Low Energy Consumption Routing Protocol for Oil and Gas Pipeline Internet of Things

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Low Energy Consumption Routing Protocol for Oil and Gas Pipeline Internet of Things

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Abstract

For ensuring effective monitoring oil and gas pipelines deployed in the field or arears with poor environment, the wireless sensor network with flexibility, scalability and ease installation has become the basis of the Oil and Gas Pipeline Internet of Things (OGP-IoT). The energy limitation of sensor nodes is the key factor to restrict the performance of OGP-IoT. In addition, the end-to-end delay of the network determines the response time of OGP-IoT to pipeline accidents. It is also the key parameter to improve the real-time performance of OGP-IoT. For solving the problems of energy limitation and end-to-end delay, the Pipeline Internet of Things—Low Energy Consumption Routing Protocol (PIoT-LERP) is proposed in the paper. It can realize the energy balance of the Internet of Things by taking the remaining energy of nodes and the distance between nodes and aggregation nodes as the index of selecting candidate forwarding nodes. So, the life of network is extended and the end-to-end delay of the network is reduced by decreasing the number of data transmission hops. The simulation results show that PIoT-LERP can effectively improve the network performance by extending the network life and reducing the network delay comparing with the classical opportunistic routing protocols ExOR and RE-OR.

Keywords: Oil and gas pipeline. Internet of Things (IoT). Energy balance. Network life. End-to-end delay

1 Introduction

With the maturity of 5G technology, the application of Internet of things (IoT) is also being promoted step by step in oil and gas long-distance pipeline [1]. Oil and natural gas are important strategic energy in various countries. The probability of oil and gas long-distance pipeline facing severe environment is very high. The leakage probability of long-distance transportation of crude oil, product oil and natural gas are also high

[2, 3]. Once leakage occurs in the process of transportation, the consequences are very serious. At present, the method of combing wired and wireless communication to monitor the oil and gas pipeline is adopted in the oil and gas industry. However, the wired communication has the problems of the infrastructure easy being damaged and high installation cost. So, the wired communication is difficult to be widely used in the oil and gas pipeline monitoring [4–7].

The IoT of oil and gas pipelines can realize network self-organization and reorganization in harsh environment. It can be laid in the transmission pipelines with harsh environment and remote area for continuous monitoring throughout the day, faults timely alarm and realizing the oil and gas pipeline leakage monitoring. As the bottom information acquisition system of the IoT, wireless sensor network has the characteristics of high flexibility, organization and low cost and it has great application value in the field of monitoring oil and gas pipeline leakage[8, 9].

Due to the self-limitation of sensor energy and communication range in the Oil and Gas Pipeline IoT(OGP-IoT), the routing protocol is very important. It is related to the energy consumption and end-to-end delay of the whole network and determines the network life partly. Therefore, researching the IoT routing protocol with the high efficiency and low energy consumption becomes the key to monitor the leakage and operation status of long distance oil and gas pipelines.

The traditional routing protocol of wireless sensor networks use fixed routing lines mostly. That means the transmission route is determined before each transmission[10]. But, every wireless link is unstable and the quality of the link changes with time and space. It is difficult to ensure the transmission quality of each link can be suitable for data transmission in the transmission process if the data is routed by predetermined route line. Once the wireless link changes in the route line, the data transmission failure and increasing end-to-end delay can be caused in the network.

The opportunistic routing protocol is proposed according to the above questions. It selects the most suitable transmission relay node from multiple candidate nodes and routes. The stability of data transmission link is guaranteed because the selection of forwarding nodes for each hop increase. So, the success rate of data transmission is improved [11, 12]. However, there are still many challenges about opportunistic routing in OGP-IoT practical application, such as how to select candidate forwarding nodes and how to optimize the energy efficiency and delay in the network.

The routing protocol of the monitoring sensor network in OGP-IoT is researched in the paper. The monitoring sensor network of oil and gas pipeline is used to monitor and detect the status and fault points of the oil and gas pipeline. The monitoring sensor network of oil and gas pipeline is placed around the pipeline for control generally and the nodes are distributed in a fixed linear network topology during the network operation. The wireless sensor network with fixed linear network topology is called linear sensor network (LSNS) in the internet of things. The LSNS has the advantages of easy installation and strong robustness in different environments [13, 14].

The significant contribution of this paper is depicted below.

1. The paper proposes a multi-objective optimization low-energy consumption routing protocol according to the energy efficiency and data transmission delay requirements of the OGP-IoT.
2. The protocol solves the problems of uneven energy use and delay in the OGP-IoT.
3. In this paper,we also consider the residual energy and the distance between nodes, the energy use is balanced in the networks as much as possible, the uneven use of energy is reduced in the network, and the end-to-end delay of data transmission is guaranteed in the network.
4. The protocol proposed in the paper can improve the life span of the OGP-IoT without affecting the performance of the network.

The abbreviations used in this work are given in Table 1.The rest of the paper is set as: Sect.2 discusses literature related to routing protocol for OGP-IoT. Sect.3 describes the wireless sensor network for OGP-IoT. Sect.4 presents low energy consumption routing protocol for OGP-IoT, followed by experiment and analysis in Sect.5. The conclusions and future research are presented in Sect.6.

