IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 21, 2018, accepted December 4, 2018, date of publication December 12, 2018,
date of current version January 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2886365

Collaborative Coexistence Management Scheme for Industrial Wireless Sensor Networks

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This work was supported in part by the National Research Foundation of Korea through the Framework of International Cooperation Program (Korea-China) under Grant NRF-2016K2A9A2A11938310 and in part by the Korea Institute of Energy Technology Evaluation and Planning through the Human Resources Program in Energy Technology, Ministry of Trade, Industry and Energy, Republic of Korea, under Grant 20174030201780.

ABSTRACT The future manufacturing environment is foreseen to be increasingly diverse with multi-vendor industrial wireless devices deployed in the same geographical area. Thus, effective medium resource sharing mechanisms are urgently needed to enable the coexistence of those heterogeneous industrial wireless sensor networks (IWSNs). To accommodate such heterogeneity, this paper proposes a collaborative scheduling algorithm (CSA) for coordinating the activation of each coexisting IWSN while guaranteeing their respective real-time communication requirements. Specifically, the proposed CSA is able to help determine a unique data transmission instantance for each network node that periodically generates time-sensitive data, through which timely data delivery is guaranteed without the interference of each other.

INDEX TERMS Coexistence, industrial wireless sensor network, heterogeneity, real-time communication.

I. INTRODUCTION

With the increasing prevalence of smart manufacturing, the conventional pyramid automation hierarchy is being transformed into a fully integrated automation structure, where all the manufacturing functions in the pyramid can be virtualized as services except those time-critical manufacturing functions dwelling at the field level [1]. The primary reason for the field level is that industrial applications usually place strict requirements on the reliability and real-time capability of communication and, in this regard, field level industrial wireless communication must rely on highly established industrial wireless sensor network (IWSN) technologies, e.g., WirelessHART [2], ISA100.11a [3] and WIA-PA [4], which have been deployed in practical industrial manufacturing processes and accepted as International Electrotechnical Commission (IEC) international standards.

Moreover, due to various emerging manufacturing services, the manufacturing environment will become increasingly diverse with multi-vendor industrial wireless devices involved in the same geographical area. In other words, several industrial wireless systems may share a common medium, resulting in influences on reliability and real-time capability. Without effective management of these coexisting networks, it will be difficult to ensure that wireless networks meet the time criticality and other performance requirements of industrial automation. Based on these considerations, IEC 62657-2 [5] recently proposed a coexistence management concept and process for wireless communications in the industrial domain, aiming to provide predictable assuredness of coexistence for a given common medium with certain application requirements.

In general, coexistence management falls into three categories [5]: *manual coexistence management (MCM)*, where the coexistence manager needs to implement manual adjustments to change the coexistence state; *automated non-collaborative coexistence management (ANCM)*, where the coexisting wireless networks are fully independent and each wireless network tries to adapt its own behavior by detecting and estimating interference caused by other wireless networks; and *automated collaborative coexistence management (ACCM)*, where a centralized arbiter or coordinator is required to implement collaborative methods among the conflicting wireless networks.

MCM requires the coexistence manager to dedicate a large amount of time to establishing and maintaining coexistence management; such a process is cumbersome and may not meet the needs of future industrial applications.

ANCM approaches might be achieved by means of cognitive radio [6], i.e., a radio device senses its electromagnetic environment and dynamically and autonomously adjusts its radio operating parameters to modify its operation. In other words, for an ANCM approach, each wireless solution dynamically modifies its communication strategy in a selfish way without taking into account other coexisting networks, which might result in lower efficiency of resource utilization. In addition, ANCM approaches need devices to be equipped with strong sensing ability, which is usually seriously constrained in field devices. Therefore, methods complying with the ANCM concept so far have been applied for solving coexistence problems in public areas [7]–[9], but are not ready, or are still controversial, for industrial automation applications [10]. A list of reasons in this regard has been discussed in works [6], [11], e.g., constrained processing ability of sensor devices, battery limitations, etc.

In contrast, an ACCM coordinator takes a collaborative approach to managing the common medium in the time, frequency or space domain and, hence, can alleviate the communication and calculation burden of constrained end devices as well as improving the overall efficiency of resource utilization. According to IEC 62657-1 [12], an entity that will perform the ACCM functionality is called a central coordination point (CCP); a CCP is responsible for making decisions in a centralized way within the controlled network with respect to resource availability and utilization. IEC 62657-2 generalizes the overall lifecycle of coexistence management considering industrial applications, whereas specific schemes for solving coexistence issues are left absent in the standard.

