# Ant Routing Optimization Algorithm for Extending the Lifetime of Wireless Sensor Networks

Xiao-Min Hu and Jun Zhang(corresponding author)
Department of Computer Science, Sun Yat-Sen University
Key Laboratory of Digital Life (Sun Yat-Sen University), Ministry of Education
Key Laboratory of Software Technology, Education Department of Guangdong Province
P.R. China
junzhang@ieee.org

***Abstract*—Since sensors are energy-limited in a wireless sensor network (WSN), how to balance the energy consumption among the sensors in the network so as to prolong the lifetime of the whole network is a critical research topic in the development of WSNs. In this paper, a novel ant routing optimization (ARO) algorithm is proposed for taking advantage of the redundant sensors in the network to help relay the sensed data traffic to the sink. By choosing suitable relay nodes, the lifetime of the sensing sensors are extended, resulting in the extension of the whole network lifetime. The ARO algorithm searches energy-efficient routing trees by considering the energy consumption of sensing, data transmission and reception. Simulation results show that ARO finds much better routing trees than the minimum transmission energy routing scheme.**

***Keywords*—Ant colony optimization, ant colony system, routing optimization, wireless sensor networks**

## I. Introduction

Wireless sensor networks (WSNs) are known for using a large number of sensors to monitor some targets. Each sensor is a simple instrument equipped with functional parts such as for sensing, data processing, radio transmission and reception. The most distinguishable feature of WSNs is that sensors are battery-powered and generally difficult to be recharged. Therefore, how to balance the energy consumption of sensors so that the lifetime of a WSN can be extended as much as possible is a critical point in the design of a WSN.

In order to ensure the performance of the task and reduce energy consumption, the development of a WSN is basically in energy-efficient hardware and the operating algorithms. Since the improvement in hardware is still at a slow pace, energy-efficient operating algorithms for sensors are more promising. Suppose a sensor has a fixed sensing range, the sensed data are processed and transmitted to the sink faraway. In that case, the quantity of data and the transmission distance are two most influential factors in energy consumption [1]. For reducing the quantity of data, there are mainly two methods. One is to acquire data periodically or on-demand, such as [2]-[4]. The other is to compress the data, resulting in various compression methods and data aggregation schemes [5]-[7].

Because long distance radio transmission is energy-consuming especially for the sensors far away from the sink, multi-hop transmission has been proven to be more energy-efficient than one-hop transmission [8]. However, conventional multi-hop routing schemes suffer from an undesirable effect. The sensors closest to the sink will run out of energy much sooner than the outer sensors because they need to relay large traffic of data from the outer sensors to the sink [9]. Clustering-based methods are viable for alleviating the unbalanced energy consumption among all sensors, but the process of electing sensors as the cluster heads induces extra energy consumption. Generally, there are always more sensors deployed in the area than necessary for accomplishing the monitoring task. That is, redundant sensors exist and they can be used as relay nodes without using their sensing components.

Suppose in a WSN, a group of sensors that completely cover the targets is determined for performing the sensing task, whereas the other nodes are redundant and can be used for relaying data traffic. Optimal routing trees for the sensors to send data to the sink can prolong the lifetime of the network to the greatest extent. In this paper, we propose an ant routing optimization (ARO) algorithm to find the routing trees.

Ant-based algorithms have gain successes in various fields [10]-[14]. In the area of wired networks, Caro and Dorigo [15] introduced an approach called AntNet to the adaptive learning of routing tables. The simulation results manifested that AntNet almost always outperformed other conventional routing protocols, such as OSPF and SPF, over a set of realistic test beds. Because wired networks are not energy-restricted, it is unsuitable to apply AntNet directly to WSNs. However, the success of AntNet shows that ant-based schemes are potential in WSNs. Based on AntNet, Chen et al. [16] proposed an improved ant-based protocol by using a type of search ant and a retry rule to avoid dead-lock. The adaptive routing (AR) and the improved AR proposed by GhasemAghaei et al. [17] combined reinforcement learning in the routing optimization. Zhang et al. [18] discussed how to adapt ant-routing algorithms to sensor networks and proposed three new ant-routing algorithms. Despite these algorithms reported some improvements than the previous algorithms in simulations, they only used the Euclidean distance between two nodes as the link cost and neglected the actual energy consumption of sensors to sense, transmit and receive data information.

Different from the previous ant-based algorithms for network routing, the proposed ARO algorithm considers the energy consumption for sensing, data transmission and

978-1-4244-6588-0/10/$25.00 ©2010 IEEE

reception, and searches for the trees that can balance the energy consumption among the sensors and the relay nodes until any one of the sensing sensors runs out of energy. The routing problem considered in this paper is a variant of the Steiner tree problem [19], which has been proven to be NP-complete [20]. By considering the actual energy consumption, the link cost is no longer a constant as the Euclidean distance between two nodes, but it is also affected by the data rate through the link and thus influences the lifetimes of the nodes.

