A routing algorithm for industrial wireless network based on ISA100. 11a[①]

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Abstract

ISA100. 11a industrial wireless network standard is based on a deterministic scheduling mechanism. For the timeslot delay caused by deterministic scheduling, a routing algorithm is presented for industrial environments. According to timeslot, superframe, links, channel and data retransmission of deterministic scheduling mechanisms that affect the design of the routing algorithm, the algorithm selects the link quality, timeslot delay and retransmission delay as the routing criteria and finds the optimum communication path by k shortest paths algorithm. Theoretical analysis and experimental verification show that the optimal paths selected by the algorithm not only have high link quality and low retransmission delay, but also meet the requirements of the deterministic scheduling. The algorithm can effectively solve the problem of packet loss and transmission delay during data transmission, and provide a valuable solution for efficient data transmission based on determinacy.

Key words: industrial wireless network, ISA100. 11a, k shortest paths algorithm, transmission delay, link quality, superframe

0　Introduction

Wireless communication technology has been widely applied to various fields and has become a fast growing technology in communication in recent years. The industrial wireless technology can meet the special requirements in industrial applications because of its low cost, high flexibility and easy update and maintenance[1]. Many countries such as the United States, Japan and Korea have begun to develop the industrial wireless communications networks, which becomes a research hot spot in the field of automation control.

Wireless sensor network is composed of nodes with sensors, data processing units and communication modules. The communication networks need a safe and reliable routing protocol[2]. Some researches show that the wireless communication network is different from traditional wired communication network and ad-hoc[3,4] network. The designs and algorithms of traditional self-organizing network are not suitable for the wireless communication networks.

There are many studies on routing algorithm in wireless sensor networks. The earliest and simplest routing algorithms are Flooding algorithm and Gossiping algorithm[5], which are easy to be implemented but have some problems such as information implosion, data overlap and the blind use of resources. AODV is a classic routing protocol[6] which is based on demand distance vector, but this algorithm can't meet the deterministic scheduling requirements of industrial applications. GEAR is a routing protocol based on location but can be only applied on fixed nodes. According to the features of the industrial wireless network this paper presents a routing algorithm based on transmission delay and link quality, meanwhile, this algorithm considers the affect of the retransmission and can find the optimal path which has the best quality of the communication link under the deterministic scheduling[7]. This algorithm can achieve stable, real-time, high-quality data transmission and reduce network power consumption.

The ISA100. 11a, wireless HART[8] and WIA-PA are three major standards of the industrial wireless communications networks. The arithmetic in this work is based on the network of ISA100. 11a[9], which is drafted by the American Instrument Association (ISA) ISA100 Industrial Wireless Committee and it is a multifunction standard which is used for industrial sensors and actuator networks. The development of the stand-

ard is based on the demand of users. It can provide reliable and safe operation process in industrial automation.

1 ISA100. 11a industrial wireless network

The researches of industrial wireless standard IS-Al00. 11a include network architecture, protocol layers, equipment roles, compatibility, etc. The key technologies include deterministic scheduling, time synchronization, channel hopping, redundancy mechanisms and security mechanisms. These techniques solve the issues of network coexistence, reliability and certainty communication. Some innovative technologies of standard have been verified in electricity, petroleum, metallurgy and other fields.

