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A Swarm Intelligence Algorithm for Routing Recovery Strategy in Wireless Sensor Networks With Mobile Sink

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ABSTRACT Considering the fault tolerance mechanism in the route optimization of the mobile wireless sensor network (MWSN), we analyze the routing fault tolerance between nodes and establish an intelligent fault-tolerant routing model for MWSN. We also propose a novel fault-tolerant routing algorithm for an MWSN based on an artificial bee colony (ABC) optimized particle swarm optimization algorithm (ABC-PSO), and this optimizes the ABC-PSO algorithm is applied to study the optimal construction strategy of an alternate route. The proposed using of the path coding, the ABC algorithm optimization, the collaborative updation, and the evolution of the principal and subordinate swarms, as well as particle selection, provide faster overall convergence performance and more accurate solutions for the network optimization. Analytical proofs and simulation experiments show that the route fault-tolerant strategy proposed in this paper can create a reliable transmission environment and an efficient route recovery mechanism for the MWSN. Moreover, it can lower the energy consumption of the network and increase the network's lifetime and improve the robustness and the reliability of MWSN.

INDEX TERMS Mobile wireless sensor networks, fault tolerant, swarm intelligence algorithm, particle swarm optimization algorithm, reliability.

I. INTRODUCTION

The environment of the wireless sensor networks (WSNs) is unpredictable because of various influence factors such as the vibrations, the electromagnetic interference, the system noise, the running down of the battery, the transmission loss of signal, the software errors, and other faults in the networks [1], [2]. These faults cause the sensor nodes to fail and degrade the data transmission quality of the network, further influence of the reliability of the WSNs and the operational stability of WSNs. The reliability and stability of the network remain challenges to WSNs technology at present [3].

The fault tolerance can improve the reliability and stability of WSNs, also it is a critical technical factor in network application [4]. In recent years, the fault-tolerant techniques have already become a major research topic in the field of mobile WSNs [5]. The fault-tolerant design focuses on various aspects of wireless sensor networks, including the fault tolerance of hardware, the coverage and topology control, the routing fault tolerance, and fault detection and the fault separation. The routing fault tolerance technology remains the basis and emphasis of research work on the routing algorithms of WSNs [6]. Currently, the fault-tolerant routing methods for WSNs that have been proposed by researchers have concentrated mainly on three aspects: the retransmission in the link circuit, the error correcting code mechanisms and multipath methods.

In recent years, designing highly efficient energy-saving fault tolerant methods, ensuring the robustness of data transmission and improving the performance of networks have become the key point of MWSN. Because of the changing the position of the mobile sink will change the topology of the network, it is feasible to solve the routing fault tolerance of a single mobile sink, and to maintain multiple non-intersect routings from the source node to the cluster head, by efficiently reconstructing an alternate route. In view of the routing fault tolerance in the MWSN, in this paper, we draw references from the characteristics of the swarm intelligence bionic algorithm. An intelligent routing fault-tolerant mechanism for MWSN based on the artificial bee colony particle swarm optimization algorithm is proposed. And we establish the corresponding fault-tolerant routing models to solve the complicated computations and application problems, such as routing fault tolerance optimization in the MWSN, so as to guarantee the stable operation of the network, enhance the network's performance, reduce the network's energy consumption, extend the network's lifetimes and improve the network's robustness and reliability.

The main contributions of our work in this paper can be summarized as follows:

1. Characterize the issues of a fault-tolerant routing protocol for the MWSN, and formulate the problem of the fault-tolerant routing algorithm.

2. Present a new fault-tolerant routing algorithm based on an artificial bee colony optimized PSO algorithm.

3. Provide extensive simulation results to demonstrate the use and efficiency of the proposed fault-tolerant routing algorithm.

4. Evaluate the performance of the proposed algorithms by comparing them with the fault-tolerant routing algorithms of AODV and AODV-PSO.

The rest of the paper is organized as follows: Section 2 discusses the related literature. Section 3 formulates the problem of the fault-tolerant routing algorithm for the MWSN. Section 4 describes the basic principles of the improved PSO algorithm and presents the applied mathematical models and optimization steps of a fault-tolerant routing mechanism for the MWSN. Section 5 provides the parameters and simulation results that validate the performance of our algorithm. Section 6 concludes the paper.

II. RELATED WORK

There is some literature about optimization-based multipath fault-tolerant routing algorithms for large-scale mobile wireless sensor networks [7]–[11]. In this literature [11], the authors proposed a distributed multipath fault tolerance routing scheme for wireless sensor network (DFTR).The multipath fault tolerance routing provides better resilience to various faults in wireless sensor network. Hasan and Al-Turjman [12] proposed a comprehensive survey of both best effort data and real-time multipath routing protocols for WMSNs, and Results of a preliminary investigation into design issues affecting the development of strategic multipath routing protocols that support multimedia data in WMSNs were also presented and discussed from the network application perspective. Hasan and Al-Turjman [13] proposed a bio-inspired particle multi-swarm optimization (PMSO) routing algorithm to construct, recover, and select k-disjoint paths that tolerates the failure while satisfying the quality of service parameters. Azharuddin *et al.* [14] proposed distributed clustering and routing algorithms jointly referred as DFCR. The DFCR used a distributed run time recovery of the sensor nodes due to sudden failure of the cluster heads In literature Chouikhi *et al.* [15] gave an overview of WSN mechanisms that provide or improve the fault tolerance property of wireless sensor networks, and proposed a new classification based on the network size, since the performance of the majority mechanisms depends on the size in terms of geographical area and number of nodes. It is reported in literature Zhou *et al.* [16] proposed a high fault-tolerant and energy-efficient multipath routing protocol based on the idea of hybrid, energy-efficient distributed (HEED) clustering protocol, called HEED fault tolerant (HEED-FT) is proposed, and improved the routing reliability and energy balance between cluster heads.

Bohacek *et al.* [17] proposed game theoretic stochastic routing for fault tolerance and security in computer networks. Hu *et al.* [18] proposed an immune cooperative particle swarm optimization algorithm in the model to provide rapid routing recovery and reconstruct the network topology to correct for path failure in heterogeneous wireless sensor networks. Multipath fault-tolerant routing protocols are the primary method used to improve the reliability of data transmission for WSNs, as compared to single-path routing mechanisms, which have obvious advantages in terms of transmission reliability, load balancing, and fault tolerance restoration.

We claim that the routing recovery strategy problem studied in this paper is essentially different from conventional wireless sensor network [16]–[18]. In previous works, the general method is to reduce data packet dropout rate and improve the network lifetime. However, in this study we explore the pervasive usage of mobile wireless sensor networks to meet different industrial application environments.

The motivation of this paper is that, we aim to develop an efficient routing recovery scheme such that the optimal transmission path can be carefully maintained and updated as the movement of the mobile Sink. We establish corresponding fault-tolerant routing models to guarantee the stable operation of the network, enhance network performance, reduce network energy consumption, extend network lifetimes and improve network robustness and reliability.