2 Related works

Wireless sensor network is a basic cognitive network composed of sensors as network terminals and routing nodes. In most cases, the nodes in the oil and gas pipeline wireless sensor network are placed in the place where the environment is bad or hard to reach. So, the energy of oil and gas pipeline wireless sensor network is limited. In the past, optimizing the network energy consumption in the network layer is proposed by many researcher. The sensor protocols for information via negotiation (SPIN)[15] is proposed. It can reduce the energy consumption by eliminating redundant data transmission in the work. In addition, the geographical and energy aware routing (GEAR) protocol[16] is proposed by the researcher. It uses the location information of relay nodes to establish routing. An optimal path to the target node can be established according to the geographical location of the node by this protocol when the data need to be transmitted. The GEAR protocol can prevent data flooding forwarding. However, this kind of protocols based on geographical location need additional location information and the cost of node arranging is increased. The low energy adaptive clustering hierarchy(LEACH) protocol [17] is proposed from the perspective of clustering. It can establish clusters by certain conditions and uses the data compression and local data fusion methods to reduce the number of data transmission and energy consumption. In addition, the cluster head conversion mechanism is also established to balance theenergy consumption between nodes and extend the life of the whole network. However, LEACH protocol is not suitable for linear sensor network, so it is not fit for OGP-IoT.

The concept of opportunistic routing was first proposed by Biswas et al. of MIT in 2004[18] according to the broadcast, time-varying and loss characteristics of wireless channels and the shortcoming of deterministic routing strategies. Then, the opportunistic routing protocol based on the shortest path of end-to-end is proposed. Such as EXOR[19], SOAR[20], ROMER[21], etc. The basic idea of these kind of protocol is utilizing Dijkstra shortest path calculation method to compute the expected transmission count (ETX) value of adjacent nodes. And the ETX is used as the judgment standard. The different methods use the value of ETX to obtain the priority of forwarding data from neighboring nodes. So, the success rate of forwarding data is improved. These methods have a good optimization effect in the end-to-end delay of network but the energy efficiency of the network can't be considered.

Secondly, the opportunistic routing methods based on the geographic location information are proposed, such as DTRP[22], LinGo[23] and COR[24] etc. These protocols can reduce the demand for the infrastructure of sensor network through the geographic location of nodes in the network. With the development of opportunistic routing, an opportunistic routing combined with network coding is also developed, including MORE[25], CORE[26]and CCACK[27] etc. These kind of routing protocols combine multiple data packets with each other by network coding, and transmit multiple data packets to the target node at one time. So, the network throughput is improved, the number of transmission and the energy consumption of data transmission are reduced. But these kinds of protocols also don't improve the disadvantage of too fast local energy consumption of nodes when they select candidate nodes. As results, the energy of nodes with high coding opportunities consumes energy too fast.

There are some researchers introducing the concept of graph theory and probability theory into opportunistic routing to reduce network transmission delay and improve energy efficiency, such as MAP[28], ORL[29], EEOR[30], CL-EE[31] and SCDA[32] etc.

In addition, the researchers also proposed the opportunistic routing protocol based on the iterative method, such as: LCOR[33], OAPF[34], and BitSOR[35] etc. The forwarding process is divided into two stages in these protocols: one is the transmission process of the current node forwarding to the candidate forwarding node, and the other is the transmission process of the candidate forwarding node forwarding to the target node[36–38]. These protocols use the iterative algorithm to calculate the weighted end-to-end transmission cost of each path in the network in order to select more reasonably candidate nodes set. However, these kinds of protocols may lead to a large amount of computation in the iterative algorithm when there are too many transmission paths for nodes in the network.

All of the protocols above don't consider the energy consumption in wireless sensor networks and only pay too much attention to optimizing link quality and end-to-end delay of data transmission. But, ignoring the energy efficiency in OGP-IoT will affect the performance of the whole network and even reduce the network life. Now, some researchers have also considered the energy efficiency in the network, such as REOR[39] and EDOR[40]. The former take the residual energy of nodes into account to prevent some nodes being used multiple times from exhausting energy, but the end-to-end delay between nodes is not considered. So, the delay is increased fast when the network energy is consumed much more. The latter takes the expected energy consumption of the next hop nodes as one of the criteria for forwarding nodes selection. A small amount of expected energy is consumed for each transmission in this way, but the impact of current residual energy of the node is ignored which may cause some nodes to overuse and die so the network performance is affected.

The Oil and Gas Pipeline Internet of Things-Low Energy Consumption Routing Protocol (PIoT-LERP) proposed in the paper. It is based on the multi-objective optimization according to the practical application requirements of the OGP-IoT. The residual energy of the nodes and the distance to the target node are taken as the optimization objective. So, it not only ensures the life of the network but also reduces the data transmission flooding and end-to-end delay.

3 Model for OGP-IoT

The wireless sensor network of OGP-IoT is shown in Fig.1. The sensor nodes are installed between the initial station, intermediate station and terminal station of the pipeline according to appropriate spacing in the OGP-IoT. The temperature, pressure and other parameters of oil pipeline are monitored in real-time. The safety situation of oil pipeline and the production situation of the oil well are also monitored in real-time. All sensor nodes can send data or receive data from other sensor nodes. The sink nodes are installed in various stations. They are supplied by power. They are responsible for data recovery, manage the whole network nodes remotely and realize network interconnection and data forwarding by protocol conversion with other networks.