1.1 ISA100. 11a network topology

In order to apply to different networks in the applications, the ISA100. 11a supports different kinds of network topologies. There are two major kinds of topologies: star topology and mesh topology. The star network can transfer data accurately and fast but is only used for single-hop network. In order to extend network coverage range ISA100. 11a network combines different topologies and divides itself into upper and lower layers. Gateway and backbone routers form the upper backbone network, which is a high-speed network and reduces data delay effectively. Field devices and routers form the DLL subnet, and the network topology is shown in Fig. 1.
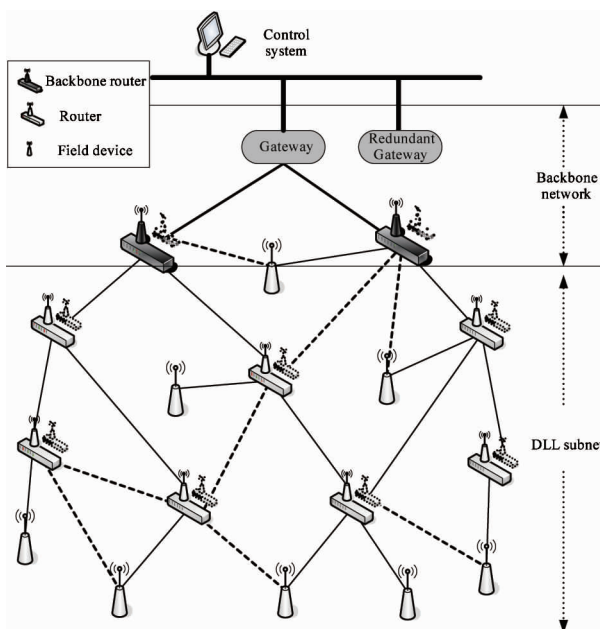

Fig. 1 Network topology of ISA100. 11a

1.2 Network function configuration

Devices in the ISA100. 11a network can be divided into four types according to function: I/O device, router, gateway and host computer. The I/O device is configured with a wireless module and sensors (e. g., smoke sensor, gas sensor, temperature and humidity sensor). The wireless module transfers data which is collected by sensor to the router; The function of router is to forward data to gateway; Gateway plays the role of network manager and security manager, which processes and passes data to the host computer via Ethernet or serial; The host computer displays data in the interface, then people analyse all the state of data and control the industrial environment.

1.3 Superframe and timeslot

The main function of data link layer (DLSL) is to allocate communication resource to avoid conflict and improve the link throughput and bandwidth utilization. The involved concepts in data link layer include timeslot, superframe and link in ISA100. 11a.

Timeslot is the smallest time unit of data transmission. The network administrator sets the length of timeslots when the device joins the network. Superframe is a set of recurring timeslot, the number of the timeslots determines the superframe cycle[10]. Link is used for communication between devices and includes time and frequency, and determines how an equipment occupies time slots to transmit data. There are three types of links: transmit link, receive link and idle link. Fig. 2 is a superframe which cycle is 10 timeslots, the timeslot 1, 3, 6, 10 are links which keep idle; the timeslot 2, 4, 8 are links which are used to transmit data and timeslot 5, 7, 9 are used to receive data.
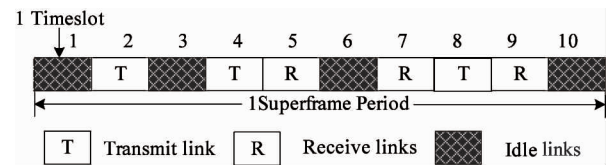

Fig. 2 Time slot, superframe and links

1.4 The routing evaluation criteria

The target of routing algorithms is to select the path which spends the least amount of time to transfer data from initial node to terminal one. The data transfer time is mainly affected by the link quality and transmission delay in the network of ISA100. 11a. In addition, the poor link quality causes packet loss and packet error which will lead data retransmission and retransmission delay. Data must be transmitted in arranged timeslot of superframe which will cause time de-

lay[11]. Existing routing algorithms generally choose one of them as the routing criteria and the selected path may not be the optimal one. The algorithm in this paper chooses link quality and transmission delays as the routing criteria and considers the affect of the retransmission to the algorithm. The best communication path selected by the algorithm is not only the path selected which has the best link quality[12] but also has a reasonable transmission delay.

(1) The quality of link

Industrial wireless communication is susceptible to the interference of the external signal. The physical layer of ISA100. 11a standard complies with IEEE 802. 15. 4 standard and works in the global 2.4GHz free frequency band and there are other wireless networks such as ZigBee, WIA-PA, WirelessHART and Bluetooth in the band. Unstable link quality leads to the failure of data transmission, main loss of packet and wrong packet. It is necessary for us to consider how to avoid signal interference in practical application and select efficient link. It is significant for the whole network to obtain communication efficiency and reliability.