In this paper, we focus on optimizing the network's performance of multipath fault-tolerant routing protocols, and different from earlier research in the following aspects:

1) In contrast to the common methods used in most existing work, we propose the mechanism of an improved PSO-based fault-tolerant routing algorithm for mobile

TABLE 1. List of notations used in problem formulations.

Symbol	Quantity
G	Graph with sensor node set N and link set E: G=(N,E)
n	Sensor node
n_b	Neighbor node
Q_j	The path from the source node n_j to mobile Sink
$N(Q_j)$	Node set of the source node to the Sink transmission path Q_j
$N(n_{sink})$	Neighbor routing table stored in the sensor node of Sink
$N(node)$	Sensor node set
h_j	The hop on the transmission path of Q_j
e_j^m	The link of m adjacent nodes on the path of Q_j
m	The hop of neighbors routing nodes to Sink

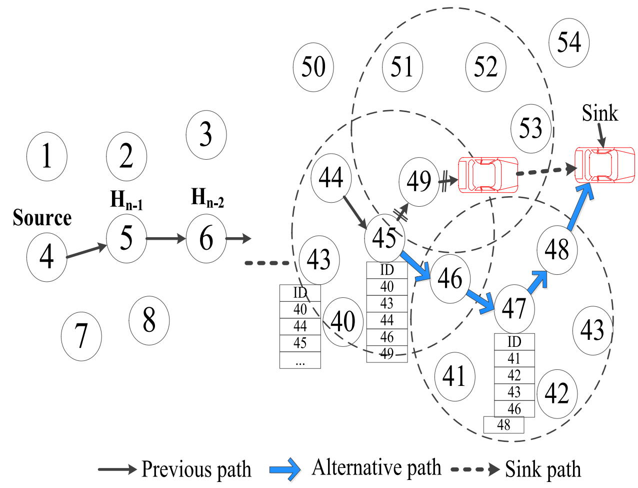

FIGURE 1. The fault-tolerance recovery process of MSWN.

wireless sensor networks, and improve the efficiency and the reliability of the network.

2) Different from the optimal fault-tolerant routing with a static sink, Our simulation environment use the Sink mobility for more efficient energy utilization, greater the network's traffic capacity, reduce the packet loss rate, and prolong the network's lifetime.

3) In addition to the energy constraints inherent with the network's lifetime, we also impose the reliability and latency constraints on the Sink mobility as related to the fault-tolerant routing problems.

III. SYSTEM MODEL AND PROBLEM STATEMENT

In this section, we formulate the problem of the fault-tolerant routing algorithms for wireless sensor network with mobile Sink. Table 1 illustrates the notations used in the rest of this paper.

In this paper, the mobility in mobile wireless sensor networks is a mobile Sink node for data collection. At the same time, it is also based on the classic LEACH clustering model and the proactive routing environment to build a mobile sensor network environment. Multi-path routing fault tolerance technology is used to establish a multiple transmission path between the source node and Sink to improve the reliability of the data transmission. Although this method increases the power consumption and complexity of the route setup, it improves the network's load balancing and the transmission bandwidth. Moreover it improves the stability and reliability of the data transmission. It is a quite common method of implementing fault tolerance at the network layer.

Every node n in the MWSN has a neighbor table that is used to store the ID number of the neighboring node and other information (residual energy, energy consumption, the neighbor table of the mobile Sink stores the nodes near it. $N(n_{sink})$ is the neighbor table that is stored in the Sink. The information is used for later path recovery. The recovery process of the routing fault-tolerance of the mobile Sink is shown in Figure 1.

Since the mobile Sink rapidly changes in the WSN's topology, we set only one valid path from the source node to the Sink, so as to reduce the communication control overhead required to restore routing after the path fails. According to the definition in the literature [19], the node in the direction from the source node to the Sink is called the downstream node, while the node in the direction from the source node to the Sink is called the upstream node. Each node of $N(Qj)$ will build one task list to store current transfer tasks in the routing protocol. Each node transfers data packages to the downstream node according to the task list. The task list includes the originating node, the ID of the Sink, the data type and the ID number of the upstream node of Q_j in the transfer path. In Figure 2, the transfer path from the source node to the Sink is 4-5-6$\cdots$ 44-45-49-Sink.

The node search package GN_m (Get Node) will be broadcast after the mobile Sink finds that it does not connect with the node and the attached task list, and it then searches the neighbor node. The parameter m represents the number of hops between nodes transferred to the Sink. The hop will reach from m to $m+1$ after receiving the node of GN_m, and it will then broadcast it repeatedly to the neighbor node. If the node received the data package of GN_m that belongs to the original path $N(Q_j)$, then the response package GNR_m will be sent with the neighbor list and task list. Therefore, the node involved in reconstructing the replacing path in the original path $N(Q_j)$ to restore routing can be implemented in the local area, so that energy may be saved. The set of nodes $N(node)$ shall be extracted after the node including the neighbor list and task list is received by the Sink to construct and take the place of path Q_j. The ABC-PSO algorithm proposed in this paper is a new path of the optimal fitness value $fitness$ (Q_j) formed by selecting suitable nodes. The new transfer path Q_j from the source node to the Sink is 4-5-6$\cdots$ 44-45-46-47 48-Sink.

The effect factors of Q_j include the following: the residual energy $Rene(n_j^k)$ of the single node and the path length

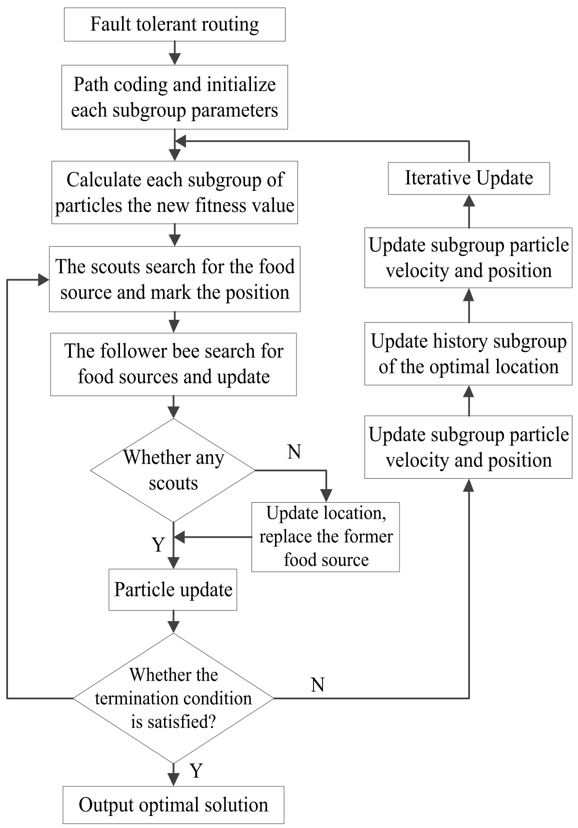

FIGURE 2. Flow chart of optimized PSO based on ABC algorithm.

