proposed algorithms can extend the lifetime of WSN effectively.*

Keywords: Wireless sensor network, Node deployment, Activity scheduling, Data routing, Mobile sink

1. **Introduction.** Wireless sensor network (WSN) is an important part of modern communication system, consisting of sensor nodes with limited energy resources, which has been widely used in various fields [1]. The performance of WSN needs to be improved due to the restriction of characteristics and application. Network lifetime is a key design issue to improve the performance of WSN [2]. Sensor nodes being deployed in harsh environment are difficult to be replaced. Moreover, the failure of sensors may cause the network to partition into disjoint blocks and would thus violate the connectivity requirement [3].

In recent years, a variety of techniques has been proposed to prolong WSNs' lifetime. The researches for the maximum lifetime of WSN mainly focus on the control of energy consumption. Wang [4] and Meng [4]built a decision model for heterogeneous WSN so as to avoid the need of geographic location information, based on which the Useful Lifetime Maximization for Partial Coverage Conserve (ULMPCC) is proposed. This protocol can decide the activity scheduling according to the nodes' remaining power, so as to control the energy consumption and prolong the lifetime of network. However, it does not consider the issues of network construction, such as node deployment and data routing. Zhang [5] and Wu [5] presented a hybrid scheme to tackle the node select problems. Bouabdallah [6] prolonged network lifetime through a multiple paths routing protocol. Latif [7] introduce a new routing technique to solve the problem of unbalanced energy utilization. Nguyen [8] and Dao [8] proposed an energy-based cluster head selection algorithm to support long-lifetime in WSNs. [5-8] optimized the data routing to extend the network lifetime, but the efficiency is not apparent enough for most large-scale application. This paper prolongs the network lifetime with the consideration of the node deployment, activity scheduling, data routing and sink mobility.

The main contributions of this paper are as follows: (1) A mathematical model is established based on node deployment, activity scheduling, data routing and sink mobility. (2) Two heuristic algorithms are proposed to solve the mathematical model in limited running time. The paper is organized as follows: Section 2 provides the mathematical model and two algorithms. Section 3 describes the simulation results and the performance analysis. Section 4 summarizes this paper.

2. **Mathematical Model and Algorithm of The Network Lifetime.** The mathematic model is established for WSN with several practical parameters. The optimal solution of sensor deployment, activity scheduling, mobile sink and data routing problem (SAMDP) can be obtained by solving the linear programming formulations. Two practical heuristic algorithms are proposed to solve these formulations, namely period iteration heuristic and sequential assignment heuristic.

2.1. **Mathematical model.** Two different working states are selected to make the problem more imaginative. The sensor may send the sensing information to its own sink directly or indirectly as in Figure 1(a), and may send the information to several relative sinks as in Figure 1(b). Figure 1 shows the position of sensors and mobile sinks in two periods, as well as the data routing information indicated by arrows. Some sensors are active in both two periods, while others are in sleep state in one period but active in the other period. Each point in the interested area is covered by at least two sensors to enhance the stability of monitoring. It can be seen that some sensors send the collected data to the sink directly, while others send the collected data to the adjacent sensors which act as the relay nodes.

