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Smooth Path Construction Algorithm for Mobile Sink based on Topological Attributes in Wireless Sensor Networks

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Abstract

Wireless sensor networks (WSNs) with static sinks are vulnerable to the energy hole problem caused by the imbalanced energy consumption of sensor nodes. Using the mobile sink to collect sensing data can efficiently conquer this problem. However, most of the existing algorithms do not consider the turning radius of the mobile sink, which makes it challenging to use the generated path in the actual scene. Therefore, we propose a smooth path construction algorithm for the mobile sink based on topological attributes (SPCMS). It consists of two phases: selection of rendezvous points (RPs) and smooth traveling path construction. In the selection of RPs, the degree and directed betweenness of the node are used as the evaluation factors to select potential RPs. In the smooth path construction phase, the traveling path of the mobile sink is constructed by processing that the turning angle at RPs. Besides, the k-means algorithm is used to reconstruct the routing path of sensor nodes. The simulation results show that the proposed SPCMS can obtain better performances than WRP and WRP-RT, in terms of network lifetime and energy consumption.

Keywords

Mobile Sink; Wireless Sensor Networks; Network Topology; Rendezvous Point; Smooth Path Construction.

1. Introduction

Wireless sensor networks (WSNs) are the product of sensor technology, distributed information processing technology, and wireless communication technology, which is widely used in intelligent transportation, environmental monitoring, target tracking, smart home, and other fields [1-5]. WSNs are generally composed of sensor nodes, sink node, internet, user node. The sensor nodes are distributed in the monitored area, sensing the changes in the environment and generating sensing data. The generated data packets are transmitted to the sink node in a multi-hop way. Sink node connects with the user node through the internet or communication satellite and finally transmits the data packets to the user node. In the actual scenarios, the sensor nodes are usually powered by mobile power. When the mobile power is exhausted, the sensor nodes cannot work normally. Therefore, how to reduce the energy consumption in data collection and improve the network lifetime has always been an important research direction in WSNs [6-10].

In WSNs, due to the nature of multi-hop transmission [11], sensor nodes close to static sink have to relay large amounts of data from other sensor nodes far from the static sink. It results in non-uniform energy consumption of sensor nodes. Then, the energy consumption of sensor nodes near the static sink will be very fast, and energy holes will be formed [12,13]. To solve this problem, the mobile sink is introduced into the network in the existing literature [14-16]. In mobile-sink WSNs, a certain number of sensor nodes are selected as rendezvous points (RPs). The RPs cache data transmitted from other sensor nodes and transmit data to the mobile sink. Mobile sink only needs to access RPs to collect data, which can significantly reduce the number of the relay hop counts in the network from general sensor nodes to the sink node. Therefore, the key problem in mobile-sink WSNs becomes how to select RPs and establish a reasonable traveling path of the mobile sink [17,18].In most cases, the mobile sink is a mobile robot equipped with a wireless transmission module. The mobility of the mobile sink is constrained by the minimal turning angle, but existing works [6,7] fail to consider the limit of the turning angle of the mobile sink, which makes the obtained traveling path hard to apply to the actual scenarios. An example is given in Fig.1, $M_{sin\,k}$ is the starting point and terminal point of the traveling path of the mobile sink. Sensor nodes 1, 3 and 5 are selected as RPs. RPs with $M_{sin\,k}$ together constitute the traveling path of the mobile sink. Fig.1(a) depicts the planned traveling path of the mobile sink, in which the mobile sink will follow the path "$M_{sin\,k}$-1-3-5-$M_{sin\,k}$" to collect all data packets in the network. Fig.1(b) depicts the actual traveling path of the mobile sink, in which the mobile sink will stop at node 3 as its turning angle at node 3 is less than the limits of minimal turning angle of the mobile sink. In this case, the planned traveling path of the mobile sink can not be implemented.

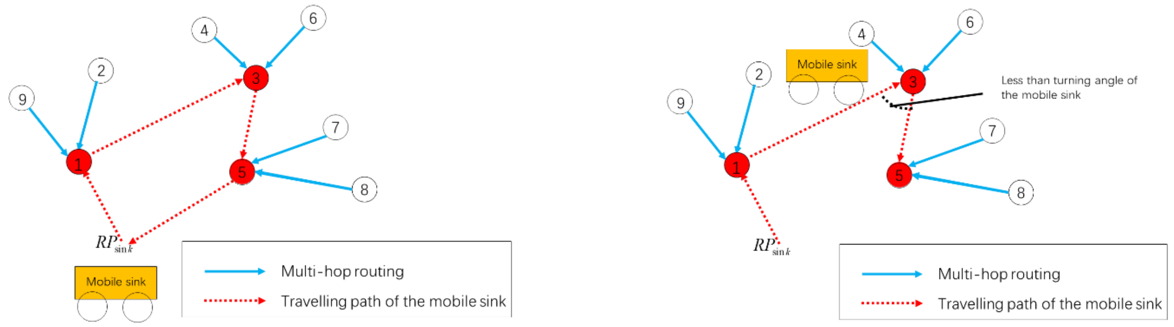
Motivated by the above observation, this paper proposes a smooth path construction algorithm (SPCMS) to select RPs based on topological attributes. The main contributions of this paper are as follows:

1) We propose an RP selection mechanism base on degree and directed betweenness of sensor nodes. The objective is to improve the energy balance level of the network by selecting high concentration level of sensor nodes as RPs. This can also maximize the number of RPs with the given traveling time of the mobile sink, such that it improves the data collection efficiency in the network.

2) We propose a smooth path construction algorithm, which can solve the limitation of the turning angle of the mobile sink. Therefore the traveling path of the mobile sink is more in line with the actual situations.

3) We propose a routing update mechanism, which can optimize the transmission path between non-RPs and RPs by reducing the number of relay hop counts.

4) A large number of simulation results show the SPCMS algorithm has better performance than the WRP algorithm and WRP-RT algorithm.



(a) The planned traveling path of the mobile sink (b) The actual traveling path of the mobile sink

Figure 1. The comparison between the planned traveling path and the actual traveling path of the mobile sink.

2. Related Work

In this section, we briefly review some research [19–24] on mobile-sink WSNs. Based on characteristics of data collection for mobile sink, the existing research is divided into two parts.

2.1 Selecting RPs

A heuristic weighted rendezvous planning (WRP) algorithm is proposed in [19]. In the initialization phase, the authors construct a shortest path tree (SPT) rooted at the starting point of the mobile sink to connect all sensor nodes. Then each sensor node is given a weight W_i to select the candidate RP.