$Dist(e_j^k)$ of the efficient link between the neighboring node on a path; the single node and $Ene(n_j^k)$; and the $Ene(e_j^k)$ of energy consumption between adjacent nodes and the single node; and the transfer delay *like* $Delay(n_j^k)$ and $Delay(e_j^k)$ between adjacent nodes; and the single node and network reliability between two adjacent nodes like $Rel(n_j^k)$ and $Rel(e_j^k)$; and the single node and the balance of the load including that between two neighbor nodes $LBF(n_j^k)$ and $LBF(e_j^k)$. The fitness degree $fitness(Q_j)$ of Q_j is as shown:

$$fitness(Q_j) = \frac{\sum_{n_j^k \in Q_j} Rene(n_j^k)}{w_1 f_1 + w_2 f_2 + w_3 f_3 + w_4 f_4 + w_5 f_5} \tag{1}$$

$$f_1 = \frac{\sum_{n_j^k \in Q_j} Ene(n_j^k) + \sum_{e_j^k \in Q_j} Ene(e_j^k)}{\sum_{n \in V} Ene(n) + \sum_{e \in E} Ene(e)} \tag{2}$$

$$f_2 = \frac{\sum_{n_j^k \in Q_j} Delay(n_j^k) + \sum_{e_j^k \in Q_j} Delay(e_j^k)}{\sum_{n \in V} Delay(n) + \sum_{e \in E} Delay(e)} \tag{3}$$

$$f_3 = \frac{\sum_{n_j^k \in Q_j} L_{BF}(n_j^k) + \sum_{e_j^k \in Q_j} L_{BF}(e_j^k)}{\sum_{n \in V} L_{BF}(n) + \sum_{e \in E} L_{BF}(e)} \tag{4}$$

$$f_4 = \frac{\sum_{e_j^k \in Q_j} Dist(e_j^k)}{\sum_{e \in E} Dist(e)} \tag{5}$$

$$f_5 = \frac{\sum_{n_j^k \in Q_j} Rel(n_j^k)}{\sum_{n \in V} Rel(n)} \tag{6}$$

$$\text{s.t.} \sum_{e_j^k \in Q_j} Dist(e_j^k) > L \tag{7}$$

$$\sum_{n_j^k \in Q_j} Rel(n_j^k) \geq R_{el} \tag{8}$$

$$\sum_{v_j^k \in Q_j} Delay(v_j^k) + \sum_{e_j^k \in Q_j} Delay(e_j^k) \leq D \tag{9}$$

$$\sum_{v_j^k \in Q_j} Ene(v_j^k) + \sum_{e_j^k \in Q_j} Ene(e_j^k) \leq Ene \tag{10}$$

$$\sum_{n_j^k \in Q_j} Ene(n_j^k) + \sum_{e_j^k \in Q_j} Ene(e_j^k) \leq L_{BF} \tag{11}$$

We adopted the normalization method for the given fitness function. The parameter f_1 of the normalization function represents the proportion of total energies consumed in this path Q_j and the total energies of all links in the network that may be consumed. f_2 means the ratio of the total delay of the nodes concluded in path and the total delay of all nodes in the WSNs. f_3 refers to the proportion of the total load of the nodes concluded in path Q_j and the total loads of all the nodes in WSNs. f_4 means that the ratio of the total distance of all links in the links concluded in path Q_j. f_5 is the total reliability of all links concluded in path Q_j and the total reliability of the total distance of all links in the WSNS. Therefore, w_1, w_2, w_3, w_4 and w_5 are respectively the weight numbers of f_1, f_2, f_3, f_4 and f_5, $w_1 + w_2 + w_3 + w_4 + w_5 = 1$. According to the different emphasis on the route recovery transmission path, we set $w_1 = 0.25$, $w_2 = 0.15$, $w_3 = 0.15$, $w_4 = 0.2$ and $w_5 = 0.25$ [26]. In the formula for path constraint, L is the constraint of the path distance, R_{el} is the constraint of network reliability, D means the constraint of link transfer delay, Ene is the constraint of link energy consumption and L_{BF} is the constraint of link load balancing.

IV. ABC-PSO ALGORITHM AND APPLICATION IN ROUTING PROTOCOL OF MWSN

Fault-tolerant technology for routing intelligent data transfer in the MWSN is analyzed in this paper. We propose to solve problems using operations such as path coding, an improved PSO algorithm based on artificial bee colony swarm optimization, and collaborative evolutions of master-slave groups and particle selections, so that the operational efficiency and reaction ability of our calculation methods will be improved, and the comprehensive fault tolerance of the MWSN and the reliability of network will be enhanced.

A. PSO ALGORITHM

Particle swarm optimization algorithms simulate the foraging action of a group of birds on the basis of the experience and cognition produced by foraging for food and sharing information. The first best solution will be found by way of individual collaborations and has wide applications [20]. In a D-dimensional vector space set, one group consists of M particles and one of the positions of particle i-th is $x_i = [x_{i1}, x_{i2}, \cdots, x_{iD}]^T$. The speed is $v_i = [v_{i1}, v_{i2}, \cdots, v_{iD}]^T$, and $i = 1, 2, \cdots, M$. The i-th particle indicates that the previous best position is p_i, and the optimal position searched by all particles is p_g.

Putting x_i into the target function allows the application value to be calculated. Each particle needs to update its speed and position basing on the following formula for the $(k+1)^{\text{th}}$ iteration [21].

$$v_{i,d}^{k+1} = w\, v_{i,d}^{k} + c_1 r_1 (p_{i,d} - x_{i,d}^{k}) + c_2 r_2 (p_{g,d} - x_{i,d}^{k}) \quad (12)$$

$$x_{i,d}^{k+1} = x_{i,d}^{k} + v_{i,d}^{k+1} \quad (13)$$

Where $d = 1, 2, \cdots, D$, w is the inertia weight, c_1 and c_2 are recognition parameters, and social parameters r_1 and r_2 are random numbers between 0 and 1.

B. ARTIFICIAL BEE COLONY OPTIMIZED PSO ALGORITHM

In the PSO algorithm, the search trajectory of guide particle $p_i (i = 1, 2, \cdots, M)$. When complicated multimodal functions are optimized, they will guide particle i to the best area, if it falls into an optimal local area and cannot jump out. Many particles will become mature earlier when they are led to the best local area and may weaken the particle's search ability. A new method of developing particle swarm optimization is proposed in this paper to overcome the problem of certain particles in the swarm maturing earlier and to promote a convergence rate and precision of optimization. The method of the proposed ABC algorithm is introduced into the PSO algorithm to search for operators, and the particle searches shall be directed to search in order to make the particles jump out of the local advantages as soon as possible.

In 2006, a new intelligent bionic artificial bee colony algorithm with metaheuristics was proposed by the doctor Karaboga and Basturk [22] on the basis of the model of the bee swarm. It has good optimization performance in optimizing complicated unequal multimodal functions, mainly because the artificial bee colony algorithm has a very strong search ability [23].

$$z_{i,j} = x_{i,j} + \phi_{i,j}(x_{i,j} - x_{k,j}) \quad (14)$$

where $k \in \{1, 2, \cdots, M\}$, $j \in \{1, 2, \cdots, D\}$, are the indexes chosen randomly, and $k \neq i$, $\phi_{i,j}$ is the random number between -1 and 1. The strong search ability of the artificial bee colony algorithm is used in this paper and guides the $p_i (i = 1, 2, \cdots, M)$ to jump rapidly out of local best option to avoid prematurity in the algorithm. A flow chart of optimized PSO based on an artificial bee colony algorithm (ABC-PSO) is shown in Figure 2.

