A Real-Time Transmission Scheduling Algorithm for Industrial Wireless Sensor Networks with Multiple Radio Interfaces

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***Abstract*—In industrial wireless sensor networks (IWSNs), monitoring data generated by field devices should be delivered to the gateway prior to deadlines. Traditional field devices with one radio interface can only work in the half-duplex mode, which may cause severe degradation of the network real-timeliness. Considering the scenarios where each field device is with multiple radio interfaces, we study the joint scheduling of slots, channels and radio interfaces in IWSNs with mesh topologies. Specifically, a new method to calculate the total and remaining resource blocks of each transmission is first given. Then, a two-level priority assignment rule is designed by jointly considering remaining resource blocks and deadlines. Finally, a remaining resource blocks based least laxity first (RRBs-LLF) algorithm based on the above rule is proposed. Simulation results show that the proposed RRBs-LLF algorithm outperforms existing works in terms of schedulable ratio.**

***Index Terms*—industrial wireless sensor network, transmission scheduling, radio interface**

I. Introduction

As one of the most promising techniques for Industry 4.0, industrial wireless sensor networks (IWSNs) are being widely deployed [1], [2]. Compared with wired communication, wireless communication has features of lower cost, better mobility and scalability [3]. However, IWSNs have to meet rigorous requirements of real-timeliness and reliability in spite of harsh industrial environments and dynamic network topologies. To address these concerns, international standards on IWSNs have been released, which include WirelessHART [4], ISA 100 [5], WIA-PA [6] and WIA-FA [7].

In IWSNs, monitoring data generated by field devices (FDs) should be delivered to the gateway (GW) prior to deadlines. Numerous contributions have been done on the transmission scheduling of delay-constrained traffics [8].

Joint link scheduling and channel assignment problems for real-time communications in networks with linear and tree topologies are studied in [9]-[11]. However, the periods of traffics are assumed to be homogeneous, i.e., packets generated by different FDs share the same update period and deadline [12]. TDMA scheduling schemes for periodic heterogeneous traffics (i.e., packets with different update periods or deadlines) are proposed in [13]-[16]. In IWSNs with mesh topologies, transmissions suffer from radio confliction problem and co-channel interference problem. The radio confliction problem is caused by the fact that multiple FDs communicate with one common FD who does not have enough radio interfaces to receive or transmit the packets simultaneously. The co-channel interference problem is due to the fact that different transmissions over the same channel will interfere with each other if they are in the communication range of others. To deal with the above two problems, Saifullah et al. in [17]-[19] propose a conflict-aware least laxity first algorithm and present a worst-case end-to-end delay analysis for periodic real-time flows under the reliable graph routing. However, previous studies assume that each FD is equipped with one radio interface (*RI*) and can only work in the half-duplex mode, which degrades the network real-timeliness significantly. With the reduction of hardware cost, more and more FDs are equipped with multiple *RI*s [20], [21].

Joint routing, transmission scheduling, channel assignment and power control problem in multi-power-level multi-radio wireless sensor networks is studied in [22]-[25]. To minimize the transmission delay and the number of *RI*s, Jin et al. in [26] propose a convergecast scheduling algorithm and a fast heuristic algorithm respectively. However, none of the existing researches [9]-[26] address the problem of real-time transmission scheduling of periodic heterogeneous traffics for IWSNs with multiple *RI*s.

This paper studies the joint scheduling of slots, channels and *RI*s in IWSNs with mesh topologies. The main contributions of this work are summarized as follows:

- We for the first time study the problem of real-time transmission scheduling of periodic heterogeneous traffics for IWSNs with multiple *RI*s, and propose a new method to calculate the total resource blocks (TRBs) and remaining resource blocks (RRBs) of each transmission.
- We design a two-level priority assignment rule which gives a full consideration of RRBs and deadlines. Trans-

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missions who have fewer RRBs are assigned higher first-level priorities. If two transmissions share the same first-level priority, the transmission who has a more urgent deadline is assigned a higher second-level priority. Based on the rule, we propose a remaining resource blocks based least laxity first (RRBs-LLF) algorithm to generate an efficient schedule within polynomial time.
- Simulation results demonstrate that the proposed algorithm achieves a higher schedulable ratio while guaranteeing the real-timeliness of every packet for different IWSN scales.

II. Problem Formulation

As illustrated in Fig. 1, an IWSN is modeled as a graph $G = (V,E)$. The node set $V = \{FD_0, FD_1, FD_2, \ldots, FD_N\}$ includes the network devices, where FD_0 denotes the GW, FD_i $(i = 1,2,\ldots,N)$ denotes the ith FD and N is the number of FDs. The edge in $E = \{(FD_i, FD_j) | i, j = 0,1,2,\ldots,N; i \neq j\}$ denotes the link between device pairs that can communicate with each other reliably. FDs are deployed to monitor environment (e.g., temperature, pressure and humidity) and send their packets to the GW periodically.

