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Research on Energy-saving Strategy of Wireless Sensor Network Based on Improved Ant Colony Algorithm

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On the basis of the ant colony routing algorithm, we propose an improved energy-efficient routing algorithm based on power-saving ant colony optimization (PSACO). Taking into account the residual energy of wireless sensors as a parameter, the proposed algorithm ensures the route between the source and destination nodes to be optimal more efficiently and quickly, and finds an optimal solution that prolongs the network's lifetime as long as possible. In improving the previous ant colony routing algorithm, an advanced bionic intelligent algorithm is integrated as it is known for its excellent distribution and the on-demand energy-saving mechanism. The proposed algorithm selects the best path to balance the network load and achieve positive feedback using distributed computing. The test of the proposed algorithm for measuring the vibration characteristics of a bridge validates that the improved ant colony routing algorithm is energy-efficient and robust, and shows excellent network load balancing with positive feedback. Therefore, the improved ant colony routing algorithm proves its superiority in wireless sensor network routing.

1. Introduction

The fundamental problem of wireless sensor networks (WSNs) is how to prolong their operational time using limited energy resources, given that they need a continuous power supply. The reduction in energy consumption or the effective energy management of the sensor network is thus critical for developing the networks. Typically, power control methods are used for saving energy for WSNs.(1) By adjusting the transmission power of the sending node, the power control algorithm improves channel spatial reuse, reduces interference to neighboring nodes, and increases the network capacity. However, the power control algorithm must be distributed, simple, robust, and scalable, adapting to different network conditions.(2)

Current research on wireless ad hoc network power control technology mainly focuses on power control at the link and network layers.(3) At the link layer, power control technology

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provides parameter information about the link using interactive control information before sending data packets with the conflict-avoidance protocol.(4) At the network layer, the power control algorithm dynamically changes the network's topology and route selection by adjusting the transmitting power to achieve optimal network performance. In this way, a power control mechanism combines the network and link layers.(5)

We consider the energy consumption problem of WSNs at the level of single nodes and the whole network.(6) Through the analysis of wireless sensor nodes including hardware, software, and collaboration between them, low-power consumption and high-reliability electronic components are selected to minimize component loss and meet the requirements. In choosing software, the ability to extract characteristic signals from the sensor unit and transmit them in fewer data frame formats is considered to reduce energy consumption during data transmission. Then, the microprocessor can be set to different sleep modes in the idle state, and the wireless module can be put to sleep to save energy when it has no data sending or receiving task.(7)

To minimize energy consumption when transmitting data from the start node to the destination node, the network layer's routing protocol algorithm extends the network's life. The ant algorithm, a bionic intelligent algorithm, is used with the remaining energy of the wireless sensor. When an on-demand energy-saving mechanism is adopted, the algorithm only starts on a request. The collective behavior of actual ant colonies inspires the ant algorithm as the ants form a highly organized group with a well-assigned role of labor, mutual communication, and information transfer to complete complex tasks beyond the ability of individual ants. The optimal path between the source and destination nodes is selected to prolong the network lifetime as much as possible.(8) These characteristics are reflected in the ant colony algorithm and fit into the use of the algorithm for WSNs.

Therefore, we develop an improved energy-efficient routing algorithm for WSNs based on the power-saving ant colony optimization algorithm (PSACO algorithm). As the PSACO algorithm uses the residual energy of wireless sensors, it has advantages in energy efficiency, network load balancing, robustness, positive feedback, and distributed computing. A simulation using the PSACO algorithm for the bridge health monitoring model was carried out to validate its efficiency. With the analysis of the energy consumption in WSNs from the perspectives of a single node and the whole network, solutions in hardware, software, and collaboration between them in WSNs can be found effectively. The algorithm can also be used for solving the energy consumption problem and finding energy-efficient routing for WSNs.