TABLE 2. Specific steps of ABC optimized PSO algorithm.

1)	Initialization, set the influence factor c_1 and c_2, the inertia weight of w, Generate M particles to form a population x_i, the initial speed of v_i, i=1,2,…,M.
2)	Calculate the fitness function value of each particle, update p_i and p_g of each particle.
3)	While the algorithm stop condition is not satisfied
4)	for i=1 to M
5)	for d=1 to D
6)	According to formula (12) to update the particle velocity
7)	According to equation (13) Update particle position
8)	end for
9)	if $f(v_i) < f(p_i)$
10)	$p_i = v_i$
11)	end if
12)	for k=1 to K
13)	According to equation (14) search for a candidate solution z_i around p_i
14)	if $f(z_i) < f(p_i)$
15)	$p_i = z_i$, $x_i = z_i$
16)	end if
17)	end for
18)	if $f(p_i) < f(p_g)$
19)	$p_g = p_i$
20)	end if
21)	end for
22)	end while
23)	Output of the optimal solution and the optimal value

Specific steps of the ABC-PSO algorithm are shown in Table 2.

C. FAULT-TOLERANT ROUTING PROTOCOL BASED ON ABC-PSO

The ABC-PSO algorithm is used to conduct fast rerouting when path failure is caused by the Sink moving to a new position. Some of the fittest nodes collections shall be adapted to assemble the path with the optimal fitness value using sensor nodes near the original path. The steps of rapid rerouting are as follows:

Step 1: The data package GN_m including any task lists will be broadcast when the mobile Sink loses connection with n_j^k.

Step 2: What belongs to the node of the original path $N(Q_j)$ should be checked after the node of $GN_{m.}$ is received. The data GNR_m will be sent with the neighbor and task lists if it is, or the m will increase to $m+1$ and broadcast to the adjacent node. Therefore, only part of the node is updated in the original path $N(Q_j)$ and the other nodes of the original path are retained in the alternative pathway. As a result, only the path restoration protocol is implemented in the local area of the network for the purpose of balancing energy consumption and saving energy.

Step 3: The information associated with the nodes of data package GNR_m sent by the Sink and the node collection N_n constructing path shall be raised and the collection $N(v_{Sink})$ of the neighbor list shall be updated. Then, the alternative path Q_j shall be calculated and constructed by the method of ABC-PSO (the path as shown in Figure 3 is 4-5-6··· 44-45-46–47-48-Sink) and the task list shall be updated at the same time.

Step 4: The broadcast of the Sink includes current data package GNR_m_ACK. Once the node receives this package and finds that its ID belongs to the node of path Q_j in the task list, then the connections will be built with those of the same upstream and downstream nodes of path Q_j. The GNR_ACK will be sent to the neighbor node until this data package is received by the source node. At this point, the construction of the new alternative path from the source node to the Sink has been completed and the protocol is finished.

V. SIMULATION COMPARISON AND PERFORMANCE ANALYSIS

A. SIMULATION ENVIRONMENT

In order to test the fault tolerance and efficiency of the algorithm in this paper, we use MATLAB to analyze the performance of the proposed algorithm. In the simulation environment set in this paper, E_s is the sensing energy consumption of the sensor node, E_{N-R} is the energy consumption of the received data, received data energy consumption, E_{N-T} is the energy consumption of the transmitted data, F_a is the average transmission delay, and R_{gad} is the average delivery rate of the group are calculated as follows:

$$E_S = l^* \varepsilon_s \tag{15}$$

$$E_{N-R} = l^* \varepsilon_r \tag{16}$$

$$E_{N-T} = \begin{cases} l^* E_{elect} + l^* \xi_{fs} d^2, & d < d_0 \\ l^* E_{elect} + l^* \xi_{mp} d^4, & d \geq d_0 \end{cases} \tag{17}$$

$$F_a = \frac{\sum (F_r + F_p - F_n)}{N} \tag{18}$$

$$R_{gad} = \frac{T_{rdp}}{T_{sdp}} \tag{19}$$

Where in formula (15), $\varepsilon_s = 60 \times 10^{-9}$J/bit, in formula (15), $\varepsilon_r = 135 \times 10^{-9}$J/bit, in formula (17), ξ_{mp} is a multipath transmission parameter, $\xi_{mp} = 0.0013 \times 10^{-12}$J/bit/m^4, ξ_{fs} is the ordinary space transmission parameter, $\xi_{fs} = 10 \times 10^{-12}$J/bit/m^2. $E_{elect} = 45 \times 10^{-9}$J/bit, Parameter l is the length of the transmitted packet data. $l = 4000$bit, $d_0 = 87$m, Initial energy of the sensing node $E_0 = 1$J. The simulation of the round frequency is set to 300, and sensor nodes for each simulation have 10 data packets transmitting from the source node to the Sink with a 4kb capacity for each packet. The initial energy of the mobile Sink is 1000J, and the Sink would move uniformly in a straight line at a speed of 1 m/s. Artificial bee colony algorithm parameters are set as follows: population number is 50, limit value is 200, and the number of iterations is 50. Particle Swarm Optimization algorithm parameters are as follows: population number is 20, inertia weight $w = 0.96$, $c_1 = 0.5$, $c_2 = 0.7$, and the maximum number of iterations is 200. Simulation environment parameters are set as shown in Table 3 [24].

TABLE 3. Simulation environment.

Parameter	Value
Network size	500×500 m^2
Node number	100, 200
Radius	140 m
V_{Sink}	1 m/s
Initial energy	2 J
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m^2
E_{mp}	0.0013 pJ/bit/m^4
Data size	4000 bits
d_0	$\sqrt{E_{fs} / E_{mp}}$=87 m

In this paper, AODV-SMS [25], AODV-SMS (PSO) [26], AODV-SMS (ABC-PSO)—three kinds of routing recovery protocols—are compared. We study the performance of average energy consumption, network lifetime, network latency, network connectivity, and reliability in this section.

- AODV-SMS: AODV routing recovery strategy for a single mobile Sink. Ad Hoc on demand distance vector routing protocol (AODV), when the source node detects the mobile Sink, the failure path will be replaced by the new path.
- AODV-SMS(PSO): Routing intelligent recovery strategy based on particle swarm optimization algorithm for wireless sensor networks with mobile Sink.
- AODV-SMS(ABC-PSO): Our proposed algorithm.

B. COMPARISON OF SIMULATION RESULTS

1) NETWORK ENERGY CONSUMPTION

Network energy consumption is an important parameter for evaluating network performance. The network energy consumption of 100 nodes and 200 nodes is shown in Figures 3(a) and 3(b) respectively.