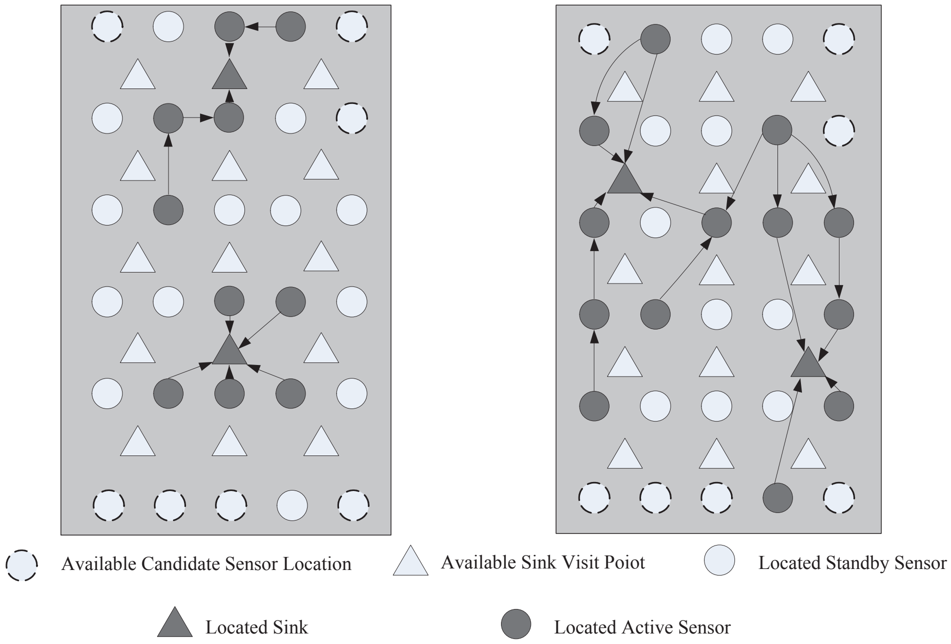

Figure 1. Network with sensors, mobile sink and data routing: (a)Data collection by particular sink; (b)Data collection by several different sinks

Mixed Integer Linear Program (MILP) mathematical model is established as follows:

Step 1: Assuming that there are K points in WSN, where P points are selected to deploy the sinks in each period t of WSN lifetime T with the number of the sinks can be obtained by $\sum_{\vartheta \in N} z_{\vartheta t} = P, t \in T$.

Step 2: The sum of data transmission between sensors and sinks (or adjacent sensors) in the whole network can form the flow balance equation as (1):

$$\sum_{s \in R} \sum_{j:i \in S_{js}} x_{jsirt} + h_r a_{irt} = \sum_{\vartheta \in N_{ir}} y_{ir\vartheta t} + \sum_{s \in R} \sum_{j \in S_{ir}} x_{irjst}, i \in S, r \in R, t \in T \tag{1}$$

Step 3: The upper limit of energy consumed by each sensor in the whole lifetime period can be deduced as (2):

$$\sum_{t \in T} (c^s a_{irt} + c^r \sum_{s \in R} \sum_{j:i \in S_{js}} x_{jsirt} + \sum_{s \in R} \sum_{j \in S_{ir}} c^t_{ij} x_{irjst} + \sum_{\vartheta \in N_{ir}} c^t_{i\vartheta} y_{ir\vartheta t}) \leq E_r, i \in S, r \in R \tag{2}$$

Step 4: There is not any data inflow or outflow, if sensors are not active or deployed. So three constraints can be formed to reduce the calculation error:

$$\begin{cases} \sum_{r \in R} \sum_{i:\vartheta \in K_{ir}} y_{ir\vartheta t} \leq M z_{\vartheta t}, \vartheta \in N, t \in T \\ \sum_{s \in R} \sum_{j \in S_{ir}} x_{irjst} \leq M q_{irt}, i \in S, r \in R, t \in T \\ \sum_{s \in R} \sum_{j:i \in S_{js}} x_{jsirt} \leq M q_{irt}, i \in S, r \in R, t \in T \end{cases} \tag{3}$$

The number of the active sensors required for the normal operation of WSN satisfies $\sum_{r \in R} \sum_{i:k \in K_{ir}} q_{irt} \geq d_k$. The total energy budget B can be calculated according to the energy consumption of sensors, which satisfies $\sum_{i \in S} \sum_{r \in R} f_{ir} p_{ir} \leq B$. The sensors which are not deployed remain in a sleep state to save battery energy, so there is $q_{irt} \leq p_{ir}$. Parameters in the above formulations satisfy $w_t, a_{irt}, y_{ir\vartheta t}, x_{irjst} \geq 0$ and $z_{\vartheta t}, p_{ir}, q_{irt} \in \{0, 1\}$. The lifetime of WSN is defined as $\max \sum_{t \in T} w_t$. There are $i \in S, r \in R, t \in T, k \in K$ in the above formulation. The specific parameters in the above formula are defined in Table 1.

It should be noted that the results of the formulations include the positions of sensors and mobile sinks, activity scheduling, data routing and the sum of data flow. It can be achieved that the sensors in work schedule remain active, and others without transmission task are sleeping after getting the accurate transmission time and total amount of data transmission.

2.2. **Algorithm analysis.** Commercial solutions such as Gurobi 4.0 or Cplex 11.0 cannot obtain the accurate result of SAMDP formulations due to the time constraints. Two practical heuristic algorithms are proposed to find an ideal result in reasonable computation time, namely period iteration heuristic algorithm and sequential assignment heuristic algorithm.

2.2.1. *Period iteration heuristic algorithm (PIH).* The difficulty of getting the accurate results of formulations lies in the large number of binary variables in the model, i.e. $z_{\vartheta t}, p_{ir}, q_{irt}$.Removing the impossible cases can simplify the subset of model and reduce the number of binary variables.