A. Transmissions and flows

We assume that the path of FD_i $(i = 1,2,\ldots,N)$ to the GW (p_i) is predefined and the number of hops is denoted by h_i. Fig. 1 gives an example of the path of FD_1, i.e., $p_1 = \{FD_1 \rightarrow FD_2 \rightarrow FD_3 \rightarrow FD_4 \rightarrow FD_5 \rightarrow GW\}$ and $h_1 = 5$.

TDMA scheduling is performed at the GW for deterministic performance. Time is divided into slots of equal length and all network devices are synchronized. Without causing ambiguity, we term one packet transmission and its acknowledgement as a transmission. Each slot allows one transmission. A transmission is called released if it is to be scheduled on a node, and scheduled if it has been allocated slot, channel and RI resources.

The data update period and deadline of FD_i are T_i and D_i, respectively. We define hyperperiod H as the least common multiple of all periods, i.e., $H = \text{LCM}\{T_1, T_2, \ldots, T_N\}$. Therefore, FD_i has $\frac{H}{T_i}$ subperiods in H. pkt_i^k, the kth packet of FD_i, is generated at the beginning of slot $t_b = (k-1) * T_i + 1$ and should be delivered to the GW before the end of slot $t_e = (k-1) * T_i + D_i$, where $k = 1,2,\ldots,\frac{H}{T_i}$.

The flow set is denoted by $F = \{F_1, F_2, \ldots, F_N\}$ where $F_i = \{\vec{f}_i^k | k = 1,2,\ldots,\frac{H}{T_i}\}$ includes all subflows of FD_i in a hyperperiod and $\vec{f}_i^k = [L_{i,1}^k, L_{i,2}^k, \ldots, L_{i,h_i}^k]$ is the sequential transmission vector of pkt_i^k. $L_{i,j}^k$ $(j = 1,2,\ldots,h_i)$ denotes the jth transmission of pkt_i^k, and the transmitting and receiving node of $L_{i,j}^k$ are denoted by $tra_{i,j}^k$ and $rec_{i,j}^k$, respectively. Therefore, $L_{i,j}^k$ can be denoted by node pair $(tra_{i,j}^k, rec_{i,j}^k)$. As shown in Fig. 1, $\vec{f}_1^1 = [L_{1,1}^1, L_{1,2}^1, L_{1,3}^1, L_{1,4}^1, L_{1,5}^1]$, and $(tra_{1,2}^1, rec_{1,2}^1) = (FD_2, FD_3)$.

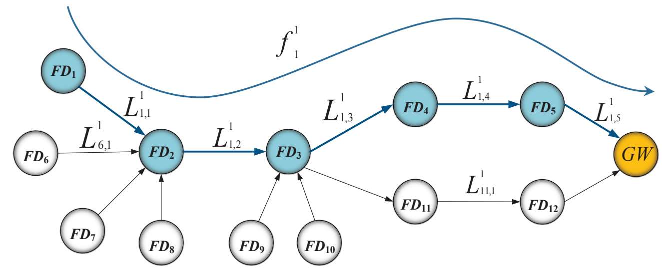

Fig. 1. Mesh topology in IWSNs

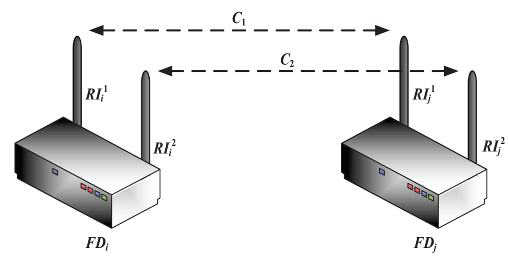

Fig. 2. An example of two parallel transmissions with two RIs

B. Radio confliction and co-channel interference

In this paper, the number of RIs of FD_i is denoted by R_{FD_i} $(R_{FD_i} \geq 1)$. Space division multiplexing is not allowed in our model to avoid co-channel interference. Fig. 2 gives an example of two parallel transmissions between FD_i and FD_j, wherein the two nodes communicate with each other on channel C_1 using their first RIs (i.e., RI_i^1 and RI_j^1) and on channel C_2 using their second RIs (i.e., RI_i^2 and RI_j^2).

Radio confliction and co-channel interference are two main factors that will result in transmission delays in IWSNs.

In slot t $(t = 1,2,\ldots,H)$, radio confliction occurs if the transmissions of FD_i and FD_j (i.e., $L_{i,n_i}^{k_i}$ and $L_{j,n_j}^{k_j}$) are released and $\{tra_{i,n_i}^{k_i}, rec_{i,n_i}^{k_i}\} \bigcap \{tra_{j,n_j}^{k_j}, rec_{j,n_j}^{k_j}\} \neq \emptyset$. In this case, $L_{i,n_i}^{k_i}$ and $L_{j,n_j}^{k_j}$ will compete for RIs and channels. As shown in Fig. 1, radio confliction occurs if both $L_{1,2}^1$ and $L_{6,1}^1$ have been released since they have the common node FD_2.

