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A probabilistic approach for energy efficient data transmission in pipeline monitoring sensor networks

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Abstract

Lifetime network is the main considering problem when deploying wireless sensor networks for integrity monitoring of pipeline infrastructures. And the low network lifetime is always caused by the unbalanced energy consumption in the monitoring networks. So in this paper, a sort of data transmission approach based on probabilistic model is put forward to solve the energy consumption unbalanced and enhance the network lifetime. The optimal problem for maximum network lifetime is introduced, which is solved by artificial fish school algorithm. A series of simulation experiments are carried out to verify the effectiveness of new method. Compared with Direct and Multi-hop methods, new method not only can efficiently balance the network energy load, but also can significantly prolong the network lifetime, meeting the requirements of real-time pipeline monitoring.

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Keywords: data transmission; probabilistic model; network lifetime; pipeline monitoring sensor networks.

1. Introduction

In recent years, wireless sensor networks (WSNs) have been applied to monitor the health of the pipeline infrastructures due to its implementation ease and economic advantage over traditional methods [1]. But at the same time, energy conservation of monitoring networks has become the main concern as a result of limitation on energy supply of sensor nodes. As is known to all, sensor nodes are generally supplied by batteries, which are not convenient to be replaced during the monitoring process. When the monitoring scope is too large, nodes in different positions may deplete different amount of energy, which will lead to network energy load unbalanced. Some nodes tend to die out earlier than other nodes, resulting in what is called energy hole. When it happens, the network lifetime will drastically reduce and there is much more energy of nodes wasted after the monitoring networks are out of work.

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Different methods for prolonging network lifetime in wireless sensor networks have been explored in the literature. In [2], authors present a type of approach based on non-uniform initial energy. The nodes closer to the sink are allocated more initial energy, considering heavy energy consumption in relaying data. However, such kind of heterogeneous energy allocation strategy may be inconvenient in node manufacture and placement. Additionally, [3] uses data compression and data fusion as a feasible scheme. Less amount of relaying load means less energy consumptions. Yet, the trade-off between data accuracy and energy should be taken into account. In [4], authors have introduced an energy efficient node deployment scheme. The main idea is that the area near the sink is deployed more nodes to alleviate the heavy data traffic burden in this area. This scheme can achieve energy consumption balanced, but is not feasible for WSNs in pipeline monitoring because nodes should be placed uniformly along the pipeline so as to obtain the distributed data of the whole pipeline.

Based on the studies above, in this paper, we probe into the feasible solution from the respective of data transmission to deal with unbalanced network load for increasing network lifetime. Nowadays, the most common data transmission schemes used in WSNs are Direct transmission and Multi-hop transmission [5]. However, both schemes inevitably suffer from the unbalanced energy consumption problem. In this paper, a type of energy efficient data transmission approach based on the probabilistic model is proposed to solve this problem. The vital idea for our approach is that each node transmits its data packet to other nodes or the sink to avoid the overuse of some nodes. The calculation of probabilistic values is accomplished by artificial fish school algorithm (AFSA). The effectiveness of new method is verified by simulation experiments. Results demonstrate that compared with two other conventional transmission methods, our method promotes the network lifetime effectively.

2. Model and problem statement

2.1 Network model

Pipeline monitoring sensor networks are made up of N sensor nodes and a sink. Sensor nodes are responsible for collecting and preprocessing the monitoring information which will be sent to the sink for further analyzing. As shown in Fig. 1, there are N sensor nodes and a sink deployed in the monitoring networks with the same spacing d. The sink is placed at the right end of the pipeline. Let s_i denote the ith sensor node in the networks where s_1 is the farthest from the sink and s_N is the closest.

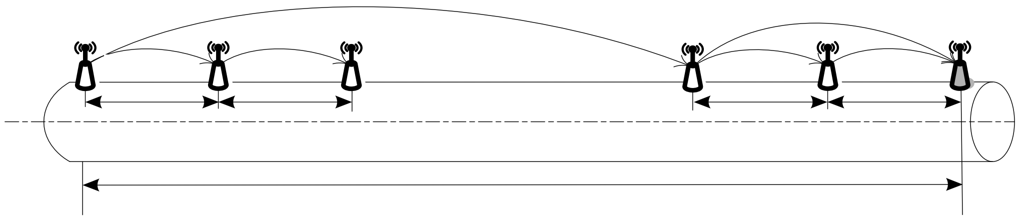

Fig. 1. Pipeline monitoring networks structure

2.2. Energy consumption model

According to [6], a classical energy consumption model is proposed. In this model, the energy consumption for transmitting a l-bit data packet over a distance d is

$$E_t = l \cdot E_{te} + l \cdot \varepsilon_{amp} d^{\gamma} \tag{1}$$

The energy consumption for receiving a l-bit data packet is

$$E_t = l \cdot E_{rx} \tag{2}$$

Where E_{te} and E_{rx} denote the energy consumption per bit in transmitter and receiver circuit, respectively. ε_{amp} accounts for the energy consumed in the transmit amplifier. γ denotes the path loss exponent, ranging from 2 to 4.