Only p_{ir} is set as the initial value to reduce the number of binary variables in SAMDP formulation. The network lifetime of different situations can be obtained by changing the value of p_{ir} in the Gurobi. Therefore, the value of the period T is a very important parameter for mathematical model. With the decline of T, the solving process of SAMDP formulation will be easier, while the quality of results will be poorer. Thus, it is better to select the lowest value of T under the prerequisite of guaranteeing quality, represented by T^*. ϕ is the iteration time, which is assigned to 1 at the beginning of operation. The continuous variables w_t, x_{irjst} and $y_{ir\vartheta t}$ keep nonzero when the period value is no more

Table 1. Notations

Parameters	Definition	Parameters	Definition
B	Sensor placement budget	w_t	Length of period t
P	Number of sinks	R	Set of sensor types
N	Set of sink locations	T	Set of time periods
c^r	Unit data reception cost	f_{ir}	Cost of placing sensor(i, r)
Sensor(i, r)	Type r sensor deployed at point i	S	Set of candidate sensor locations
d_k	Coverage requirement of point k	K_{ir}	Set of points covered by sensor(i, r)
E_r	Battery energy of type r sensor	h_r	Data production rate of type r sensor
K	Set of points to be covered	a_{irt}	Auxiliary variable replacing $w_t q_{irt}$
M	A very large number	c^s	Unit sensing and coordination cost
N_{ir}	Set of sink locations neighboring sensor(i, r)	c^t_{ij}	Unit data transmission cost of arc ij
S_{ir}	Set of sensor locations neighboring sensor(i, r)	$y_{ir\vartheta t}$	Amount of flow from sensor(i, r) to sink deployed at point ϑ in period t
p_{ir}	Indicates whether or not sensor(i, r) is deployed	x_{irjst}	Amount of flow from sensor(i, r) to sensor(j, s) in period t
q_{irt}	Indicates whether or not sensor(i, r) is active in period t	$z_{\vartheta t}$	Indicates whether or not a sink is located at point ϑ in period t

than ϕ, i.e. $t \leq \phi$. In other words, the values of w_t, x_{irjst} and $y_{ir\vartheta t}$ will be zero when the period value is more than ϕ.

A mathematical model can be established after determining the variable value. Only p_{ir} relates to the locations of sensors in this mathematical model. Therefore, the analysis of this model is relatively easy. The model can be solved by Gurobi in a short time, then we can obtain the optimal results or the approximate optimal results. The next iteration will be carried out after getting the optimal solution of the ϕth iteration model, i.e. $\phi = \phi + 1$. The network lifetime would be prolonged with the increasing of ϕ theoretically, but there will not be significant changes when the number of iteration reaches a certain value in the actual analysis process. At this time, the algorithm is considered to obtain the optimal solution. The constraint conditions of the algorithm are presented in the following proposition.

Definition 2.1. *$O^{(\phi)}$ and $O^{(\phi+1)}$ are used to represent the solution of the ϕth and the $\phi+1$th iteration operation respectively. $w_t^{(\phi)}$ is the results of the tth calculation in the ϕth iteration. The operation result of model in iteration process follows descending order, i.e. $w_1^{(\phi)} \leq w_2^{(\phi)} \leq \ldots \leq w_\phi^{(\phi)}$, and $w_{\phi+1}^{(\phi)} = \ldots = w_T^{(\phi)} = 0$. Similarly, $w_1^{(\phi+1)} \leq w_2^{(\phi+1)} \leq \ldots \leq w_{\phi+1}^{(\phi+1)}$ and $w_{\phi+1}^{(\phi+1)} = \ldots = w_T^{(\phi+1)} = 0$. Finally, it can be proved that $O^{(\phi+1)} \leq O^{(\phi+1)} + w_\phi^{(\phi)}$.*

Definition 2.1 sets the upper limit for the solution of next iteration. The upper and lower bounds of the optimal solution could accelerate the calculation process. The periodic iterative heuristic algorithm is formally summarized in the theorem 2.1.

