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A Graph Route-Based Superframe Scheduling Scheme in WirelessHART Mesh Networks for High Robustness

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Abstract WirelessHART is considered to be one of the most promising wireless network protocols for its high robustness comparing to other similar wireless networks. The high robustness comes from its unique routing protocol and redundant superframe scheduling scheme. This paper focuses on the time-slot scheduling and channel assignment of WirelessHART and a graph route-based superframe scheduling scheme is proposed. In order to improve the communication reliability, our scheme applies hop-level retransmission mechanism in a multi-hop and multi-channel circumstance. Moreover, time-slot conflict and channel interference are considered and an effective solution strategy is proposed. To meet the real-time communication requirements, time-slots are assigned in the order of actual communication sequence which can effectively reduce the retransmission delay. Further more, we propose the implementation algorithm of our scheme. The performance analysis shows that our scheduling scheme has a higher robustness than the traditional non-redundancy scheme.

Keywords WirelessHART · Superframe · Re-transmission · Collision avoidance · Time delay

1 Introduction

There is great interest in migrating substantial parts of the traditional wired industrial infrastructure to its wireless counterparts to improve flexibility, scalability, and efficiency. However, concerns about the network latency, reliability and security along with the lack of device interoperability have hampered the deployment rate [1]. The first open wireless communication standard for process measurement and control—WirelessHART communication specification, was approved and released by HART Communication Foundation (HCF) at Sept, 2007 [2]. The aim of wirelessHART is specially to address the critical needs of industrial

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applications to improve their reliability, latency and security. To meet the stringent reliability and latency requirements in harsh and unfriendly industrial environments, the WirelessHART is designed to be a centralized mesh network management architecture, based on radios compliant with the IEEE 802.15.4-2006 physical layer standard, supporting 16 channels in the 2.4 GHz ISM band. Direct sequence spread spectrum (DSSS) is utilized to resist interference from jamming and time division multiple access (TDMA) is utilized to ensure collision free transmission [3].

In a wireless communication network, superframe scheduling scheme which allocate time-slots and channels to each route is critical for network robustness and communication latency. As the industrial wireless network continues to evolve in process industries, real-time transmission scheduling issues are becoming increasingly important for WirelessHART networks. WirelessHART utilizes advanced techniques such as time diversity, frequency diversity and path diversity to achieve high level of reliability and latency required to support advanced industrial applications. These characteristics introduce challenges for time-slot scheduling and channel assignment in WirelessHART networks.

With the consideration of multiple RF channels and multiple communication retries, a graph route-based superframe scheduling scheme is presented in this paper, by which time-slots and RF channels can be effectively used, a hop-level collision-free retransmission mechanism is also proposed in our scheme. The analysis result shows that the communication robustness can be significantly improved while the retransmission delay can be effectively reduced.

The rest of this paper is organized as follows: Sect. 2 discusses the background of WirelessHART and existing related work. Section 3 presents the proposed scheduling scheme and the implementation algorithm. The analysis is presented in Sect. 4. Finally, the paper is concluded in Sect. 5.

2 Background and Related Works

WirelessHART is a wireless mesh networking communication protocol which is centrally controlled by network manager. Its network structure is illustrated in Fig. 1. The network manager, which typically is a PC, is responsible for the management, scheduling and optimization of the whole wirelessHART network. The gateway enables communication between network manager and field devices, and it connects the network manager via a secure wire. As a part of gateway, access point (AP) is the bridge which connects the wireless part and the wired part of the network. WirelessHART is a convergecast network, in which data from a set of sources is routed toward one data sink, which is a critical functionality for wireless networks deployed for industrial monitoring and control. Usually, AP plays the role of data sink and there are two communication directions in wirelessHART: upstream communications from field devices to AP and downstream communications from AP to field devices. In this way, all data must pass through AP. It is noteworthy that the network manager collects global network information through health report which is periodically uploaded by field devices, and the convergecast schedule must be first computed centrally by the network manager and then disseminated to all network devices [4].