Co-channel interference occurs if both $L_{i,n_i}^{k_i}$ and $L_{j,n_j}^{k_j}$ are released and $\{tra_{i,n_i}^{k_i}, rec_{i,n_i}^{k_i}\} \bigcap \{tra_{j,n_j}^{k_j}, rec_{j,n_j}^{k_j}\} = \emptyset$. In this case, $L_{i,n_i}^{k_i}$ and $L_{j,n_j}^{k_j}$ will only contend for channels. As shown in Fig. 1, co-channel interference occurs if both $L_{1,2}^1$ and $L_{11,1}^1$ have been released since they do not have common nodes.

The number of channels is C. The vector of RI number is $\vec{R} = [R_{FD_1}, R_{FD_2}, \ldots, R_{FD_N}]$. The flow set is $F = \{F_1, F_2, \ldots, F_N\}$. The period vector and relative deadline vector are $\vec{T} = [T_1, T_2, \ldots, T_N]$ and $\vec{D} = [D_1, D_2, \ldots, D_N]$, respectively. With the quintet vector $< C, \vec{R}, F, \vec{T}, \vec{D} >$, this paper aims to design a scheduling algorithm by allocating slots, channels and RIs to each transmission in a hyperperiod, in order to ensure that every packet of FD_i arrives at the GW prior to its deadline if this situation is inherently schedulable.

III. RRBs-LLF Algorithm

The above resource allocation problem is NP-hard and a heuristic algorithm is proposed to address the hardness. We first illustrate the lifetime of a transmission. Then, we give the method to calculate TRBs and RRBs, and design a two-level priority assignment rule. Finally, we propose a RRBs-LLF algorithm based on the rule.

A. Lifetime

As illustrated above, $\frac{H}{T_i}$ new packets will be generated by FD_i in a hyperperiod, and all transmissions of pkt_i^k are denoted by $\vec{f}_i^k = [L_{i,1}^k, L_{i,2}^k, \dots, L_{i,h_i}^k]$. As shown in Fig. 3, in slot t, a transmission will be in one of the three states: unreleased (UR) state, released but unscheduled (RUS) state, and released and scheduled (RS) state. At the beginning of slot 1, pkt_1^1 is generated by FD_1, and therefore $L_{1,2}^1$ and $L_{1,3}^1$ are both in state UR. Then, at the beginning of slot 2, pkt_1^1 is transmitted to FD_2, and therefore the state of $L_{1,2}^1$ is changed from UR to RUS. Then, at the beginning of slot 3, pkt_1^1 is transmitted to FD_3, and therefore the state of $L_{1,2}^1$ is changed from RUS to RS and the state of $L_{1,3}^1$ is changed from UR to RUS. Finally, at the beginning of slot 4, pkt_1^1 is transmitted to FD_4, and therefore the state of $L_{1,3}^1$ is changed from RUS to RS.

According to the above process, $L_{i,j}^k$ will go through three states in sequence and $L_{i,j+1}^k$ cannot get to the state RUS before $L_{i,j}^k$ get to the state RS. Therefore, the earliest released time of $L_{i,j}^k$ is $s_{i,j}^k = (k-1)*T_i + j$, and the latest released time of $L_{i,j}^k$ (i.e., the deadline of $L_{i,j}^k$) is $d_{i,j}^k = (k-1)*T_i + D_i - rh_{i,j}^k$, where $rh_{i,j}^k$ denotes the remaining hops from $L_{i,j}^k$ to the GW. The lifetime of $L_{i,j}^k$ is $lt_{i,j}^k = [s_{i,j}^k, d_{i,j}^k]$, which means that $L_{i,j}^k$ should be released not earlier than $s_{i,j}^k$ and not later than $d_{i,j}^k$ to avoid the timeout of pkt_i^k. An example is given in Fig. 3, where $\vec{f}_1^1 = [L_{1,1}^1, L_{1,2}^1, L_{1,3}^1, L_{1,4}^1, L_{1,5}^1]$. We assume that $T_1 = 8$ and $D_1 = 7$, therefore $s_{1,2}^1 = 2, d_{1,2}^1 = 4$, $lt_{1,2}^1 = [2,4]$.

As the transmissions of $\vec{f}_i^k$ are released in sequence, there will be only one transmission of $\vec{f}_i^k$ that is in state RUS in any slot t $(t = 1,2,\dots,H)$. Without causing ambiguity, in slot t, we write the transmission of $\vec{f}_i^k$ that is in state RUS as L_i, and its lifetime is $lt_i = [s_i, d_i]$. The transmitting and receiving nodes of L_i are denoted by tra_i and rec_i, respectively.