(2) Transmission delay

System manager allocates timeslots to the devices to send data in specified timeslot. It will generate transmission delay[13] when sending data in superframe. The algorithm will define a threshold T_d for transmission delay and choose the path which has less sum of transmission delay than threshold T_d. Fig. 3 illustrates the slot allocation and transmission delay of the communication link. The cycle of superframe is 10 timeslots, and timeslot 2 is the communication link for node A to send data to node B and the data transmission generates 2 timeslot delays. In the same way about
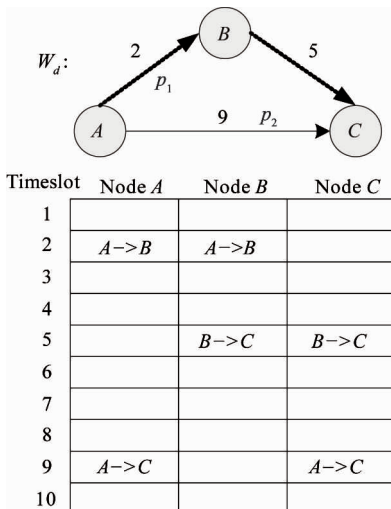

Timeslot	Node A	Node B	Node C
1			
2	A->B	A->B	
3			
4			
5		B->C	B->C
6			
7			
8			
9	A->C		A->C
10			

Fig. 3 Timeslot allocation and timeslot delay

other links, there are two paths for node A to send data to B, $p_1 = < A, B, C >$, $p_2 = < A, C >$, p_1 has total 7 timeslot delays and p_2 has total 9 timeslot delays, in comparison, p_1 is the better transmission path.

2 The design of routing algorithm

2.1 Preprocessing of data

Link quality is the index of the data packet loss rate. It is the number of obtained data frames ratio to the sent data frames. The routing algorithm selects path based on the minimization of total weighting. The higher the initial link quality q_{ij} (link quality between node i to j), the lower Q_{ij} after pre-process is. In order to make the data easy to be handled. The initial link quality q_{ij} is preprocessed in accordance with Eq. (1) before running the algorithm, and the relative link quality Q_{ij} is got by using inverse proportional function.

$$Q_{ij} = 10(1 - q_{ij}) \qquad (1)$$

Low link quality causes the failure of data transmission, and the failure of data transmission causes data retransmission which will impact on the routing algorithm. Fig. 4 is an example, weight W_q is used for the total link quality, there are two paths from node 1 to 6: $p_1 = < 1, 2, 3, 6 >$, $W_{q1} = Q_{12} + Q_{23} + Q_{36} = 9.7$, $p_2 = < 1, 4, 5, 6 >$, $W_{q2} = 12.8$, it is obvious that the link quality weight of path P_1 is better than p_2 according to the minimal path algorithm, but the link quality between node 2 and 3 is too low to send data successfully. The retransmission will increase time greatly. So one should choose path p_2 to send data.
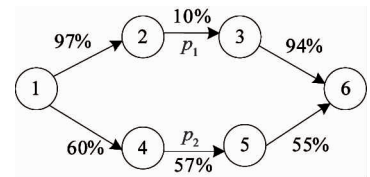

Fig. 4 Weighted graph of link quality

In order to select the optima path and avoid the time delay caused by retransmission to affect the speed of data transmission, one needs to preprocess the total time delay between two nodes according to Eq. (2),

$$D_{ij} = \begin{cases} T_d & 0 \leq q_{ij} < q_1 \\ (1 - q_{ij}) C + d_{ij} & q_1 \leq q_{ij} < q_2 \\ d_{ij} & q_2 \leq q_{ij} \leq 100\% \end{cases} \qquad (2)$$

where T_d is the threshold of transmission delay, d_{ij} is transmission delay from node i to j and C is the time of data retransmission (i. e. super frame cycle), D_{ij} is the total transmission delay that includes transmission

and retransmission delay. If the link quality is lower than a certain ratio q_1 (e. g. , $q_1 = 10\%$), It is difficult to send data successfully, which will be discarded directly by setting the value to T_d. If the link quality is within a range of q_1 and q_2 (e. g. , 10% , 90%), with the increasing of the link quality, the total transmission delay is reducing. The packet loss rate is small if the path has high link quality, and we can ignore the impact on the routing algorithm. After preprocessing the path will get a new transmission delay D_{ij}.