When the weight of the sensor node is larger, the higher the priority of the sensor node is selected as the candidate RP. An RP set is selected by the WRP algorithm, and the traveling distance of the mobile sink is calculated based on the RP set. The traveling path of the mobile sink is repeatedly iteratively calculated until the traveling distance of the mobile sink approaches the maximum distance L_{max} . This strategy enables the mobile sink to gather all sensing data in given delay time (traveling time of the mobile sink), while saving energy consumption of sensor nodes. However, the authors do not take into account the change of multi-hop routing of non-RPs, which leads to an increase in the number of relay hop counts of multi-hop transmission. The authors in [20] put forward an efficient data-forwarding strategy (WRP-RT) for WSNs. After selecting the RP set, sensor nodes of non-RP are reclassified by the clustering algorithm. Then, the authors reconstruct the SPT rooted at RPs to contact all sensor nodes, which reduces the number of relay hop counts of multi-hop transmission and optimizes the routing path of the network.

The authors in [23] propose an efficient rendezvous node selection and routing algorithm (RNSRA). The article has multiple factors affecting (hop distance, data packet transmission rate, sensor node remaining energy and the number of neighbor nodes) the selection of RP nodes. Compared with the weighting factor in [19], more factors are considered in [23], which can make the energy consumption more balanced and the network lifetime longer. In addition, artificial bee colony optimization (ABC) algorithm is used to optimize the path between non-RPs and RPs, so as to minimize the number of relay hop counts in the transmission path. However, when the mobile sink in the study [23] is moving at a low speed, this method may result in a significant increase in the delay time of data gathering. The authors in [24] propose a bounded relay hop mobile data gathering algorithm (BRH-MDG). By exploring a balance between the traveling distance of the mobile sink and the relay hop counts of data aggregation, the data packets can be uploaded to the mobile sink in time when the mobile sink visits each RP. It can effectively reduce the delay time of data gathering.

2.2 Construct The Traveling Path Of The Mobile Sink

The authors in [21] propose a data gathering method based on one mobile sink moving along the fixed traverse points (DGFP). The feature of [21] is to construct the traveling path of the mobile sink in the virtual mobile terminal platform (VTP), which reduces most of the external environmental interference (electromagnetic interference, thermal interference, etc.). The scheme can achieve better scalability with lower energy consumption. However, in [21] with a path-fixed mobile sink, due to the limited communication time of the mobile sink and random deployment of the sensor nodes, it is quite difficult to increase the amount of data collected and reduce energy consumption simultaneously. The authors in [22] propose an effective collection mechanism to prevent packet loss due to buffer overflow (EARTH). Using data transmission rate to calculate the number of packets received by RPs, so as to change the number of sub-nodes of each RP, and ensure that RP has enough cache space to cache data packets. In addition, an enhanced EARTH algorithm is proposed to ensure that data packets can be transmitted to the mobile sink in the shortest hop counts.

According to above discussion, we can clearly find that the existing work does not consider the load of sensor nodes and the actual traveling path of the mobile sink. The SPCMS algorithm proposed in this paper has certain practical significance. The degree of sensor nodes can represent the number of neighbor nodes of sensor nodes, and the directed betweenness of sensor nodes represent the centralization level of sensor nodes. The degree and the directed betweenness of sensor nodes can well reflect the load capacity of sensor nodes. Then, the weighted sum of the degree and the directed betweenness is used to select nodes as RPs, which not only solve the energy hole problem, but also reduce the network energy consumption. In addition, this paper considers the turning angle constraint of the mobile sink and constructs a smooth traveling path of the mobile sink, which can make the traveling path of the mobile sink closer to the actual situation.

3. Energy Model And Problem Formulation

We assume that sensor nodes periodically generate data packets under mobile-sink WSNs, and each data packet must be transmitted to the RPs. In addition, the mobile sink collects data packet from RPs within maximum delay time (traveling time of the mobile sink). Then, the smooth traveling path of the mobile sink is constructed according to the actual situation. Finally, the multi-hop routing between RP and non-RP is reconstructed.

3.1 Energy Model

We use Eq.(1) and Eq.(2) to calculate the energy required to transmit and receive packets, respectively. This is the same energy model which is used in [25,26]. Free space (fs) model is applied when the transmission distance (d_{ij}) is less than a threshold value d_0 (threshold value d_0 is the calculated as $\epsilon_{\mathrm{fs}}/\epsilon_{\mathrm{mp}}$), otherwise the multipath (mp) model is applied. E_{elec} is energy consumption per bit for the electronics circuit. ϵ_{fs} and $\epsilon_{\mathrm{mp}}$are the energy consumption factors of amplification for the free space and multipath radio models, respectively. Therefore, the energy required for transmitting l bits of data packets over the distance d is given by:

$$E_T(l,d)=\begin{cases} lE_{elec}+l\epsilon_{fs}d_{ij}^{2} & for\ d_{ij}<d_0, \\ lE_{elec}+l\epsilon_{mp}d_{ij}^{4} & for\ d_{ij}\geq d_0, \end{cases} \tag{1}$$

The energy consumed to receive the data packet of l bits is calculated by Eq.(2).

$$E_R(l)=lE_{elec}, \tag{2}$$

The mobile sink moves with a constant speed v and allows maximum traveling time T of the mobile sink. Hence, the maximum length of the traveling path is calculation by Eq.(3)

$$L_{\max}=T\upsilon, \tag{3}$$

3.2 Problem Formulation

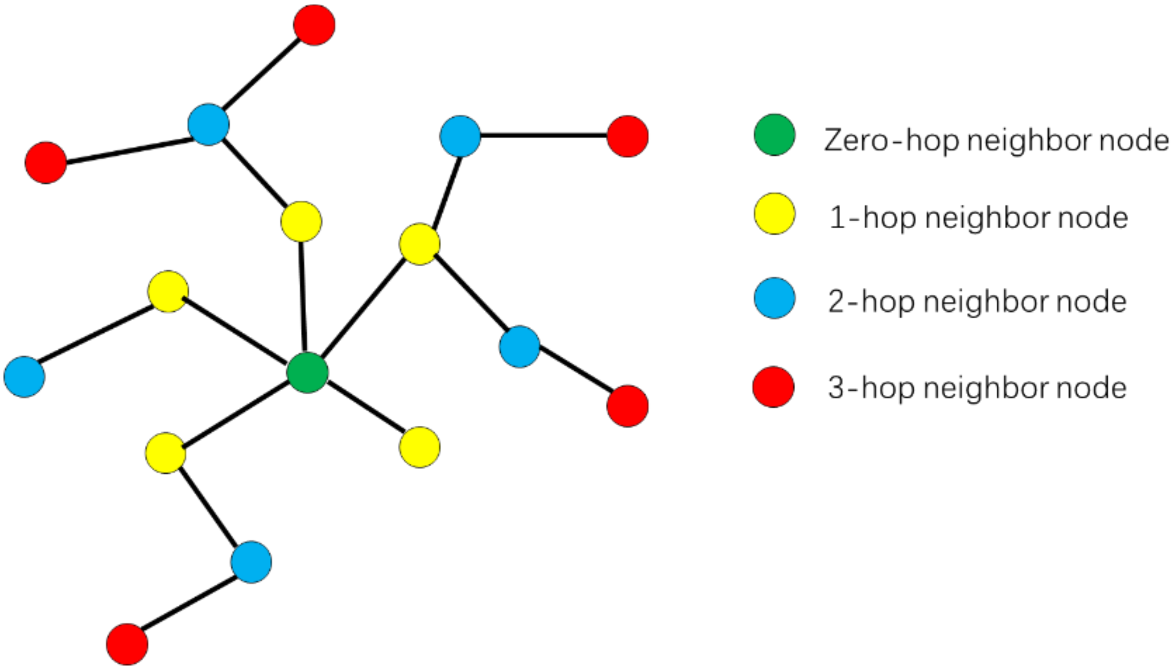


Figure 2. Multi-hop neighbor nodes.