3.1 Network model

It is assumed the OGP-IoT is a linear multi-hop wireless sensor network deployed in the sparsely populated environment because the most of long-distance pipeline are laid in theremote areas with poor environment. Each node in the network model has its own number j(j$\in [1, m]$).The single hop transmission distance of the node is 1$\sim 100m$. The OGP-IoT could be represented by graph theory model. Let $G = [U, K]$, where U represents the set of all nodes in the network, and K means all links that can be directly connected in the network. Let x,y$\in$ U denote any two nodes that can be connected directly in a network. So, x,y$\in$K represents the link that directly connect any two nodes in the network. Each link has a weighted value which indicates the probability of successful transmission between nodes. The probability of successful transmission between nodes may change because of channel attenuation and noise interference. But, it is assumed the probability of successful transmission of each link is fixed in the paper. At initial stage, the energy of each node in the network is initial value E_0. The residual energy after operation of the node is E_{res} . The residual energy of the sink node is ∞. The energy consumed for transmit data package once time is E_t, and the energy consumed for receive data package once time is E_r.

3.2 Node energy model

The residual energy of node plays an important role in the routing protocol of OGP-IoT. Therefore, it is necessary to model and analyze the node energy in the network. The energy consumption of each node when the proposed protocol is used for routing in each hop is determined by the model. And, the residual energy of each node in the next data transmission can also be calculated by this energy model.

In this model, maintaining initial power E_0 of each node in the network is defined firstly when the network is initialized. The nodes involved in communication are generally divided into two types in the paper. One is the sending node which includes the source node and the forwarding node.

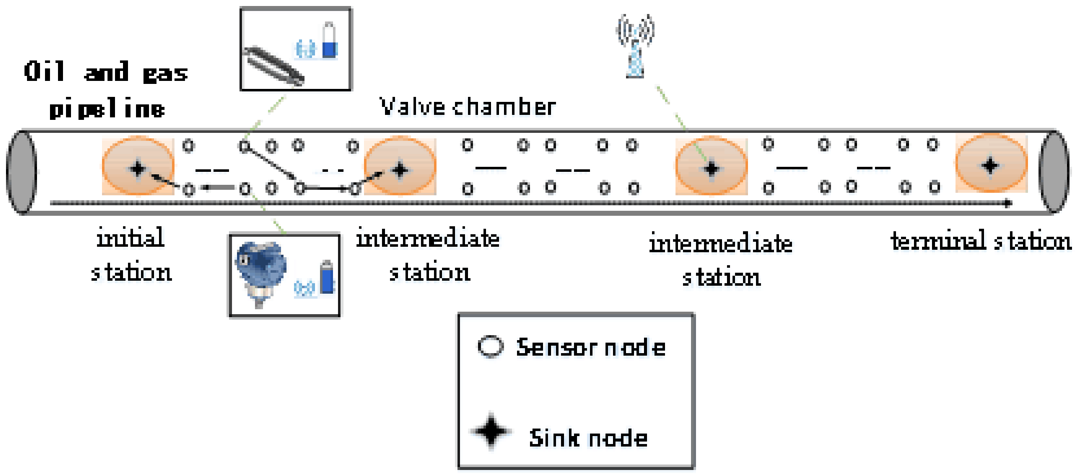

Fig. 1 The diagram of the wireless sensor network of OGP-IoT

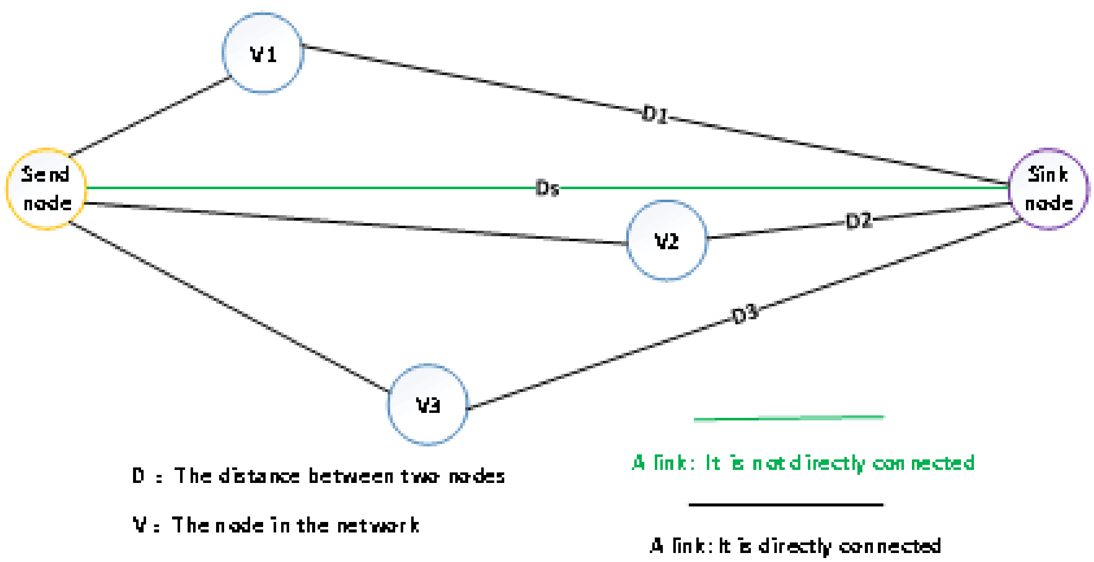

Fig. 2 The network model with inconsistent distance between nodes

And, its main function is selecting the most suitable node among the candidate forwarding nodes. Another is the candidate forwarding node, which is generated by the location information of the sending node, own residual energy level and own location information. After the candidate forwarding node set is generated, it sends own forwarding priority to the sending node. Finally, the highest priority node is selected to forwarding data by the sending node.

The communication process of the sending node for transmission is as follows.