2.3. Data transmission model

During the monitoring process, each sensor node sends the monitoring information to the sink according to its own data transmission structure $u_{i,j}$ (i,j=1,2,…,N). $u_{i,j}$ denotes the probability value of node s_i transmitting its information to node s_j. For ease of presentation, we define $u_{i,N+1}$ as the probability value of node s_i directly sending its information to the sink. The expression of $u_{i,N+1}$ is

$$u_{i,N+1} = 1 - \sum_{j=1}^{N} u_{i,j}, \quad 1 \le i \le N \tag{3}$$

From the perspective of lowering energy consumption, all sensor nodes in the networks should always transmit their information towards the sink. Accordingly, the data transmission structure should satisfy the following constraint:

$$\begin{cases} 0 \le u_{i,j} \le 1, & 1 \le i, j \le N, \\ 0 \le u_{i,N+1} \le 1, & 1 \le i \le N, \\ u_{i,j} = 0, & 1 \le j \le i \le N. \end{cases} \tag{4}$$

2.4. Problem statement

Before the problem statement is given, the definition of network lifetime for pipeline monitoring sensor networks is first introduced. In this paper, the time is divided into rounds as it has been done in most of previous studies [7]. Exactly in each round, every sensor node generates one data packet. If a certain percentage of nodes are out of work, the sink will be lack of sufficient information to monitor the overall state of the pipeline. Here, the lifetime definition is introduced as follows: the number of rounds when the first node exhausts its power, denoted as T.

Moreover, to make it clear, we also make the following assumptions regarding the monitoring networks.

- The transmission power of sensor nodes is able to be adjusted according to the transmission distance. Neither conflict nor retransmission is considered during the data transmission process.
- Regardless of communication radius, all sensor nodes have capabilities to communicate with the sink directly.
- Energy consumption mainly focuses on receiving and sending data packets, whereas power consumed for sensing is negligible.

Based on the definition of network lifetime and relevant assumptions above, the optimization problem of data transmission is summarized as how to design the optimal data transmission structure to satisfy the following requirements: 1) All the sensor nodes deplete the same power in a round; 2) The network lifetime arrives at the maximum value.

3. Optimal transmission structure

From [7], the expression of network lifetime is formulated as follows:

$$T = \frac{E_0}{\max E(i)} \tag{5}$$

Where $E(i)$ denotes the total energy consumption of node s_i in a round and its expression is

$$E(i) = \sum_{k=1}^{N+1} l \cdot u_{i,k} \cdot (E_{te} + \varepsilon_{amp}((k-1)d)^{\gamma}) + \sum_{k=1}^{N} l \cdot u_{k,i} \cdot E_{rx} \tag{6}$$

Regardless of γ which is a constant when the monitoring environment is certain, we can see that the network lifetime T only has a close relationship with the data transmission structure $u_{i,j}$. By adjusting the value of $u_{i,j}$ properly, we could ensure energy load balanced among nodes, thereby promoting the network lifetime dramatically. The expression of optimization problem is

$$\begin{aligned} & maximize \quad T \\ & subject\ to: \; E_1 = E_2 = \mathrm{L} = E_N \\ & \qquad 0 \le u_{i,j} \le 1, \;\; 1 \le i \le N-1, \\ & \qquad 0 \le u_{i,N+1} \le 1, \;\; 1 \le i \le N, \\ & \qquad u_{i,j} = 0, \;\; 1 \le i \le j \le N. \end{aligned} \tag{7}$$

4. Numerical and simulation experiment

In our experiment, there are five sensor nodes evenly deployed along the pipeline. And all the nodes equip with the same initial energy of 5J and node spacing 10m. The parameters of energy consumption model are set: E_{te}=1.066μJ/bit, E_{rx}=0.533μJ/bit, ε_{amp}=3.076nJ/bit/m^2 and γ=2. The optimization problem is solved by AFSA and its parameters are set: N=50, *Visual*=0.5, *Step*=0.1, δ=0.618, *Genmax*=400. By calculation, the probabilities of each node transmitting data to other nodes or sink are shown in Table 1.