2. Methods

2.1 Principle of ant colony algorithm

Ants in nature have the behavior of releasing pheromones along their foraging paths.(9) Released pheromones leave pheromone trajectories that have the information on ants' movements to complete the complex task of finding the shortest path from the nest (source node) to the food source (destination node). Ants can make a decision on the basis of the pheromone concentration on the path, and the path with the highest pheromone concentration is found to be optimal. In the beginning, the path chosen by ants is not necessarily the shortest. Assuming that all ants advance at the same speed, the path taken by the first ant returning to the nest is the shortest path found. The short path has a higher pheromone concentration, which attracts more ants to take this path. This positive feedback mechanism enables the colony to find the shortest path between the nest and the food source as illustrated in Fig. 1.[10]

2.2 Measuring point optimization principle based on improved ant colony algorithm

Power-saving ant colony optimization (PSACO) is an on-demand algorithm, derived from the ant colony algorithm. In using PSACO for WSNs, the energy of the battery of the wireless sensor node and its variance are used as the objective functions of pathfinding.[11] The algorithm only needs to use local network state information, so it has strong distribution and robustness. The random small probability mutation strategy is designed to prevent premature convergence and avoid the routing result falling into the local optimal solution. At the same time, to ensure Quality of Service (QoS), the algorithm sets a hop limit.

In this algorithm, artificial ants play different roles at different times. The artificial ants that start from the source node and do not reach the destination node are called advancing ants, which follow the local pheromone release rule. The artificial ants that arrive at the destination node are called return ants, which follow the global pheromone release rule. The initial pheromone concentration is set as constant. To avoid stagnation in the searching path, the upper and lower limits of pheromone concentration are set in the pathfinding process by referring to the idea of the max-minimum ant system. The mutation strategy is added in the advancing ant path finding process to prevent the search from falling into the local optimal. Returning ants must release more pheromones than advancing ants to speed up the convergence of the algorithm

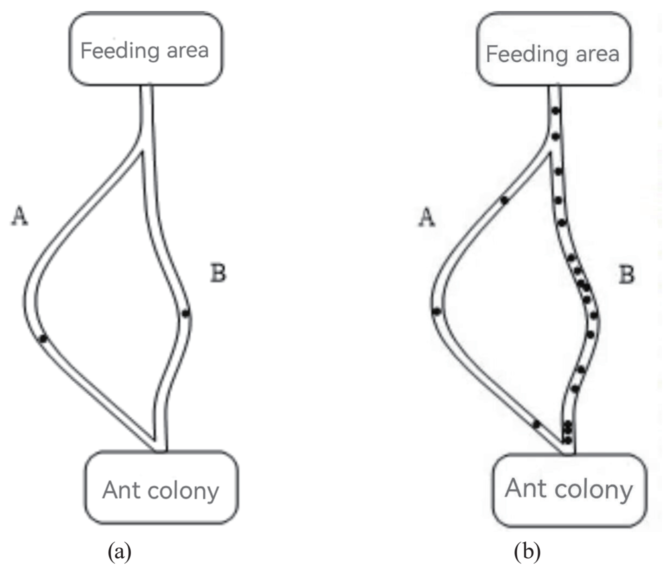


Fig. 1. (a) Ant foraging map 1 and (b) ant foraging map 2.

for finding the optimal solution in a short time. According to the actual needs of WSNs, the optimal route except the optimal solution is saved as the standby route in case of link failure, thus increasing the robustness of the algorithm.

2.2.1 Definition of algorithm

According to Eq. (1) of the basic ant colony algorithm, the amount of pheromone deposited by the kth ant on the path (i, j) at the time interval $(t, t+1)$ is defined as

$$\Delta\tau_{ij}^{k}(t,t+1)=\begin{cases}\lambda\cdot\left(p_i+p_j\right)\\ 0\end{cases}, \tag{1}$$

(i and j are neighbor nodes)

where p_i and p_j are the remaining battery energies of nodes i and j, respectively, and $\lambda > 0$ is the coefficient parameter. λ is generally set to 0.2–0.8.

$$\eta_{ij}=\begin{cases}\dfrac{\theta}{\left(p_i-p_j\right)^2+\varphi}\\ 0\end{cases} \tag{2}$$

(i and j are neighbor nodes)

In this algorithm, the visibility reflects the degree of balance of energy consumption between nodes. If the energy consumption of nodes is unbalanced, the variance increases, the visibility decreases, and the probability of ants choosing the visibility also decreases. $\theta > 0$ is the coefficient parameter, which is usually set to 0.5–1. φ is a small coefficient generally between 0.1 and 0.5.