2.2 Description of the algorithm

In order to research and analyse the algorithm this paper abstracts the network of ISA100. 11a into a mathematical model, and turns the edge of all the nodes from the source node to destination one into two weighted graphs. This work uses weight W_d for the transmission delay of deterministic scheduling and retransmission delay, and uses the weight W_q for the link quality.

Operating k shortest path algorithm[14] in weighted graph W_q, the algorithm will get a path during every cycle time and obtain the optimal, suboptimum, third-optimum path in turn. Each time takes the path to the weighted graph W_d to calculate the total of all transmission delay among all nodes of this path, and then compares it with transmission delay threshold T_d of whole network scheduling. If W_t is less than T_d, which indicates that this path is the optimal one which has the best quality of the communication link under the requirement of deterministic scheduling and then stops the k shortest path algorithm, and this path is the optimal communication path. If not, continue to run the algorithm until the path meets two metrics.

The Yen algorithm[15] is used to select k shortest path which is based on the A star search algorithm[16]. The following content introduces the Yen algorithm, assuming s is the initial node and t is the terminal one, v is one of nodes in path p_{sv}, $p_{st} = p_{sv} <> p_{vt}$. Assuming p_k is the k shortest acyclic path from node s to t, p_1, p_2, p_3, $\cdots$, p_k can be seen as a tree T_k which root node is s, and puts all the candidate path into set X. v is the deviation node of p_k. It's the first (according to the order from s to t) node which is outside of tree T_{k-1}, obviously, v is at least the second node of p_k, and the v' is the node behind v in the path p_k. The edge from v' to v is the deviation edge of p_k, and the path from node v' to the terminal node t is the deviation path of p_k. The concrete steps of Yen algorithm are described as follows:

First one can calculate p_1 which is the shortest

path from s to t easily by Dijkstra, Bellman-Ford or BFS algorithm, every time when one calculates p_k, a quantity of candidate paths based on P_k can be developed. Taking Fig. 5 as an example, the black nodes form path p_k, u_i is the node between v' and the previous node of the terminal node in p_k, $u_1 = v'$, $u_2 = v$, and so on. For each node u_i, a candidate path $P_k(u_i, t)$ can be sought out, i. e. , the path of dotted line in the figure which is the shortest path from u_i to t except the path in p_k. The selection of $p_k(u_i, t)$ must meet the following conditions:

Condition 1: Assuming u_i' is the node in tree T_k which is corresponding to u, the edge starting from node u_i in path $p_k(u_i, t)$ is not the same with any edge which starts from node u' in the tree T_k. This condition ensures that the candidate paths must not be the same with any path in the tree T_k.

Condition 2: The nodes in $p_k(u_i, t)$ except u_i cannot appear in $p_k(s, u_i)$. This condition ensures the candidate path has not any loop.
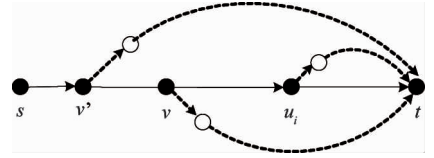