The RTS information is broadcasted to the surrounding nodes by the sending node when data need to be sent. Then, the sending node waits for the CTS reply of surrounding nodes to determine the information of candidate forwarding nodes. Finally, the node with the highest priority is selected to send the information. When one of the candidate nodes receives the forwarding data, it will send the ACK information. After the ACK information is received by the sending node, the forwarding task is completed. The energy consumption formula of forwarding task and the energy consumption equation of transmitting K bytes are as follows[41]:

$$\mathrm{E_{scum}} = \mathrm{N} * \mathrm{E_t} + \mathrm{E_{st}} + \mathrm{E_{ACKr}} + \mathrm{SUM} * \mathrm{E_{cr}} \quad (1)$$

$$\mathrm{E_t} = \mathrm{k} * \varepsilon * \mathrm{R}^2 + \varepsilon * \mathrm{k} \quad (2)$$

Where E_{scum} represents the energy consumption of the sending node in the process of complete single hop transmission. N indicates the number of the packet for the data successfully transmitted. E_t represents the energy required to send data one time. E_{st} describes the energy consumed to send RTS messages. E_{ACKr} is the energy consumed for receiving ACK messages. SUM means the total number of alternative forwarding nodes. E_{cr}represents the energy consumption for receiving CTS information. K is the size of packet. ε is the energy consumption for per byte in per unit area. R means the transmission distance.

So, the energy consumed of sending node in the process of one hop transmission can be obtained from Eq.(1).

The candidate forwarding nodes can be divided into three types according to different energy consumption patterns. The communication process of these three types of candidate forwarding nodes is described as follows.

(1) The candidate node being selected as forwarding node

Firstly, it receives the RTS information from the sending node and it is automatically selected as the candidate node in combination with its own information. Then, it sends the CTS information to the sending node and the content of information is its own information. Once it is determined as the highest priority candidate node by the sending node, it starts to receive the forwarding data and broadcasts the ACK information to the surrounding after receiving successfully. Next, it waits for a period of time. The two priorities P are compared once it receives the ACK information of other nodes. The data packet is discarded if its priority P is lower than the priority P of other ACK information. Otherwise, it is determined as the forwarding node and become the sending node for the next hop transmission.

The energy consumption of the selected forwarding node is calculated as:

$$E_{\mathrm{cumc}} = E_r + E_{\mathrm{sr}} + E_{\mathrm{ct}} + E_{ACKr} + E_{ACKt} \quad (3)$$

$$\mathrm{E_r} = \varepsilon * \mathrm{k} \quad (4)$$

Where E_{cumc} represents the total energy consumption of the selected forwarding node. E_{sr} is the energy consumption of receiving RTS message. E_{ct} describes the energy consumption for sending CTS message. E_{ACKt} means the energy consumption of sending ACK message. E_{ACKr} is the energy consumption for receiving ACK message.

(2) The candidate forwarding node being not selected as forwarding node but receiving the forwarding data unexpectedly

The communication process of the second type candidate forwarding node is basically same as the first type candidate forwarding node. For the second type candidate forwarding node, the difference is the forwarding data is discarded after completing the one hop forwarding process and the next step is not carried out. The energy consumption of this kind of candidate forwarding nodes is calculated as:

$$\mathrm{E_{cumN1}} = \mathrm{E_r} + \mathrm{E_{sr}} + \mathrm{E_{ct}} + \mathrm{E_{ACKr}} + \mathrm{E_{ACKt}} \quad (5)$$

Where E_{cumN1} represents the energy consumption of the candidate node being not selected but the forwarding data being received. E_r is the energy consumption of receiving the forwarding data. E_{sr} is the energy consumption of receiving RTS message. E_{ct} represents the energy consumption of sending CTS message. E_{ACKr} describes the energy consumption of receiving ACK message.

(3) The candidate forwarding node being not selected as a forwarding node and no forwarding data is received

This kind of node has the same communication process with other candidate forwarding nodes before sending data. But, once the ACK message sent by the selected forwarding node is received, this kind of node end this single hop communication task and waits for the next task again. The energy consumption of this kind of candidate forwarding nodes is calculated as:

$$\mathrm{E_{cumN2} = E_{sr} + E_{ct} + E_{ACKr}} \tag{6}$$

Where E_{cumN2} represents the energy consumption of the candidate node being not selected without receiving the forwarding data. E_{sr} is the energy consumption of receiving RTS message. E_{ct} represents the energy consumption of sending CTS message. E_{ACKr} describes the energy consumption of receiving ACK message.

To sum up, the energy consumption of each location node in a complete transmission process can be obtained, and the residual energy of each node after each data transmission can be calculated by the model.

3.3 The influence of distance between nodes to model

The node needs to send RTS detection packets to the surrounding nodes once it needs to send data packets. The detection packets include D_s (the distance from the current node to the target node) and the location of the target node. If the surrounding nodes are idle, after the RTS sent by other nodes being received, it is necessary to determine whether these idle surrounding nodes are suitable for forwarding data. The parameters need to be determined are E_{resi} (the residual energy of surrounding idle nodes) and D_i (the distance from itself to the target node). If the parameter can meet the Eq.(7) and Eq.(8), the node is suitable for forwarding data.

$$\mathrm{D_i < D_s} \tag{7}$$

$$\mathrm{E_{resi} \geq E_{th}} \tag{8}$$

Eq.(7) shows that the nodes closer to the converging node are screened out to ensure that the data is sent forward. Eq.(8) ensures that the selected node can't fail due to too little residual energy. E_{th} in the Eq.(8) means the minimum energy required to complete the receiving and forwarding data. E_{th} is determined by the maximum number of times that the sending node sends data during the data transmission process. Therefore, E_{th} can be calculated as:

$$\mathrm{E_{th} = C * E_t + E_{cumc}} \tag{9}$$

The Eq.(9) is composed of two parts. The first part represents the energy required to transmit data in the next transmission process assuming the node is selected. Where, C is the maximum number of times for sending packets by the sending node. E_t represents the energy required to send data once time. If the data packet has not been sent successfully after times, the data packet will be automatically discarded by the node. This operation can reduce the invalid energy consumption of node. The second part E_{cumc}represents the energy consumption for receiving data in the process of data transmission.