The local pheromone renewal equation for advancing ant k is

$$\tau_{i,j}(t,t+1)=(1-\rho)\cdot\tau(t)+\rho\cdot\Delta\tau_{i,j}^{k}(t,t+1). \tag{3}$$

The pheromones released by advancing ants along the path help ants accelerate the search. The global pheromone update equation for returning ants is as follows.

$$\tau(i,j)=(1-\rho_1)\cdot\tau(i,j)+\rho_1\cdot\Delta\tau(i,j) \tag{4}$$

Returning ants release pheromones only to the links on route L between the source node and the destination node. Thus, when (i, j) belongs to the links on this route, Eq. (5) is deducted from Eqs. (1)–(4).

$$\Delta\tau(i,j) = p_{max}\frac{(p_i - \overline{p})^2 + \delta}{\sum_{k\in L}(p_k - p)^2}, \tag{5}$$

where P_{max} is the maximum remaining battery energy of a node on the path, $\overline{P}$ is the average remaining battery energy of a node on the path, and δ is a small constant, i.e., 0.1 in this study.

2.2.2 Implementation of algorithm

A. Model initialization

The initialization process of the model is shown in Fig. 2. The number of ants must be set according to the actual requirements. If there are too few ants, the search scope becomes small, and it is easy to fall into a local optimal route with the obtained route suboptimal. If there are too many ants, although the search scope is expanded, the convergence becomes slow. An experiment shows that better routing is obtained when the number of ants is similar to the number of nodes. Therefore, the number of ants selected is supposed to be equal to the number of nodes. A taboo table is set to prevent ants from visiting nodes that have already been visited; otherwise, a loop is formed. Then, all nodes are initially set as unvisited nodes. The pheromone concentration of all links is set to a constant. The initial state of all ants is set to be alive. To simulate the different requirements of different service types on delay, a hop limit is selected according to the characteristics of a WSN for structural health monitoring.

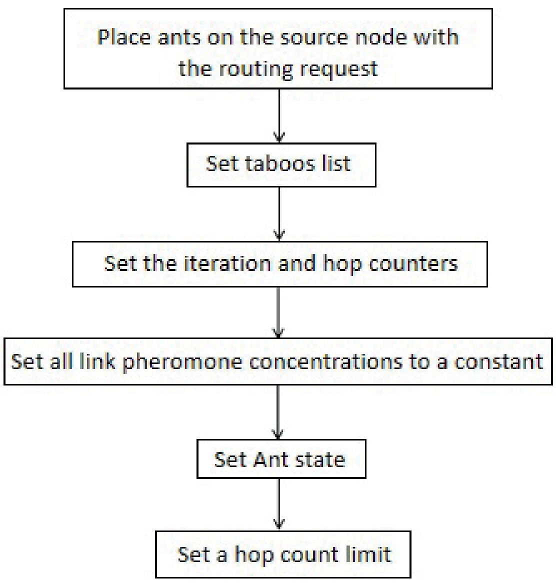


Fig. 2. Initialization of improved ant colony algorithm.