In mobile-sink WSNs, the degree of sensor nodes represents the number of neighbor nodes. According to the characteristics of neighbor nodes, the more neighbor nodes of sensor nodes, the more data packets they accept. Therefore, the higher the degree of sensor nodes, the more load they can bear. Degree is positively related to load capacity. The directed betweenness of sensor nodes represents the centralization level of the node. The more centralization level the sensor node is, the more data packets it needs to store temporarily. Therefore, the larger the directed betweenness of sensor nodes is, the larger the workload of sensor nodes is. In addition, we introduce the concept of multi-hop neighbor node. We call the node i the zero-hop neighbor node of the node i, and the hop distance from the node j to node i is m as the m-hop neighbor node of the node i (as shown in Fig.2). Moreover, the influence of neighbor nodes with different hop distances on the current nodes is different. According to the article [27], it shows an exponential decay trend with the increase of hop distances. Then, this paper constructs an important evaluation function based on the degree and the directed betweenness of multi-hop neighbor node. The importance evaluation function is expressed as follows:

$$\begin{aligned} I_i = {} & (\alpha\delta_i + \gamma \sum_{j\in\pi^{(1)}(i)} \delta_j + \gamma^2 \sum_{j\in\pi^{(2)}(i)} \delta_j + \cdots + \gamma^m \sum_{j\in\pi^{(m)}(i)} \delta_j)\omega_1 \\ & + (\alpha\theta_i + \gamma \sum_{j\in\pi^{(1)}(i)} \theta_j + \gamma^2 \sum_{j\in\pi^{(2)}(i)} \theta_j + \cdots + \gamma^m \sum_{j\in\pi^{(m)}(i)} \theta_j)\omega_2, \end{aligned} \quad (4)$$

In Eq.(4), I_i is the importance evaluation of node i. δ_i represents the degree of the node $i$and θ_i represents the directed betweenness of the node i. α, γ are two adjustable parameters, which are used to adjust the influence of attributes of different nodes on the importance function (α is used to adjust the attributes of the zero-hop neighbor node, γ is used to adjust the attributes of 1 to m hop neighbor node). Here the values of α and γ are defined to satisfy $1 > \alpha > 0$ and $1 > \gamma > 0$. ω_1, ω_2 represent the weighting factors of degrees and directed betweenness in the evaluation process of the mobile-sink WSNs. They are respectively used to adjust the dependence of importance evaluation function on degrees and directed betweenness, and $\omega_1 + \omega_2 = 1$ (in the Section V, the value of $\omega_1$and ω_2 is analyzed).

The physical meaning and measurement unit of each index are not necessarily the same, which may lead to different dimensions and magnitudes of data. Therefore, it is necessary to normalize the importance evaluation function of the node. We give the following expression to normalize the importance function.

$$\delta_i^{(m)} = \sum_{j\in\pi^{(m)}(i)} \delta_j, \quad (5)$$

$$k_i^{'(n)} = \frac{\delta_i^{(n)} - \min\{\delta_i^{(0)}, \delta_i^{(1)}, \ldots, \delta_i^{(m)}\}}{\max\{\delta_i^{(0)}, \delta_i^{(1)}, \ldots, \delta_i^{(m)}\} - \min\{\delta_i^{(0)}, \delta_i^{(1)}, \ldots, \delta_i^{(m)}\}}, \quad (6)$$

$$I_i^d = \alpha k_i^{'(0)} + \gamma^2 k_i^{'(1)} + \gamma^3 k_i^{'(2)} + \cdots + \gamma^m k_i^{'\,(m)}, \quad (7)$$

In Eq.(5), the sum of degree of multi-hop neighbor node i represented by $\delta_i^{(m)}$. Eq.(6) is the normalization formula to normalize the degree of node i. The numerator of Eq.(6) is the difference between the degree of n-hop neighbor node of node i and the minimum degree of multi-hop neighbor node of node i. The denominator of Eq.(6) is the difference between the maximum degree of multi-hop neighbor node of node i and the minimum degree of multi-hop neighbor node of node i. Eq.(7) is a normalized importance evaluation function, which only considers the degree of the multi-hop neighbor node (reference [28] of standardized evaluation model). $k_i^{'(0)}$, $k_i^{'(1)}$, $k_i^{'(2)}, \cdots$, $k_i^{'(m)}$ is the data obtained by normalizing the degree of multi-hop neighborhood node.

In this paper, the importance evaluation function is used to determine the key nodes in the network topology, which can be used as RP. After the importance evaluation function is simplified and normalized by Eq.(5) and (6), the details are shown in Eq.(8).

$$I_i = (\alpha k_i^{'(0)} + \gamma k_i^{'(1)} + \gamma^2 k_i^{'(2)} + \cdots + \gamma^m k_i^{'(m)})\omega_1 + (\alpha b_i^{'(0)} + \gamma b_i^{'(1)} + \gamma^2 b_i^{'(2)} + \cdots + \gamma^m b_i^{'(m)})\omega_2, \tag{8}$$

Where $k_i^{\prime(0)}, k_i^{\prime(1)}, k_i^{\prime(2)}, \cdots, k_i^{\prime(m)}$ and $b_i^{\prime(0)}, b_i^{\prime(1)}, b_i^{\prime(2)}, \cdots, b_i^{\prime(m)}$ represent the data obtained by normalizing the degree and the directed betweenness of multi-hop neighbor node of node i, respectively.

In mobile-sink WSNs, the data packet of all nodes must be gathered on the mobile sink, which has a decisive impact on the data transmission of nodes. Based on this phenomenon, we consider the convergence characteristics of the mobile sink. In previous work, We proposed a directed betweenness index, which can accurately reflect the direction of data transmission of nodes. Therefore, this index is still used in this paper. The expression for this indicator is as follows:

$$\theta_i = \frac{\sum_{k \in v} m_k(i)/m(i)}{\text{n - 1}}, \tag{9}$$

$m_k(i)$ denotes the number of the shortest path from node k to sink node passing through node i. $m(i)$ denotes the number of the shortest path from node k to sink node. Obviously, the shortest path of other nodes all passes through the node i, which can cause directed betweenness centrality θ_i of node i is 1.