B. Total resource blocks

In our model, resource blocks are defined as transmission chances which are combinations of slots, channels and RIs. According to previous analysis, pkt_i will not arrive at the GW prior to D_i if L_i cannot obtain a resource block before d_i. In slot t, The RI number of tra_i and rec_i are denoted by R_{tra_i} and R_{rec_i}, respectively. As R_{tra_i} may not equal to R_{rec_i}, the TRBs of L_i should be considered from the perspective of tra_i and rec_i, respectively.

From the perspective of tra_i, the number of TRBs of L_i is calculated by

$$TRB_i^{tra} = (d_i - t + 1) * \min\{R_{tra_i}, C\}, \tag{1}$$

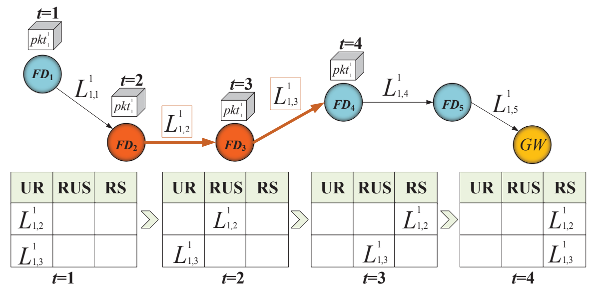

Fig. 3. An example of state transitions

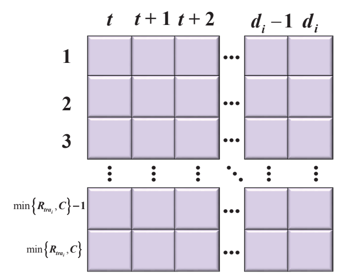

Fig. 4. Total resource blocks

where C is the number of total channels. That is because L_i will use one slot, one channel and one RI from tra_i to finish its transmission. If $R_{tra_i} < C$, there are no enough RIs for L_i, as a result of which TRB_i^{tra} is dominated by R_{tra_i}; otherwise, dominated by C.

Similarly, the number of TRBs of L_i from the perspective of rec_i is calculated by

$$TRB_i^{rec} = (d_i - t + 1) * \min\{R_{rec_i}, C\}. \tag{2}$$

An example of the TRBs of L_i in slot t is shown in Fig. 4.

C. Priority assignment rule

In slot t $(t = 1,2,\dots,H)$, we propose a two-level priority assignment rule that can effectively assign a priority for transmission $L_i \in set_{RUS}$, where $set_{RUS} = \{L_i | L_i \text{ is in state RUS}, i = 1,2,\dots,N\}$. This rule can help us decide which transmission has a higher priority to obtain the transmission chance. The details of the rule are given as follows.

Step 1: As for $L_i \in set_{RUS}$, search for transmissions L_j such that $L_j \in set_{RUS}$ and $d_j \in [t, d_i]$.

As shown in Fig. 5, the lifetime of L_j is in one of the four cases if $L_j \in set_{RUS}$.

Case 1: $s_i > s_j, t \le d_j \le d_i$.

Case 2: $s_i \le s_j \le t, t \le d_j \le d_i$.

Case 3: $s_i \le s_j \le t, d_i < d_j$.

Case 4: $s_i > s_j, d_i < d_j$.

d_j is more likely to occupy a resource block of d_i if $d_j \in [t, d_i]$. Therefore, transmissions in Case 1 and Case 2 are what we search for. We define $\gamma_i = \{L_k | L_k \text{ is in Case 1 or Case 2}, k = 1,2,\dots,N\}$.

Step 2: Calculate the number of resource blocks occupied by radio confliction and co-channel interference.

we denote $\alpha_i = \{L_k | L_k$ involves $tra_i, k = 1,2,\ldots,N\}$ and $\beta_i = \{L_k | L_k$ involves $rec_i, k = 1,2,\ldots,N\}$. Firstly, from the perspective of tra_i, the numbers of resource blocks occupied by radio confliction (denoted as n_{rc}^{tra}) and co-channel interference (denoted as n_{cc}^{tra}) are obtained as follows.

(1) As for L_i, if it has radio confliction with L_j, which means that $L_j \in \alpha_i \cap \gamma_i$ (e.g., $L_{1,2}^1$ has radio confliction with $L_{6,1}^1$ in Fig. 1), L_j will occupy one resource block of L_i. Therefore, $n_{rc}^{tra} = |\alpha_i \cap \gamma_i|$.

(2) As for L_i, if it has co-channel interference with L_j, which means $L_j \in \overline{\alpha_i} \cap \overline{\beta_i} \cap \gamma_i$ (e.g., $L_{1,2}^1$ has co-channel interference with $L_{11,1}^1$ in Fig. 1), whether L_j will occupy one resource block of L_i or not depends on the comparison between C and R_{tra_i}. We define $n = |\overline{\alpha_i} \cap \overline{\beta_i} \cap \gamma_i|$. n_{cc}^{tra} is given by **Theorem 1**.