B. Formulation of algorithm rules

The improved algorithm employs the following rules:

1) Rule 1: During initialization, an ant is in the "alive" status, and it dies when the node is not the destination node and it cannot be moved according to the rule. In this case, a skip limit is exceeded.
2) Rule 2: Advancing ants follow local pheromone update rules according to Eq. (3). The upper and lower limits of pheromone concentration are set as τ_{min} and τ_{max}, respectively. If the concentration is outside the range, the upper and lower limits are imposed.
3) Rule 3: When advancing ants reach the destination node, they become returning ants. Returning ants save the routing information, including the routing node and the remaining battery energy of the routing node and its variance.
4) Rule 4: Returning ants follow the global pheromone update rule according to Eq. (4). The upper and lower limits of pheromone strength are set as τ_{min} and $3\tau_{max}$, respectively. If the concentration is outside the range, the upper and lower limits are imposed.
5) Rule 5: Local optimality is avoided, and a mutation strategy is adopted, in which an ant chooses any node as the next hop node among its optional neighbor nodes with a small probability (0.05–0.1).
6) Rule 6: Ants identify unique serial numbers for each detected node. When an ant arrives at a node, it first determines whether the node and its neighbors have a serial number. If not, it marks its serial number and sets the initial pheromone to τ_0. If there is a serial number, the node is marked as available. If the ant finds that the node marked as available by the previous ants cannot be detected, the node will be marked as a failed node without modifying its pheromone concentration. If the detected node is marked as a fault, the fault mark is changed to an available mark.
7) Rule 7: When sending data, each packet carries "route guides". The "routing ants" carry the optimal routing information and use this information to reconstruct the route when the link fails in the process of sending data. In general, each data group carries four to six road guides.
8) Rule 8: The termination condition of the algorithm is as follows. Within the number of iterations, when 90% of ants choose the same route, the route is considered the best route. The second and third most optimal routes are saved as standby routes.

C. Flow of the algorithm program (Fig. 3)

Firstly, m ants are placed on the node with the routing request (i.e., the source node) and sent out randomly from the source node. The initial pheromone value is set to τ_0, the taboo table is set, and the visited nodes are added to the taboo table. The iteration and hop counters are initialized. Then, each ant detects the neighbor node, operates on the node according to rule 7, selects the next node according to the pheromone table and mutation probability, and updates the pheromone table according to the local update rule. Secondly, the ants that arrive at the destination node and do not die return to the source node along the original route according to