Theorem 2.1. *Let* $DIF = O^{(\phi)} - O^{(\phi-1)}$ *represent the difference between two iterations. The parameter* ε *is adopted to indicate the accuracy of calculation with the specific value based on the network settings. Let* $\phi = 1$*,* $DIF = 100$ *at the beginning of the operation. The upper and lower bounds will be confirmed when* $DIF > \varepsilon$ *and* $\phi > 1$*. Then, Gurobi solver will run the* ϕ *th model, and the process can be sped up through the upper and lower bounds.* $O^{(\phi)}$ *represents the optimal solution obtained by Gurobi solver. Operations will be carried out until* $DIF < \varepsilon$*, at this time* $\phi = T^*$*. Finally, the final results and the corresponding target values can be obtained.*

2.2.2. *Sequential assignment heuristic algorithm (SAH).* There is a logical order among the parameters design of WSN. The locations of sensors are prerequisites to set the activity scheduling. In addition, mobile nodes need to collect data from the active sensor, so the location of the mobile node and data routing can be determined after setting the work scheduling. Usually, the best locations of sensors are determined before setting the activity scheduling of the deployed sensors. Finally, mobile nodes and data routing can be identified.

Three sub problems are proposed for hierarchical WSN design. The first sub problem S1 is to determine the locations of the sensors, which is defined as $S_1 \leftarrow max \sum_{k\in K} u_k$. u_k represents the number of sensors that monitor the k point, which satisfies $0 \le u_k \le \sum_{r\in R}\sum_{i:k\in K_{ir}} p_{ir}$, $k \in K$. More sensors are deployed to enhance the flexibility of the activity scheduling.

$$\sum_{r\in R}\sum_{i:k\in K_{ir}} p_{ir} \ge d_k + 2, k \in K \tag{4}$$

(4) can ensure that there are enough sensors deployed near the K point, so at least $d_k + 2$ sensors can be used to monitor the environment of k point. The budget B and p_{ir} satisfy $\sum_{r\in R}\sum_{i\in S} f_{ir}p_{ir} \le B$ and $p_{ir} \in \{0, 1\}$ $(i \in S, r \in R)$ respectively.

The locations of sensors can be determined by solving S1. Then two other sub problems S2 and S3 are proposed to obtain the solutions of activity scheduling, mobile sink location and data routing.

The mathematical model of S2 is the same as MILP model except for $\sum_{r\in R}\sum_{i\in S} f_{ir}p_{ir} \le B$. p_{ir} can be obtained by solving S1, then p_{ir} and $z_{\vartheta t}$ are regarded as the initial values for S2. q_{irt} can be obtained by solving S2. The mathematical model of S3 is the same as MILP mathematical model except for $\sum_{\vartheta\in N} z_{\vartheta t} = P, t \in T$. p_{ir} in S1 and q_{irt} in S2 are regarded as the initial values to solve the sub problem S3. Then, we can get the position of mobile sink $z_{\vartheta t}$ which is taken as a new initial value for the S2 operation in next iteration process.

The theory of cycle iteration in period iterative heuristic algorithm can improve the network efficiency. The core of periodic iteration is to find the minimum number of iterations, which can make the maximum of the network lifetime, and this is the core of two heuristic algorithms. Finally, it should be pointed out that $Z_{\vartheta\phi} = Z_{\vartheta(\phi-1)}, \vartheta \in N$. The specific steps of the sequential assignment heuristic algorithm are shown in theorem 2.2, where L_2 and L_3 represent the network lifetime of S2 and S3 respectively, and L represents the whole network lifetime.

Theorem 2.2. *Let* $\phi = 1$*,* $DIF_1 = 100$*,* $DIF_2 = 100$ *at the beginning of the algorithm. Among them, there is* $DIF_1 = L_3 - L$ *and* $DIF_2 = L_3 - L_2$*. Firstly, the position parameter*

p_{ir} can be determined by solving S1. The value of calculated precision ε_1 and ε_2 depend on specific conditions. q_{irt} and L_2 can be obtained by solving S2 when $DIF_1 > \varepsilon_1$ and $DIF_2 > \varepsilon_2$. S3 can be solved by S1's p_{ir} and S2's q_{irt} to get L_3 and $z_{\vartheta t}$. $z_{\vartheta t}$ is taken as the new initial value for S2's model, and the iteration process will continue until $DIF_2 < \varepsilon_2$. We change the value of q_{irt}, and re-calculate the mathematical model of S3 at the beginning of each iterative process. Then the value of L_3 is given to L, i.e. $L = L_3$. The algorithm will continue until $DIF_1 \leq \varepsilon_1$, and then the maximum value of network lifetime L will be obtained.