Fig. 5   Candidate path

1	**Routing algorithm based on k shortest path:**
2	Find the shortest path p_1 and set $k = 1$;
3	Put p_1 into $\{T_1\}$;
4	Calculate the transmission delay of p_1: W_d;
5	**While** ($W_d > = T_d$)
6	Define v, v';
7	**For** each node $u_i \in \{v', v, \cdots, t\}$
8	**If** $\{$edge $< u_i, u_{i\,next} > \notin \{T_k\}\}$ && $\{\{v \in p_k(u_i, t)\} \cup \{v \notin p_k(s, u_i)\} = \varnothing\}$
9	Get the candidate path $p_k(u_i) = p_k(s, u_i) + p_k(u_i, t)$;
10	Put each $p_k(u_i)$ into $\{X\}$;
11	**If** $\{T_k\} \neq \varnothing$
12	The optimal path of $\{X\}$ is p_{k+1};
13	**End If**
14	**End If**
15	Remove the p_{k+1} in the $\{X\}$ and put it into $\{T_k\}$;
16	$T_k = T_{k+1}$;
17	$k = k + 1$;
18	**End For**
19	Calculate the transmission delay of p_{k+1};
20	**End**

If $p_k(u_i, t)$ meets the conditions, a new candidate path $P_k(u_i)$ is found, which is $p_k(s, u_i)$ connecting to $p_k(u_i, t)$.

Choosing all the candidate path $p_k(u_i)$ of p_k and putting them into candidate paths set X, one can get the optimal path in the set X as the path p_{k+1}. Delete the path p_{k+1} from T_1 and put it into the deviation tree T_k to form a new tree T_{k+1}.

3　Performance evaluation

3.1　Examples of routing algorithm

The following three figures show an example of routing algorithm, Fig. 6 shows the k shortest path from initial node 1 to terminal node 12 obtained by operating the routing algorithm, Fig. 7 shows the weighted graph of network, and Fig. 8 shows the procedure the algorithm operates. Threshold T_d of transmission delay is set

to 20 slots, the cycle of data retransmission C is 8 slots, q_1, q_2 of Eq. (2) are 10% and 90%.

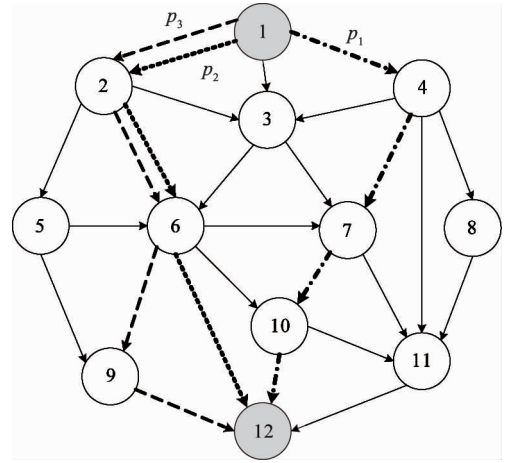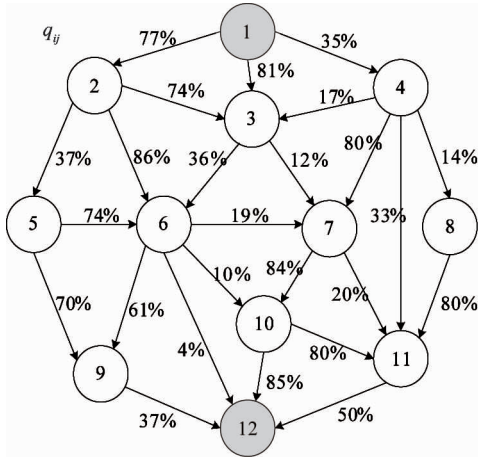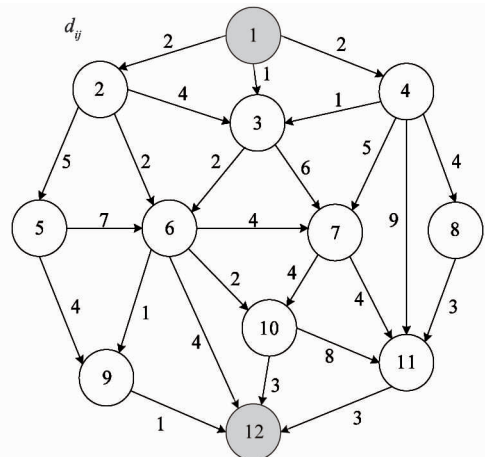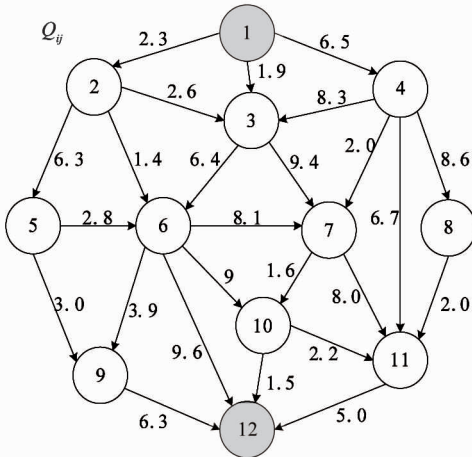(1) Using the Dijkstra algorithm to obtain optimal