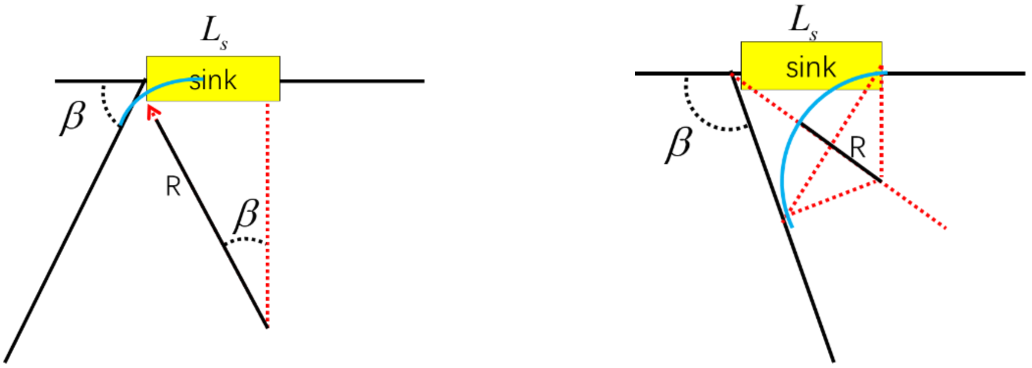
How to select candidate RP nodes according to the importance evaluation function of nodes and plan the traveling distance of the mobile sink through TSP model is an important part of this paper. TSP is a famous problem in the field of mathematics, which is often used to plan traveling path in graph theory. The TSP model is as follows:

$$\text{Minimize} L = \sum_{\forall i, j \in V, i \neq j} d_{ij}\, x_{ij}, \tag{10}$$

$$\begin{cases} \sum_{i=1}^{|s|} x_{ij} = 1, & \\ \sum_{j=1}^{|s|} x_{ij} = 1, & x_{ij} \in \{0,1\}, \forall i, j \in s, i \neq j, \\ \sum x_{ji} \leq |s| - 1, & \end{cases} \tag{11}$$

Where d_{ij} is the physical distance between node i and node$j$. $x_{ij} = 1$ When node i and node j are both selected as RP, otherwise $x_{ij} = 0$. Where s is all non-empty subsets of V, and $|s|$ is the total number of vertices of graph G contained in set s. The first two constraints of Eq.(11) represent that there is only one edge in and one edge out for each node, while the latter one guarantees that there is no subloop solution.

In most cases, The sink is placed on the moving object, and the sink is used to acquire the event of interest collected by the sensor node in the monitoring area. The traveling path of the mobile sink is planned by TSP model. In fact, there are often many angles too small in the traveling path of the mobile sink, and the mobile sink can not drive in a steep turning path. In order to enable the mobile sink to move smoothly, we need to find the best traveling path under the constraint of turning angle. In addition, it can be seen from Fig.3 that the smaller the turning angle of the mobile sink, the larger the turning radius of the mobile sink, and the larger the turning arc of the mobile sink. Therefore, the turning angle of the mobile sink is inversely proportional to the turning angle of the mobile sink. If the constraint of turning radius is satisfied, the traveling path of the mobile sink is constructed as follows.



(a) Turning angle in $(0, \frac{\pi}{2})$. (b) Turning angle in $(\frac{\pi}{2}, \pi)$

Figure 3. Multi-hop neighbor nodes.

$$R = \begin{cases} L_s / \sin\beta & \beta \in (0, \frac{\pi}{2}), \\ L_s \times \tan(\frac{\pi - \beta}{2}) & \beta \in (\frac{\pi}{2}, \pi), \end{cases} \tag{12}$$

when $\beta \in (0, \frac{\pi}{2})$

$$\begin{cases} y = kx + b, \\ (x - v_i(x))^2 + (y - v_i(y))^2 - R^2 = 0, \end{cases} \tag{13}$$

when $\beta \in (\frac{\pi}{2}, \pi)$

$$\begin{cases} y = kx + b, \\ D_x = R - R\sin\left(\frac{\pi - \beta}{2}\right), \\ D_y = R - R\cos\left(\frac{\pi - \beta}{2}\right), \\ (x - (v_i(x) + \eta_i))^2 + (y - (v_i(y) + \mu_i))^2 - R^2 = 0, \end{cases} \tag{14}$$

Eq.(12) is to calculate the minimum turning radius of the mobile sink. L_s represents the actual length of the mobile sink, β represents the maximum turning angle of the mobile sink, and Rrepresents the minimum turning radius of the mobile sink. In Eq.(13) and Eq.(14), $v_i(x)$ and $v_i(y)$ are the abscissa and ordinate coordinates of the RP, respectively. $y = kx + b$ is the angle bisector of the angle formed by the previous node, the current node and the next node, where k is the slope and b is the intercept. Eq.(13) is to calculate the center coordinates of the minimum turning radius, when the turning angle of the mobile sink is within $(0, \frac{\pi}{2})$. Eq.(14) is to calculate the center coordinates of the minimum turning radius, when the turning angle of the mobile sink is within $(\frac{\pi}{2}, \pi)$. η_i represents the horizontal distance between the current node and the intersection of the turning circle and the angle bisector. μ_i represents the vertical distance between the current node and the intersection of the turning circle and the angle bisector.

When we find a traveling path of the mobile sink, we also need to re-planning the routing path of the network by the clustering algorithm and the shortest path algorithm. This can solve the load imbalance problem of non-RP, find the optimal routing path and reduce the energy consumption of nodes.

4. Algorithmic Description

In this section, the section is divided into two parts to describe. In the first part, we discuss the SPCMS algorithm. In the second part, we propose the smooth path construction algorithm to determine the turning arc of the mobile sink and construct the turning function.

4.1 The Rps Selection And Smooth Path Construction

Algorithm 1 is a specific description of the SPCMS algorithm. The initial environment of the input is the network topology as Fig.4(a) show. $L_{\max}$ is the maximum traveling distance of the mobile sink. The output values are a traveling path of the mobile sink and routing path. Lines 1-7 calculate the degree and directed betweenness of multi-hop neighbor node, and normalizes the value. Lines 8-12 select the node with the greatest importance evaluation index as the candidate RP. (line 18-19) TSP model and smooth path construction algorithm are used to calculate the traveling distance of the mobile sink between candidate RP and RP set, and a smooth traveling path is constructed to satisfy the actual moving conditions of the mobile sink. (line 20-23) When the traveling distance of the mobile sink is less than the maximum traveling distance $L_{\max}$, the candidate RP is added to the formal RP set. The k-means algorithm and shortest path algorithm are used to update the routing path. (line 24-26) If the traveling distance of the mobile sink is greater than the maximum traveling distance $L_{\max}$, the candidate RP is discarded and the program is jumped to line 8. Then, the node with the greatest importance evaluation index (the discarded candidate node does not participate in the calculation) is selected as the candidate RP again. Lines 14-17 determine whether the node has completed traversal. If traversed all the nodes, no node can be used as a candidate RP, and then jump out of the loop and end the operation.