2.1 Graph Routing

Graph routing is widely used in wirelessHART for data communication, which contains a direct list of paths that connect network endpoints. It reserves redundant connections in each

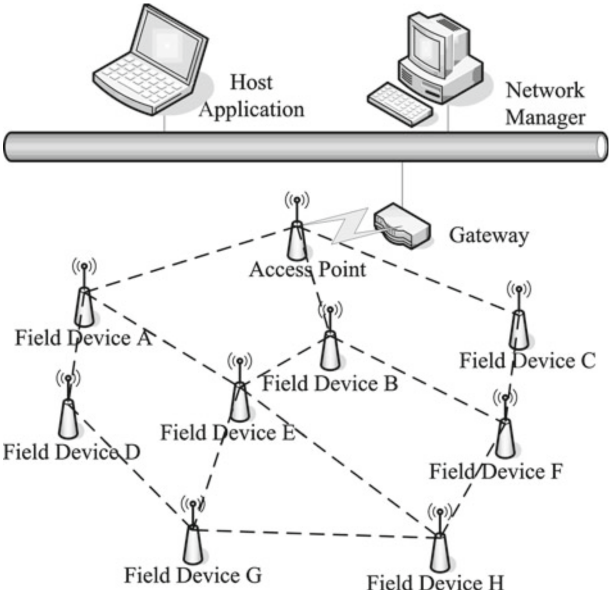
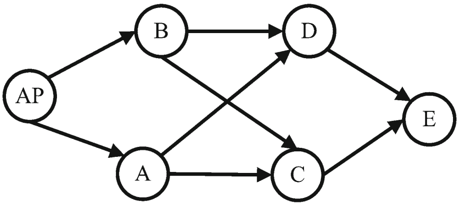


Fig. 1 WirelessHART network topology

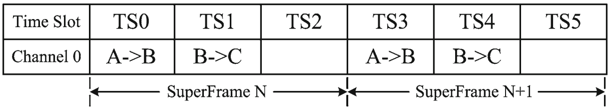
Fig. 2 A graph routing example



hop by which the robustness of network routing can be effectively improved. In a properly configured network, all devices will have at least two neighbors in a graph through which they may send packets. A device can send the packet to any of the listed neighbors. If the chosen neighbor is dropped, it will turn to another neighbor to transmit this packet when it is well scheduled in the superframe. The graph routing strategy from AP to network device E is illustrated in Fig. 2. To send a packet on this graph, AP can forward it to device A or B. From those devices, the packet may take several alternate routes: [AP, B, D, E], [AP, B, C, E], [AP, A, C, E], [AP, A, D, E]. By either way, it will end up at device E [4]. In practice, a properly configured graph routing strategy selects the neighbors with the best RSL (Receive Signal Level) for each node, so that the connections in the graph route have the best communication quality.

2.2 Superframe

WirelessHART uses TDMA, which is a widely used medium access control (MAC) technique in wireless communication protocols. Network-wide synchronization of clocks is needed for successful and efficient TDMA communications. Based on TDMA, WirelessHART uses time-slots with the length of 10ms, in which communications between neighbor



Time Slot	TS0	TS1	TS2	TS3	TS4	TS5
Channel 0	A->B	B->C		A->B	B->C	

Fig. 3 A superframe example

devices occur. The transmission of a packet from a node to its neighbor and the acknowledgement (ACK) packet by the addressed neighbor must be accomplished within one time-slot. A superframe is composed of a number of time-slots. And the number of time-slots within a given superframe is called the superframe length, which form a network cycle with a fixed repetition rate. Superframes are repeated continuously, the more time-slots it contains, the longer the superframe is and the slower the repetition rate is. Figure 3 shows how devices may communicate in a superframe containing three time slots. Device A and B communicate during slot 0 while device B and C communicate during slot 1, and slot 2 is not used. After every three slots, the superframe repeats. Channel should also be allocated when a time-slot is given to a pair of adjacent devices. Since the IEEE 802.15.4-2006 used in WirelessHART supports up to 16 channels, up to 16 pairs of adjacent devices may be fixed in the same time-slot with free collision by using different channels.

The most important thing the network manager does is to schedule communication resources. In order to obtain efficient and optimized schedules, the network manager needs information about the network topology and information about required communication rate. Both of the information is reported by field devices periodically. As this information is discovered, the network manager adjusts the schedule to meet the communication requirements. A given wirelessHART network may contains several concurrent superframes of different sizes which may be used to define different communication schedules for various groups of devices. The supported communication rate will be defined as 2^n times of the basic rate, where ‘n’ is an integer. As an example, assuming the basic rate is 250 ms, then the rate selections can be 250 ms, 500 ms, 1 s, 2 s and so on [5].