The rest of the paper is organized as follows. Section II gives a formal definition of the considered lifetime model of WSNs. The implementation of the proposed ARO algorithm is presented in Section III. The performance of ARO is analyzed in Section IV. Section V concludes the paper.

## II. Definition of the Lifetime Model for WSNs

After sensors are deployed in the target area, some of them start to perform their task, such as environmental monitoring (e.g., recording temperature, humidity) or tracking intruders. The sensing part of a sensor is responsible for collecting the above sensing data, whereas the data are sent to the data center (or termed sink) via the communication part. The lifetime of a WSN is measured by the time since the network begins operations until it can no longer accomplish its task. Suppose there are redundant sensors in the network and the sensors can be divided into several groups, with each group being able to accomplish the task. The formal definition of the lifetime model for a WSN is described as follows.

### A. Model of System Lifetime of a WSN

*Definition* 1: Suppose there are $K$ groups of sensors (with each group accomplishing the objective task) and each group can operate for time $T_g$, $g$=1,2,…,$K$, then the *lifetime of a WSN* is

$$T_{\text{WSN}} = \sum_{g=1}^{K} T_g \tag{1}$$

The lifetime of a WSN depends on the lifetime of each group of sensors in operation.

*Definition* 2: According to Definition 1, the *lifetime of a group of sensors* $S_g = \{s_{j1}, s_{j2}, ..., s_{j|S_g|}\}$ is determined by the sensor having the minimum lifetime, as

$$T_{\text{g}} = \min(t_1^g, t_2^g, ..., t_{|S_g|}^g) \tag{2}$$

where $T_g$ denotes the lifetime of group $g$, $t_i^g$ is the estimated lifetime of sensor $s_{j_i}$ during the operation in group $g$, $i = 1,2,...,|S_g|$.

The estimated lifetime of a sensor $s_i$ during the operation in group $g$ is affected by its residual energy $E_i$ and the way it consumes energy. Besides sensing and communication, data storage and processing also consume energy. In order to have a simpler model representation, we only detail the energy consumption by sensing and communication for the lifetime of a WSN.

### B. Energy Consumption by Sensing

Each sensor has a sensing range $R_i$, which covers a certain area. In the application of point-coverage or area-coverage problems, active sensors in a WSN must keep the targets or the target area under surveillance at any time. Therefore, the coverage of sensors influences the formation of the complete coverage sensor groups. When sensors are randomly deployed, e.g., dropped from an airplane, an efficient scheduling plan is useful for selecting sensors into groups by turns to monitor the targets [21].

The sensing range of a sensor has a direct impact on its energy consumption by sensing. The energy consumed by a sensor $s_i$ for collecting a data bit of information using a sensing range $R_i$ can be estimated as

$$e_i^{\text{sen}} = w^{\text{sen}} R_i^v \tag{3}$$

or

$$e_i^{\text{sen}} = w^{\text{sen}} \exp(vR_i) \tag{4}$$

where $w^{\text{sen}}$ and $v$ are constants that depend on the signal and the medium properties. The larger the range of a sensor, the more energy is consumed, but the number of feasible complete coverage sensor groups may be bigger and thus the overall lifetime of a WSN is prolonged.

### C. Energy Consumption by Communication

When a complete coverage group of sensors is formed, each sensing sensor in the group collects sensed data and transmits them to the sink. Similar to sensing, the energy consumed by a sensor $s_i$ for transmitting per data bit to another sensor $s_j$ is closely related to the distance between the two sensors. According to [22], the energy consumption is computed as

$$e_{ij}^{\text{tran}} = e_{\text{tran}} + bd_{ij}^v \tag{5}$$

where $e_{\text{tran}}$, $b$, and $v$ are constants that depend on the transmission medium properties, $d_{ij}$ stands for the Euclidean distance between sensors $s_i$ and $s_j$ when sensor $s_j$ is the receiver of the data.

When a sensor $s_j$ receives data from the other sensor $s_i$, it also consumes its energy. Generally, the energy consumed for receiving data is considered as a constant for a specific data reception mechanism. We use $e_i^{\text{rec}}$ to denote the energy consumed by sensor $s_i$ for receiving per data bit.

It can be noted that the energy consumption by communication depends on the distance between any two communication sensors and the amount of data to be sent or received. In a WSN, sensors communicate via wireless signals. A new way for finding a proper route for each sensor to send the data and thus maximizing the lifetime of a WSN is the contribution of this paper.

### D. Impact of Routing for the Lifetime of a Group of Sensors

Fig. 1 shows a group of sensors for monitoring the target area. Only sensing sensors are responsible for sensing, but both the redundant sensors and the sensing sensors can send or receive data. The sensing sensors in the group are sufficient to monitor the target area. The sensing range of each sensor is represented by a circular area in the figure. The sink locates in the middle of the area and it is denoted by a symbol '*'.