The node satisfying the above requirements sends a CTS packet to the node which prepares to send data. The CTS packet includes the geographical location of the node, the current residual energy of node and D_i . And the RTS messages sent by other nodes can't be accepted so as to ensure that the node can't be selected as the prepared forwarding node by multiple nodes. After the sending node receiving the CTS message replied by each alternative forwarding node, the residual energy of the node and the distance between the node and the sink node are normalized according to the information of the alternative forwarding nodes. The equation of normalization is shown as:

$$\mathrm{\overline{D_i} = \frac{D_s - D_i}{D_s}} \tag{10}$$

$$\mathrm{\overline{E_{resi}} = \frac{E_0 - E_{resi}}{E_0}} \tag{11}$$

Where, $\overline{E_{resi}}$ represents the proportion of the used energy of the node to the initial energy. The value of E_{resi} is higher means the energy that the node can use is less. $\overline{D_i}$ is the ratio of the distance between the node and the sending node to the distance between the sending node and the target node. The value of $\overline{D_i}$ is larger means the node is closer to the target node. D_s represents the distance from the current node to the target node. D_i is the distance of from itself to the target node. E_0 is the initial power of each node in the network. E_{resi} represents the residual energy of surrounding idle nodes.

The forwarding priority of candidate node can be described as:

$$P_i = \left(\bar{D}_i - \overline{E_{\mathrm{resi}}}\right) + 1 = \left(\frac{D_s - D_i}{D_s} - \frac{E_0 - E_{\mathrm{resi}}}{E_0}\right) + 1 \tag{12}$$

Where P_i represents the forwarding priority of candidate node i. $\overline{E_{resi}}$ means the proportion of the used energy of the node i to the initial energy. $\overline{D_i}$ is the ratio of the distance between the node and the sending node to the distance between the sending node and the target node. D_s represents the distance from the candidate forwarding node i to the target node . D_i is the distance of from candidate forwarding node i to the target node . E_0 is the initial power of each node in the network. E_{resi} represents the residual energy of candidate forwarding node i.

From Eq.(12), the node with more residual energy and closer to the target node is the optimal node and the priority is higher. The purpose of adding 1 in the equation is to ensure the priority is not negative. A set of prepared forwarding nodes ProM(x) is selected by Eq.(12).

Theorem: if the sink node is included in the prepared forwarding node, the sending node must choose the sink node as the next hop node.

Prove: if the sink node is included in the forwarding node and E_{res}=∞,D_i=0 for the target node, the priority calculated by the sending node is:

$$\begin{aligned}\mathrm{P_i} &= \left(\overline{\mathrm{D_i}} - \overline{\mathrm{E_{resi}}}\right) + 1 = \left(\frac{\mathrm{D_s} - \mathrm{D_i}}{\mathrm{D_s}} - \frac{\mathrm{E_0} - \mathrm{E_{resi}}}{\mathrm{E_0}}\right) + 1 \\ &= \left(\frac{\mathrm{D_s} - 0}{\mathrm{D_s}} - \frac{\mathrm{E_0} - \infty}{\mathrm{E_0}}\right) + 1 = \infty + 1 = \infty\end{aligned} \tag{13}$$

The equation above shows that the priority of the target node is infinite when it is in the set of forwarding node. Therefore, if the sink node is included in the prepared forwarding node, the sending node must choose the sink node as the next hop node.

4 Low energy consumption routing protocol for OGP-IoT

The protocol consists of four parts: sensing neighbor node, selecting the set of candidate forwarding node, designing the new backoff strategy and finally forwarding node selected.

The process of calculating the priority P_i according to the residual energy of neighbor nodes and the distance to the target node has been discussed in the section 3. The process of selecting the candidate forwarding set ProM(x) according to the priority to wait for the sending nodes to send data also has been described in the section 3. Therefore, the process of data transmission and the strategy of backoff can be described in this section.

4.1 The policy of sending data

The traditional sending strategy is to send data to the highest priority nodes directly and change to the second high priority nodes until multiple transmission failures. The longer transmission waiting time and greater transmission delay are caused. The new transmission strategy is proposed in the paper and it is described as follows:

(1) The maximum sending times C is determined before sending. If the data can't be transmitted successfully after the sending node sends data for C times, the sending node discards the data packet.

(2) The number of times that the sending node forwards data to each preparatory node is calculated according to the priority of different nodes and the maximum transmission times C .