Table 1. Transmission probabilities when node spacing is 10m

Sender/Receiver	Node 2	Node 3	Node4	Node5	Sink
Node 1	0.2426	0.3216	0.1478	0. 0696	0.2184
Node 2	0	0.2368	0.4438	0.0779	0.2414
Node 3	0	0	0.5547	0.1407	0.3045
Node 4	0	0	0	0.3726	0.6274
Node 5	0	0	0	0	1

It can be seen from Table 1 that when the node space is 10m, some nodes have higher chances to transmit their data packets to non-neighbouring nodes rather than neighbouring nodes. In addition, the farther the node is away from the sink, the lower of probabilistic value of this node transmitting the data to the sink. This is because the nodes have to send their data packets to other nodes with certain of probabilities in order to balance energy consumption.

In order to evaluate the effectiveness of new algorithm, we utilize two other conventional approaches for performance comparison: (a) Direct transmission; (b) Multi-hop transmission. Fig.2 describes the energy consumption of each node via three sorts of approaches above. Compared with approaches (a) and (b), our approach can ensure that all the nodes consume the same power in a data collection, which is beneficial to the network lifetime. Although some nodes by approach (a) or (b) consume less energy than by our approach in a data collection, approaches (a) and (b) bring about the unbalanced energy consumption of nodes. For approach (a), due to the fact that all nodes send their data packets directly to the sink, the node 1 consumes the most amount of energy. For approach (b), in contrast, node 5 consumes the most amount of energy because it has to relay all the data packets from other four nodes.

Fig. 3 and Fig. 4 show the effect of network size and node spacing on variation of network lifetime. We can see from the Fig. 3 that when the node spacing is a constant, network lifetime declines with the increase of network size. This is mainly because each node has to receive or transmit more data from or to other nodes, which will add the network load. Fig. 4 shows the lifetime of network with different node spacing. Same as Fig. 3, network lifetime in Fig. 4 also declines with the increase of node spacing. However, it alters more drastically than that in Fig. 3. The reason for this is that network lifetime has a square relationship with node spacing instead of linear relationship with network size. All in all, under the given ranges of network size and node spacing, our approach performs outstandingly over two others.

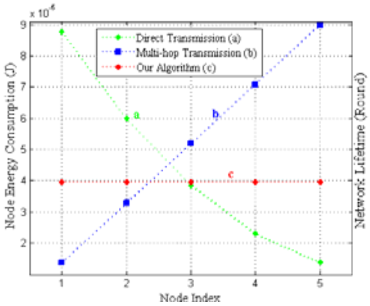

Fig. 2. Node energy consumption.

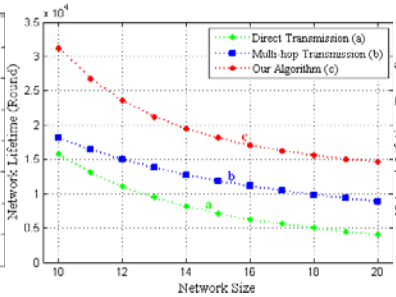

Fig. 3.Network lifetime for different network sizes

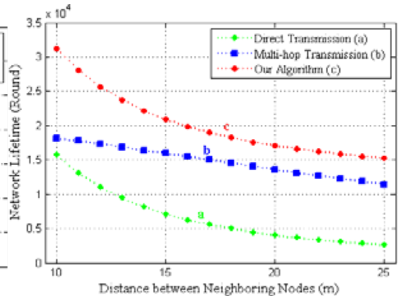

Fig. 4.Network lifetime for different node spacing

5. Conclusion and future work

We exploit the transmission features of sensor nodes to balance the energy consumption and present a probabilistic approach for energy efficient data transmission, by adjusting the probabilities of nodes transmitting their data to others and the sink. We introduce the theoretical model and adopt AFSA to solve the optimal problem. The experimental results show that our approach can effectively balance the energy consumption and maximizes the network lifetime. Practically, the calculation of probabilities is accomplished at sink. However, as the network size increases, the calculation amount will rise drastically, which requires sink to have a high computational capacity. So in the future work, we will focus on how to enhance the solution efficiency and decrease the calculation cost of the sink as much as possible.

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