2.3 Related Works

Communication scheduling scheme in wireless mesh networks has been widely studied in previous works [6]. However, very few of those are applicable to WirelessHART networks. Although scheduling in convergecast network has been studied in [7,8], these works do not address multi-channel communication or multi-path routing. A mathematical schedule algorithm is described in literature [9], for a linear network with N single-buffer devices. It demonstrates that the minimum time to complete convergecast is $2N - 1$ time-slots and that the minimum number of channels required is N/2. Limited by the maximum number of channels, WirelessHART can only support up to 32 devices for that operation. In literature [10], The same authors improve their algorithm by analyzing the performance bounds of WirelessHART networks for multi-line and tree routing topology, presenting time-optimal scheduling policies which can complete convergecast in $\max\{2n_1 - 1, N\}$ time-slots, and establishing lower bounds on the number of channels for time-optimal convergecast. In literature [11], a scheduling scheme of real-time periodic data flows in a WirelessHART network to real-time multiprocessor scheduling is proposed. They exploit a response time analysis for multiprocessor scheduling and propose a novel method for the end-to-end delay analysis of the real-time flows. In literature [2], a hop-level retransmission convergecast schedule algorithm is proposed to improve the schedule reliability. But the algorithm requires each device to buffer at most one packet at any time-slot, so that it can't be applied practically. In literature [12,13], devices are able to switch channels within a single slot, which gives devices two transmission chances in a single time-slot. In this way, the slot waste can be significantly reduced, but the network conflict may be increased. Two types of conflicts in wirelessHART networks are analyzed in [14,15] and link scheduling solutions are also proposed. Literature [16] aims at improving the response time of the control system and an interference free link allocation scheme is proposed. But the entire superframe scheduling scheme has not been mentioned.

Cross layer method is widely used in wireless mesh networks [17–20]. A new joint route-based scheduling method, which is particularly suitable for centralized networks, is used in [14,21], and it is proved that its performance is better than the separated method. In literature [22,23], efficient and practical scheduling algorithms managing a multihop multi-channel networked system based on the WirelessHART standard is presented. But hop-level retransmission is not considered in the channel assignment algorithm. Some technical challenges are discussed in literature [24].

In conclusion, the majority of published literatures do not provide a complete scheduling scheme which can be directly practiced in wirelessHART network.

3 The Proposed Scheduling Scheme

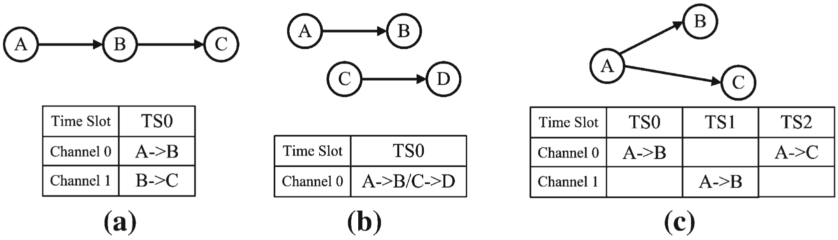
3.1 Schedule Restrictions Analyze

In a wirelessHART network, graph routing which connects AP and network devices is used to transmit data. When a device requests for communication resources, the network manager needs to assign communication time-slots and routing devices in the graph for the data transmission. All the time-slots form a superframe based on that graph and its length is adjusted according to the required communication rate. Graph routing presents end-to-end routing paths in the network, while the superframe which has been assigned according to the graph provides communication opportunities. Therefore, the consideration of graph routing helps the superframe to improve the scheduling efficiency. So we present a graph route-based scheduling scheme that also takes multiple RF channels and multiple communication retries into account. In order to avoid network conflicts, to enhance the robustness and to reduce the transmission delay, there are some restrictions that need to be considered:

(1) Allocating time-slot to each connection. In order to ensure that each device in the graph routing has the communicate opportunity, time-slot should be allocated to each connections of graph in a well scheduled superframe.

(2) Scheduling time-slot sequence with actual communication needs. That means an early slot should be allocated to the connection that will communicate earlier, and in contrast a later slot should be allocated to the connection that will communicate later. This strategy helps to reduce the communication latency and retransmission delay. A packet can be transmitted as soon as possible after it is received by this strategy and accordingly, the memory efficiency can also be improved.