Theorem 1. As for L_i, the number of resource blocks occupied by co-channel interference is

$$n_{cc}^{tra} = \begin{cases} n, & \text{if } C \leq R_{tra_i} \\ \max\{n - (C - R_{tra_i}) * (d_i - t + 1), 0\}, & \text{otherwise.} \end{cases} \quad (3)$$

Proof. (1) If $C \leq R_{tra_i}$, all channels are used by L_i to form its TRBs, and there are no channels left for $L_j \in \overline{\alpha_i} \cap \overline{\beta_i} \cap \gamma_i$. Therefore, each L_j will obtain a resource block from L_i and n resource blocks will be occupied by n transmissions who have co-channel interference with L_i.

(2) If $C > R_{tra_i}$, the number of TRBs of L_i is $R_{tra_i} * (d_i - t + 1)$ and there are $(C - R_{tra_i})$ channels that will not be used by L_i. If $(C - R_{tra_i}) * (d_i - t + 1) \geq n$, the resource blocks formed by extra $(C - R_{tra_i})$ channels are enough for $L_j \in \overline{\alpha_i} \cap \overline{\beta_i} \cap \gamma_i$, and L_j will not occupy resource blocks of L_i. Otherwise, $(n - (C - R_{tra_i}) * (d_j - t + 1))$ resource blocks of L_i will be occupied by L_j. Therefore, the number of resource blocks occupied by co-channel interference is $n_{cc}^{tra} = \max\{n - (C - R_{tra_i}) * (d_i - t + 1), 0\}$.

In summary, the proof of **Theorem 1** is completed. □

Step 3: Calculate the number of RRBs of L_i.

As RRBs are the resource blocks that are not occupied by radio confliction or co-channel interference, the number of RRBs is calculated by

$$RRB_i^{tra} = \max\{TRB_i^{tra} - n_{rc}^{tra} - n_{cc}^{tra}, 0\}. \quad (4)$$

Similarly, from the perspective of rec_i, the number of RRBs is calculated by

$$RRB_i^{rec} = \max\{TRB_i^{rec} - n_{rc}^{rec} - n_{cc}^{rec}, 0\}, \quad (5)$$

where n_{rc}^{rec} and n_{cc}^{rec} are the numbers of resource blocks occupied by radio confliction and co-channel interference, respectively.

Step 4: Two-level priority assignment rule.

Notice that, in slot t $(t = 1,2,\ldots,H)$, RRB_i^{tra} may be different from RRB_i^{rec}. Fig. 6 gives an example to illustrate the difference. The final number of RRBs of L_i is determined by the minimum value between RRB_i^{tra} and RRB_i^{rec}. Therefore, the priority of L_i is

$$pri_i = \min\{RRB_i^{tra}, RRB_i^{rec}\}. \quad (6)$$

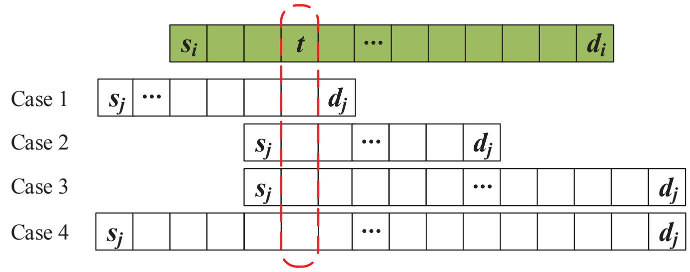

Fig. 5. Four cases of lifetime relationship between L_i and L_j

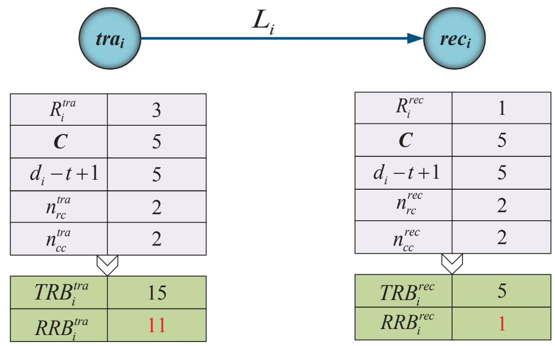

Fig. 6. An example of the difference between RRB_i^{tra} and RRB_i^{rec}

The priority set of all transmissions in state RUS is

$$pri_{set} = \{pri_i | L_i \in set_{RUS}\}. \quad (7)$$

The lower the value of pri_i is, the higher priority L_i has to obtain a transmission chance. If there is a tie, then the transmission (among those having the least priority value) that has the earliest deadline is selected.