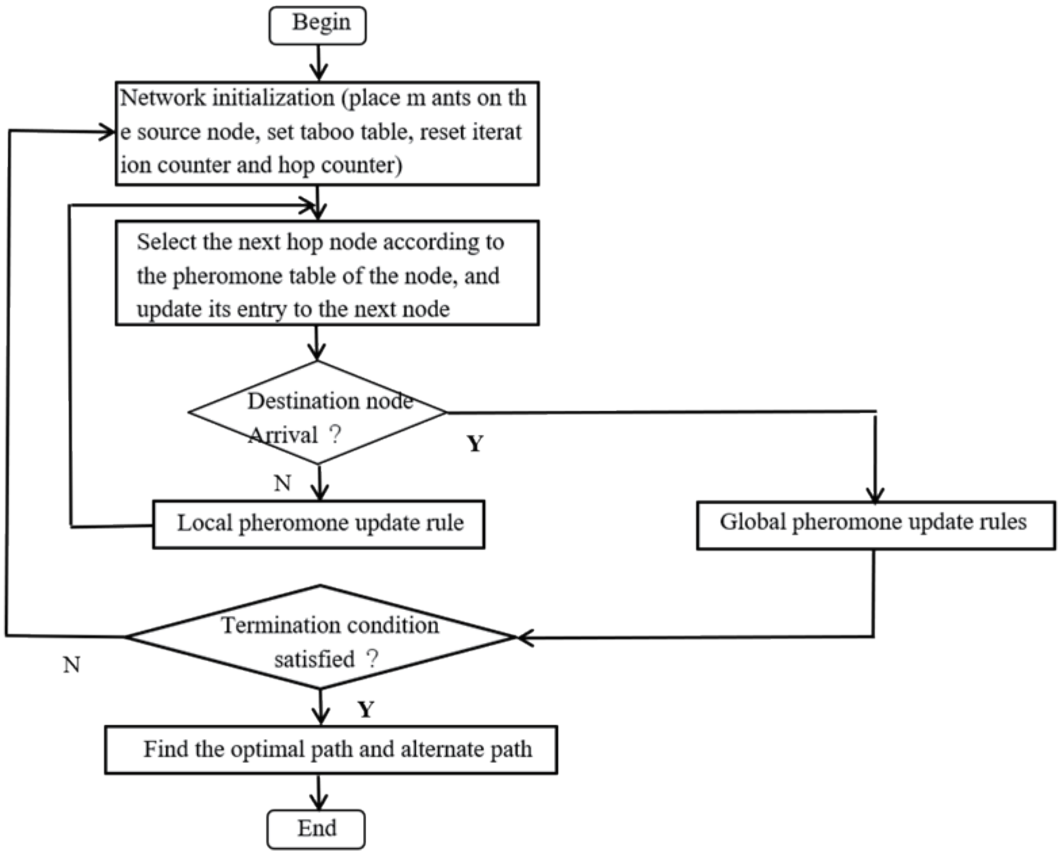


Fig. 3. Flowchart of PSACO algorithm.

rule 4 and bring back the routing information found. Thirdly, each returning ant updates the returned route by releasing pheromones, and if the returning ant finds that the link fails as it returns to the source node, then the route is reconstructed. Finally, the iteration termination conditions are examined according to rule 8. If the conditions are not satisfied, the algorithm returns to the beginning. If they are satisfied, the optimal solution is obtained and the two next most optimal solutions are saved as alternative solutions.

3. Improved Genetic Algorithm for Sensor Position Optimization

The core parameter of the proposed algorithm is the energy of the wireless sensor (i.e., the capacity of the lithium battery used). In the algorithm, the initial residual battery energy of each node is randomly generated by the program and varies between 10 and 100, which linearly corresponds to the actual capacity of the battery. Figure 4 shows the details of the corresponding relationship. The capacity of the battery used is 600 mAh, and its power consumption in different working statuses is given by equations. In the algorithm, it is assumed that each node does not consume energy when it is not part of an active route since the power consumption is extremely low in the idle state. After the route is established, the nodes on the route randomly wait for 0.4–1.2 s after sending data, then become sleeping nodes to save energy.

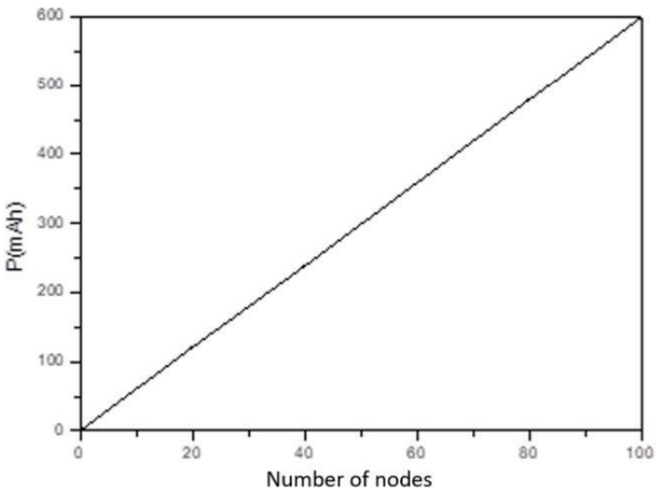


Fig. 4. Details of corresponding relationship.

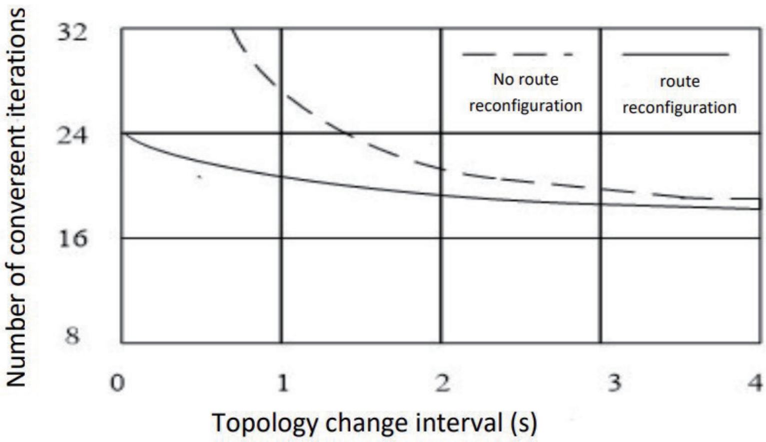


Fig. 5. Graph of number of convergence iterations changing with topology.

