Node Placement in WSN for Rail Track Monitoring System

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Abstract. Railway environmental monitoring is essential to ensure the safe operation of trains. WSN has great potential in environmental detection, space exploration, smart home, military and other fields. In this paper, The WSN monitoring network is built by deploying relay/sensor nodes along two sides of the rail, to realize the railway environmental monitoring. The problem of “energy hole” caused by uneven energy consumption of nodes in linear WSN is discussed, and a non-uniform distance correlation deployment strategy is designed. In the strategy, the rectangular monitoring region is divided into multiple triangular region. And, the relationship among the number of sensor nodes, the area of unit triangle, the distance between the triangle vertices (relay nodes) and the energy consumption of relay nodes is analyzed. The simulation results have showed that the proposed algorithm has the smaller energy consumption gap between relay nodes, compared with uniform and non-uniform uncorrelated deployment algorithms. It ensures the stability of the whole network energy consumption, and has better performance in prolonging the network lifetime.

1. Introduction

Railway technology has been developing rapidly, and the speed of high-speed train has reached 350km/h, so the environmental monitoring system on both sides of rail is important to ensure the operation of trains. WSN has the characteristics of simple deployment, low maintenance cost, flexible networking, and relay et al. The WSN-based rail monitoring system can be used to collect environmental data efficiently and reliably, so as to make correct protection measures for train operation. The nodes in WSN are usually battery powered and cannot be replaced. The data collected by sensor nodes will be transmitted to the sink node through multi-hop and forwarding, the network lifetime depends on the condition of nodes’ energy consumption. Particularly, the WSN along the rail is a linear structure, which leads to uneven energy consumption of nodes, and shortened the network lifetime. The node which is closest to the sink node transmits largest data and its energy will be used up first. The phenomenon is called "energy hole".

There has been a lot of research on solving the "energy hole" and prolong the network lifecycle. A new cluster mechanism is suggested in [1], to balance the network energy consumption. In [2], the mobile relay nodes are introduced to share the load of nodes near the base station, thereby prolonging the network lifetime. Two node deployment schemes are proposed in [3], in which the effect of node density and distance between nodes on the network lifecycle is analyzed. In [4], the expected cost of energy consumption is defined. And, the expected cost is reduced by adjusting the communication radius of sensors. In addition, an adaptive radius adjustment algorithm is put forward in [5], and the network energy consumption is decreased by adjusting the transmission power. An efficient and equidistance deployment method is suggested in [6], for linear node placement. In [7], the density and location of relay node are derived, by balancing the power consumption between relay node and sensor node. In [8], a non-uniform node placement algorithm is proposed, which prolongs the network lifetime by adjusting the number of nodes proportionally according to area of the monitoring region, and the network lifetime is prolonged.

The existing node deployment algorithm does not take into account the influence of changing distance between adjacent relay nodes on the network energy consumption, which restricts the further performance...
improvement. In the paper, a non-uniform distance correlation deployment strategy is proposed, in which the relationship of the unit monitoring region, the number of sensor nodes, the distance between the triangle vertices (relay nodes) and energy consumption of relay node is analyzed. The proposed strategy optimizes the transmission distance of relay node, and avoids the phenomenon of "energy hole" caused by uneven energy consumption. In addition, it prolongs the network lifetime.

2. Node Placement Model
The node placement along the railway track is divided into two types: uniform deployment and non-uniform deployment. In the uniform deployment, the distance between adjacent relay nodes on the same side is equal, and the number of sensor nodes in unit monitoring region is the same, shown in Figure 1.

![Figure 1. Uniform deployment.](image)

In our non-uniform distance correlation deployment strategy, the distance between relay nodes is not equal, and the distribution of the relay nodes along two sides of the track follows the "from far to near" placement, depicted in Figure 2.

![Figure 2. Non-uniform distance correlation deployment.](image)

In Figure 2, the monitoring region along the track is a rectangular with length of \( L \) and width of \( h \). Let \( R_1, R_2, \ldots \) be the relay nodes, \( S_1, S_2, \ldots \) is the area of unit triangle, \( N_1, N_2, \ldots \) represents the number of sensor nodes in unit triangle, and \( d_0, d_1, \ldots \) is the distance between relay nodes. In the node placement model, the data collected by sensor nodes is transmitted by relay nodes along one side of the rail track, i.e., \( R_1 \rightarrow R_3 \rightarrow \ldots \) Sink, and \( R_2 \rightarrow R_4 \rightarrow \ldots \) Sink.