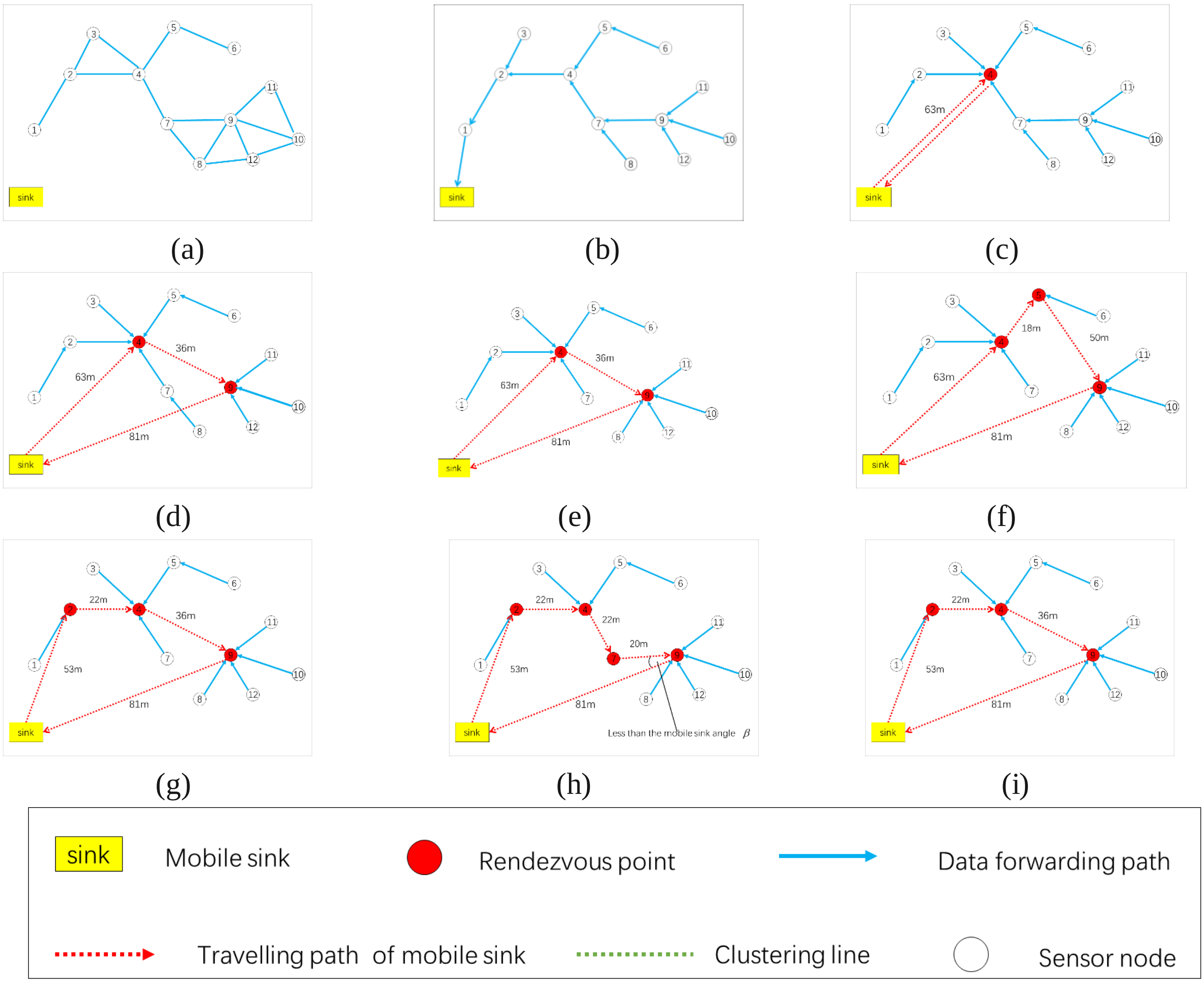


Figure 4. A example of SPCMS algorithm.

Fig.4 shows an example of how SPCMS algorithm finds a traveling path of the mobile sink. Fig.4(a) and Fig.4(b) represent the initial environment topology and the initial network routing, respectively.

Suppose the maximum traveling distance is $L_{\max}$ = 200m. Add the initial point of the traveling path to the RP set, RP=[Sink]. The initial position is also the endpoint of the traveling path of the mobile sink. As Fig.4(c) shows, In the first iteration (select candidate RP and construct traveling path of the mobile sink), due to node 4 has the highest importance evaluation index. Node 4 is added to the traveling path as a candidate RP, get RP=[Sink, 4]. The traveling path of the mobile sink is calculated by TSP model and smooth path construction algorithm, and its length is less than the required maximum length (200m), which means that node candidate 4 can be used as RP. Besides, the shortest path algorithm and clustering algorithm are used to re-planning the routing path. In the second iteration, node 9 is selected as a candidate RP, RP=[Sink, 4, 9], and the routing path is re-planned, as shown in Fig.4(e). As shown in Fig.4(f), node 5 is selected as candidate RP in the third iteration, RP=[Sink, 4, 9, 5]. However the traveling length is longer than $L_{\max}$, so delete candidate node 5,