3. **Simulation Results and Performance Analysis.** The performance of the two heuristic algorithms proposed in this paper will be evaluated on NS2 by comparing with the metrics of Gurobi and hybrid scheme (HM) [5]. The simulations refer to scenarios in which sensor nodes are deployed in a grid-like topology over a square area, and the distance between two nearby grid intersections is 15m. The operating duration threshold of the algorithms is 3 hours in each test to ensure the convergence. The calculation performance cannot satisfy the actual operation need, if the durations of algorithms are more than 3 hours. The lifetime is defined as the operate time until the proportion of the failed sensors reaches to 50%.

3.1. **Performance analysis of network lifetime in different ways.** The average network lifetime of each algorithm is simulated 5 times to evaluate the performance, as shown in Figure 2. Figure 2(a) shows that the maximum network lifetime value of Gurobi is higher than that of PIH and SAH in the case with 20, 30 and 40 candidate sensors. The maximum value of two heuristic algorithms are higher than that of Gurobi when the number of candidate sensors is larger than 50. The maximum network lifetime value of HM is higher than that of SAH when the number of candidate sensors is less than 200. Moreover, the heuristic algorithms have more obvious advantages for large networks. The network lifetime of PIH is longer than that of SAH when the number of candidate sensors is 20 and 30. The network lifetime of PIH and SAH is relatively close when the number of candidate sensors is less than 90. The situation in figure 2(b) and figure 2(c) is similar to that of figure 2(a). In summary, the performance of SAH and PIH are better than that of Gurobi and HM with respect to network lifetime in most cases.

3.2. **Average calculation time of different methods.** In each simulation process, the duration of Gurobi, PIH and SAH is limited in 3 hours. The results will be immediately recorded if the algorithms obtain the optimal solution within 3 hours, and the next experiment will begin.

Figure 3(a) shows the average computation time of Gurobi, PIH and SAH with 3 nodes. Two heuristic algorithms need less computation time than Gurobi. And Gurobi could get effective solution of the model after several rounds of iteration, while PIH and SAH can rapidly converge and obtain the results. In most cases, the computation time of SAH is longer than that of PIH. More accurately, the computing time of PIH and SAH is almost the same when the number of candidate sensors is 20 and 200. In other cases, PIHs computation time is 1.71∼4.01 times longer than that of SAH. Figure 3(b) and Figure 3(c) show the average computation time of Gurobi, PIH and SAH respectively when the number of nodes is 5 and 7 respectively. It is observed that the performance of PIH and SAH are similar to the situation with 3 nodes. Gurobi is difficult to obtain a satisfactory solution within limited computing time for large networks. Therefore, the performance advantages of PIH and SAH are more obvious

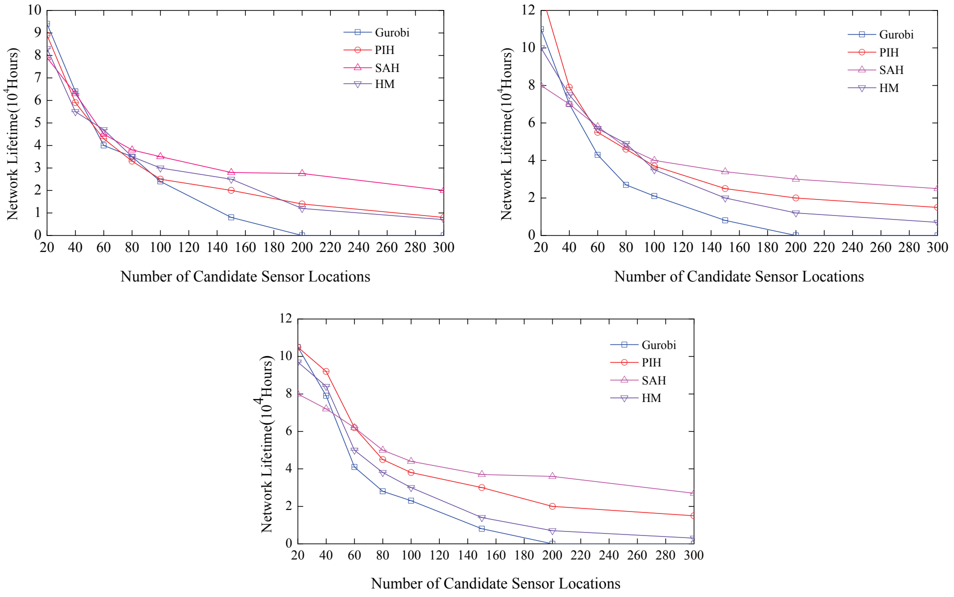

Figure 2. The maximum network lifetime of PIH, Gurobi, HM and SAH with different number of nodes: (a)The number of nodes is 3; (b)The number of nodes is 5; (C) The number of nodes is 7.