From Fig. 3, we can see that with the increase of network polling, whether for 100 nodes or 200 nodes, the network's total energy consumption increases, and the energy consumption of the AODV routing recovery protocol increases quite significantly, followed by that of the AODV-SMS(PSO) algorithm, while energy consumption increase for the AODV-SMS(ABC-PSO) algorithm is minimal. After the nodes increase, node density also increases. At this moment, the first died nodes of the AODV are generally located at the place where the path most commonly used by multiple nodes is closest to the Sink. Due to increased node density, more

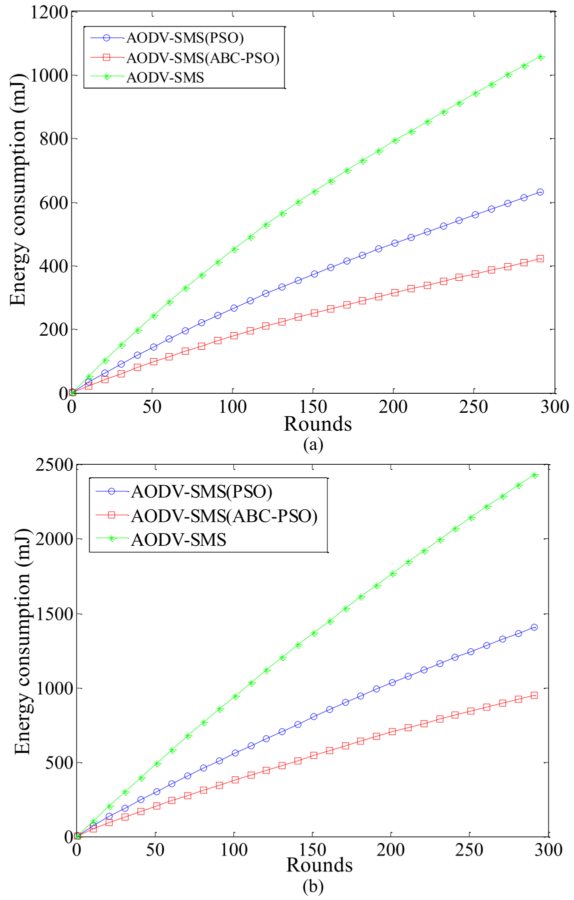

FIGURE 3. Network energy consumption. (a) 100 nodes. (b) 200 nodes.

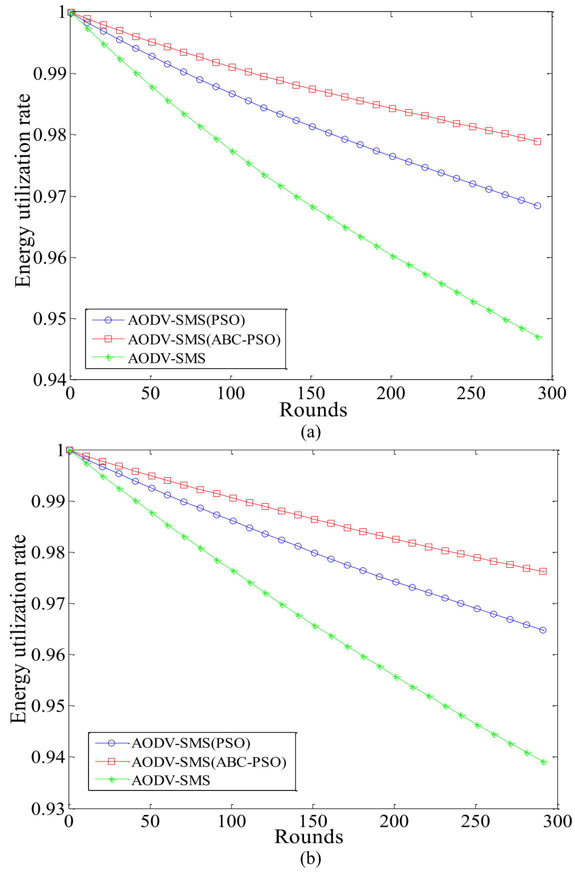

FIGURE 4. Energy utilization rate. (a) 100 nodes. (b) 200 nodes.

nodes tend to use the same path, and the energy consumption of the nodes in "hot spots" begins to increase dramatically, resulting in a significant decline over the lifetime of the network. The routing recovery mechanisms of multiple paths based on the AODV-SMS (ABC-PSO) bring the path structure closer to the net, select a path using residual energy to reduce the chances of overheating the individual path, and alleviate energy loss at "hot spots" so as to control the energy consumption of these nodes to some extent.

2) ENERGY UTILIZATION RATE

Figures 4(a) and 4(b) show the comparison in the energy utilization rate of the three routing recovery protocols in each round; a round refers to the Sink node initiating a data query instruction to all common nodes, the common nodes then responding, and the time required for the return of the data. The x-axis is a current round, and the y-axis is the energy utilization rate.

It can be seen from the above figure that, the algorithm proposed in this paper has a higher efficiency than AODV routing protocol. The main reason is that AODV-SMS (ABC-PSO) algorithm only repairs failure paths within the local area near the Sink, thus as Sink mobile network energy consumption gets more balanced, AODV-SMS(ABC-PSO) energy consumption is lower than other protocols. So this algorithm adopted high efficiently saves energy of nodes and extends the network lifetime. Similarly, although swarm intelligence optimization algorithm AODV-SMS(ABC-PSO) consumes parts of energies to optimize search, this algorithm can offer faster global convergence and higher-quality fitness solutions. It allows those nodes with superior QoS parameters to build alternative paths, so as to get a more stable transmission condition to save energy and extend network lifetime. It can also be seen that, with the expansion of the network scale, the energy loss of protocol also gradually increases. This suggests that a larger network scale will extend the path distance, which in turn will cause unstable routing and increased power consumption.

3) PACKETS LOSS RATE

In the case of testing different number of nodes, this experiment runs comparison in packet loss rate of AODV-SMS, AODV-SMS(PSO) and AODV-SMS(ABC-PSO). In this experiment, it refers to the ratio of lost data packets sent by sensor nodes and normally received data packets by Sink, which can test the correctness and completeness of the routing protocols. Figure 5(a) and 5(b) are the comparison of packet loss rate of three protocols in each round, of which the x-axis is current rounds, and y-axis is the packet loss rate.