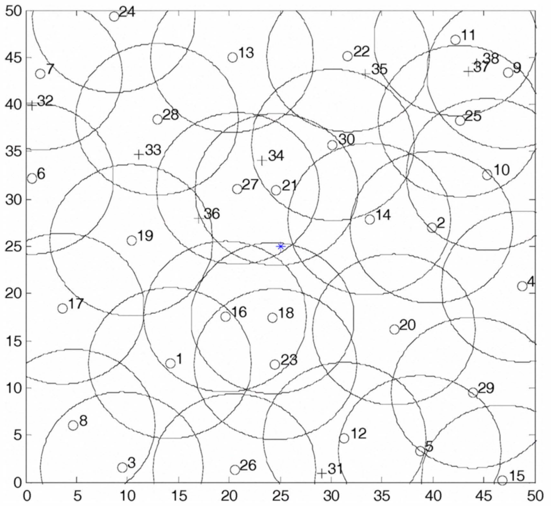

Figure 1. Illustration of complete coverage of sensing sensors and redundant nodes. The sensing sensors are denoted with a symbol o, whereas redundant nodes are denoted as +.

The lifetime of a group of sensors is determined by the time when at least one sensing sensor runs out of energy. Suppose the initial energy for each sensor $s_i$ is $E_i$, the estimated lifetime of a sensing sensor $s_i$ in the group $g$ is

$$t_i^g = \frac{E_i}{c_i^{\text{sen}} e_i^{\text{sen}} + \sum_{j\in\Omega_i} c_{ji} e_i^{\text{rec}} + (c_i^{\text{sen}} + \sum_{j\in\Omega_i} c_{ji}) e_{il}^{\text{tran}}} \quad (6)$$

and the estimated lifetime of an active node $s_i$ in the group is computed as

$$t_i^g = \frac{E_i}{\sum_{j\in\Omega_i} c_{ji} e_i^{\text{rec}} + \sum_{j\in\Omega_i} c_{ji} e_{il}^{\text{tran}}} \quad (7)$$

where $c_i^{\text{sen}}$ is the data generation rate of sensor $s_i$, $c_{ij}$ denotes the data rate passed from sensor $s_i$ to sensor $s_j$, $\Omega_i$ is the set of sensors that transmit data to $s_i$, and $s_l$ is the receiver of the data sent by $s_i$.

Because sensing sensors determine the lifetime of the network, it is better to transmit the sensed data to the relay nodes rather than use a closer sensing sensor to relay the data. In Section IV, we will use an experiment to show how different routing schemes impact the lifetime of a WSN.

## III. The Proposed Ant Routing Optimization (ACO) Algorithm for WSNs

The optimization objective is to maximize the lifetime of the whole network. When a complete-coverage group of sensors is determined, finding the optimal lifetime preservation routing strategy for transmitting the sensed data is an important step for prolonging the lifetime of a WSN. Ant colony optimization algorithms have shown great potential in network optimization. A novel ARO algorithm for finding the best routing and scheduling scheme of sensors is presented in this section. The flowchart of ARO is illustrated in Fig. 2.

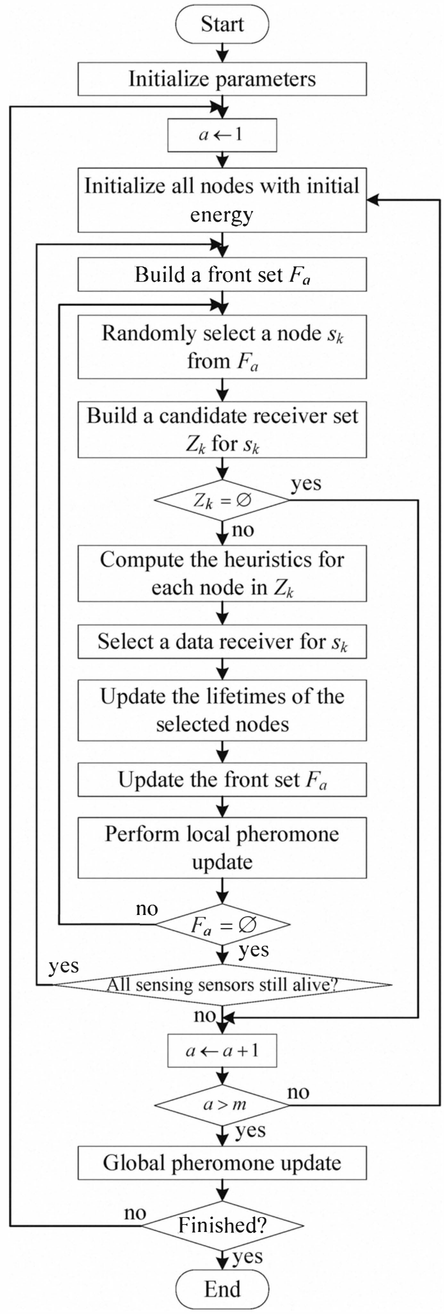


Figure 2. Flowchart of the proposed ARO algorithm.