D. RRBs-LLF Algorithm

We formally present the RRBs-LLF algorithm in Algorithm 1. In each slot t $(t = 1,2,\ldots,H)$, we set pri_{set}, c_u and r_{FD_i} $(i = 1,2,\ldots,N)$ to their initial values firstly (lines 3∼7), where c_u and r_{FD_i} are the numbers of used channels and RIs, respectively. Then, as for FD_i, if current slot t is the first slot of the kth subperiod (i.e., pkt_i^k is generated at the beginning of slot t), the state of $L_{i,1}^k$ is set to RUS (lines 8∼11). Then, we calculate the lifetime of $L_{i,j}^k$ $(L_{i,j}^k \in set_{RUS})$. If $t > d_{i,j}^k$, i.e., $L_{i,j}^k$ is not scheduled prior to its deadline $d_{i,j}^k$, and therefore pkt_i^k would not arrive at the GW prior to its deadline D_i, which means that our algorithm cannot schedule this situation (lines 12∼15); otherwise, we calculate $pri_{i,j}^k$ according to the equations (4)∼(6), and refresh pri_{set} (lines 16∼18). Transmissions in A_pri_{set} are sorted in an ascending order, and the first one has the highest priority to get slots, channels and RIs (lines 19∼29). If remaining channels or RIs are enough for $L_{i,j}^k$, the state of $L_{i,j}^k$ is transferred from RUS to RS. If $L_{i,j}^k$ is not the last transmission of pkt_i^k, the state of its subsequent transmission $L_{i,(j+1)}^k$ is changed from UR to RUS, and $L_{i,(j+1)}^k$ will be considered in the next slot (lines 25∼29).

Finally, we get the scheduling list sch, with

$$sch[t][c_u] = \left\langle L_{i,j}^k;\ tra_{i,j}^k,\ r_{tra_{i,j}^k};\ rec_{i,j}^k,\ r_{rec_{i,j}^k} \right\rangle. \tag{8}$$

From equation (8), we know that slot t and channel c_u are allocated to $L_{i,j}^k$ which uses the $r_{tra_{i,j}^k}$th RI of $tra_{i,j}^k$ and the $r_{rec_{i,j}^k}$th RI of $rec_{i,j}^k$.

E. Time Complexity

In the RRBs-LLF algorithm, the time complexities of the first inner loop (lines 6∼7) and the second inner loop (lines 8∼11) are $O(N)$ and $O(N \cdot H)$, respectively. Based on above analysis, in slot t, there is at most one transmission of FD_i ($i = 1,2,\dots,N$) that is in state RUS, and the time complexity of calculating $pri_{i,j}^k$ (line 17) is $O(N)$. Therefore, the time complexity of the third inner loop (lines 12∼18) is $O(N^2)$. To sort $L_{i,j}^k \in pri_{set}$ (line 19), we use the fast sorting algorithm whose time complexity is $O(N \cdot \log N)$. The time complexity of the last loop (lines 20∼29) is $O(N)$. In summary, the time complexity of the RRBs-LLF algorithm, $T_{\text{RRBs-LLF}}$, is given by

$$\begin{aligned} &T_{\text{RRBs-LLF}} \\ &= H \cdot (O(N) + O(N \cdot H) + O(N^2) + O(N \cdot \log N) + O(N)) \\ &= O(H \cdot N \cdot (H + N)). \end{aligned}$$

IV. Performance Evaluation

In this section, we evaluate the performance of the RRBs-LLF algorithm through simulations and make comparisons with five existing scheduling algorithms.

Baselines. *(a) Dynamic priority scheduling algorithm.* (1) Least Laxity First (LLF) that schedules a transmission whose packet has the least laxity defined as its remaining time minus its remaining number of transmissions; (2) Conflict-aware Least Laxity First (C-LLF) [17] that combines LLF and the degree of conflicts associated with a transmission; (3) Earliest Deadline First (EDF) that schedules a transmission whose packet has the least remaining time.

(b) Static priority scheduling algorithm. (1) Rate-Monotonic (RM) that schedules a transmission who has the greatest packet generating rate; (2) Extended Rate-Monotonic (E-RM) [16] that gives an extension to RM by considering the distance of a transmission to the GW.

Simulation setup. In simulations, two network scales are considered: small scale (20 nodes) and large scale (60 nodes), and 2000 test cases are run for each scale.

In each test case, our network topology is generated with a given number of FD ($N = 20$ or $N = 60$) in a square area (SA). As [16][27] suggests, the GW is placed at the center, and FDs are placed randomly. N (the number of FDs) and A (the area of the SA) should satisfy $\frac{N}{A} = \frac{2*\pi}{\sqrt{27*(TR)^2}}$, where TR denotes the transmission range of each FD and in our experiments $TR = 40$m.