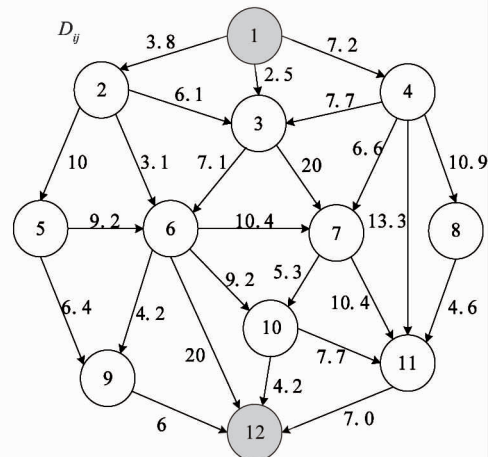**Fig. 6**　k shortest path of network

(a) Weighted graph of link quality before preprocessing

(b) Weighted graph of transmission delay before preprocessing

(c) Weighted graph of link Quality after preprocessing

(d) Weighted graph of transmission delay after preprocessing

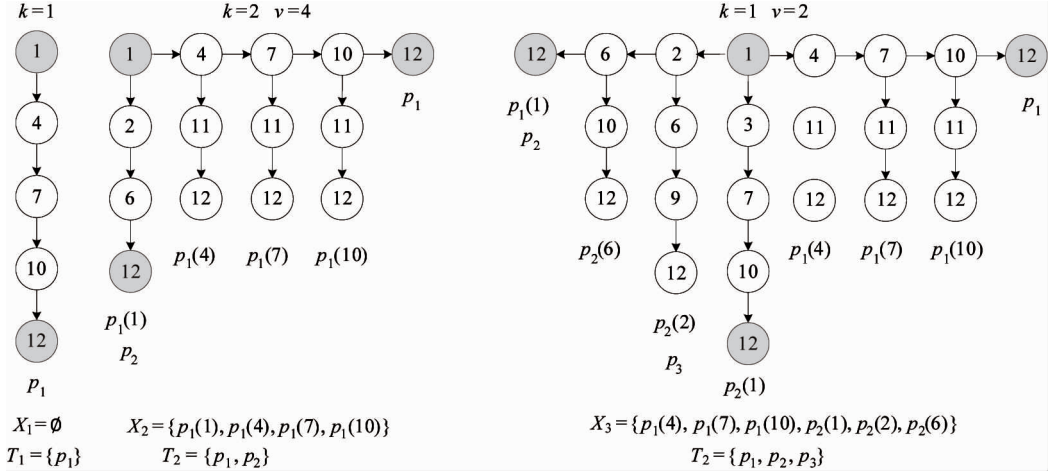**Fig. 7**　Weighted graph of routing algorithm

Fig. 8   The procedure to obtain the best path

path p_1 = < 1, 4, 7, 10, 12 > from initial node 1 to terminal node 12, k = 1. We can figure out the weight of the link quality and the transmission delay of path p_1, W_q = 11.6, W_d = 23.3, $W_d > T_d$, which can't meet the condition. Put p_1 into the deviation tree T_1 then continue to operation the algorithm. The deviate node of p_1 is node 4.