### A. Initialization of ARO

When a complete coverage group of sensors is determined, the energy of each sensor and their locations are known. A graph is thus formed, with the sensors in the group as nodes. Suppose the maximum transmission range of a sensor $s_i$ is $r_i$, $i$=1,2,…,$|S_g|$. The sensors within the range $r_i$ around sensor $s_i$ are neighbors of $s_i$. Any sensor can send data directly to its neighbors and there is an edge between these two nodes in the graph.

In the algorithm, each ant is a metaphor for a constructive process for selecting components to form a solution. Initially, each edge has a small amount of pheromone deposit, which is used for attracting ants to select the edge.

*B. Construction Behavior of an Ant*

For a group of sensors, there are $n_1$ sensing sensors and $n_2$ redundant relay nodes. Each ant $a$ has a front set $F_a$ initially containing all sensing sensors. The ant constructs a routing tree based on the nodes in the front set and finishes a tree when the front set is empty. The solution construction behavior of an ant is described step by step as follows.

Step 1: Randomly select a sensor from the front set $F_a$. Suppose the selected sensor is $s_k$.

Step 2: Build a candidate receiver set $Z_k$ for $s_k$. The set $Z_k$ contains the sink $s_0$ and the sensors that satisfy

$$E_l > \varepsilon \text{ and } d_{kl} < r_k \text{ and } d_{l0} < d_{k0} \text{ and } d_{kl} < d_{k0} \quad (8)$$

where $s_l \in Z_k$. That is, the sensors in $Z_k$ must have enough energy ($E_l > \varepsilon$), locate in the neighborhood of $s_k$ ($d_{kl} < r_k$), be closer to the sink than $s_k$ does ($d_{l0} < d_{k0}$), and $s_k$ is closer to the sensors than to the sink ($d_{kl} < d_{k0}$).

Step 3: If $Z_k = \varnothing$, go to Step 11. Otherwise, compute the heuristic values for each sensor in $Z_k$ as the receiver of the data from $s_k$. There are two kinds of heuristics for each sensor. For any sensor $s_l \in Z_k$, the heuristic $h_{1l}$ is simply based on whether the sensor $s_l$ is a sensing sensor or a relay node.

$$h_{1l} = \begin{cases} 1, & \text{if } s_l \text{ is a sensing sensor} \\ w, & \text{otherwise} \end{cases} \quad (9)$$

where $w$ is a predefined reinforcement weight with $w \geq 1$.

The heuristic $h_{2l}$ is used to measure the influence of selecting $s_l$ as the receiver of the data from $s_k$. It equals to the minimal estimated lifetime of $s_k$ and $s_l$ once $s_l$ is chosen as the data receiver.

$$h_{2l} = \min(\tilde{t}_k, \tilde{t}_l) \quad (10)$$

where $\tilde{t}_k$ and $\tilde{t}_l$ are the estimated lifetime of $s_k$ and $s_l$.

For sensor $s_k$, if it is a sensing sensor and has not been visited by the ant before, it now needs to send its sensing data rate $c_k^{\text{sen}}$ to $s_l$. The data rate through the edge from $s_k$ and $s_l$ becomes

$$\tilde{c}_{kl} = c_k^{\text{sen}} \quad (11)$$

Its estimated lifetime for sending the data is computed as

$$\tilde{t}_k = \frac{E_k}{c_k^{\text{sen}} e_k^{\text{sen}} + c_k^{\text{sen}} e_{kl}^{\text{tran}}} \quad (12)$$

If the sensing sensor $s_k$ has been visited by the ant, it has a previous estimated lifetime $t_k$ and a total input data rate $F_k^{\text{in}}$. By adding its own sensing data, the data through the edge from $s_k$ and $s_l$ becomes

$$\tilde{c}_{kl} = F_k^{\text{in}} + c_k^{\text{sen}} \quad (13)$$

The new estimated lifetime of $s_k$ by selecting $s_l$ as the data receiver is computed as

$$\tilde{t}_k = \frac{1}{\dfrac{1}{t_k} + \dfrac{c_k^{\text{sen}} e_{kl}^{\text{tran}}}{E_k}} \quad (14)$$

Otherwise, if $s_k$ is a relay sensor, based on the construction of the front set, the sensor $s_k$ must have been selected by the ant and has a previous estimated lifetime $t_k$. Because a relay sensor does not generate new data, the data rate through the edge from $s_k$ to $s_l$ equals to its input data rate, as

$$\tilde{c}_{kl} = F_k^{\text{in}} \quad (15)$$

and its new estimated lifetime is computed the same as (14).