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Algorithm 1: A Rendezvous Point Selection and Smooth Path Construction
Input:   G=(V,E),R,$L_{max}$
Output: $V_{RP} = (V_{RP1},V_{RP2},\cdots V_{RPn}),E = (e_{c1},e_{c2},\cdots e_{cn})$
while $Tn \le |V|$ do
    For $i \leftarrow 0$ to $|V|$
        The sum of degree of the m-hop neighbor node is $\delta_i^{(m)}$
        The sum of diected betweenness of the m-hop neighbor node is$\theta_i^{(m)}$;
        $k_i^{\prime(x)}$ ←The result of normalization of $\delta_i^{(m)}$,$b_i^{\prime(x)}$ ←The result of normalization of$\theta_i^{(m)}$
    End For
    If $mark(i) = flase$ and$I_i > 0$then
        flag =1; RP=i;
        $I_i$ represents the important evaluation index of node $i$
        $I_{max} = max\{I_1, I_2, \cdots I_n\}$;
    End If
    Select the node with the largest important evaluation index as the RP set
        If ! flag  then
        flag=1; RP=$i$;
            The node exits the loop after traversing
    End If
        $L_H$=TSP($V_{RP}$);
        $L_{cos\,t} = smoothpath(L_H)$;
    If $L_{cos\,t} \le L_{max}$ then
        $C_i = k - means(G)$
        $E_{ci} \Leftarrow SPA(C_i)$
    End If
        If $L_{cos\,t} > L_{max}$ then
            Remove the newly added RP and recalculate the largest important estimate
    End If
End While
```

RP=[Sink, 4, 9]. In the fourth iteration, as shown in Fig.4(g), when node 2 is selected as a candidate RP, node 2 satisfies all constraints of SPCMS algorithm, then RP=[Sink, 4, 9, 2]. In the fifth iteration, node 7 is used as a candidate RP, RP=[Sink, 4, 9, 2, 7]. However, we can see from Fig.4(h) that the turning angle of node 7 is smaller than that of the mobile sink, so candidate node 7 is deleted, RP =[Sink, 4, 9, 2]. After continuous iterative calculation, the traveling distance of RP=[Sink, 4, 9, 2] is 192m, which is less than the required maximum traveling distance of the mobile sink, and the turning angle in the traveling path of the mobile sink satisfies the actual turning angle of the mobile sink. The final traveling path is shown in Fig.4(i).

4.2 Smooth Path Construction Algorithm

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Algorithm 2: Smooth path construction
Input: $T = \{V_1, V_2, V_3, \cdots V_n\}$ Where T is derived by the TSP algorithm
Outpu: $F(t)$
1—If the turning angle at RP is greater than the turning angle of mobile sink then
2—    Calculate turning radius R
3—    For all $v_i$ in the set of $f(t)$ do
4—        $\hbar_i \leftarrow \{x - v_i(x)\}^2 + \{y - v_i(y)\}^2 - R^2$
5—        or $\hbar_i \leftarrow \{x - [v_i(x) + \eta_i]\}^2 + \{y - [v_i(y) + \mu_i]\}^2 - R^2$
6—        $H = H \cup \{\hbar_i\}$
7—    End For
8—    For all $h_i$ in the set of $H$ do
9—        $l_i$ ←The line between two arcs$(h_i, h_{i+1})$
10—        L=L ∪ $l_i$
11—    End For
12—    For $i \leftarrow |T|$do
13—        $f(t)$ is the line between two points and it's made up of$(l_i, l_{i+1}, h_i)$
14—        $F(t) = F(t) \cup f(t)$
15—    End For
16—End If
```

The smooth path construction algorithm aims to solve the difference between the planned traveling path and the actual traveling path when the mobile sink gathers data packets. When constructing a traveling path, the turning angle at the RP should be greater than the minimum angle that mobile sink can execute. As shown in Fig.5(d), the mobile sink moves the sharp turn at the node 4 that cannot pass when collecting the data packet, so that the planned traveling path cannot be used. Therefore, we propose a smooth path construction algorithm to solve this phenomenon. As shown in Fig.5(e), we discard node 4 and reselect node 1 as RP. The turning angles of RP=[Sink, 1, 3, 5] are larger than that of the mobile sink, so we choose RP=[Sink, 1, 3, 5] as the final RP set. The structure of the turning arc at RP is shown in Fig.5(f).

Algorithm 2 is a specific description of smooth path construction algorithm. The initial environment input of the algorithm is the traveling path of the mobile sink designed by TSP model. Firstly, the minimum turning radius of the mobile sink is calculated by Eq.(12). Then, the arc function at RPs is calculated by Eq.(13)and Eq.(14) (line 3-7). Lines 8-11 are used to find the line function between arcs. Finally, the smooth traveling path function consists of arc function and line function (line 12-15).

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5. Simulation Comparison

We evaluated our SPCMS algorithm (a smoothing path construction algorithm for mobile sink based on topological attributes) with simulation-based experiments. The simulation was conducted in an environment based on Matlab 2016a. The experimental hardware environments are Intel®i7-4600M, 2.90GHz CPU and 4GB memory. The whole network is simulated in the area of 400m*400m. The field is static and 10-200 sensor nodes are deployed uniformly. The maximum communication range of the sensor node is 20m, and the sensor does not move after deployment. The location information is fixed. Assume that the mobile sink has no energy limitation and gathers data packets at a speed of 5 m/s. All sensor nodes have fully charged battery with 200J of energy. The sensor nodes send data packets at the rate of 3000 data packets per round, with a data packet size of 30b. It is assumed that the adjustable parameter are$\alpha = 1$and $\gamma = 0.5$ [28]. Other parameters are shown in Table 1. In order to reduce the error, all the data of the simulation experiment are the average value of 50 random experiments.

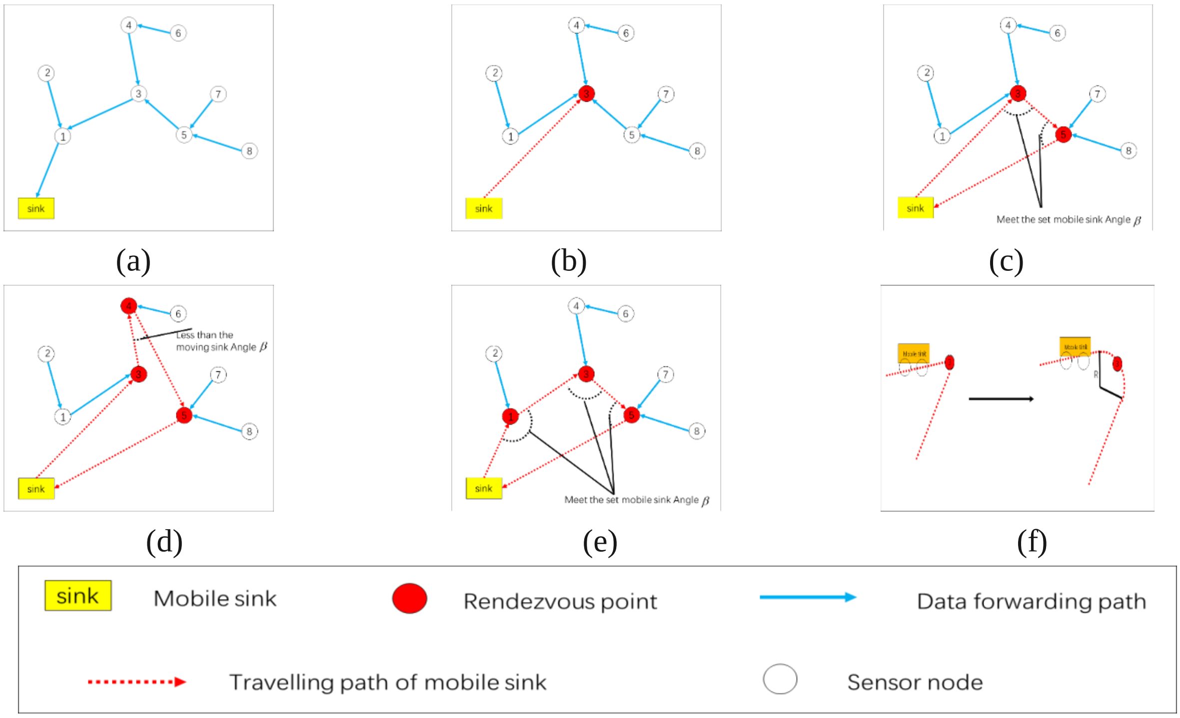


Figure 5. An Example of Smooth Path Construction.