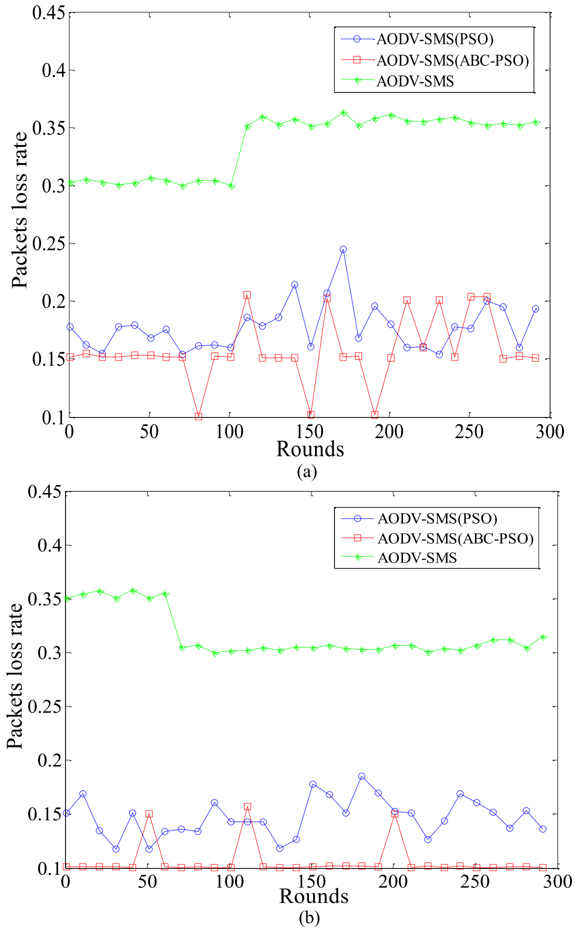

FIGURE 5. Packets loss rate. (a) 100 nodes. (b) 200 nodes.

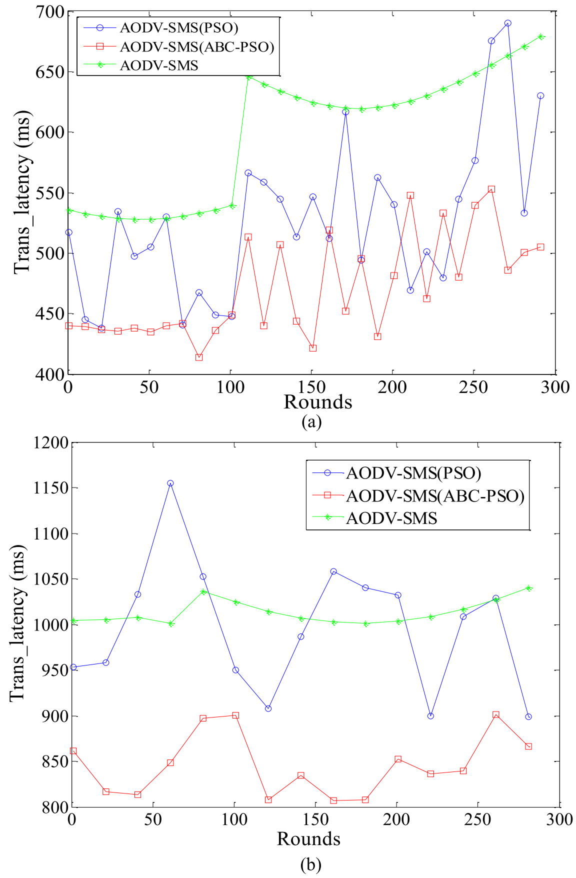

FIGURE 6. Data transmission latency. (a) 100 nodes. (b) 200 nodes.

From Figures 5(a) and 5(b), we can see in terms of packet loss rate that the AODV-SMS(ABC-PSO) algorithm has a lower rate than the AODV-SMS and AODV-SMS (PSO), and it can transfer 20% and 5% more data packets, respectively, than the AODV-SMS and AODV-SMS (PSO) to the Sink in most cases. The reason for this is that when the AODV-SMS (ABC-PSO) detects a broken routing path, it provides a rapid and efficient routing recovery mechanism to find the best alternative path, so as to enhance the success rate of the data transfer. When the network scale expands, the packet loss rate will also go up. Apparently, the expansion of the network scale results in longer paths from the source node to the Sink, increasing the packet loss rate. Overall, the packet loss rate of the algorithm presented in this paper is still the lowest.

4) DATA TRANSMISSION LATENCY

The time-delay of end-to-end data transmission refers to the average time the data groupings require to go from the routing layer of the source nodes to the routing layer of the destination nodes, including the route discovery time-delay, queue delay on the interface of the data packets, and transmission delay and re-transmission delay in the MAC layer, reflecting the overall routing efficiency. The packet transmission delay from the source nodes to the Sink is as shown in Figures 6(a) and 6(b); the x-axis is the current rounds, and the y-axis is the average packet transmission delay after 50 simulations.

From the above Figure we can see that with a lower number of nodes (for example, 100 nodes), the end-to-end delay of the AODV protocol is longer than that of the original AODV-SMS(PSO) and AODV-SMS(ABC-PSO) protocols. This is mainly because with fewer nodes, the congestion of the network is not serious. However, the multiple path mechanism of the AODV-SMS(PSO) and AODV-SMS (ABC-PSO) means that the chances of using the non-shortest paths increases, and thus the end-to-end delay performance is higher than that of the AODV. The AODV-SMS (ABC-PSO) routing recovery protocol shows the trend of having a larger difference in packet transmission delay than the other protocols, which suggests that a greater network scale may bring about a greater path of distance and delay. Therefore, the proposed algorithm may have advantages in that it can choose more suitable nodes to build better alternative paths and make the distribution of network power consumption more balanced.

5) NETWORK CONNECTIVITY

For mobile networks, generally, the continuous motion discretization method is used to calculate the rate of network

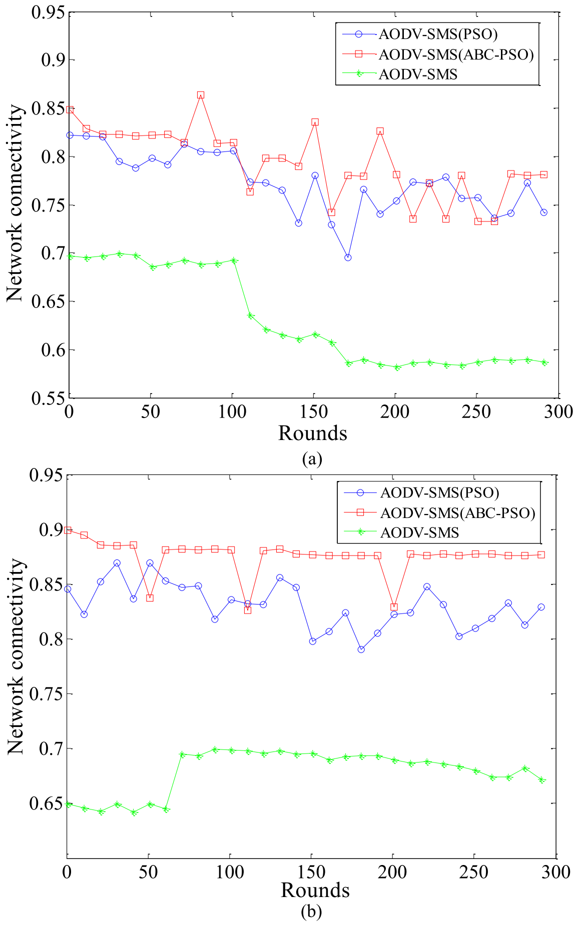

FIGURE 7. Network connectivity. (a) 100 nodes. (b) 200 nodes.

connectivity. That is, over a relatively short time period, it is believed that the network topology does not change. For the network at a moment, the method of node traversal is used to calculate network connectivity. The node traversal method is set up to select an initial node and directly connected nodes, and then binary-hop connected nodes and three jump connected nodes are searched in sequence, until the node number connected to the initial nodes does not further increase, and the connectivity rate is calculated as:

$$N_{con} = \frac{N_l}{n} \tag{20}$$

Where N_l is the number of neighboring nodes in the communication range, and n is the number of nodes in the network. Comparisons of the network connectivity of the three methods of recovery strategy using route algorithms are shown in Figure 7.