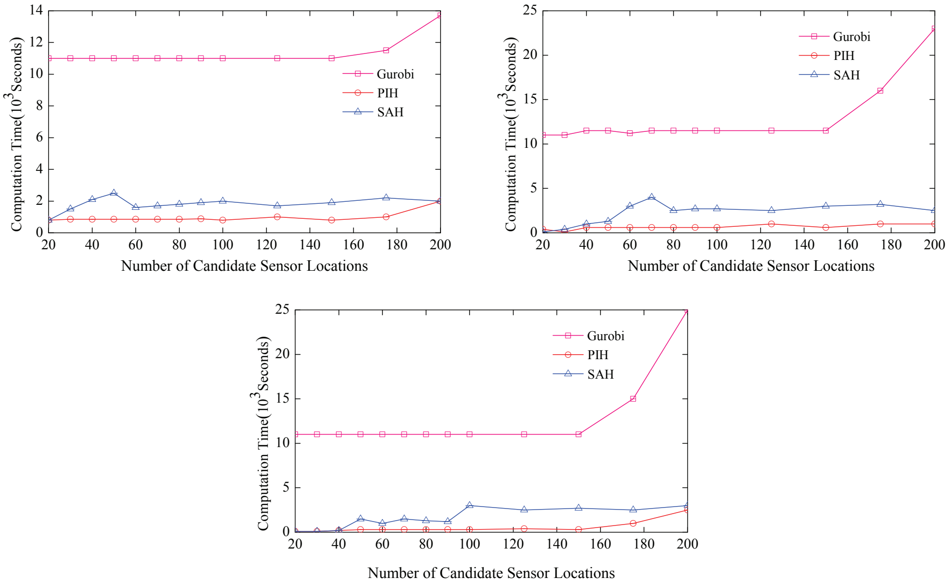

Figure 3. The average computation time of PIH, Gurobi and SAH with different number of nodes: (a)The number of nodes is 3; (b)The number of nodes is 5; (C) The number of nodes is 7.

3.3. **Stability analysis of algorithms with different data generation rates.** Figure 4(a) shows the percent deviations of PIH and SAH versus Gurobi with $h_r = 2048$bits/h respectively. Figure 4(b) shows the percent deviations with $h_r = 8192$bits/h. The data generation rate and the energy of sensors have opposite effect on network lifetime, and the percent deviation of SAH is more stable than that of PIH. It can be proved that PIH and SAH are more stable when the input parameters are constantly changing based on these observations, and the two heuristic algorithms can increase network lifetime better for larger network and more complex planning cases.

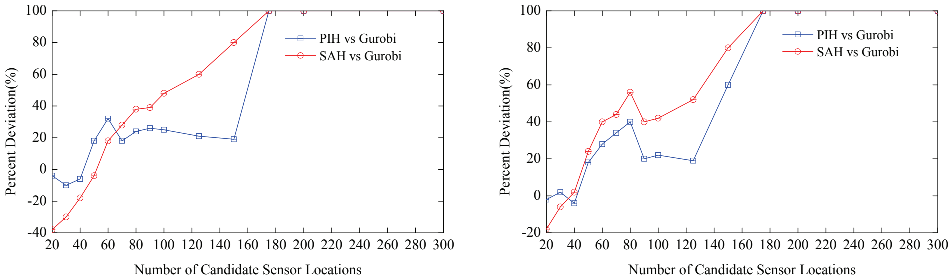

FIGURE 4. The different percent deviations of PIH and SAH with Gurobi: (a)h_r=2048bits/h; (b)h_r=8192bits/h.

4. **Conclusion.** Wireless sensor network (WSN) is an important part of modern communication system, composed by large number of sensor nodes with limited energy resources. Considering the practical application and large-scale deployment, the network lifetime is a key design issue to improve the performance of WSN. In this paper, a mathematical model is established based on the sensor deployment, activity scheduling, data routing and mobile sink. Then, the results of SAMDP formulations in the model are obtained by two proposed heuristic algorithms. The simulation results show that the performance of two heuristic algorithms is better than that of Gurobi and HM with limited computation time. The calculation ability of PIH and SAH can also cope with large network according to the data obtained in this paper.

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