The result is that: k = 1, p_1 = < 1,4,7,10,12 >, v = 4, T_1 = {p_1}, X_1 = ∅.

(2) Calculate the candidate paths based on path p_1 and put them into set X, where $p_1(1)$ = < 1, 2, 6, 12 >, W_q = 13.3; $p_1(4)$ = < 1, 4, 11, 12 >, W_q = 18.2; $p_1(7)$ = < 1, 4, 7, 11, 12 >, W_q = 21.5; $p_1(10)$ = < 1, 4, 7, 10, 11, 12 >, W_q = 17.3. X_2 = {$p_1(1)$, $p_1(4)$, $p_1(7)$, $p_1(10)$}, The best path $p_1(1)$ in X_2 is selected as the second optimal path which has the best link quality, p_2 = $p_1(1)$ = < 1, 2, 6, 12 >, but the retransmission delay from node 6 to node 12 is very big because of its relatively low link quality, therefore, we discard path p_2 directly. Delete $p_1(1)$ from X_2 and put it into the deviation tree T_2. The deviate node is node 2.

The result is that: k = 2, p_2 = < 1, 2, 6, 12 >, v = 2, T_2 = {p_1, p_2}, X_2 = {$p_1(4)$, $p_1(7)$, $p_1(10)$}.

(3) Similarly, calculate the candidate paths based on path p_2 and put them into set X, $p_2(1)$ = < 1, 3, 7, 10, 12 >, W_q = 14.4; $p_2(2)$ = < 1, 2, 6, 9, 12 >, W_q = 13.3, $p_2(6)$ = < 1, 2, 6, 10, 12 >, W_q = 14.2; X_3 = {$p_1(4)$, $p_1(7)$, $p_1(10)$, $p_2(1)$, $p_2(2)$, $p_2(6)$}. The best path $p_2(6)$ in X_3 is setected as the third optimal path p_3 = $p_2(6)$ = < 1, 2, 6, 9, 12 >. Calculate and judge the transmission delay of p_3 in weighted graph W_d, W_d = 17.1, $W_d < T_d$, i. e., path p_3 meets the transmission delay requirements and the best path from source node 1 to the des-

tination node 12 is the path p_3 = < 1, 2, 6, 9, 12 >.

3.2   Vertification results

The routing algorithm verification system is built based on laboratory resources and operated algorithm in the ISA100.11a protocol stack to test its performance. The test system operating the algorithm in the wireless modules based on CC2530 chip. Fig. 9 shows the network of ISA100.11a that includes a gateway, several routers and terminal nodes.
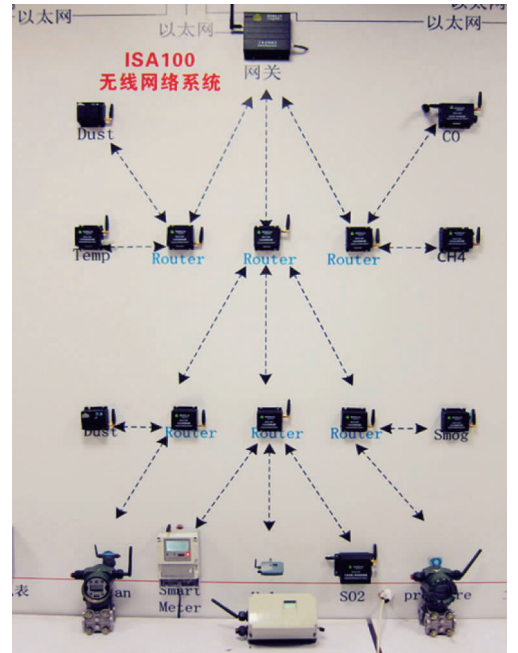