As seen in Figure 7, with increases in the round number of simulation, the network connectivity rate of the AODV-SMS method of recovery is low and volatile, ranging between 0.56 and 0.71. The network connectivity of the AODV-SMS(PSO) algorithm is high and more stable, ranging between 0.70 and 0.82. The network connectivity of the proposed algorithm has the highest overall stability, ranging between 0.70 and 0.82, but there are large fluctuations in some points, ranging from 0.75 to 0.88. On the whole, the network connectivity of the proposed algorithm has the highest performance.

6) NETWORK RELIABILITY

We define R_{net} is the reliability of the integrated network, the reliability of the integrated network R_{net} consists of I_1, I_2 and I_3 respectively. Where I_1 is the connectivity reliability of the sensor node, I_2 is the connectivity rate of the network and I_3 is the capacity of the network. The calculation formula of the reliability of the integrated network R_{net} is [27]:

$$R_{net} = 0.1667I_1 + 0.5I_2 + 0.3333I_3 \tag{21}$$

The connectivity reliability of the sensor node I_1 refers to the interconnected reliability of the end-to-end nodes, and the reliability matrix is calculated in line with the distance between nodes in particular, according to the reliability matrix and the random edge reliability matrix sample, and then on the basis of a Monte Carlo analysis in which the average node connectivity reliability value is obtained after 50 times. The capacity of the network I_3 is the survival probability of the network, and the survival probability of the network is usually obtained by dividing the surviving node of the network nodes by the number of all network nodes. A comparison of the network reliability of the three algorithms is shown in Figure 8.

As can be seen from Fig. 8, whether there are 100 or 200 sensor nodes, as the number of simulations increases, the integrated network reliability of the AODV-SMS algorithm is gradually decreased and becomes highly volatile, ranging between 0.68 and 0.85, and the integrated network reliability on average is 0.75. The integrated network reliability of the AODV-SMS(PSO) algorithm is relatively stable and slightly fluctuant, in the range of 0.81 to 0.89, with an average of 0.84. The integrated reliability volatility of the AODV-SMS(ABC-PSO) algorithm is high, ranging from 0.87 to 0.94, with an average value of 0.9. It is thus clear that the reliability of the artificial bee colony algorithm is the highest, which is consistent with the expectations of the simulation. In the data collection process for the WSNs, the artificial bee colony algorithm has the highest collection efficiency, the lowest energy consumption, the least latency and the best reliability of the network.

7) PATH RECOVERY EFFECT DIAGRAM

In order to demonstrate the effects of the protocol used in this paper, we took some snapshots in the simulation process. From Figures 9 and 10, the Sink's valid path moves from a source node to a destination node in the network simulation. When the Sink moves, we can see the source node will rapidly establish an optimal alternative path to connect to the Sink node.

As can be seen from Figures 9 and 10, with 100 nodes, the shortest path of the three algorithms is the following: Source node 26 to destination node Sink the path of AODV-SMS is:

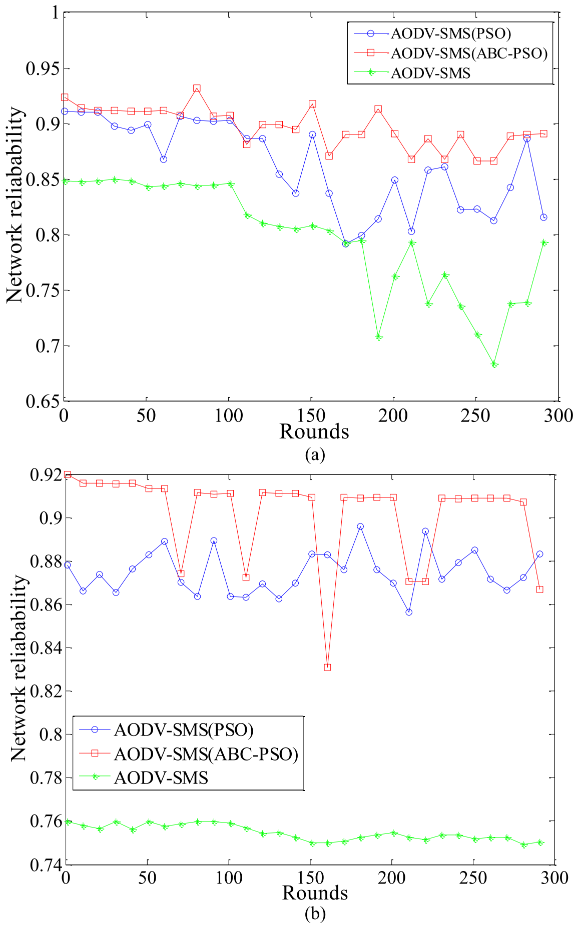

FIGURE 8. Network reliability. (a) 100 nodes. (b) 200 nodes.

26 -> 6 -> 96 -> 61 -> 10 -> 73 -> 5 -> 32 -> 15 -> 7 -> Sink, there are 10 hops. Source node 26 to destination node Sink the path of AODV-SMS(PSO) is: 26 -> 61 -> 74 -> 84 -> 20 -> 21 -> Sink, there are 6 hops. Source node 26 to destination node Sink the path of AODV-SMS(ABC-PSO) is: 26 -> 61 -> 73 -> 32 -> 7 -> Sink, there are 4 hops. With 200 nodes, the shortest path of the three algorithms is the following: Source node 191 to destination node Sink the path of AODV-SMS is: 191 -> 112 -> 46 -> 26 -> 50 -> 8 -> 49 -> 159 -> 1 -> 53 -> 18 -> Sink, there are 11 hops. Source node 191 to destination node Sink the path of AODV-SMS(PSO) is: 191 -> 46 -> 26 -> 49 -> 89 -> 52 -> 20 -> Sink, there are 7 hops. Source node 191 to destination node Sink the path of AODV-SMS(ABC-PSO) is: 191 -> 46 -> 26 -> 49 -> 1 -> 18 -> Sink, there are 5 hops.

Using the proposed algorithm in this paper, we can find the shortest path as quickly as possible, and with the best performance. Regardless of whether the simulated sensor network is placed in 100 or 200 nodes, compared with the other two methods, the proposed algorithm has better network connectivity and reliability, longer network lifetime, and shorter delay. The main reason for this success is that after the routing recovery strategy replaces the path by using the proposed algorithm, it will redesign the shortest path will rarely overlap the paths before. The proposed algorithm is not confined to the original shortest path, but searches for the shortest path again according to the surviving nodes to find the global optimal path.