The parameters of the algorithm are selected as follows. The number of nodes ranges from 6 to 100, and the number of ants is the same as the number of nodes. The network lifetime is defined as the period from the start of the simulation until the first node is exhausted.

3.1 Network topology analysis

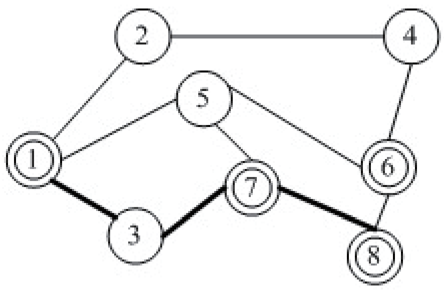
Figure 5 shows the number of iterations required for the convergence of the algorithm plotted against the topology. The dotted line is the curve without the route reconstruction policy, and the solid line is the curve with the route reconstruction policy. The route reconstruction policy adopts changes in network topology better than the route reconstruction policy. After about 3 s, the number of iterations required for convergence has little difference between the two policies.

This means that the algorithm already converges, so it is not sensitive to the interval between changes in network topology.

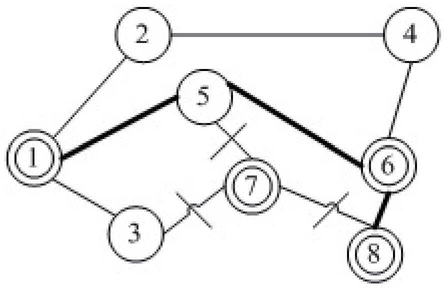
Figure 6 shows an example of algorithmic route reconstruction. For example, in an eight-node network, node 1 is the source node and node 8 is the destination node. Figure 6(a) shows the artificial ant route 1-3-7-8 without failure, and Fig. 6(b) shows that when node 7 fails, paths 3-7, 5-7, and 7-8 do not exist. In this case, the standby route 1-5-6-8 is started for route reconstruction to ensure that data can continue to be transmitted from source node 1 to destination node 8.

3.2 Energy consumption analysis

Table 1 and Fig. 7 show the consumption of the remaining battery energy of nodes in the 16-node network as the network operation time changes. In the simulation process, when the network is initialized, the remaining battery energy of 16 nodes is randomly selected (the energy range selected in this example is 10–20). As shown in the figure and table, the remaining battery energy of the eight nodes differs when the network starts running. The remaining battery energies of the source node (node 1) and destination node (node 16) decrease linearly because



(a)



(b)

Fig. 6. (a) Before and (b) after route reconstruction.

Table 1
8-node energy changes with operation time.

Operating hours	Node 1	Node 4	Node 6	Node 9	Node 10	Node 13	Node 14	Node 16
0	20	18.1933	17.86	19	19	18	17	19.9
2	19.513	17.7063	17.373	18.997	18.997	17.513	16.997	19.413
4	19.046	17.7032	16.906	18.53	18.53	17.51	16.994	18.946
6	18.579	17.7002	16.439	18.063	18.063	17.507	16.991	18.479
8	18.112	17.6972	16.436	18.06	18.06	17.504	16.988	18.012
10	17.645	17.2303	16.433	18.057	18.057	17.037	16.985	17.545
12	17.178	16.7633	16.43	18.054	18.054	16.57	16.982	17.078
14	16.711	16.7603	16.427	17.587	17.587	16.567	16.515	16.611
16	16.244	16.3023	16.424	17.584	17.584	16.564	16.044	16.144
18	15.777	16.2993	16.421	17.297	17.581	16.561	16.041	15.677
20	15.31	16.2963	15.954	17.294	17.578	16.558	15.574	15.21
22	14.843	16.2933	15.951	16.83	17.291	16.555	15.571	14.743
24	14.376	15.8293	15.474	16.827	17.288	16.088	15.568	14.276