The number of times the sending node sends data to the prepared forwarding node is represented as:

$$\mathrm{N_i} = \left\lfloor \frac{\mathrm{P_i}}{\sum_{\mathrm{i=1}}^{\mathrm{sum}} \mathrm{P_i}} \times \mathrm{C} \right\rfloor, \quad \sum_{\mathrm{i=1}}^{\mathrm{sum}} \mathrm{N_i} \leq \mathrm{C} \tag{14}$$

Where N_i represents the maximum number of times that the sending node sends data to the prepared forwarding node i. P_i means the forwarding priority of candidate node i. sum is the number of selected candidate relay nodes. The number of times for the sending node forwarding data to each preparatory node is calculated by Eq.(13). The

Algorithm 1 The selection algorithm for the set of candidate forwarding nodes

Require:
Input1: Residual energy of all adjacent nodes (E_{resi})
Input2: The distance to the target(D_i)
Input3:Distance from sending node to target node(D_s)

Require:
Output1: The set of candidate forwarding nodes (F)
Output2:The set of priority of corresponding candidate forwarding nodes (P)

Let K being the set of candidate forwarding nodes and K←∅;
Let M being a set and M←∅ ;
for $i = 1 : W$ **do**
  for M←any adjacent nodes of the sending nodes ∈ N(s) **do**
    if d∈M do
    if E_{resi} and D_i Meeting conditions (7) and (8) do
    Let F←n_i
    Using (12) calculating p_i;
    Let P←p_i
    end if
    end if
  end for
end for
return P and F
END

higher the priority is, the more times the sending node sends the data. So, the number of additional forwarding times is reduced, the loss of energy and the end-to-end delay are also reduced.

There is a cycle whose length is the number of all adjacent nodes in the algorithm. The algorithm can save all the adjacent nodes at most. Therefore,the time and space complexity of the algorithm is O(M),M is the number of all the adjacent nodes.

There are two layers for loops in the algorithm. The length of outer layer is the total number of candidate nodes (S) and the maximum length of the second layer is the maximum number of node sending data (C). Therefore, the time and space complexity of the algorithm are both O(S*C) .

Algorithm 2 The selection algorithm for the set of candidate forwarding nodes

Require:
Input1: Total number of candidate nodes (S)
Input2: The maximum transmission times (C)

Require:
Output: Selected candidate node K ;

Let P being a set of node priority;
Let N_i being the maximum transmission times of each candidate forwarding node;
for $i = 1 : S$ **do**
  $K = x$, p_x=$max(P)$
  Use equation (13) to calculate the maximum transmission times N_i;
  for $j = 1 : N_i$ **do**
    Sending node forwards data to forwarding node i ;
    if send node receives ACK message
    Stop sending data;
    else
    $j = N_i + 1$
    end if
  end for
end for
return K
END

4.2 The backoff strategy

How to filter out the alternative forwarding nodes is described above. However, there are still some potential problems in the process of data transmission. For example, the packet may be received by multiple candidate forwarding nodes when the sending node sends data packet to a candidate forwarding node. As results, the collision may occur and the alternative forwarding node may send multiple copies without knowing. It means invalid energy consumption and network invalid throughput. Therefore, a simple collision backoff strategy is proposed in the paper. It determines whether to send or discard the received packets by comparing the priority among the candidate forwarding nodes. The backoff strategy is described as follow.

In the process of transmission, the node receiving data broadcasts ACK to the surrounding once the transmission is successful. The ACK contains the priority P of the sending node. The sending node starts to prepare for sending the next packet when it receives the ACK. And, other prepared forwarding nodes stop receiving the packet after receiving the ACK. The node that has received the data packet waits for a time T to compare the priority P contained in the ACK information. The node with the lower priority discards the packet and the node with the higher priority is ready to forward the packet. In the extreme cases, the same priority appears. In this case, the node with high residual energy is preferred to forward data.

4.3 Network communication process

At first, the network needs to be initialized. The network is built by the sink node broadcasting to the nodes in the network for waking up the nodes. And, the sink node informs its location to other nodes. After other nodes receive the wake-up message from the sink node, they will calculate and store the distance from themselves to the sink node by comparing their location with the sink node. In addition, each node needs to calculate its own residual energy and store it during initialization. For each complete data transmission process, the nodes involved include: selected prepared forwarding nodes, selected forwarding node, sending node and receiving node. These nodes need to update and calculate their own residual energy.

Fig.3 shows the communication process of the protocol. After the network is initialized completely, the network is ready to start transmitting and forwarding data. When the node prepares to send data, the first step is to broadcast RTS information to the surrounding nodes within one hop. The geographical location of the sending node and the target node is involved in the RTS message. The surrounding nodes are notified to determine whether they can become the prepared forwarding node by RTS according to Eq.(7) and Eq.(8). After the surrounding nodes complete their judgment, the second step is the nodes that meet the requirements reply CTS messages to the sending nodes. The CTS message includes the geographical location of the prepared forwarding node and the current remaining energy. The prepared forwarding node that becomes the sending node no longer accepts the RTS information of other sending nodes. After receiving the CTS message, the sending node calculates the priority of each node according to the Eq.(12) and allocates the transmitting times of each node according to the Eq.(13). The third step is to adopt the back-off strategy to prevent the network from invalid energy consumption and invalid throughput. In addition, other prepared forwarding nodes need to cancel the identity of the prepared forwarding nodes and release these nodes to participate in the data transmission of other nodes.

5 Experiment and analysis

5.1 Experimental parameters

In order to test the effectiveness of the proposed routing protocol, the paper uses Matlab 2018a as the simulation platform to evaluate the network performance using the proposed protocol. The network is built in an area of 200m in length and 20m in width, the relay nodes are randomly distributed in the range of 20m×200m. Each node is on a node of 1m×1m area to ensure the coordinates of each node are known. The coordinate system is established with the lower left corner of the region being the origin, the coordinates of the sending node being at (200, 20) and the coordinates of the sink node being at (0, 20). In the simulation, the network parameters required by the whole network are gathered in Table 1 according to the energy model and communication model proposed in the paper.