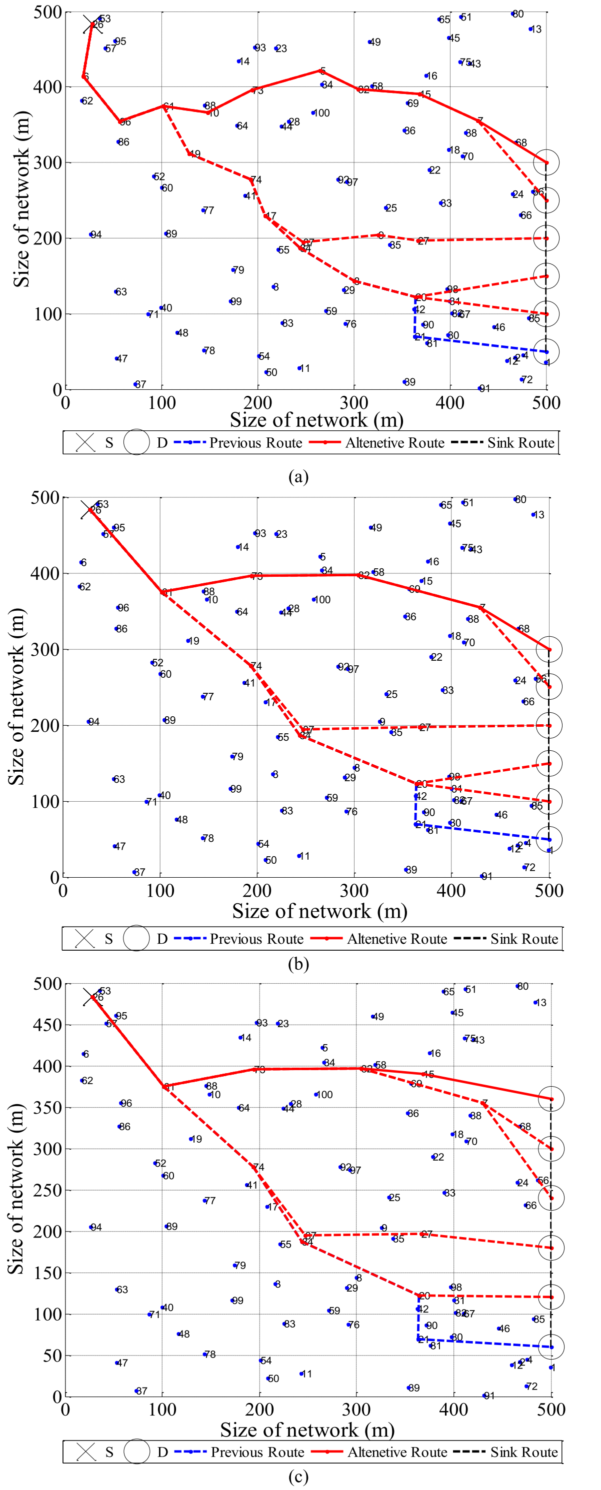

FIGURE 9. Comparison of three algorithms for path recovery (100 nodes). (a) AODV-SMS. (b) AODV-SMS(PSO). (c) AODV-SMS(ABC-PSO).

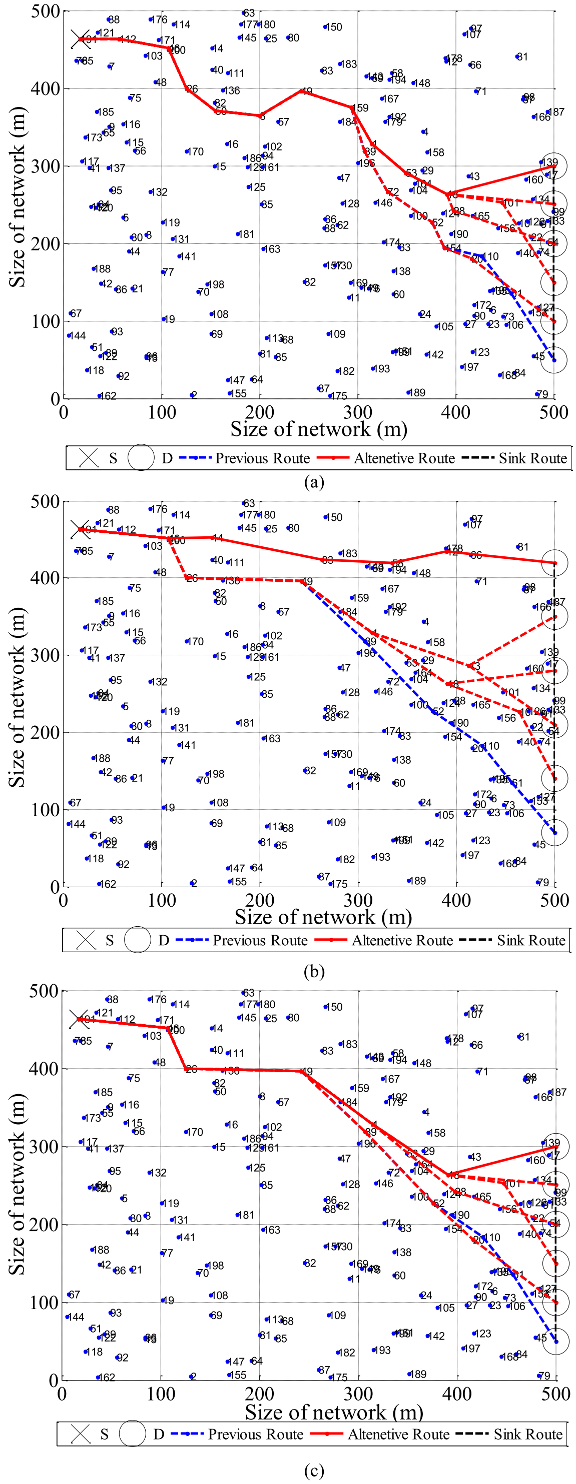

FIGURE 10. Comparison of three algorithms for path recovery (200 nodes). (a) AODV-SMS. (b) AODV-SMS(PSO). (c) AODV-SMS(ABC-PSO).

VI. CONCLUSION

Given the routing fault tolerance in mobile WSNs, and giving consideration to the energy balance mechanism in the optimization process, in this paper we analyze the fault-tolerant routing between nodes in the MWSN and establish an intelligent fault-tolerant routing model within the clusters. We adopt an artificial bee colony particle swarm optimization algorithm to study the optimal recovery strategy of an alternate route. We then further enhance the exploration and optimization capacity of the algorithm to prevent convergence to a local optimum, and we improve the optimization efficiency and optimal performance, as well as the operational efficiency and response capabilities, of the sensor network, which ultimately enhances the overall fault tolerance and reliability of the MWSN.

In this paper, we consider only the mobility of a single Sink node. In future research, we will explore the routing fault tolerance problems of multiple mobile Sink nodes and heterogeneous WSNs; further improve the efficiency of fault tolerance, network reliability and energy utilization rates; enlarge the message capacity of the network; and extend the network lifetime. These further research directions will be important topics for studies on the fault tolerance of the MWSN.

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