3. Non-uniform Distance Correlation Deployment Algorithm
The phenomenon of "energy hole" is due to the excessive energy consumption gap between relay nodes in WSN. When the data acquisition rate of sensor node is the same for each unit monitoring region, the energy consumption gap among relay nodes will be reduced and the network lifetime is prolonged. In order to ensure the same information acquisition rate, the number of sensor nodes in unit monitoring region \( N_i \) and the area of unit monitoring region \( S_i \) need to meet the recursive equation, (1)

\[
\begin{align*}
N_2 / N_1 &= S_2 / S_1 = d_1 / d_0 \\
N_3 / N_1 &= S_3 / S_1 = d_2 / d_0 \\
&\vdots \\
N_i / N_1 &= S_i / S_1 = d_i / d_0
\end{align*}
\]

(1)

Assume that the data acquisition rate of sensor node in unit time is \( k \), then the energy model of relay node can be expressed by [9]

\[
E_T = \begin{cases} 
  kE_{elec} + kE_{amp} \cdot d^a & d < d_0 \\
  kE_{elec} + kE_{amp} \cdot d^a & d \geq d_0
\end{cases}
\]

(2)
And

\[ E_R = kE_{elec} \]  \hspace{1cm} (3)

where \( E_T \) is used to represent the energy consumption for transmitting data, \( E_R \) is used to represent the energy consumption for receiving data, of relay node, the value of \( \alpha \) is 2 in free space model, or 4 in multipath fading model, \( d \) is the distance between transmission and receiving, \( E_{elec} \) is the energy consumed by transmitting circuit, \( \epsilon_{fs} \) is the power amplification factor in free space model, \( \epsilon_{amp} \) is the power amplification factor in multipath fading model, and \( d_0 \) is the distance threshold, expressed by

\[ d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{amp}}} \]  \hspace{1cm} (4)

\( E_1 \) is the energy consumption of relay node \( R_1 \) per unit time, which is written as

\[ E_1 = E_{r1} + E_{t1} = 2NikE_{elec} + Nk\epsilon_{fs} \cdot d_1^2 \]  \hspace{1cm} (5)

Where \( E_{r1} \) is the energy used during receiving the data from region \( S_1 \) and \( E_{t1} \) is the energy used during transmitting the data to \( R_2 \). And, the energy consumption of relay node \( R_2 \) per unit time is given by

\[ E_2 = 2NikE_{elec} + Nk\epsilon_{fs} \cdot d_2^2 \]  \hspace{1cm} (6)

The energy consumption of relay node \( R_i \) per unit time consists of the energy for receiving the data from region \( S_i \), the energy for receiving the data from \( R_1 \), and the energy for transmitting the data to \( R_3 \), which is written as

\[ E_i = 2(Ni+N_i)kE_{elec} + (N_i+N_1)k\epsilon_{fs} \cdot d_i^2 \]  \hspace{1cm} (7)

Then, for \( j=1,2,\ldots \), the energy consumption of relay node per unit time is obtained as

\[
\begin{cases}
E_{2j-1} = 2(N_{2j-1} + N_{2j-3} + \ldots + N_1)kE_{elec} + (N_{2j-1} + N_{2j-3} + \ldots + N_1)k\epsilon_{fs} \cdot d_{2j-1}^2 \\
E_{2j} = 2(N_{2j} + N_{2j-2} + \ldots + N_2)kE_{elec} + (N_{2j} + N_{2j-2} + \ldots + N_2)k\epsilon_{fs} \cdot d_{2j}^2
\end{cases}
\]  \hspace{1cm} (8)

Introduce variable \( M_{2j-1} \) and \( M_{2j} \), \( (j=1,2,\ldots) \), which is defined as

\[
\begin{align*}
M_{2j-1} &= \sum_{i=1}^{N_i} S_{2j-1} = \frac{N_i}{d_0} \sum_{i=1}^{N_i} d_{2j-1} \\
M_{2j} &= \sum_{i=1}^{N_i} S_{2j} = \frac{N_i}{d_0} \sum_{i=1}^{N_i} d_{2j-1}
\end{align*}
\]  \hspace{1cm} (9)

Substituting equation, (9) in equation, (8), then energy consumption \( E_i \) is

\[ E_i = 2MkE_{elec} + Mk\epsilon_{fs} \cdot d_i^2, \hspace{1cm} i=1,2,\ldots \]  \hspace{1cm} (10)

When the relay nodes have equal energy consumption, the whole network is in equilibrium state. If \( d_0 \) and \( d_1 \) are given (The values of \( d_0 \) and \( d_1 \) are determined by simulation experiment, see Section 4), \( d_2 \) can be calculated by

\[ d_2 = \left( d_0d_1 + 2\frac{(d_0-d_1)}{d_1}E_{elec}/\epsilon_{fs} \right)^{\frac{1}{2}} \]  \hspace{1cm} (11)