(3) Time-slot conflict avoidance. A device can not transmit and receive simultaneously and can not transmit/receive more than one packet at the same slot with a single transceiver. A simple example of time-slot conflict is shown in Fig. 4a. A $\longrightarrow$ B



Time Slot	TS0
Channel 0	A->B
Channel 1	B->C

Time Slot	TS0
Channel 0	A->B/C->D

Time Slot	TS0	TS1	TS2
Channel 0	A->B		A->C
Channel 1		A->B	

Fig. 4 Two kinds of conflict and multi-retransmission. **a** Time-slot conflict, **b** channel interference, **c** multi-retransmission

Time Slot	TS0	TS1	TS2	TS3	TS4	TS5	TS6	TS7
Channel 0	AP->A		AP->B	A->D	A->C	B->C	D->E	C->E
Channel 1		AP->A	A->D	B->C	B->D	D->E		

Fig. 5 Example of a graph route-based superframe

and B $\longrightarrow$ C are two connections that are assigned in the same time slot. In this case device B is scheduled more than once in a slot and therefore causes a time-slot conflict.

(4) Channel interference avoidance. Channel interference occurs when two pairs of devices using the same RF channel at the same slot. Figure 4b shows two connections A $\longrightarrow$ B and C $\longrightarrow$ D which are assigned the same channel in the same slot. This causes radio interference. Both time-slot conflict and channel interference should be avoided in the superframe scheduling scheme.

(5) Hop-level retransmission. To obtain higher network robustness, we propose a strategy that assigns redundancy time-slots with the consideration of graph routing to support hop-level retransmission. Except the last hop, there are at least two neighbors for each device in graph routing. Moreover, three transmission opportunities is assigned to each transmission, i.e., if the initial transmission fails, there are two retransmission opportunities followed: the first retransmission tries to transmit the packet through another channel to the same neighbor device that the initial transmission used, while the second retransmission uses anther neighbor through either channel. Figure 4c illustrates the hop-level retransmission. If the initial transmission from A to B using channel 0 fails, the first retransmission using channel 1 can be followed in TS1 (time-slot 1). After that, the second retransmission forwards the packet to device C in TS2 using channel 0.

After considering the above constraints, the superframe of the graph shown in Fig. 2 can be illustrated in Fig. 5. Time-slots of the superframe are strictly assigned in the order of sequence that actual communication occurs. For example, time-slots for the transmission AP $\longrightarrow$ A and AP $\longrightarrow$ B are assigned first, followed by time-slots that devices A and B used to communicate with their neighbors D and C, and then time-slots for devices C and D to E are assigned in the last. Both time-slot conflict and channel interference are avoided in this case. According to this scheme, a packet can be transmitted from AP to device E by using up to eight slots, as shown in Fig. 5.

3.2 Basic Scheduling Strategy

According to the constraints that have been analyzed in last subsection, our superframe scheduling strategy is proposed as follows.

(1) A given wirelessHART network may contains several concurrent superframes of different sizes to meet different communication rate demands. As time-slots and RF channels are extremely limited resources, the communication with a higher rate should be performed with a higher priority. So superframes should be scheduled starting with the highest to the lowest communication rate until all the communication requests are replied.

(2) The connection list in a given graph is usually ordered based on actual communication sequence. So in order to meet the actual communication requirement, time-slots need to be scheduled to agree with the connection sequence which is indicated in the graph table. In our scheme, we set a temporary variable named ***LastSlot*** for each device. Its value is updated timely to make sure that it always records the latest slot that the device has been assigned. During the scheduling process, the first available slot after ***LastSlot*** will always be selected. In this way, the time-slot sequence is always strictly accordant with the actual communication.

(3) To avoid time-slot conflict, one must guarantee that a device can only be scheduled once in a given time-slot. And channel interference can be avoided by not allocate duplication channel in the same time-slot. Therefore, a table named ***SlotNumber*** is needed to record channels and devices which are assigned in each time-slot. During the scheduling process, this ***SlotNumber*** table must be traversed to find the first allowed time-slot in which neither the source nor the destination of the connection are involved in. And then assign the first free channel in the given slot to that connection. If all the 16 channels have been occupied, the next available time-slot should be found. In addition, conflict and interference must be avoided between multiple superframes, and so that this ***SlotNumber*** table should be shared by all superframes.