For sensor $s_l$, if it is the sink, its lifetime is considered to be infinite, that is, $\tilde{t}_l = \infty$. Otherwise, it takes additional energy to receive the data. We use $E_l^{\text{in}}$ to denote the total energy consumption rate for receiving data before considering the data from $s_k$. If $s_l$ is a sensing sensor, the new estimated lifetime of $s_l$ is

$$\tilde{t}_l = \frac{E_l}{E_l^{\text{in}} + \tilde{c}_{kl} e_l^{\text{rec}} + c_k^{\text{sen}} e_k^{\text{sen}} + (F_l^{\text{in}} + c_k^{\text{sen}} + \tilde{c}_{kl}) e_{l,p(l)}^{\text{tran}}} \quad (16)$$

If $s_l$ is a relay node, the new estimated lifetime of $s_l$ is

$$\tilde{t}_l = \frac{E_l}{E_l^{\text{in}} + \tilde{c}_{kl} e_l^{\text{rec}} + (F_l^{\text{in}} + \tilde{c}_{kl}) e_{l,p(l)}^{\text{tran}}} \quad (17)$$

where $p(l)$ is the index of the data receiver node of $s_l$. Initially, sensor $s_l$ has not determined a data receiver node. Then its greedy best neighbor node is used as $p(l)$ in (16) and (17). Otherwise, if sensor $s_l$ has a receiver, the new data rate from $s_k$ to $s_l$ also needs to be added to the upstream visited route and the new lifetimes of the passed sensors are computed. If the new estimated lifetime of any one of the passed sensors is shorter than that of $s_l$, the shortest lifetime is used as the value of $\tilde{t}_l$.

Step 4: Apply a state transition rule to select the data receiver node for $s_k$. Similar to the realization in ant colony system (ACS) [23], the state transition rule takes into account both the exploitation and biased exploration for the selection. The rule is presented as

$$l = \begin{cases} \arg\max_{s_i \in Z_k} \{h_{1i} h_{2i} \tau_{ki}\}, & \text{if } q < q_0 \text{ (exploitation)} \\ L, & \text{otherwise (biased exploration)} \end{cases} \quad (18)$$

where $l$ is the index of the selected sensor, and $q$ is a uniform random value in [0,1). The parameter $q_0$ controls the probability of an ant to choose a neighborhood node that has the largest production of heuristic and pheromone values, or randomly choose a sensor from $Z_k$ according to the probability distribution given by

$$p(s_l) = \frac{h_{1l} h_{2l} \tau_{kl}}{\sum_{s_i \in Z_k} h_{1i} h_{2i} \tau_{ki}}, \; s_l \in Z_k \quad (19)$$

Step 5: Suppose the selected sensor is $s_l$, then update the lifetimes and the data rates along the affected edges. The realization is similar to (11)-(17) except that the updated values of lifetimes and data rates are assigned to $t_k$, $t_l$, $c_{kl}$, and the corresponding upper selected sensors in the route connecting $s_l$. If $s_l$ has not determined a receiver, the value of $e_{l,p(l)}^{\text{tran}}$ is considered as zero.

Step 6: Remove $s_k$ from the front set, i.e., $F_a \leftarrow F_a - \{s_k\}$.

Step 7: If $s_l$ is a relay sensor and has not been unvisited by the ant before, and does not have a receiver node, it is added to the front set, i.e., $F_a \leftarrow F_a + \{s_l\}$.

Step 8: Mark $s_l$ and the edge ($s_k$, $s_l$) having been visited by the ant, and set the receiver node of $s_k$ as $s_l$.

Step 9: Perform local pheromone updating to the selected edge as

$$\tau_{kl} \leftarrow (1-\rho)\tau_{kl} + \rho\tau_0 \tag{20}$$

where $\rho$ is the predefined pheromone evaporation rate, $\tau_0$ is the initial pheromone value.

Step 10: If $F_a \neq \varnothing$, go to Step 1. Otherwise, go to Step 11.

Step 11: If all the sensing sensors are still alive (i.e., the node having the shortest lifetime is a relay node), then go to Step 1 and construct another routing tree based on the residual energy on nodes. Otherwise, ant $a$ finishes its construction and a complete routing solution is constructed.

### C. *Cooperation of a Colony of Ants*

After an ant constructs a routing scheme for the network, the lifetime of the sensor group is determined. The local pheromone updating is used for reducing the attractions of the selected edges and thus the other ants have a higher probability to select other edges. The ants communicate indirectly via the pheromone density on the edges of the construction graph. Each time a colony of ants are dispatched to construct solutions. After all of them have finished constructing their own solutions, a global pheromone updating process is performed and the pheromones along the edges of the best solution are reinforced. The global pheromone updating rule is

$$\tau_{kl} \leftarrow (1-\alpha)\tau_{kl} + \alpha T_g^{\text{MAX}} \tag{21}$$

where $\alpha$ is the pheromone reinforcement rate, $T_g^{\text{MAX}}$ is the maximum lifetime of the sensor group $g$ found by the ants so far.