5.2 The influence of node out-degree on protocol

The focus of the experiment is the impact of different node out-degree on the life cycle of network under the same transmission distance and the number of relay nodes. The optimal node out-degree at different transmission distance is found out according to changing the network transmission distance to make the comparative experiment. In the simulation, the transmission distance is set as 30m, 35m, 40m, and 45m, and the number of relay nodes is set as 110.

Fig.4 shows increasing the out-degree of node reduces the life of relay nodes in different transmission distance. The higher priority of candidate forwarding nodes is, the higher the probability of being selected as forwarding nodes is. When the out-degree of node is expander, the priority of the

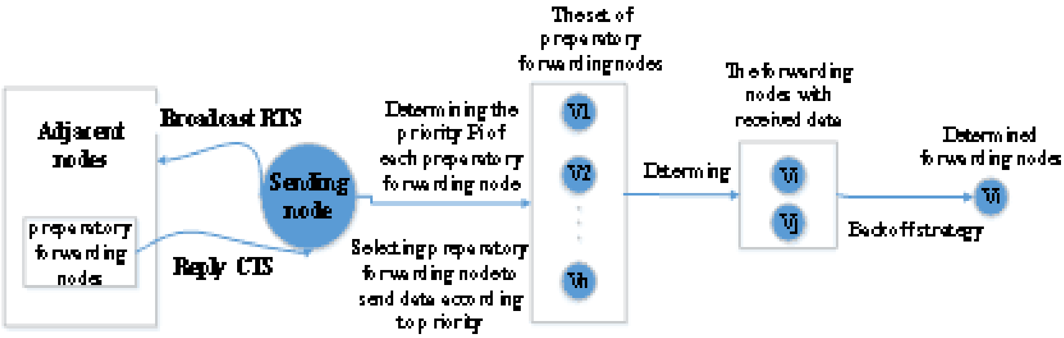

Fig. 3 The diagram of the wireless sensor network of OGP-IoT

Table 1 Network Parameters

The name of network parameters	Value
Network communication range	200m x 20m
Node communication radius	30m∼50m
The number of nodes	110∼130
E_0	5000000nJ
E_{st}	3200nJ
E_{sr}	3200nJ
E_{ACKt}	3200nJ
E_{ACKr}	3200nJ
E_{cr}	3200nJ
E_{ct}	3200nJ
E_r	25600nJ
C	50
ε	100pJ/bit/ m^2
Packet size	512bit

nJ = nanoJoules, pJ = picoJoules, m = meter, J = joule.

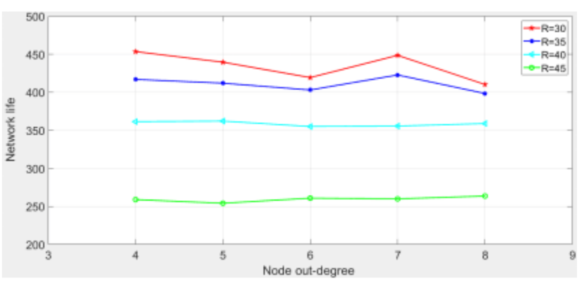

Fig. 4 The diagram of the wireless sensor network of OGP-IoT

increased candidate node must be lower. In general, data is transmitted to higher priority nodes and the new nodes added can't participate in the transmission process. So the new node added can't improve the network life. It can also be seen from the figure that the network life slightly decreases with out-degree increased because the total consumption of candidate nodes increases and the network life decreases with out-degree increased.

5.3 The influence of network transmission distance on the protocol

The influence of different transmission distances on the network lifetime is researched under the condition of the same node out-degree and the number of relay nodes. The influence of transmission distance on network lifetime is compared under different number of relay nodes. The number of relay nodes is set to 100,110 and 120. The out-degree of node is set to 4.

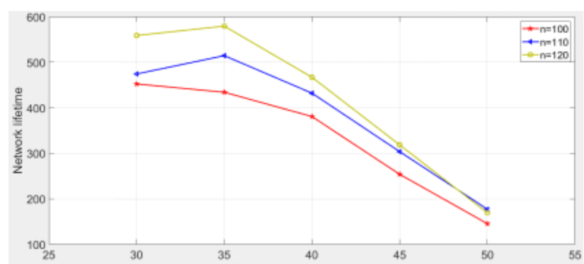

Fig. 5 The diagram of the wireless sensor network of OGP-IoT

It can be seen from Fig.5 that when the transmission distance is less than 40m, the network life remains unchanging or increasing with the transmission distance increasing. But, the network life decreases with the transmission distance increasing when the transmission distance is more than 40m. The reason is when the transmission distance is less than 40m and the transmission distance of the node is increased. The energy consumption decreasing by reducing the number of transmission hops is greater than the energy consumption increased by increasing transmission distance. The maximum value of the network life can be obtained in the transmission distance range of 30m to 40m by analyzing the data in the figure. In addition, the network life is increased with increasing the number of relay transmission nodes by comparison. Therefore, the choice of the transmission distance of node is also crucial when the network is built because it directly affects the network life.

5.4 The influence of the number of relay nodes on the protocol

The influence of relay nodes on the network lifetime under the condition of same node out-degree and transmission distance is researched in the experiment. And, the influence of relay node number on network life is compared under the condition of different transmission distance. The transmission distance is set to 30m, 35m, 40m and 45m and the node out-degree is set to 4.