(4) For a given source device, redundant transmission time-slot should be provided. And the retransmission slot should follow the original transmission time-slot closely in order to reduce unnecessary delay. Our strategy set a Boolean variable named ***First***. It is TRUE for an initial slot and FALSE for retransmission slots. A variable named ***FirstChannel*** is used to record the channel that was assigned to the initial time-slot and by checking this variable the same channel can be avoided to be selected again in the first retransmission slot. In addition, each connection in the graph is assigned a time-slot. Therefore, the retransmission slot to anther neighbor is already included in the superframe.

(5) Once the required time-slots of all connections in the given graph are assigned, some idle slots are filled in the superframe to meet superframe length which is decided by required communication rate. In addition, since time-slots and channels are limited communication resource, once large numbers of superframes are on operation, the remaining communication resources may be not enough to meet a new subsequent request. In this case the new request will be rejected.

3.3 Scheduling Algorithm

According to the above scheduling strategy, our superframe scheduling algorithm is presented in this subsection. Here we assume that the graph table is already available:

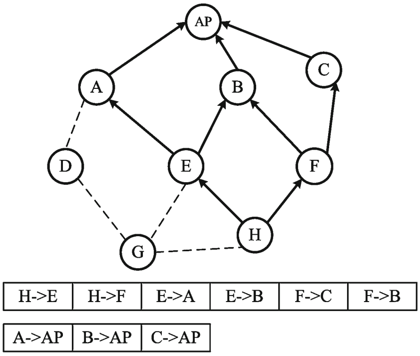
```
Notations:
        Length denotes the superframe length.
        Start denotes the first slot in a superframe.
        con(A, B) is a connection in which A represents the source device and B is the destination.
        S/D is the source/destination device.
        SlotNumber is a table used to record the scheduled slots with devices and channels in that slot.
        LastSlot records the time slot that each device uses at the last time. Its initial value is -1.
        Channel indicates the channel numbers, range from 0 to 15.
        First/FirstChannel record the first used slot/channel for each source device.
Begin: 1. for length–get superframe from the shortest length to the longest.
            1.1 Graph-get the Graph related to this superframe.
            1.2. for all con(A, B) from Graph, according to communication sequence.
                2.1 $S \leftarrow A$; $D \leftarrow B$; $First = 1$.
                2.2 for traverse SlotNumber, find the first slot that S and D are both free, named tmp_slot.
                    3.1 if (tmp_Slot>S_LastSlot && tmp_Slot>D_LastSlot).
                        $Slot \leftarrow tmp\_Slot$.
                        else return to 2.2 and find anther slot.
                    3.2 if (A is the source of Graph) $Start \leftarrow Slot$.
                        else if ( length<Slot-Start) break and return failure.
                    3.3 traverse SlotNumber, find a free channel in Slot, if there is no free channel,
                        then return to 2.2 to find anther slot.
                        4.1 if (First = 0 && FirstChannel = Channel), return to 3.3 find anther channel.
                            else $FirstChannel \leftarrow Channel$.
                    3.4 put A, B in the Slot list, put Slot and Channel in the SlotNumber table.
                        $S\_LastSlot \leftarrow Slot$, $D\_LastSlot \leftarrow Slot$.
                    3.5 if (First=1), $First \leftarrow 0$. else return to 1.2.
End.
```

Figure 6a shows an upload graph from H to AP with the connection list. The superframe corresponding to that graph, which is processed by our scheduling algorithm, is illustrated in Fig. 6b. Time-slots are arranged in the order of actual communication requirement. For example, suppose the actual communication path is [H, F, B, AP]. It can use the time-slots TS2 for H $\longrightarrow$ F, TS6 for F $\longrightarrow$ B and TS8 for B $\longrightarrow$ AP. It can be seen that the slot sequence is well scheduled to meet the actual communication requirement. There is no time-slot conflict between con(E, A) and con(H, F), or between con(E, B) and con(F, C). So they are assigned in the same slot with different channels. Redundant time-slots that including two retransmissions slots are perfectly realized. For device E, it has the original transmission chance to A in TS2 on channel 1. The first retransmission takes place in TS3 on Channel 0, while the second retransmission will forward the packet to device B in TS4 on Channel 0.

4 Analysis and Evaluation

In this section, we analyze the proposed scheduling scheme.

