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An Energy Efficient and QoS Aware Routing Algorithm Based on Data Classification for Industrial Wireless Sensor Networks

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ABSTRACT In industrial wireless sensor networks, an energy-efficient quality-of-service (QoS) routing algorithm is very important to ensure that the key sensing data can be forwarded in a reliable path and solve the energy balance problem. In this paper, we classify the industrial sensing data into three data types and set their priority. Furthermore, we give the reliability parameters and timeliness parameters, and we propose and establish the candidate forwarding node set in order to balance the energy consumption. Subsequently, an energy-efficient and QoS aware routing algorithm is designed, and in this routing algorithm, different kinds of data can be forwarded with different strategies. Furthermore, the most important industrial sensing data are guaranteed to be transmitted to the sink node reliably and timely and common data can be transmitted effectively, too. All these data will be forwarded to the optimal relay node under the circumstance of that the data requirements of real time and reliability are satisfied. The simulation results show that the high timeliness event data can be transmitted real time and reliability than the other type of data. And our proposed routing algorithm is effective compared with the similar algorithms.

INDEX TERMS Industrial wireless sensor network, routing algorithm, reliability, timeliness, EEQA.

I. INTRODUCTION

Industrial wireless sensor networks (IWSNs) are very important to improve and simplify the way to manage, monitor, and control industrial factories [1], [2]. IWSNs are an emerging class of WSN that face specific constrains linked to the particularities of the industrial production [3]. IWSNs have been widely used and their applications can be classified in to three groups. (1) environment sensing; (2) condition monitoring; (3) process automation. IWSN applications for environmental sensing cover the problems of air, water (together with waster water) pollution, etc [4]. The applications of condition monitoring generally covers the problems of structure and human condition monitoring and the machine condition monitoring including possible factory automation [5]. The applications of process automation provide the users with the information regarding the resources for the production and service provision, including the materials, current stock and supply process and building automation.

In IWSNs, there is a lot of important data such as control instructions and real-time monitoring data, which have to be transmitted reliably and in a timely manner. In such complex circumstance, some applications are not only delay-tolerant but also time-critical [6]. Therefore, it is vitally important to respond the requirement in time to avoid the damage that would lead the network or the industrial production fault alarm [7]. Hence, a reliable quality-of-service (QoS) routing strategy is very important to meet those QoS requirements and has an important impact on the overall system performance [8].

IWSNs have their inherent routing characteristics compared with traditional wireless sensor networks (WSNs) [9]. Similar to WSNs, in industrial environment, IWSNs nodes also have limited transmission range. So the source node transmit packets to the destination node, usually the sink [10], with the help of other sensor nodes that are selected as relay nodes. Consequently, the routing protocol in IWSNs should not only facilitate the data transmission, but also consider sensor constraints and to provide reliability and latency requirements since routing decisions can influence the network performance, such as the end-to-end packet delays, the packet delivery rates, and the network lifetime [11]. Up to now, there are two standards within the space of industrial monitoring, they are ISA100.11a and WirelessHART. In those standards, only some key design guidances are provided such as routing functionality [12]. IETF (Internet Engineering Task Force) define a standard protocol of routing in low power lossy networks, it is called RPL (Routing for IPv6 Low Power Lossy Networks) [13] and RPL can be applied in IWSN [14].

IWSNs have been employed to enable reliable monitoring and control functionality in a wide variety of industrial applications [15]. In time-varying and complex industrial environments, advanced communication skills and energy-efficient routing algorithm is required in order to overcome the significant challenges for connectivity, reliability, latency and energy efficiency [16]. For example, delay-bounded industrial process control, require timely transfer of sensed information to control devices [17]. Compared with WSNs, IWSNs routing algorithm must provide higher real-time and reliability [18]. Then the exiting routing algorithm designed for WSNs could not be directly used in IWSNs [19].

In order to improve the performance and guarantee the sensed data can be transmitted reliably and timely, we proposes an Energy Efficient and QoS Aware (EEQA) Routing Algorithm based on data classification for IWSNs that performs routing [20] according to the data type and related requirements [21]. Firstly, we classify the industrial sensed data into four types. Then we define a reliable parameter and a real-time parameter. Based on those, we establish the candidate forwarding node set to conserve the energy consumption of the relay nodes. In EEQA routing algorithm, different types of data requirement can be routed in different strategy and the sensed data would be forwarded to the nodes in the candidate forwarding node set in the case of real time and reliability [6], [22].

The rest of this paper is organized as follows: Section II reviews the limitations of existing QoS routing algorithms; Section III classifies the industrial sensing data into three types; Section IV presents the define the reliability parameter and timeliness parameter, proposes EEQA routing algorithm; Section V presents the results of our experiments and Section VI offers the conclusion.