## IV. Performance Analysis of ARO

We use a series of WSNs to check the performance of ARO. Table I tabulates the attributes of the twelve WSNs, including the numbers of sensing sensors and relay nodes. All nodes are placed in a $50 \times 50$ area with the sink in the middle. The initial energy of each sensor is set to be 20 J. The parameters of energy consumption are set as $e_i^{\text{sen}} = 150$ nJ/bit, $e_{\text{tran}}$ = 50 nJ/bit, $b$ = 100 pJ/bit/m$^4$, $v$ = 4, $e_i^{\text{rec}} = 150$ nJ/bit. The data rate generated by each sensing sensor is 10 kbps. The sensing sensors in each test case can completely cover the target area and the number of complete sensing group $g$=1.

TABLE I. Attributes of the Tested WSNs

| Case | No. of Sensors | No. of Relays | Case | No. of Sensors | No. of Relays |
|---|---|---|---|---|---|
| 1 | 30 | 8 | 7 | 79 | 7 |
| 2 | 30 | 16 | 8 | 77 | 10 |
| 3 | 31 | 18 | 9 | 77 | 10 |
| 4 | 30 | 21 | 10 | 78 | 11 |
| 5 | 33 | 20 | 11 | 81 | 52 |
| 6 | 35 | 18 | 12 | 35 | 103 |

The parameter settings of ARO are the number of ants $m$ = 10, $w$ =1.5, $q_0$ = 0.95, $\rho = 0.1$, $\alpha = 0.9$. The initial pheromone $\tau_0$ is set equal to the lifetime of the network using a minimum transmission energy (MTE) routing tree. Each route in the MTE tree is the path with the minimum total transmission energy consumption to the sink.

The routing trees for case 1 are illustrated in Fig. 3. In Fig. 3(a), the sensors take the MTE routes to send data to the sink. It can be estimated that the nodes near to the sink take the largest traffic and prone to become dead first. The total lifetime of the WSN using the MTE routing tree is 295.927. On the other hand, Fig. 3(b)-(d) illustrate the three routing trees found by the proposed ARO algorithm. It can be seen that more nodes are involved in routing the data in the three trees. The energy consumption among the active sensors is more balanced than using the MTE tree. The lifetimes of the three trees are 382.139, 190.767, and 14.8569, respectively. The total lifetime of the network is the summation of the three trees as 587.7629.

Fig. 4 shows the lifetimes of the tested WSNs by using the routing schemes generated by ARO and MTE. Because ARO is a stochastic search algorithm, it is run for 10 times independently. The mean solution lifetime and the best lifetime are presented in the figure. The results demonstrate that ARO can extend the lifetime of the network almost twice of that by the MTE routing scheme. The performance of ARO is robust because the difference between the mean solution value and the best value is relatively small.

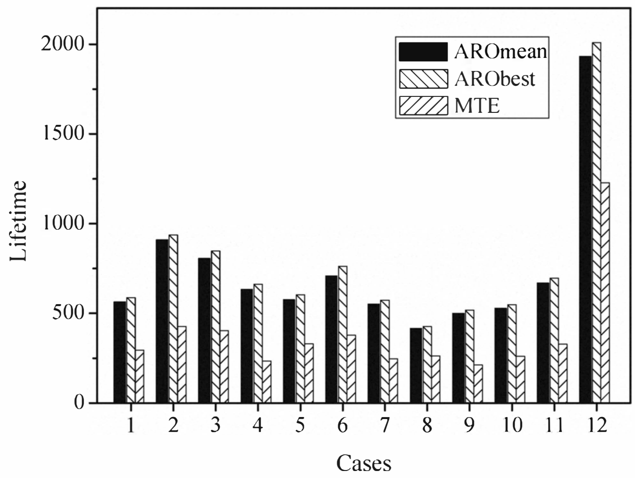


Figure 4. Comparison of the lifetimes of the twelve tested networks by using routing schemes generated by ARO and MTE.