Our proposed SPCMS algorithm is then compared with WRP algorithm in [19] and WRP-RT algorithm in [20]. The performance metrics used for the comparison are energy consumption, standard deviation of energy consumption, and network lifetime.

In the simulation, we use standard deviation (SD) to measure the imbalance between the remaining energy of sensor nodes. For example, a wider variation mean that some parts of the network are more likely to deplete their energy quickly. The metric SD is calculated as follow:

$$SD = \sqrt{\frac{\sum_{v_i \in V}(E_N(v_i) - \overline{E}_N)^2}{|V|}}, \tag{15}$$

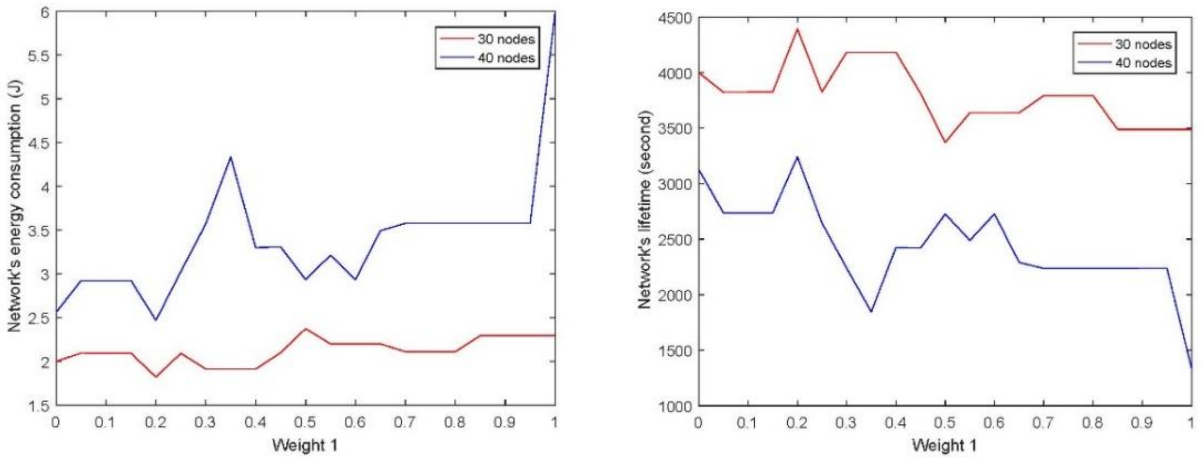
$E_N(v_i)$ represents the energy consumption of node v_i, V is the set of sensor nodes, $\overline{E}_N$ is the average energy consumption of sensor nodes.

Table 1. Simulation parameters

Parameters	Value
Maximum allowed delay time	100s-300s
The allowed traveling path length of the mobile sink node	10 to 50m
Speed of the mobile sink node(v)	5m/s
Length of packet	30bytes
Communication range of sensor nodes(R)	20m
Energy consumption per bit for the electron circuit(E_{elec})	50×10^{-9}J/bit
Energy required by amplifer in free space radio ($\in_{fs}$)	10×10^{-12}J/bit/m^2
Energy required by amplifer in multipath radio ($\in_{mp}$)	$0.0013pJ/bit/m^4$

5.1 Weight Analysis Of Degree And Directed Betweenness ω_1,ω_2

Fig.6 is a weight analysis of the degree and the directed betweenness as important evaluation function. When the number of nodes is 30 and 40 and the maximum traveling distance is 200 m, we have carried out experimental analysis, as shown in Fig.6(a) and Fig.6(b). We can see that the energy consumption and network lifetime can not reach the optimal value when a single factor (degree or a directed betweenness) is used to construct the traveling path of the mobile sink. In Fig.6(a), the red curve representing energy consumption of 30 nodes, and the blue curve representing energy consumption of 40 nodes. They are the minimum when ω_1 = 0.2, ω_2= 0.8. Also, in Fig.6(b), the red curve representing network lifetime of 30 nodes, and the blue curve representing network lifetime of 40 nodes. The network lifetime at ω_1= 0.2, ω_2 = 0.8 is significantly higher than other weights. So in this paper, the weight of degree and directed betweenness are ω_1= 0.2, ω_2 = 0.8, respectively. At the same time, the comparison experiments of algorithms are carried out under the optimal weights.

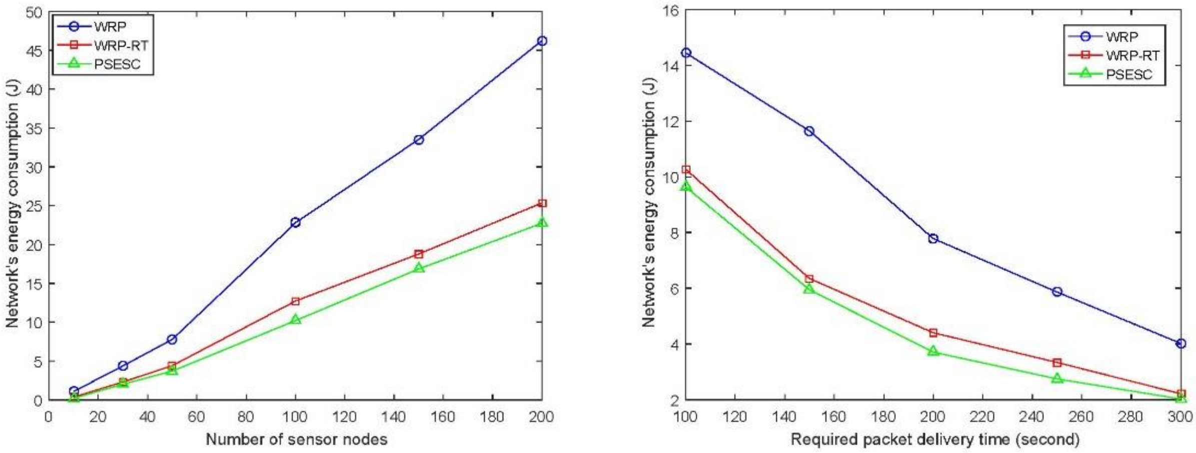


(a) Energy consumption (b) Network lifetime

Figure 6. Energy consumption and network lifetime under different weights.