II. RELATED WORKS

A lot of routing algorithms have been put forward for WSNs which provide QoS service [23]–[25]. SPEED is a QoS routing algorithm based on geography location [26]. In this algorithm the location and delay of one-hop neighbors are stored in the neighbor table of each node. Furthermore, this algorithm use the node in the forwarding candidate node set as the next-hop relay node if the speed of this node is larger than the desired speed. The tradeoff between load balancing and optimal delivery delay is also considered in this algorithm. But this algorithm do not estimate the route quality that is important to the routing performance.

In [27], a multi-constraint and multi-objective routing optimization algorithm is proposed. This algorithm has strict resource constraints in order to meet reliability requirement and high speed delivery need. In this algorithm, the maximum residual energy, minimum traffic load and better link quality are selected as the network parameters to estimate the routing quality based on fuzzy rules. This algorithm can guarantee the reliability and fast delivery in some conditions. However, the quality of wireless link is not considered.

SHE (Self-stabilizing Hop-constrained Energy-efficient) protocol is a hard real-time routing protocol [28]. In SHE, after clustering in wireless sensor network, the aggregate data packets can be routed from cluster heads to the sink node in different routes. AT(Aging Tag) is defined and used to meet QoS need. However, the reliability of route is not considered although its timeliness is distinguished.

Liu *et al.* [29] put forward an effective agent-assist QoS-based routing algorithm for WSN. This routing algorithm make use of a particle swarm optimization algorithm to optimize the performance of the network. In this routing algorithm, an intelligent software agent is designed and implemented. The agent can not only monitor some performances of WSN, such as each node‘s routing state, network topology and network communication flow, but also maintain the network and its routing. However, the reliability and timeliness of transmitted data is not concerned.

Faheem and Gungor [30] propose an energy efficient and QoS-aware routing protocol (EQRP) based on clustering for mart grid. This algorithm is inspired by the true action of the bird mating optimization (BMO) and based on a highly reliable communication infrastructure. The proposed routing protocol can improve network reliability, throughput, packet delivery ratio and reduces excessive packets retransmissions, the end-to-end delay for WSN-based SG applications. But the timeliness requierment of sensed data is not concerned.

In IWSNs, some sensed data are sensitive to timeliness and reliability which has an important impact on the performance of the monitoring system [31]. For IWSN, it is vital to transmit sensed industrial data to the sink node in a timely and reliable manner, otherwise the disastrous consequences will emerge because of lost or delayed data which may lead to wrong decisions in the control unit [32].

Razzaque *et al.* [33] develop a distributed adaptive cooperative routing protocol (DACR). In this algorithm, a lightweight reinforcement learning method is employed to select the next hop relay nodes with knowledge of expected performances. Furthermore, the trade-off between the reliability and delay is optimized at every hop. However, the type of data in IWSN is different and their importance is also different. Different kind of data should be transmitted with different strategies. That is not considered in DACR.

A real-time and energy aware routing protocol (RTEA) is proposed in [34] for IWSN. This algorithm is origin from THVR (Two-Hop based Velocity based Routing protocol) and two-hop neighborhood information is introduced. In order to reduce the number of forwarding hops, the distance from source node to the sink node is considered. Moreover, the time spent by packets transmitted from the first hop to the second hop is used to estimate the delay. However, in RTEA, the reliability of the whole route is not considered.

The main contributions of this study are as follows:

- We classify the industrial sensed data into three types, high timeliness event data, low timeliness event data and periodic data. Each kind of data is assigned a priority. Different type of data will be routed with different strategy.
- We propose a reliability estimation method. In this method, we define a reliability parameter LQMA (Link Quality Measure Algorithm), a link with the minimum sum of LQMA value of all nodes along the link will be selected as the reliable route.
- A routing algorithm based on data classification technology is designed and implemented. The routing algorithm relies on the energy model and trigonometric function of the data transmission for the modeling analysis to select a forwarding candidate set and to calculate the reliability and timeliness of each node. Then, multi-priority routing is processed according to different data levels of the application data to meet the corresponding QoS requirements.

III. CLASSIFICATION

In an industrial wireless sensor network, the node in the sensing region transmits a large number of monitoring data to the sink node and different types of data have different requirements for QoS. If the unified processing standards for all nodes and the requirement of high timeliness of the data are not met, the high reliability of the data cannot be guaranteed.

IWSNs data are divided into three categories based on the data type, high timeliness event data, low timeliness event data, and periodic data.

High timeliness event data: the generation of event data-based applications includes alerts data reports. some alarm data are more critical such as machine reporting failure alarm or fire monitoring system notification. This type of event-based data requires high timeliness for delivery and certain reliability. Otherwise, the transmission delay will lead to a series of disastrous consequences.

Low timeliness event data: applications such as pressure and air flow control are also important and require timeliness. But the transmission delay will not lead to disastrous consequences. For low timeliness event data, their timeliness and reliability is lower than that of high timeliness event data, but higher than that of the periodic data.

TABLE 1. Rank of data priority.