(1) Equitable communication chance for each path. Graph routing has a unique feature of hop-level redundancy that includes several routing paths with the highest communication quality for a source-destination pair. Our scheduling scheme is based on graph routing and the obtained superframe will include time-slots to meet the communication



(a)

Timeslot	TS0	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
Channel0	H->E		H->F	E->A	E->B	F->C	F->B	C->AP	B->AP	
Channel1		H->E	E->A	H->F	F->C	E->B	C->AP	F->B		B->AP
Channel2					A->AP					
Channel3						A->AP				

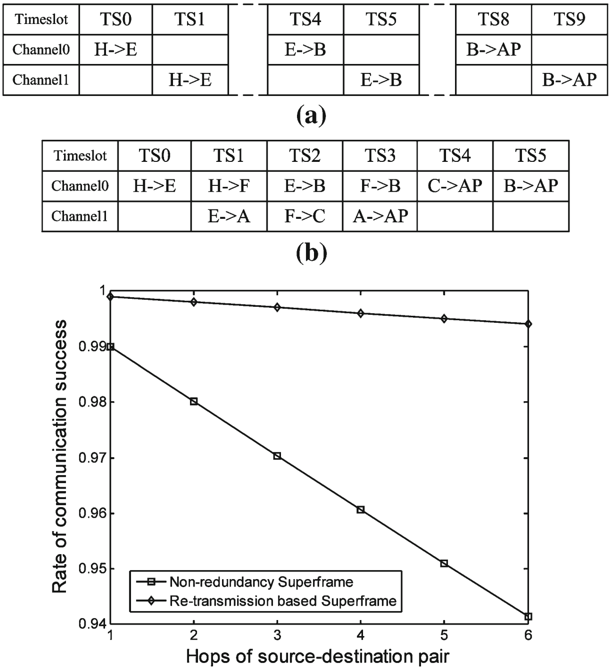
(b)

Fig. 6 Upload graph and Superframe from H to AP. **a** Upload graph from H to AP, **b** upload Superframe from H to AP

requirement from each path in a graph. For example, assuming the path with highest communication quality in Fig. 6a is [H, E, B, AP], the communication time-slots for this routing path is included in the superframe which is obtained by our scheme, and its time-slots is shown in Fig. 7a.

(2) Improvement of network robustness. Our scheme implements a hop-level retransmission mechanism which is based on graph routing with its hop-level redundant characteristic. Compared to multi-path routing, routing robustness can be effectively improved by graph routing. Supposing hop-level loss probability for each routing is $p_l = 0.1$, we make a general robustness comparison among the ordinary single-path routing, multi-path routing and graph routing, and the results are shown in Table 1. It demonstrates clearly that in normal conditions, the robustness of the graph routing is even higher than the multi-path routing which has three routing paths, in contrast, graph routing has a fewer resource-occupation.

Our superframe scheduling scheme based on graph routing, will further enhance its communication robustness. In our scheduling algorithm, two retransmission slots are assigned promptly following the original slot with smaller delay. In this way, the retransmission can be performed in the shortest time when the original transmission fails, and accordingly, the network robustness can be effectively improved with fewer resource consuming. For example, Fig. 7b shows a non-redundancy superframe scheduling scheme for the graph shown in Fig. 6a. we assume hop-level loss probability in the network is $p_l = 0.1$. Then the communication success rate of non-redundancy scheme which is shown in Fig. 7b is 88.2 %. In contrast, the success rate of the proposed hop-level retransmission scheme is 98.8 %, which is 12 % higher than the non-redundancy scheme. Figure 7c gives the success rate in the general case. It can be seen that our scheme has a higher robustness than the ordinary non-redundancy one.