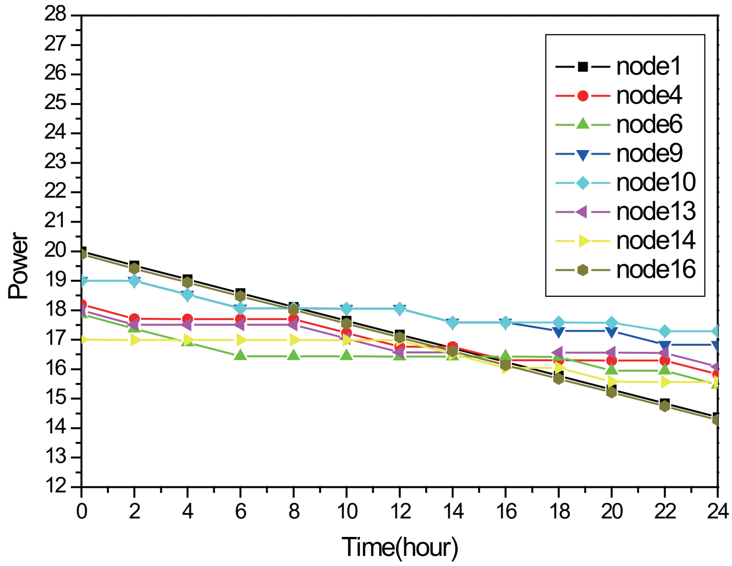


Fig. 7. (Color online) Energy consumption of some nodes during network operation.

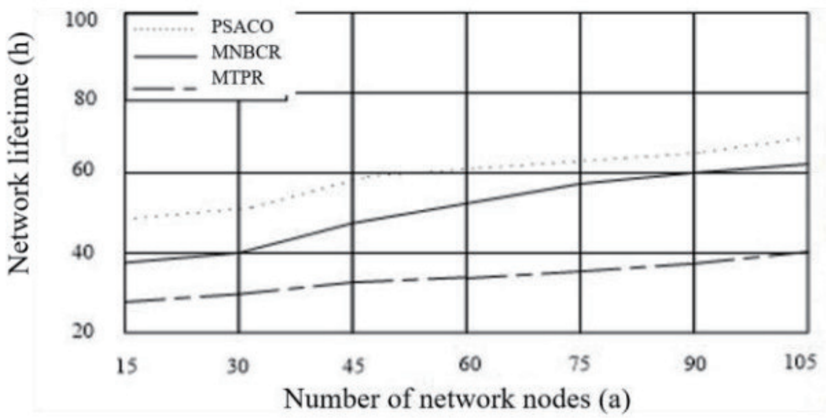


Fig. 8. Performance comparison of three algorithms.

these nodes keep sending and receiving data. With time, the difference between the remaining battery energies of the other nodes decreases, and the nodes with a larger remaining energy perform more forwarding tasks. After 8 h, the energy consumption between the nodes becomes more balanced. These results provide further evidence of the feasibility of the algorithm.

3.3 Performance comparison

Figure 8 shows the performance of the proposed algorithm compared with those of minimum transmission power routing (MTPR)[12] and minimum maximum battery consumption routing (MMBCR).[13] When the number of nodes in the network is small, the PSACO algorithm uses less energy than the other two algorithms. The MTPR algorithm has the lowest performance because its routing objective function is the minimum transmission power consumption.[14] Thus, the excessive power consumption of several nodes leads to network segmentation in a short time. With an increasing number of nodes, the lifetime of the network is extended, and the energy-saving effect of the PSACO algorithm is reduced.[15] This is because the convergence speed of the algorithm is reduced, which leads to a long operation time for the algorithm and a large battery consumption. When the number of nodes is about 45, the PSACO algorithm uses the least energy. Compared with MTPR, MMBCR can prolong the network lifetime, but there is a large difference in network lifetime between MMBCR and PSACO.