No.	Attribute	Priority
1	High timeliness event data	1
2	Low timeliness event data	2
3	Periodic data	3

Periodic data: applications such as temperature monitoring and humidity monitoring are usually periodic. The monitoring data are generated periodically and require predictable and pre-determined bandwidth. This kind of data has no requirement for real-time and reliability. Therefore, the best-effort delivery service is provided for it.

The data priority levels is shown in Table 1.

As shown in Table 1, the event data is divided into two types of data. One is the high timeless event data, e.g. urgent control data. The other is the low timeless event data, such as the inventory arrival. Every type of data has its own priority level. This priority level is required to distinguish between the following routing processes.

IV. QoS ROUTING ALGORITHM FOR IWSNS

In this study, the QoS routing algorithm of IWSNs considers three aspects: reliability, timeliness, and energy consumption. The first two aspects are measured by calculating the two parameters. The calculation criteria of the reliability parameters and timeliness parameters are described in the following section. In order to save energy for routing, the best relay node sets generation is proposed before designing the routing algorithm.

A. RELIABILITY

The reliability parameter is used to measured the quality of the link to transmit packets.

In IWSN, for the data packets are transmitted in wireless channel, and a wireless channel is complex, random and variable, that will cause channel bandwidth narrowing, channel fading and congestion. In the most serious circumstances, the path will be lost. It is obvious that data transmission in IWSN is affected by many factors. In this study, we propose a Link Quality Measure Algorithm (LQMA) to estimate the quality of link. In LQMA, the Received Signal Strength Indicatior (RSSI) value and the Exponentially Weighted Moving Average (EWMA) algorithm is introduced. The RSSI value is used to obtain the communication characteristics of the link, and the EWMA algorithm is to estimate the link quality.

Suppose that the active window is n, I_{RSSIi} is the RSSI value of the window n at time i. So the statistical average value of RSSI at time k in a window is

$$\bar{I}_{RSSI_k} = \frac{1}{n} \sum_{i=k-n+1}^{k} I_{RSSIi} \tag{1}$$

According to the concept of EWMA and equation (1), it can be determined that the statistically average value of

RSSI at time $k+1$ is

$$\bar{I}_{RSSI_{k+1}} = \frac{1}{n+1}\sum_{i=k-n+1}^{k=1} I_{RSSI_i} = \frac{1}{n+1} I_{RSSI_{k+1}} + \frac{n}{n+1}\bar{I}_{RSSI_k} \tag{2}$$

With a regression for a point of time, then

$$\bar{I}_{RSSI_k} = (1+\frac{n}{n+1}) I_{RSSI_k} + \frac{n}{n+1}\bar{I}_{RSSI_{k-1}} \tag{3}$$

From equation (3), if the RSSI value at time k and its previous RSSI statistical average value is known, it is easy to get the RSSI statistical average value at time k.

R_p and R_f indicate the success rate of sending a packet in the forwarding link and the reverse link repectively. The physical meaning of $\frac{1}{R_p}$ is the number of times that a packet needs to be sent in the forwarding link and $\frac{1}{R_f}$ is that in the reverse link. Combined with equation (3), the LQMA value of adjacent node I_{LQMA} is defined as follows

$$I_{LQMA} = \frac{110}{\bar{I}_{RSSI_p}}\frac{110}{\bar{I}_{RSSI_f}} \tag{4}$$

Where $\bar{I}_{RSSI_p}$ is the RSSI value of the forwarding link and $\bar{I}_{RSSI_f}$ is the RSSI value of the reverse link. They can be get from EWMA algorithm respectively.

Step 1: Estimating both I_{RSSI_p} and I_{RSSI_f} of adjacent nodes;

Step 2: Making use of I_{RSSI_p} and I_{RSSI_f} by equation (1), calculating $\bar{I}_{RSSI_p}$ and $\bar{I}_{RSSI_f}$ based on equation (3);

Step 3: Calculating the LQMA value of each node and that of its neighbors;

Step 4: Establishing a link with the minimum sum of LQMA value of all nodes along the link.

B. TIMELINESS

Timeliness is determined by the transmission rate. When considering the requirement of timeliness, the node with a high transmission rate has priority for selection as a routing forwarding node. From source node a to destination node b, the length of a packets transmitted from nodes a to b is expressed by $PacketLength(a, b)$, the transmission rate between nodes a and node ab is expressed as:

$$TransVelocity(a, b) = \frac{PacketLength(a, b)}{T} \tag{5}$$

where

$TransVelocity(a, b)$ is the transmission rate between the nodes a and b;

$PacketLength(a, b)$ is the length of a packets transmitted from nodes a to b.

T is the time spent on data transmission.

The time T includes the media access (MAC) layer delay $Delay_{MAC}$ and the send packet delay $Delay_{send}$. The two coefficients are determined by the size of the nodes, the data packet capacity, and the bandwidth. The time delay of transmission is:

$$T = (Delay_{MAC} + Delay_{send}) * C \tag{6}$$

where C is the number of data packet retransmissions caused by network failure, link failure, etc.