Timeslot	TS0	TS1	TS4	TS5	TS8	TS9
Channel0	H->E		E->B		B->AP	
Channel1		H->E		E->B		B->AP

(a)

Timeslot	TS0	TS1	TS2	TS3	TS4	TS5
Channel0	H->E	H->F	E->B	F->B	C->AP	B->AP
Channel1		E->A	F->C	A->AP		

(b)

(c)

Fig. 7 Robustness comparison with ordinary scheme. **a** Time-slots for path [H, E, B, AP], **b** non-redundancy supreframe, **c** robustness comparison

Table 1 The robustness comparison result among 4 routing types (hop-level success rate is 90 %)

Route type	1 hop	2 hops	3 hops	4 hops	5 hops
Single path route	0.9	0.81	0.729	0.6561	0.59049
Double path route	0.9	0.9639	0.926559	0.881045	0.833776
Triple path route	0.9	0.993141	0.946461	0.959328	0.931326
Graph route	0.9	0.9801	0.970299	0.960596	0.950990

(3) Reduce the retransmission delay. In order to improve the robustness of WirelessHART network, our scheme takes the way of assign redundant time-slots, which may cause a higher end to end delay than the non-redundant schemes. However, in our scheme the retransmission slots are assigned under the efficient use of free channels, so that the delay caused by redundant slots can be efficiently reduced. We have made a transmission-delay comparison among our scheduling scheme and no redundant schemes based on multi-path routings which is shown in Fig. 8 and graph routing as shown in Fig. 7b, results are listed in Table 2, and it show that our scheduling scheme takes fewer timeslots than non-redundant scheme in the triple path routing, and besides, the proposed scheduling scheme takes a higher robustness than the triple path routing. For graph routing that is shown in Fig. 6a, non-redundant scheme needs 6 slots to complete the communication as shown in Fig. 7b. Once the communication fails, the retransmission has to wait for the next superframe cycle and at least 12 slots is needed to complete the communication in that case. As a comparison, at most 10 slots are enough in our scheme

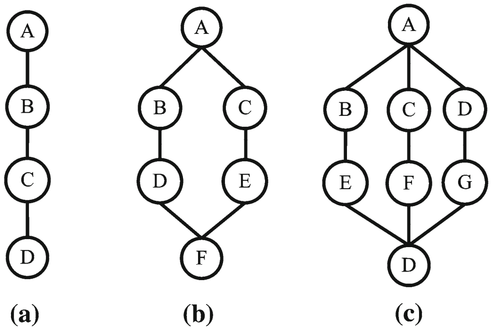


Fig. 8 The compared multipath routings. **a** Single path routing, **b** double path routing, **c** triple path routing

Table 2 Transmission-delay comparison result for 2 scheduling scheme apply to 3 routing types

Scheduling scheme (routing type)	Transmission-delay (timeslot/TS)
non-redundant (single path)	3 TS
non-redundant (double path)	6TS
non-redundant (triple path)	9 TS
non-redundant (graph)	6 TS
non-redundant with a retry (graph)	12 TS
Our scheduling scheme (graph)	5–10 TS

when the same fail happens. In a word, compared to non-redundant scheduling schemes for both multi-path routings and graph routing, our schedule scheme can provide higher robustness and takes in smaller transmission delay.

It can be seen that our scheme can effectively improve the overall communication robustness without bring in too-much delay. In fact, the retransmission delay can be significantly reduced when there is a communication failure.

(4) Memory efficiency. Constrained by the volume of wireless device, memory is also a kind of extremely limited resource. The transmission slot is assigned immediately following the receiving slot for a given device, so that the received packet can be timely forwarded and thus the memory occupation is reduced. For each device, the maximum number of consecutively received packets is the same with the number of its neighbors, so the maximum memory usage is determined by the up limit of neighbors in a graph, and generally this number is 2.

(5) Effective network conflicts avoidance. This paper indicates the existence of time-slot conflict and channel interference, and an effective solution strategy is also proposed. The proposed scheme can completely eliminate the conflicts and interference to ensure the efficient operation of wirelessHART network.

5 Conclusion

In this paper, we present a joint scheduling scheme for WirelessHART mesh networks with high robustness. In order to improve the robustness of the network, our scheme implements the retransmission mechanism based on graph routing which has a characteristic of hop-level redundant. Time-slots are ordered with the actual communication sequence to reduce the communication latency, and accordingly the retransmission delay is also reduced. In addition, both conflicts and interference can be completely eliminated by the solution strategy proposed in this paper. Our scheme also takes lower memory occupation.

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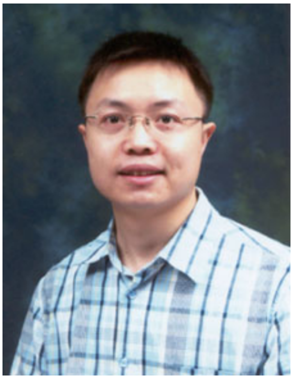

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