## V. Conclusion

This paper proposes a novel ARO algorithm for finding the optimal routing trees to maximize the lifetime of a WSN. Different from the other ant-based routing algorithm, ARO considers the energy consumption of sensors in sensing, data transmission and reception. The ants in the algorithms estimate the most desirable nodes to be data receivers that minimize the

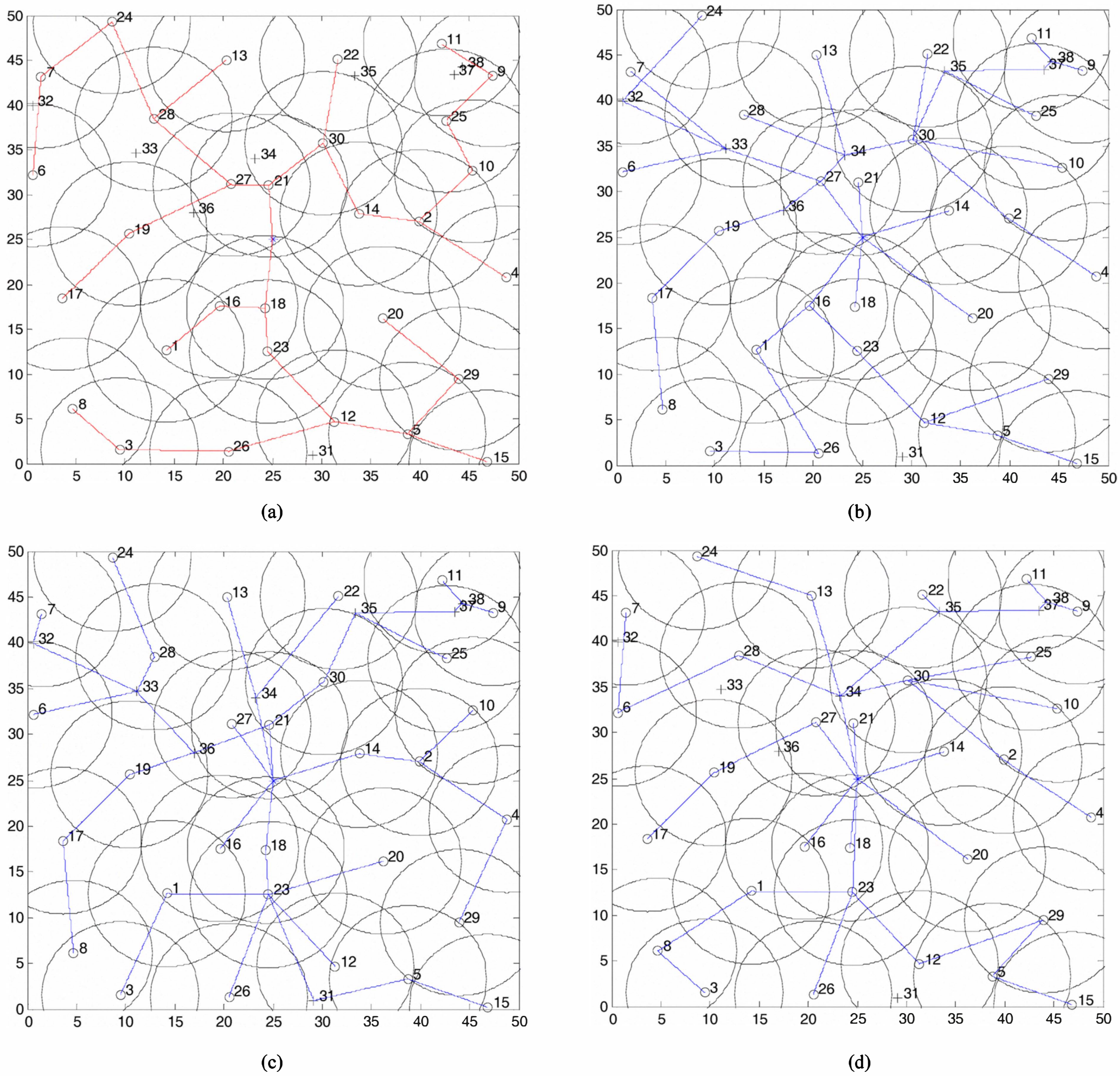

Figure 3. Routing trees of Case 1. (a) MTE tree. (b) Tree No. 1 by ARO. (c) Tree No. 2 by ARO. (d) Tree No. 3 by ARO.

influence to the lifetime of the sensor nodes. The simulation results show that ARO finds energy-efficient routing trees reliably. Future work of the research is to incorporate data aggregation techniques into the algorithm so that the amount of data traffic for transmission can be reduced.

## ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China Joint Fund with Guangdong under Key Project U0835002, by the National High-Technology Research and Development Program ("863" Program) of China No. 2009AA01Z208, and by the Sun Yat-Sen Innovative Talents Cultivation Program for Excellent Tutors No. 35000-3126202.

## REFERENCES

[1] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 40-50, 2002.

[2] X. Tang and J. Xu, "Adaptive data collection strategies for lifetime-constrained wireless sensor networks," *IEEE Trans. on Parallel and Distributed Systems*, vol. 19, no. 6, pp. 721-734, June 2008.