C. CANDIDATE FORWARDING NODE SET

Because the energy storage of WSN nodes is limited and basically depends on the battery supply, the first consideration is energy consumption. For a given threshold distance d_0, if the distance between node a and node b is $D(a, b) < d_0$, the energy consumption of the transmission per unit message is proportional to the square of the distance; if the distance $D(a, b) > d_0$, the energy consumption of the transmission per unit message is proportional to the fourth power of the transmission distance.

$$E(a, b) = mE_{elec} + m\varepsilon_{fs}D(a, b)^2 \qquad D(a, b) < d_0 \tag{7}$$

$$E(a, b) = mE_{elec} + m\varepsilon_{mp}D(a, b)^4 \qquad D(a, b) > d_0 \tag{8}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{9}$$

where E_{elec} is consumed energy for circuit transmission unit data for receiving and transmitting, and the threshold value d_0 is a constant. ε_{fs} and ε_{mp} are constants and are the consumed energy of the power amplifier when the two sensor nodes transmit one unit of data to a near and far distance, respectively.

The specific distance of d_0 is the square of the ratio of the near-distance energy consumption constant and the long-distance energy consumption constant of the two sensor nodes to the relative transmission in the plane.

Eq.(10) and Eq.(11) show that the transmission energy consumption is quite large when $D(a, b)$ is greater than d_0 and that more energy is saved when $D(a, b)$ is less than d_0. Therefore, in order to avoid the occurrence of this phenomenon, the transport distance must be shortened to d_0. We use a node in the perceptual region as the center of a circle and draw a circle with a radius of d_0 (Figure 1).

Assuming that the sink node is A and a source node is B, and we select the forwarding set N.

$$N = \{X | D(X, B) < d_0, X \in S\} \tag{10}$$

Node X in the set of candidate forwarding nodes must be located in the shadow region S. Nodes in this shadow region S consume less energy as relay nodes rather than directly transmitting energy from the source node to the sink node.

As shown in Fig.1, the distance between the sink node A and the source node B is first used as the diameter of the circle; and node B is at the center of the smaller circle with a radius of d_0. The shadow area that intersects the two circles is called S. A point X in the shadow area is selected arbitrarily and the connection between points A, B, and X create a triangle $\triangle ABX$. According to the trigonometric functions, it can be concluded that:

$$D^2(A, B) = D^2(B, X) + D^2(X, A) - 2 * D(B, X) * D(X, A) * \cos\angle AXB \tag{11}$$

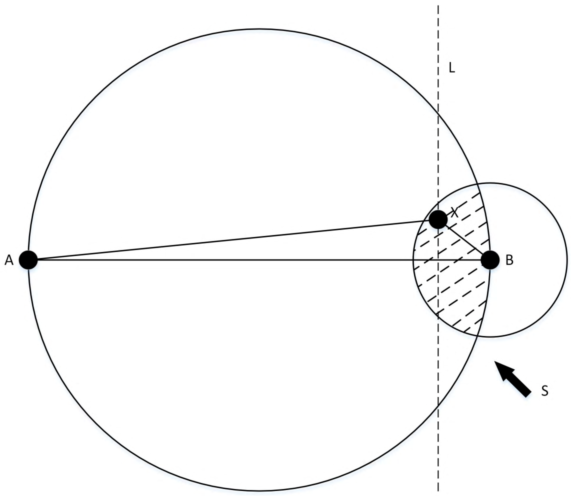

FIGURE 1. Candidate forwarding node selection in case.

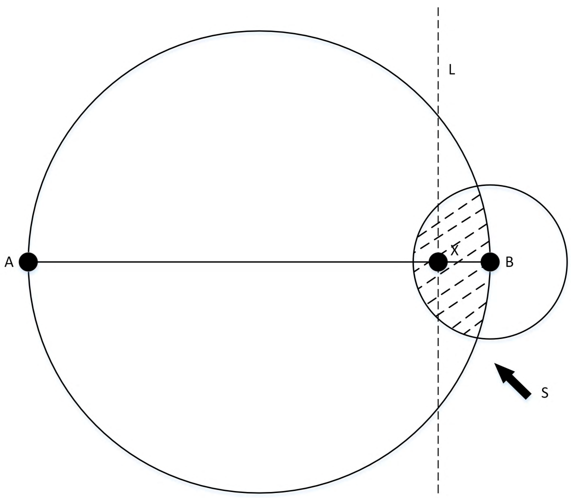

FIGURE 2. Candidate forwarding node selection in case 2.

Using the node X to create an auxiliary line L and $L \perp AB$, we can obtain $\angle AXB > 90°$. Therefore, $\cos\angle AXB < 0$ and we know that $2 * D(B, X) * D(X, A) * \cos\angle AXB > 0$. By substituting this into the Eq.(14), we obtain:

$$D^2(A, B) > D^2(B, X) + D^2(X, A) \quad (12)$$

It is known from equation (7) and equation (8)that the consumed energy of the node is proportional to the communication distance of the node.

$$W = PT \quad (13)$$

It is known from equation (13)that the size of the transmission power P is proportional to the energy consumption W at the same time T. Therefore, we obtain:

$$P(A, B) = P(B, X) + P(X, A) \quad (14)$$

Next, considering a special case where node X is located on the line connecting AB (Fig.2).