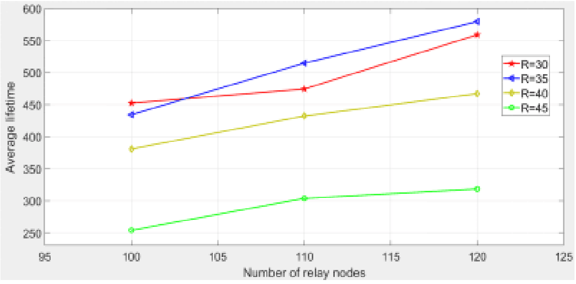

Fig. 6 The diagram of the wireless sensor network of OGP-IoT

The Fig.6 shows the node life increases with the number of transmission nodes increasing in terms of single comparison. The reason is the more candidate nodes that a transmission node can select with increasing the density of node and the probability of choosing out the nodes with the higher priority increases. It can be seen from the comparison that the overall trend is the transmission life decreases with the transmission distance increasing. However, the network life with a transmission distance of 35m is higher than 30m under the condition of the number of node from 110 to 120. It means the node transmission distance is not the smaller the better, but a suitable value of transmission distance needs to be chosen to maximize the network life.

5.5 Average end-to-end delay comparison

The PIoT-LERP proposed in the paper is compared with the classic EXOR protocol and REOR protocol in the average end-to-end delay test. With the transmission distance increasing, the average end-to-end delay of each protocol is compared under the condition of the same number of relay nodes. The number of relay nodes in the experiment is set to 110 and the out-degree is set to 4.

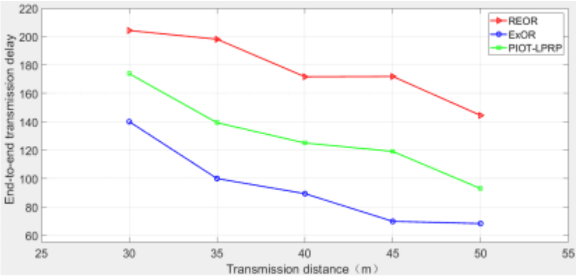

Fig. 7 The diagram of the wireless sensor network of OGP-IoT

The Fig.7 shows the end-to-end delay of network decreases with the transmission distance increasing. Because the number of network transmission hops is greatly reduced with the transmission distance increased leads to the end-to-end delay of network decreasing.

It is seen from the Fig.7 that the end-to-end average delay of the PIoT-LERP proposed in the paper is much lower than REOR protocol but higher than EXOR protocol. The network life is the largest with R=35m according to the previous experiments.

The delay of PIoT-LERP proposed in the paper is about 42% lower than REOR and about 28% higher than EXOR protocol. The reason is the REOR protocol only considers the residual energy of the nodes in the transmission process without considering the end-to-end delay of the network. But EXOR protocol only considers the distance from the candidate node to the target node. The results of experiments show the end-to-end delay of the PIoT-LERP is slightly higher than EXOR protocol, but it can reduce the network delay effectively comparing with REOR protocol.

5.6 Average network life comparison

The network life of PIoT-LERP, REOR and EXOR protocol is compared in the paper. The network lifetime of these protocols is obtained by simulation under the condition of different transmission distance. The number of relay nodes is set to 110 and the out-degree is set to 4.

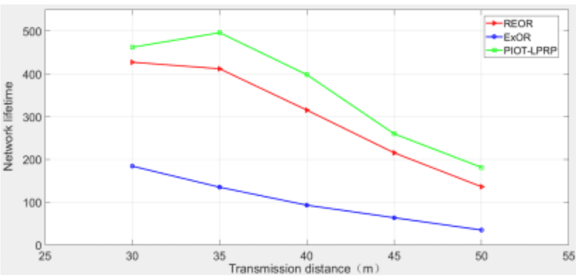

Fig. 8 The diagram of the wireless sensor network of OGP-IoT

The Fig.8 shows the average network life of PIoT-LERP is far higher than the classic opportunity routing protocol ExOR and slightly higher than REOR. The network life of PIoT-LERP is about 73% higher than ExOR and about 17% higher than REOR under the condition of the transmission distance being 35m. The reason is the PIoT-LERP takes into account the residual energy of nodes and the end-to-end distance. Compared with the REOR protocol, PIoT-LERP can reduce the number of hops of each complete transmission to reduce the energy consumption. In addition, the ExOR protocol considers the transmission distance of node transmission only, but it is lack of considering the network life.

To sum up, the PIoT-LERP proposed in the paper can effectively increase the network life and reduce the end-to-end delay. The overall performance of PIoT-LERP is better than ExOR and REOR protocol.

6 Conclusion

The low-energy routing protocol is proposed in the paper for the detection and monitoring sensor network in the OGP-IoT. Oil and gas pipeline detection and monitoring sensor network is used to monitor and detect the status and fault points of oil and gas pipeline. The nodes of detection and monitoring sensor network are distributed in a fixed linear network topology. So, this sensor network belongs to linear sensor network (LSNS). The low-energy consumption routing protocol is designed for the application scenario of the multi-pipeline linear sensor network. The network energy can be balanced and the network life can be extended by using the low-energy routing protocol. In addition, the protocol can also reduce the number of wireless transmission hops, reduce the energy consumption and network delay. In the future, Cognitive Radio and energy acquisition technology will be introduced into OGP-IoT to improve the radio spectrum utilization and solve the problem of large-scale sensor battery replacement. It can improve the reliability of the OGP-IoT and guaranteeing the safe transportation of national strategic resource.

Declarations

Authors Contributions. Liu Miao conceived and designed the study.Yang-yang Liu and Yao Rong designed the study and performed experiments. Liu Miao and Yang-yang Liu wrote the paper. Zhen-xing Sun edited the manuscript.

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Data Availability. Data can be shared and is available on request. Data can be requested by sending an email to the main author.

Conflict of interest. The authors declare that they have no conflict of interest.

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