Furthermore, for \( j=1,2,\ldots \), the distance between relay nodes is given by
\[
\begin{align*}
\left\{ \begin{array}{l}
d_{\text{j}+1} = \left( \frac{N_{\text{j}}}{M_{\text{j+1}}} d^2 + 2 \left( 1 - \frac{N_{\text{j}}}{M_{\text{j+1}}} \right) E_{\text{elec}} l E_{\text{fs}} \right)^{1/2} \\
d_{\text{j+2}} = \left( \frac{N d_{\text{j+1}}}{M_{\text{j+1}} + d_{\text{j+1}}} d^2 + 2 \left( 1 - \frac{N d_{\text{j+1}}}{M_{\text{j+1}} + d_{\text{j+1}}} \right) E_{\text{elec}} l E_{\text{fs}} \right)^{1/2}
\end{array} \right.
\end{align*}
\]

Let \( L \) be the length of monitoring rail track, the sum of distances between relay nodes need to satisfy the constraint equation, (13)

\[
\min \left( \sum_j d_{\text{j+1}}, \sum_j d_{\text{j+2}} \right) \geq L, \quad j=0,1,2,\ldots
\]

In the non-uniform distance correlation deployment model, when the distance between relay nodes satisfies equation, (11) ~ (13), the energy balanced WSN can be obtained.

It is assumed that \( E_0 \) is the initial energy of the relay node, \( t_i \) is the lifecycle of relay node \( i \), and \( T \) is the network lifetime, which is usually regarded as the lifetime of the earliest dead node due to battery power consumption. And, \( t_i \) and \( T \) is expressed respectively by

\[
t_i = \frac{E_0}{E} \quad i=1,2,\ldots
\]

\[
T = \min \{ t_i \} \quad i=1,2,\ldots
\]

4. Simulation Results

In simulation experiments, the monitoring region along the track is a rectangular with length of \( L \) and width of \( h \). The relay nodes are placed in non-uniform distance correlation deployment strategy. The values of the simulation parameters are provided in Table 1[9].

| Parameters | Values |
|------------|--------|
| \( L \) (m) | 1000 |
| \( h \) (m) | 2.5 |
| \( \epsilon_{\text{amp}} \) (pJ/bit/m^4) | 0.0013 |
| \( \epsilon_{\text{fs}} \) (pJ/bit/m^2) | 10 |
| \( E_{\text{elec}} \) (nJ/bit) | 50 |
| \( E_0 \) (J) | 2 |
| \( k \) | 5 |

Firstly, we need to determine the value of \( d_0 \) and \( d_1 \). Figure 3 illustrates the relationship between \( d_0 \) and \( d_1 \).

Figure 4 shows the number of relay nodes and sensor nodes required for different values of \( d_1 \). It can be seen that when \( d_0 = 275 \) m, the number of nodes required is the least. We know the number of sensor nodes in unit triangle \( N_i \) obtained by equation, (1), might not be an integer. In the actual deployment, top integral function is needed for \( N_i \).

Figure 5 gives a comparison of theoretical energy consumption and the actual one of relay nodes with various values of \( d_1 \).

Figure 6 reveals the relationship between different values of \( d_1 \) and network lifetime. Obviously smaller values of \( d_1 \) increase the longer network lifetime. However, as in Figure 4, the number of nodes required for smaller values of \( d_1 \), is not the least. Therefore, the number of nodes should be taken into account, in addition to the network lifetime, in determination of values of \( d_0 \) and \( d_1 \).

The comparisons of energy consumption and relay node lifecycle for three node deployment algorithms are shown, respectively, in Figures 7 and 8. In the figures, the number of relay node is 16, with \( d_0 = 171 \) m, \( d_1 = 275 \) m. It can be seen that compared with uniform and non-uniform uncorrelated deployment [10, 11], the proposed non-uniform distance correlation algorithm has the least energy consumption gap among relay nodes, and the longer node lifecycle.
5. Conclusion
The WSN along the rail track is a linear structure, which leads to uneven energy consumption of relay nodes, and shortens the network lifetime. The non-uniform distance correlation deployment strategy is proposed in this paper, to overcome the “energy hole”. Compared with uniform and non-uniform uncorrelated deployment algorithms, the proposed deployment strategy has the least energy consumption gap among relay nodes, and the longer node lifecycle.

For future research, we need to investigate the effect of different path loss factors on energy consumption of relay node in energy model, so that the proposed strategy can be applied to the actual rail environment monitoring system.
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