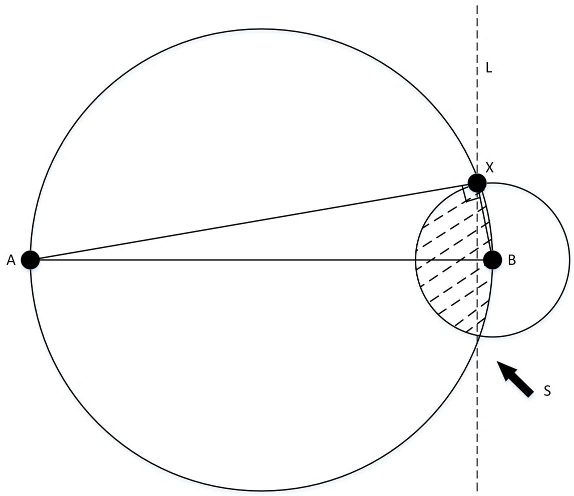

FIGURE 3. Candidate forwarding node selection in case 3.

In this case, $D(A, B) = D(B, X) + D(X, A)$, $\angle AXB = 180°$. After squaring both sides of the equation, $D^2(A, B) > D^2(B, X) + D^2(X, A)$. The corollary is that $P(A, B) > P(B, X) + P(X, A)$.

Finally, we consider the case, in which the node X is in the shadow region S and at the edge of the circle with the diameter of AB, as shown in Fig.1.

Because of the geometrical relationships of the two circles, we can use the diameter of the small circle as the oblique edge and any point on the edge of the circle to create a triangle. The angle corresponding to the oblique edge is a right angle. Therefore, $\angle AXB = 90°$. We know from the previous analysis that $D^2(A, B) = D^2(B, X) + D^2(X, A)$. Because of the data transmission energy model, we also know that $P(A, B) = P(B, X) + P(X, A)$. Thus, when the node X is in the shadow region S and on the edge of a circle with a diameter of AB, it is a critical point for the energy consumption. When the node is in the shadow area, $\angle AXB$ must be greater than 90° and it is an obtuse angle. We know that $\cos\angle AXB < 0$, $D^2(A, B) > D^2(B, X) + D^2(X, A)$. Therefore, $P(A, B) > P(B, X) + P(X, A)$. Only nodes in the shadow region S have the characteristics of energy saving during transmission, which is an important basis for selecting the candidate forwarding node set.

D. DESIGN OF QoS ROUTING ALGORITHM

1) ASSUMPTIONS AND BRIEF ALGORITHM DESCRIPTION

Assumptions:

(1) In IWSN, there is only sink node and its energy is not limited. Other nodes are deployed densely and networks faults and energy hole do not exist;

(2) All IWSN sensors have the same structure, performance and initial energy. Every sensor node has its own serial number;

(3) The location is not the problem that should be considered in this study, so the location of each node in IWSN is known.

Algorithm description:

Based on reliability and timeliness requirement, an energy-efficient and QoS aware routing algorithm named EEQA is proposed for IWSN. This algorithm is focused a variety of application data with different level of priority types. Nodes can depend different data of level to select different next-hop nodes to meet different QoS requirements.

The first phase is initialization process. In this phase, the sink node broadcasts signal over the whole IWSN. Every node in IWSN periodically send notification messages and processes the received information to create neighbor tables. The routing information of nodes is included in these tables such as the serial number, location, residual energy of neighbor nodes in IWSN. Furthermore, the information that will be used to estimate the link reliability and timeliness is also stored in these tables for selecting the optimal next hop.

Data classification is the second phase. In this phase, the sensing nodes give different priorities to the sensed data to the QoS requirement before these data are integrated, packaged and transmitted.

Selecting candidate forwarding node is the third phase. Before the data packet is forwarded, the source node selects the node in candidate forwarding node set as an optimal forwarding node based on the information in the neighbor table and the information sent by the sink node, and selects the node in the best relay area as the nest hop node to save energy.

The last phase is multi-priority routing. According to the different priority levels in the data packet, different routing choices can be made to meet different QoS requirements. The routing order is determined based on the priority when multiple-level data packets get to the forwarding node at the same time. For data with the same priority, the timeliness and reliability requirement coefficient is calculated.

The data classification technology has been described in this study. The selection of the best relay node area and multi-priority routing processing are introduced in the next section.

2) MULTI-PRIORITY ROUTING PROCESSING

After the best relay node area is determined, different next-hop relay nodes are selected according to the different priorities in the data packet identification information.

For the periodic data with a priority of 4, a best-effort strategy is used. The requirements for timeliness and reliability of the data with this priority are low and any routing algorithm can meet the needs of its QoS; therefore, it is not our research focus. The algorithm will not be evaluated in depth and the best-effort strategy is used for routing.