4. Results of Vibration Characteristics of Bridge with PSACO Algorithm

The PSACO algorithm was used to measure the vibration characteristics of a bridge with the on-demand energy-saving mechanism. We tested the route between the source node and the destination node and the working stability of the whole system. Nodes could be added to or disconnected from the network at any time without affecting the operation of other nodes. In the quasi-real-time transmission process, the nodes sent the collected data to the monitoring center in time with only a small amount of data loss. The test results of the vibration data collected from sensor nodes of two different units at sampling frequencies of 200 and 100 Hz are shown in Fig. 9.

Energy efficiency is related to the use of haptic feedback in sensor networks. Thus, haptic technology was used to provide feedback to users, such as vibration or tactile sensation, to indicate the status of the network or to alert the user to energy-saving opportunities. The arrays and flexible hardware were also used for the implementation of PASCO in sensor networks as the arrays of sensors can improve the accuracy and reliability of data collection, while flexible hardware enables the network to adapt to changing environmental conditions or user requirements.

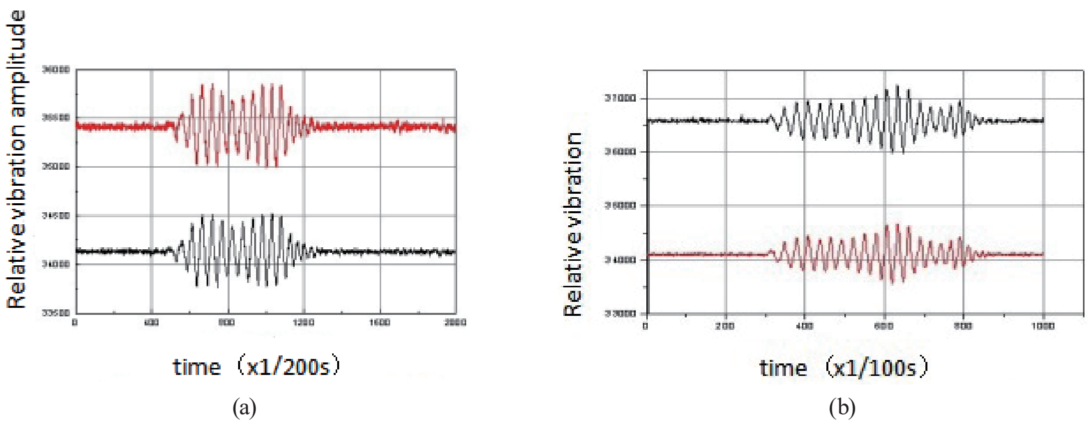


Fig. 9. (Color online) (a) Vibration signal (200 Hz) and (b) vibration signal (100 Hz) collected by sensor nodes in different cells.

5. Conclusions

The energy-efficient ant colony routing algorithm is proposed on the basis of PSACO with a better ant message design, probability selection, and pheromone update. On the basis of the routing characteristics of the ant colony algorithm, an algorithm with PSACO was used to test the performance of a WSN in measuring the vibration characteristics of a bridge. The results revealed that the PSACO algorithm showed significantly improved performance compared with the energy-efficient ant colony routing algorithm. The performance of the PSACO algorithm is superior to that of the energy-efficient ant colony routing algorithm when the network is scaled up, indicating that the PSACO algorithm is more appropriate for complex network structures. According to the measurement results, the nodes with the PSACO algorithm were turned off later than those with the energy-efficient ant colony routing algorithm. The number of active nodes in the network was significantly higher than that of the energy-efficient ant colony routing algorithm after 70 s of initial operation. These results indicate that the life cycle of a sensor network using the PSACO algorithm was longer than that using the energy-efficient ant colony routing algorithm. The PSACO algorithm had the advantages of energy efficiency, network load balancing, robustness, positive feedback, and distributed computing, making it advantageous for WSN routing.

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