[3] G. Anastasi, M. Conti, and M. D. Francesco, "Extending the lifetime of wireless sensor networks through adaptive sleep," *IEEE Trans. on Industrial Informatics*, vol. 5, no. 3, pp. 351-365, Aug. 2009.

[4] Y. T. Hou, Y. Shi, and H. D. Sherali, "Rate allocation and network lifetime problems for wireless sensor networks," *IEEE/ACM Trans. on Networking*, vol. 16, no. 2, pp. 321-334, April 2008.

[5] X. Tang and J. Xu, "Optimizing lifetime for continuous data aggregation with precision guarantees in wireless sensor networks," *IEEE/ACM Trans. on Networking*, vol. 16, no. 4, pp. 904-917, Aug. 2008.

[6] C. Hua and T.-S. P. Yum, "Optimal routing and data aggregation for maximizing lifetime of wireless sensor networks," *IEEE/ACM Trans. on Networking*, vol. 16, no. 4, pp. 892-903, Aug. 2008.

[7] H. Zhang and H. Shen, "Balancing energy consumption to maximize network lifetime in data-gathering sensor networks," *IEEE Trans. on Parallel and Distributed Systems*, vol. 20, no. 10, pp. 1526-1539, Oct. 2009.

[8] J. Li and G. AlRegib, "Network lifetime maximization for estimation in multihop wireless sensor networks," *IEEE Trans. on Signal Processing*, vol. 57, no. 7, pp. 2456-2466, July 2009.

[9] S. D. Muruganathan, D. C. F. Ma, R. I. Bhasin, and A. O. Fapojuwo, "A centralized energy-efficient routing protocol for wireless sensor networks," *IEEE Radio Communications*, pp. S8-13, March 2005.

[10] M. Dorigo and T. Stützle, *Ant Colony Optimization*. Cambridge, MA: MIT Press, 2004.

[11] J. Zhang, H. S.-H. Chung, A. W.-L. Lo, and T. Huang, "Extended ant colony optimization algorithm for power electronic circuit design," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 147-162, Jan. 2009.

[12] W.-N. Chen and J. Zhang, "An ant colony optimization approach to a grid workflow scheduling problem with various QoS requirements," *IEEE Trans. Syst. Man Cybern. C, Appl. Rev.*, vol. 39, no. 1, pp. 29-43, Jan. 2009.

[13] Z.-H. Zhan, J. Zhang, and Y. Li, "An efficient ant colony system based on receding horizon control for the aircraft arrival sequencing and scheduling problem", *IEEE Trans. on Intelligent Transportation Systems*, in press.

[14] S. S. Iyengar, H.-C. Wu, N. Balakrishnan, and S. Y. Chang, "Biologically inspired cooperative routing for wireless mobile sensor networks," *IEEE Systems Journal*, vol. 1, no. 1, pp. 29-37, Sept. 2007.

[15] G. D. Caro and M. Dorigo, "Antnet: Distributed stigmergetic control for communications networks," *J. Artif. Intell. Res.*, vol. 9, pp. 317–365, 1998.

[16] G. Chen, T.-D. Guo, W.-G. and T. Zhao, "An improved ant-based protocol in wireless sensor networks," In *Proc. of Int. Conf. Collaborative Computing: Networking, Applications and Worksharing*, pp. 1-7, 2006.

[17] R. GhasemAghaei, Md. A. Rahman,W. Gueaieb, and A. El Saddik, "Ant colony-based reinforcement learning algorithm for routing in wireless sensor networks," In *Proc. of Instrumentation and Measurement Technology Conference*, pp. 1-6, 2007.

[18] Y. Zhang, L. D. Kuhn, and M. P. J. Fromherz, "Improvements on ant routing for sensor networks, M. Dorigo et al. (Eds.), *ANTS* 2004, *LNCS* 3172, pp. 154-165, 2004.

[19] E. N. Gilbert and H. O. Pollak, "Steiner minimal tree," *SIAM Journal on Applied Mathematics*, vol. 16, no. 1, pp. 1-29, 1968.

[20] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*, W. H. Freeman & Co., New York, NY, USA, 1979.

[21] X.-M. Hu, J. Zhang, Y. Yu, H. S.-H. Chung, Y.-L. Li, Y.-H. Shi, and X.-N. Luo, "Hybrid genetic algorithm using a forward encoding scheme for lifetime maximization of wireless sensor networks," *IEEE Trans. on Evolutionary Computation*, in press.

[22] Q. Zhao and M. Gurusamy, "Lifetime maximization for connected target coverage in wireless sensor networks," *IEEE/ACM Trans. on Networking*, vol. 16, no. 6, pp. 1378-1391, Dec. 2008.

[23] M. Dorigo and L. M. Gambardella, "Ant colony system: a cooperative learning approach to the traveling salesman problem," *IEEE Trans. on Evolutionary Computation*, vol. 1, no. 1, pp. 53-66, April 1997.