The requirement of the low timeliness event data class data with a priority level of 2 for reliability is relatively high. We can calculate the value of I_{LQMA} of each candidate relay node in the best relay node area by using Eq.(7). The node with the lowest value of I_{LQMA} is selected during each calculation and the requirement for high reliability can be ensured at each step. When the value of I_{LQMA} at each step is lowest, the path has the highest reliability in the network.

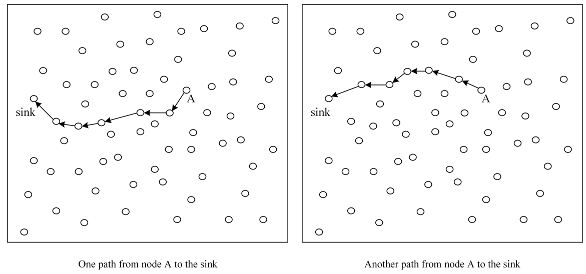

FIGURE 4. The method of non-disjoint path building.

The requirements of the high timeliness event data class with a priority level of 1 for timeliness and reliability are high. Therefore, we need a path selection approach that can guarantee both the timeliness and reliability of the system.

For the data with a priority level of 1, the sensor nodes with the optimal transmission rate in the candidate forwarding node set are selected to meet the timeliness requirement. Then, based on the reliability probability I_{LQMA} of all the selected nodes, the value of all nodes in the entire route is calculated. It is supposed that the total reliability value of the entire route is $sumI_{all}$ and the reliability parameter of the application requirement is $sumI_{need}$. If $sumI_{all}$ does not meet the requirements, another route from the source node to the sink node should be selected, and according to the reliability parameter values I_{LQMA} of all the selected nodes, the value of $sumi_{all}$ of the entire process is calculated. If the reliability parameter of this new path can not meet the requirements either, a new path from source node to destination node will be tried and the reliability value will be calculated, until the application requirements $sumI_{need}$ is met or no new path can be selected. However the reliability can not be met, the path with the lowest $sumI_{all}$ that was just calculated will be selected.

For the method of establishing a multipath routing, the routing algorithm uses the method of non-disjoint path building. In this method, there is no common path and no common nodes between the paths. A single path cannot be the same between individual nodes and the paths must be different. In the iterative process, after the optimal routein has been selected, the node in the route is removed directly from the network during the calculation of the algorithm. If there are enough sensor nodes deployed in IWSN, there will be enough nodes to create a number of redundant lines to ensure the end-to-end reliability requirements. In addition, this method avoids the problem of single-node damage, which leads to the fault of multiple lines. As shown in Fig.4, when the sink node receives a complete data packet, the duplicate packet received will be discarded.

The following is the pseudo code of creating a multipath routing of the data with a priority level of 1, including the path creation selection and final decision.

In order to route data of different priority levels, when different priority data reach the same node at the same time, the node uses a priority avoidance mechanism. High-priority data always have priority of transmission and low-priority

Algorithm 1 Create Multipath Routing

Require: Make a request for creating a multipath routing;
Ensure: Select the node with the largest value of V and create a path;
if the number of paths less than R_{max} **then**
  Create a new path by using the same;
  Measure the end-to-end reliability $sumI_{all}$of source node convergence node;
  if $sumI_{need} > sumI_{all}$ **then**
    Create the routing;
  else
    Make the existing path;
    Return whether the number of paths is less than R_{max};
  end if
else
  Unable to create the routing that meets the QoS requierments;
  Send error reports;
end if

data avoid waiting. If high-priority data arrive while transmitting the low-priority data, after the current data packet has been transmitted, the low-priority data will pause and the high-priority data will be transferred first. For data at the same priority level, we measure the timeliness demand of the data at the same level according to a timeliness requirement coefficient δ. The residual time limit that the application data need to reach the sink node is RT. The distance between the sink node and the current can be calculated; this is RD. Thus, the timeliness requirement coefficient δ is:

$$\delta = \frac{RD}{RT} \tag{15}$$

When the data with the same priority level reach the same node at the same time, we determine the timeliness using this coefficient. Data with large coefficients have a high timeliness requirement and they are preferentially transmitted.

V. SIMULATION AND ANALYSIS

It is supposed that 181 nodes (a sink node and 180 common sensor nodes) are deployed randomly in a region whose size is 400m *400m. Moreover, the transmission power of the nodes can be adjusted and the limited energy cannot be replenished, including the sink node, which is located inside the monitoring area and has sufficient energy. The further parameters used in this simulation are given in the following Table 2.

It is shown in Fig.5 that the connectivity increases with the number of nodes increasing. When the number of nodes is few, the delivery ratio of all three kinds of data is very low because few nodes can be select as the next hop to forwarding data or the quality of link is bad. It is difficult to search a optimal route for timeliness and reliability. When the number of nodes become more and more, the delivery ratio of all kinds of data increase. The high timeliness event data with

TABLE 2. Simulation parameters.