Then, we set the value of period vector $\vec{T} = [T_1, T_2, \dots, T_N]$. To meet the industrial requirements, the periods should satisfy $T_i = b * 2^a$. In the simulations, we set $b = 1$ and a as a positive integer which satisfies $T_i \geq h_i$, where h_i is the hop number from FD_i to the GW. The number of RI of each FD is randomly chosen from 1 to $maxRN$ ($maxRN = 1,2,\dots,6$).

We use schedulable ratio [16][17] as a metric which is measured as the percentage of test cases for which an algorithm is able to find a feasible schedule.

Simulation results. Fig. 7 shows the schedulable ratio analysis of the RRBs-LLF algorithm when the numbers of channels and

Algorithm 1: RRBs-LLF Algorithm

Input: $C, \vec{R}, F, \vec{T}, \vec{D}$
Output: sch (scheduling list) or *unschedulable*

1 $H =$LCM$\{\vec{T}\}$;
2 $set_{RUS} = \emptyset$;
3 **for** t=1 to H **do**
4 $\quad pri_{set} = \emptyset$;
5 $\quad c_u = 0$;// set the number of used channels to 0
6 $\quad$**for** i=1 to N **do**
7 $\quad\quad r_{FD_i} = 0$;// set the number of used RIs of FD_i to 0 initially
8 $\quad$**for** i=1 to N **do**
9 $\quad\quad$**for** k=1 to $\frac{H}{T_i}$ **do**
10 $\quad\quad\quad$**if** $t = ((k-1) * T_i + 1)$ **then**
11 $\quad\quad\quad\quad set_{RUS} = set_{RUS} \bigcup L_{i,1}^k$; // set the state of $L_{i,1}^k$ to RUS if pkt_i^k is generated at slot t
12 $\quad$**for** $L_{i,j}^k \in set_{RUS}$ **do**
13 $\quad\quad lt_{i,j}^k = [s_{i,j}^k, d_{i,j}^k]$; // calculate the lifetime of $L_{i,j}^k$
14 $\quad\quad$**if** $t > d_{i,j}^k$ **then**
15 $\quad\quad\quad$**return** *unschedulable*;
16 $\quad\quad$**else**
17 $\quad\quad\quad$calculate $pri_{i,j}^k$ according to the equations (4)∼(6);
18 $\quad\quad\quad pri_{set} = pri_{set} \bigcup pri_{i,j}^k$;
19 $\quad$Sort pri_{set} in ascending order and we get A_pri_{set};
20 $\quad$**for** $L_{i,j}^k \in A\_pri_{set}$ **do**
21 $\quad\quad c_u = c_u + 1;\ \ r_{tra_{i,j}^k} = r_{tra_{i,j}^k} + 1;\ r_{rec_{i,j}^k} = r_{rec_{i,j}^k} + 1$;
$\quad\quad$**if** $(c_u > C)$ **then**
22 $\quad\quad\quad$break; // channels are used up
23 $\quad\quad$**else if** $((r_{tra_{i,j}^k} > R_{tra_{i,j}^k})$ *or* $(r_{rec_{i,j}^k} > R_{rec_{i,j}^k})$ **then**
24 $\quad\quad\quad$continue;
25 $\quad\quad$**else**
26 $\quad\quad\quad sch[t][c_u] = \left\langle L_{i,j}^k;\ tra_{i,j}^k,\ r_{tra_{i,j}^k}; rec_{i,j}^k,\ r_{rec_{i,j}^k} \right\rangle$;
27 $\quad\quad\quad set_{RUS} = set_{RUS} - L_{i,j}^k$; //set the state of $L_{i,j}^k$ to RS
28 $\quad\quad\quad$**if** $j < h_i$ **then**
29 $\quad\quad\quad\quad set_{RUS} = set_{RUS} + L_{i,(j+1)}^k$; //set the state of $L_{i,(j+1)}^k$ to RUS
30 **return** sch;

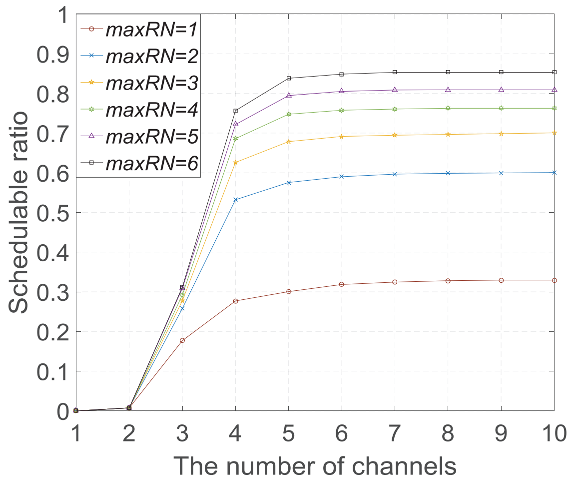

Fig. 7. Schedulable ratio analysis of the RRBs-LLF algorithm. $N = 20, T_i \in [2^3, 2^5]$, $maxRN \in [1, 6]$.