5.2 The performance of different algorithms

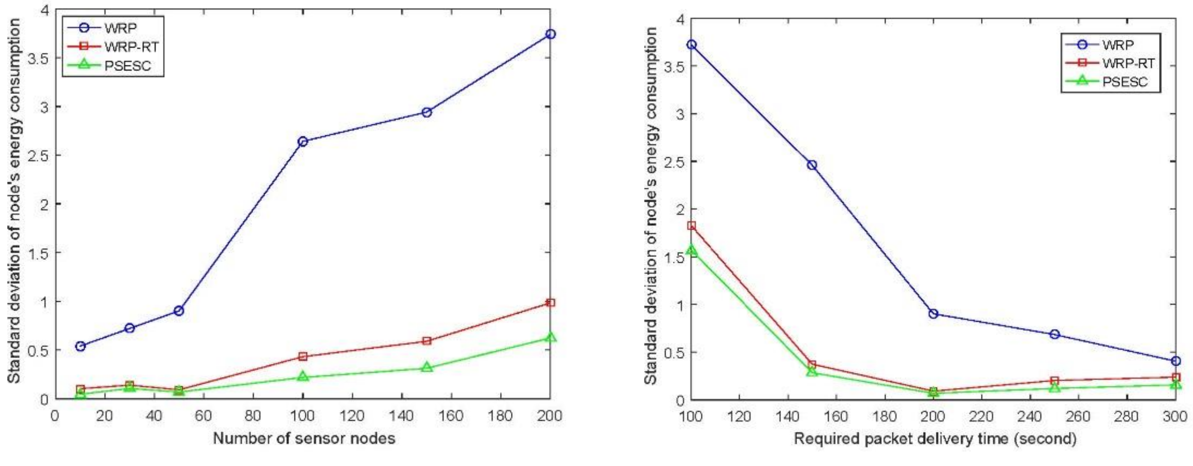
The simulation results are shown in Fig.7-10. Fig.7 shows the trend of network energy consumption under these algorithms. In Fig.7(a), the network energy consumption of the three algorithms increases with the increase of the number of sensor nodes. Compared with WRP-RT algorithm, the network energy consumption of SPCMS algorithm decreases by more than 10%. Compared with WRP algorithm, SPCMS algorithm reduces network energy consumption by more than 48%. The reason is that SPCMS algorithm uses importance evaluation function to select the RP, and continually updates the transmission path of non-RP, so as to build a more reliable transmission environment and reduce the energy consumption of nodes. Fig.7(b) shows that network energy consumption decreases with the increase of delay time. Because the longer the delay time, the longer the traveling distance of the mobile sink, and more nodes can be selected as RP. This can reduce the number of relay hop counts of multi-hop transmission and energy consumption. The energy consumption of SPCMS algorithm under different delay time is less than that of other algorithms. Especially when the delay time is very short, and the number of nodes is very large, this phenomenon is more prominent.



(a) Diffierent number of sensor nodes (b) diffierent delay time

Figure 7. Network energy consumption for WRP, WRP-RT and SPCMS algorithms.

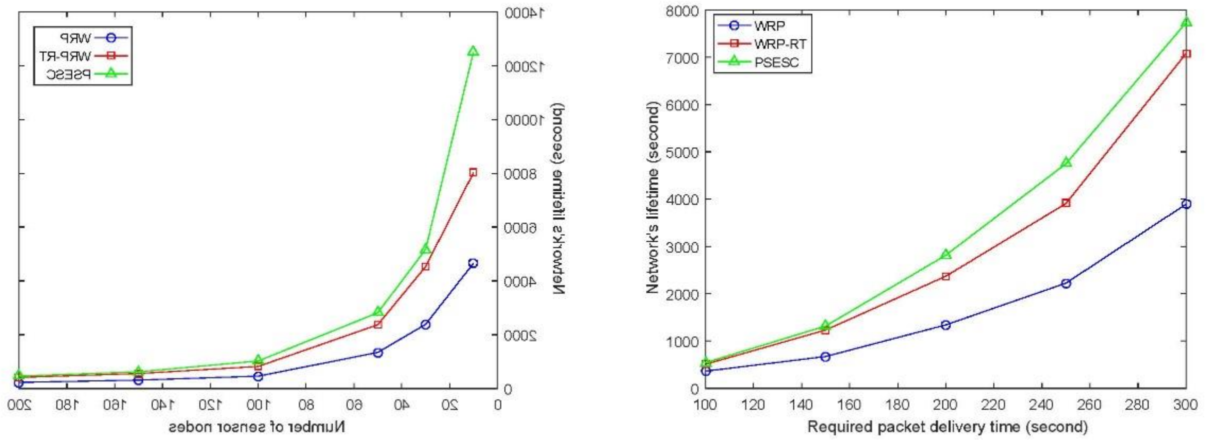
The energy consumption uniform distribution capability of the three algorithms is shown in Fig.8. The energy balance level of sensor nodes is expressed by SD. The smaller the SD value, the more uniform the energy consumption between nodes. As shown in Fig.8(a), the SD value of SPCMS algorithm does not change much with the increase of the number of nodes compared with the SD value of the other two algorithms. Because the degree and the directed betweenness can well reflect the load of nodes, and the load balance is positively related to the energy balance. In Fig.8(b), the SD value of the SPCMS algorithm is always smaller than that of the other two algorithms in different delay time. When the delay time is from 100s to 200s, SD value of the three algorithms drops rapidly, and the number of RP selected is too few due to the short delay time, so the SD value is not stable. From Fig.8, we can conclude that SPCMS algorithm has more uniform energy distribution than the other two algorithms, especially compared with WRP algorithm.



a) Diffierent number of sensor nodes (b) diffierent delay time

Figure 8. Standard deviation for WRP, WRP-RT and SPCMS algorithms.

Fig.9(a) shows the network lifetime with different network sizes. As the number of nodes increases, the network lifetime decreases gradually. The network lifetime in SPCMS algorithm increase by 51% compared with WRP algorithm. The network lifetime in SPCMS algorithm increased by 7% compared with WRP-RT algorithm. In Fig.9(b), we further analyze the lifetime under different delay time. It can be seen that the network lifetime of the SPCMS algorithm is longer than that of the other two algorithms under different delay time. This is because the re-planning routing path in SPCMS algorithm can reduce energy consumption of routing path. Therefore, SPCMS algorithm is better than the other two algorithms in extending the network lifetime.



(a) Diffierent number of sensor nodes (b) diffierent delay time

Figure 9. Network lifetime for WRP, WRP-RT and SPCMS algorithms.

6. Conclusion

In this paper, a smooth path construction algorithm for the mobile sink based on topological attributes (SPCMS) is proposed. The best nodes are selected as the RPs in the mobile-sink WSNs based on the topology attribute. Add turning angle constraints and construct a smooth traveling path for the mobile sink, which makes the traveling path of the mobile sink more suitable for the actual situation. The k-means algorithm and the shortest path algorithm are used to re-planning the routing path of the network, which can reduce the energy consumption of sensor nodes, improve the network lifetime and avoid the energy hole problem. The simulation results show that compared with WRP algorithm, the proposed algorithm reduces energy consumption by 48% and increases network lifetime by 51%. Compared with WRP-RT algorithm, the proposed algorithm reduces energy consumption by 10% and increases network lifetime by 7%. In this paper, we focus on how to construct a smooth traveling path for a mobile sink. We do not consider the traveling path for multiple mobile sinks in the network. In the future, we will explore the application of multiple mobile sinks in the intelligent port platform. Mobile sink has a large range of communication, how to construct the traveling path of multiple mobile sinks. In addition, considering that mobile sink has certain storage space. How to design the data collection strategy of multiple mobile sinks.

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