Parameters	Value
Size of the region	400 m * 400 m
Number of nodes	180
Communication distance	20m-40m
Initial energy	2J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
Packet Size	4000 bit

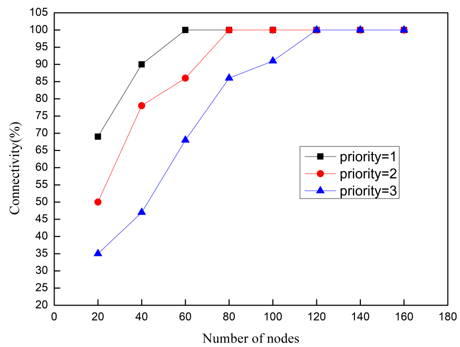

FIGURE 5. Connectivity of different types of data.

a priority level of 1 has a better connectivity than the other two types. This is because that with the number of nodes increase, many more nodes are added in IWSN and more nodes can be selected as relay nodes and many more optimal route may be provided. These results demonstrate that the routing algorithm can effectively determine the importance of the data so that the high timeless event data can be transmitted reliably and timely.

As shown in Fig.6, the time delay increases with the distance from the source node to the sink increasing, because the longer the distance, the more nodes are selected as relay nodes and the longer route will be established. The data is transmitted using more hops. Then many more calculations will be done for selecting the timely and reliable next hop. Furthermore, the different types of sensing data have different hops. The high timeliness event data with a priority level of 1 has the least number of hops and the route used by transmitted this kind of data packets is more timely and reliable. Therefore, this kind of data can be transmitted to the sink node more quickly and reliable than the other data. The periodic data with a priority level of 3 has the most hops. These results indicate that the routing algorithm can effectively determine the importance of the data so that the high timeless event data can be transmitted through a shorter and more robust than the other types of data.

As shown in Fig.7, as the number of nodes increases, the delivery ratio of all kinds of data increases too. This is because that when more nodes are added in IWSN, many more nodes can be selected as the next hop. The data packet has higher probability to be transmitted to the sink node.

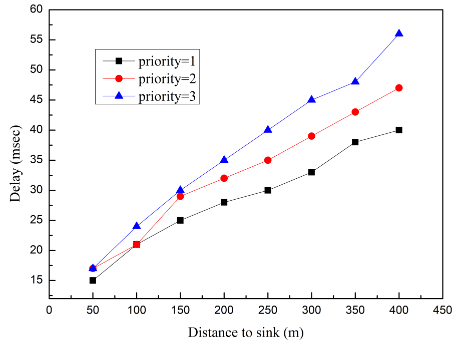

FIGURE 6. Time delay of different types data.

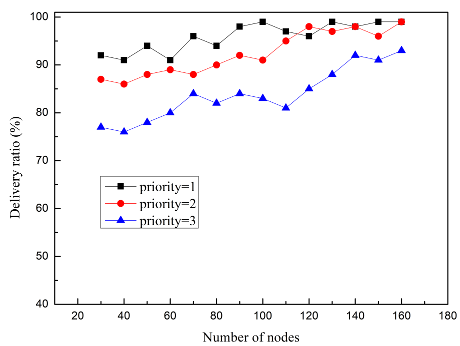

FIGURE 7. Delivery ratio vs. number of nodes for different types of data.

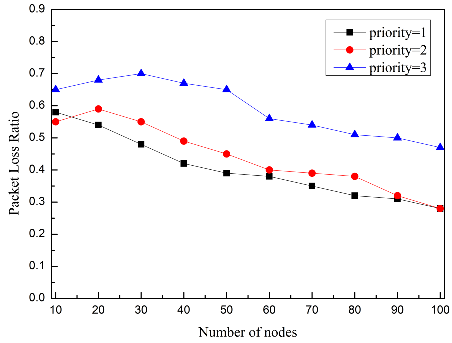

FIGURE 8. Packet loss rate.

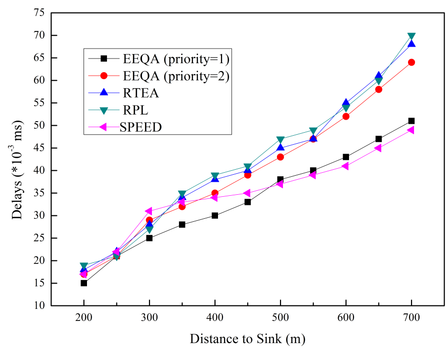

FIGURE 9. Delays of different routing algorithms.

Furthermore, the different types of sensed data have different delivery ratios. The high timeliness event data with a priority level of 1 has the highest delivery ratio because this kind of data can be transmitted in a timely and reliable manner. The better relay nodes and more selectable route could be chosen for forwarding data. The periodic data with a priority level of 3 has the lowest delivery ratio. This indicates that the routing algorithm can effectively determine the importance of the data so that the high timeless event data data can be transmitted more reliably and timely than the other kinds of sensed data.