Fig. 9   Testing system

The routing algorithm of this paper uses link quality as the route criterion to select the optimum communication path, and then calculate whether the timeslot latency of deterministic scheduling and retransmission

delay meet the requirements of network. In order to analyze the performance of routing algorithm, it is compared with the other three algorithms, in which the first algorithm selects transmission delay and link quality as the routing criterion, but the data retransmission is not taken into account; the second algorithm selects link quality and the third selects transmission delay as the routing criteria. The verification system establishes four different ISA100.11a networks and the number of nodes are 10, 15, 20 and 25, respectively, and operates the different routing algorithms in the network of certain numbers of nodes and compares the performance of algorithms by the data transfer time of different paths selected by the algorithms.
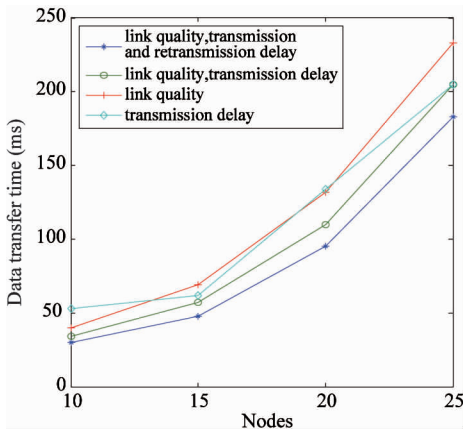

Fig. 10   Data transfer time contrast of different algorithm

The four routing algorithms are operated in the network of different number nodes to obtain four optimal communication paths from source node to the destination. Fig. 10 shows the average data transfer time contrast of four paths selected by different algorithms, wherein the abscissa represents the number of nodes on different networks and the ordinate values represents the average data transfer time of four paths. It can be seen in Fig. 10 that only choosing transmission delay or link quality as routing criterion will generate bigger data transfer time, because the paths selected by algorithms may have poor link quality or the biggish scheduling time. Routing algorithm uses transmission delay and link quality as the criteria to obtain better path quality but the data retransmission is not taken into account, therefore, the path may have poor link quality between some nodes. The path of proposed routing algorithm comparing with other algorithms requires less data transfer time and better performance.

Four routing algorithms are run in the ISA100.11a network that has 20 nodes, and the average data transfer time of four paths selected by different algorithms at different values of k are contrasted. As shown in

Fig. 11, generally the optimum communication path can be got when the k value is less than 3, and the path selected when the k value is 1 maybe not the optimum path. It's necessary to select multiple routing criteria to balance the effects of different factors on the routing algorithm. After the routing algorithm obtains the optimal path, data transfer time increases with k value. The results conclude that the algorithm considering the transmission delay and link quality and retransmission has better performance under the same conditions and the algorithm proposed in this paper is superior to others obviously and has certain advantages.
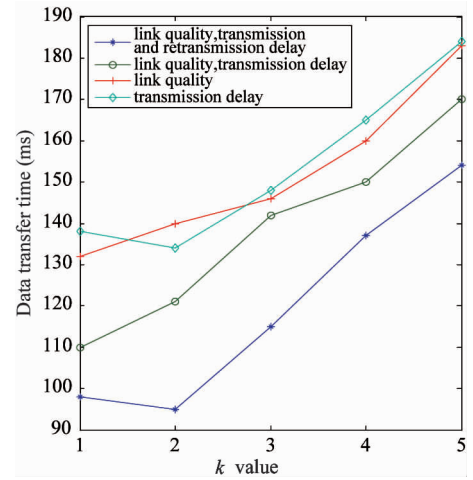

Fig. 11   Data transfer time contrast of different algorithm

4   Conclusion

This paper investigates the deterministic scheduling technology of industrial wireless network standard ISA100.11a and designs a routing algorithm for industrial environments according to network standards and characteristics. Routing algorithms take into account the link quality, schedule delays and data retransmission and uses the k shortest path algorithm to obtain the optimal path. the proposed algorithm is compared with other algorithms under different routing criteria, the results show that the routing algorithm designed in this work can operate stably and reliably in ISA100.11a stack and the optimal path selected by the routing algorithm not only has high channel quality and small retransmission delay, but also meets the requirements of the deterministic scheduling. It can effectively solve the problem of packet loss and transmission delay, and provides a solution to realize efficient data transmission.

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