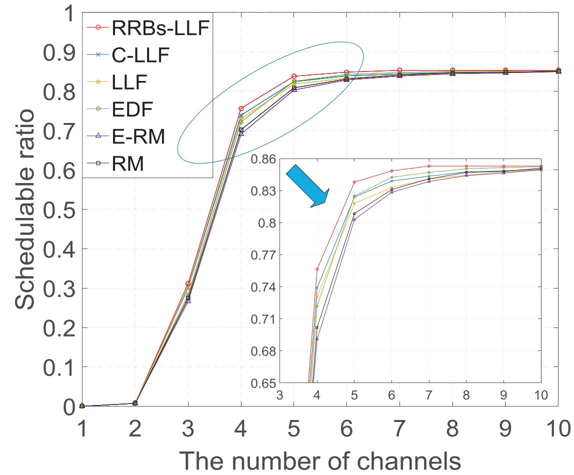

Fig. 9. Schedulable ratio comparisons between RRBs-LLF and other existing algorithms. $N = 20, T_i \in [2^3, 2^5]$. $maxRN = 6$.

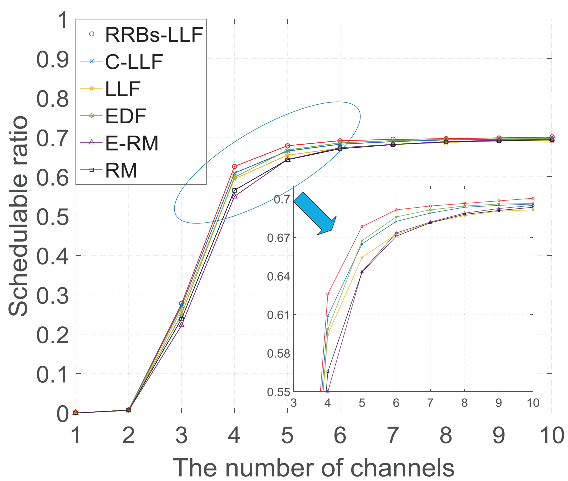

Fig. 8. Schedulable ratio comparisons between RRBs-LLF and other existing algorithms. $N = 20, T_i \in [2^3, 2^5]$, $maxRN = 3$.

*RI*s change, respectively. In each test case, there are 20 *FD*s in IWSNs and we set the period as $T_i \in [2^3, 2^5]$ randomly. Schedulable ratio increases with the increase of the number of channels when the number of *RI*s is fixed. However, when the number of channels reaches a certain value (e.g., 5 in Fig. 7), the schedulable ratio increases slowly and converges to a certain value asymptotically. That is because the priority of each transmission is determined by its number of RRBs which is dominated by channels and *RI*s together. Therefore, *RI* number will be the bottleneck of the schedulable ratio when channel resources are sufficient. Otherwise, the number of channels will be the bottleneck of the schedulable ratio.

Fig. 8 and Fig. 9 show the comparisons of the schedulable ratio between the RRBs-LLF algorithm and other existing algorithms with $maxRN = 3$ and $maxRN = 6$, respectively. As shown in Fig. 8, no matter what the number of channels is, the RRBs-LLF algorithm can always achieve higher schedulable ratio than other algorithms. When the number of the channel is 4, the schedulable ratio of the RRBs-LLF algorithm is more than 8% and 1.1% of that of the E-RM algorithm and C-LLF algorithm, respectively. This stems from the fact that all existing algorithms do not consider the slot, channel and *RI* resources simultaneously. For example, the E-RM algorithm gives higher priorities to the transmissions that have shorter periods, without considering their deadlines. Though the C-LLF algorithm takes periods, deadlines and hops into consideration, it ignores the co-channel interference when designing priority assignment rules for transmissions and does not take the difference of RRBs calculated by the transmitting node and receiving node of a transmission into consideration.

When used in IWSNs with a larger scale (60 nodes), the RRBs-LLF algorithm can still obtain better performance than existing algorithms. Due to the page limit, the results are not displayed.

Conclusion

In this paper, we have studied the joint scheduling of slots, channels and *RI*s in IWSNs with mesh topologies. First, we have given a new method to calculate the total and remaining resource blocks of each transmission. Then, we have proposed a dynamic scheduling algorithm based on a two-level priority assignment rule. Simulation results have demonstrated that the RRBs-LLF algorithm yields higher schedulable ratio than existing algorithms.

Acknowledgment

This work was supported in part by the National Key Research and Development Program of China (2017YFE0123000), the National Natural Science Foundation of China under grant (61673371 and 71661147005), Youth Innovation Promotion Association, CAS (2015157), and International Partnership Program of Chinese Academy of Sciences (173321KYSB20180020). The corresponding author is Wei Liang (weiliang@sia.cn).

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