As shown in Fig.8, the packet loss rate of the different types of data decreases as the number of nodes increases. Here, the size of transmitted data packet is 30pkts/min. This occurs because as the number of nodes increases, the sensed data will be transmitted on a longer path from the source node to the sink and the more relay node will be invalid that will cause more data packets lost. The important data with high priority such as the high timeless event data will be transmitted on a reliable route, so its packet loss rate is lower the other kinds of data packets. Before the nodes begin to transmit the high timeless event data, they compute the reliable relay node to forward data packets.

In this study, we compared our proposed QoS aware routing algorithm - EEQA with other similar QoS routing algorithm. Those routing algorithms that have been proposed for WSNs include SPEED and for IWSNs include the RPL and the RTEA routing algorithms.

As shown in Fig.9, for the high timeless event data, our proposed routing algorithm has a shorter delay from the source node to the sink. That is, the data can be transmitted to the sink faster with the EEQA than the RTEA, RPL and SPEED algorithms. This is because that for the high timeless event data, the nodes select a more timely and reliable path to transmit those data before they forward the packet to the next hop. Of course, the RTEA is also a outstanding QoS routing algorithm. From Fig.9, it is obvious that when the priority is equal to 1, that is, the data is the high timeless event data, our proposed routing algorithm is better than RTEA, because in our algorithm, we must guarantee this type of data transmitted real-time and reliability.

In this paper, we define the delivery ratio is the success delivery rate of one time transmission from the source node to the sink. As shown in Fig.10, EEQA routing algorithm has a better delivery ratio than that of the RTEA, RPL and SPEED algorithms when the data priority level is 1. That means that more data with this priority level of 1 can be transmitted to the sink successfully with our routing algorithm. These data are the high timeliness event data and they are very important to IWSNs. They must be transmitted reliability and timely in order to ensure the smooth progress and safety of industrial production. Although RTEA algorithms is also a QoS aware routing algorithm, but it did not classify the data and transmit the dada with the same policy.

In EEQA routing algorithm, the nodes must calculate the next hop for reliability and real time because the high timeless

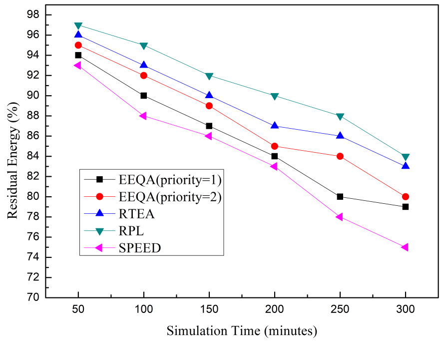

FIGURE 10. Delivery ratios of different routing algorithms.

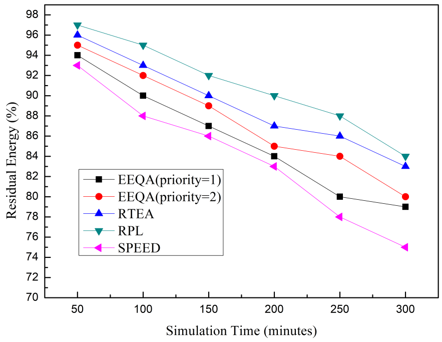

FIGURE 11. Average residual energy of network.

event data must be transmitted reliability and timely. However, those calculation consumed more energy of node in EEQA. But in RTEA, RPL and SPEED algorithms, there are no more redundant calculation. As shown in Fig.11, the average residual energy of nodes in EEQA routing algorithm decreased more rapidly than the average residual energy of nodes in RTEA and RPL algorithms. That means that due to the higher performance, we sacrifice the energy consumption of the nodes. Our proposed routing algorithm is computationally more expensive than the other algorithms and more energy is required before the data are forwarded to the next node. As time goes by, EEQA routing algorithm consumed more energy than the other three routing algorithms. From Fig.11, it is obvious that the average residual energy of nodes in EEQA routing algorithm is higher that in SPEED because SPEED algorithm is not a energy aware algorithm.

VI. CONCLUSION

In IWSNs, it is very critical for the important controlling and monitoring data transmitted timely and reliably. However, for common data, the real-time requirements are not strictly. So we classify the industrial sensed data into three kinds, high timeliness event data, low timeliness event data and periodic data. Based on this, we propose a link reliability estimation method - LQMA and gibe the timeliness parameters to measure the performance of the QoS routing algorithm. Then, we proposed the EEQA routing algorithm. The different types of data packet was routed by different routing strategy. The proposed routing algorithm can guarantee that the high timeliness event data can be transmitted more reliably and timely than the other kinds of sensing data. The higher the priority is, the more reliable the data transmit. Compared with other similar QoS routing algorithm used in WSNs or IWSNs, the simulation result shows the EEQA routing algorithm is more efficient and effective.

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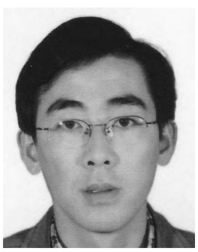

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