Some studies have been proposed for enabling the coexistence of multiple industrial wireless networks following the concepts of ACCM, which are summarized and analyzed herein. The work in [13] proposed a centralized cooperative framework for the CCP to manage coexisting industrial wireless systems, specifically IEEE 802.11g devices were chosen as the targets to be managed. With the aid of a spectral sensing unit, the CCP was supposed to sense external interferences, accumulate the status of wireless channels and then perform automatic resource allocation accordingly. Under a similar framework, a reinforcement learning based mechanism was proposed in [14] to predict future medium utilization before frequency resource was allocated, and then an optimal policy was learned to allocate conflict-free resources to each wireless system based on the prediction in advance. A stochastic geometry-based approach was proposed in [15] to minimize the number of frequency channels required by coexisting IEEE 802.15.4 networks. Zheng *et al.* [16] designed a cooperative spectrum sensing scheme by combining cognitive radios and industrial wireless networks, where the sensing results were gathered at a fusion center to make a centralized decision, aimed at minimizing the total sensing error rate of coexisting industrial wireless networks; however, the feasibility of adopting cognitive radio in industrial applications is still doubtful, as discussed earlier. There are also some works focusing on improving the synchronization capability of coexisting IWSNs through avoiding beacon collisions [17], [18]. To summarize, most existing works dealt with the coexistence management of homogeneous IWSNs in frequency domain, which usually requires a CCP to be equipped with an advanced sensing unit. Moreover, the heterogeneity of coexisting industrial wireless networks has not been extensively reported in existing studies, a fact emphasized by IEC 62657-2. It warrants attention that the capability of managing the heterogeneity of device types can have a serious impact on the total cost of ownership of factory automation systems [19].

In parallel with the above-mentioned works, this paper paves the way for managing the coexistence of heterogeneous IWSNs (i.e., WirelessHART, ISA100.11a and WIA-PA) that are co-located in the same geographical area (e.g., an industrial plant) and share the common frequency domain. It is apparent that without effective management, each IWSN might be a potential interference of the other. In view of this, a collaborative scheduling algorithm (CSA) is proposed from the viewpoint of a CCP to coordinate the activation of each network. The proposed CSA will be performed by the CCP to allocate the time domain medium resource in a centralized way, while guaranteeing the real-time communication requirement of each coexisting network. To this end, the contributions of this study are summarized as follows:

- Establish a collaborative management framework, over which the coexistence feasibility of heterogeneous IWSNs is discussed.
- Devise a novel superframe structure named the Integrated Superframe Duration (ISD), which serves as the key enabler to achieve collaborative scheduling of coexisting IWSNs.
- With ISD being the basic scheduling unit, a collaborative scheduling algorithm (CSA) is then proposed from the CCP perspective to allocate the common medium resource among coexisting networks while guaranteeing the real-time communication requirement of each IWSN.

The rest of this paper is organized as follows. Section II provides an overview of existing IWSNs with respect to their basic characteristics. In Section III, a collaborative coexistence management framework is established based on heterogeneous IWSNs. Section IV introduces the proposed algorithm, named CSA, for allocating the common medium resource from the CCP perspective. The performance of CSA is evaluated and discussed in Section V, and Section VI concludes this paper.

II. OVERVIEW OF INDUSTRIAL WIRELESS SENSOR NETWORKS

This section provides a brief overview of three Industrial Wireless Sensor Networks, including WirelessHART [2], ISA100.11a [3] and WIA-PA [4], which are all IEC standards adopting wireless technology in real-time process automation and manufacturing. The Physical Layer and MAC Layer of these protocols are built upon IEEE 802.15.4 [20]. Next, some key characteristics of these three protocols will be summarized with respect to IEEE 802.15.4.

A. SUPERFRAME STRUCTURE

IEEE 802.15.4 divides the superframe into an active period (in which devices can transmit data) and an inactive period (in which devices are sleeping). For WirelessHART and ISA100.11a, the superframe duration is configurable, and the superframe structure is not specified but consists of a collection of repeating time slots [2], [3]. In general, shorter-period superframes result in lower latency while increasing the requirement for network bandwidth, whereas longer-period superframes may cause increasing latency but have lower energy consumption. Therefore, these tradeoffs need to be carefully considered when determining the length of the superframe [21]. In comparison with WirelessHART and ISA100.11a, the basic superframe duration of WIA-PA is defined as thirty-two time slots. Accordingly, the WIA-PA superframe duration (SD_{WP}) is defined as 2^M (M is a natural integer) multiplied by the WIA-PA basic superframe duration. Moreover, the duration of a single time slot (TS) in WIA-PA is configurable. Finally, the length of SD_{WP} is regulated by equation (1).

$$SD_{WP} = 32 \times 2^M \times TS \tag{1}$$

B. NETWORK TOPOLOGY

The network topologies of the three protocols are differentiated from each other: WirelessHART supports either mesh or star topology, ISA100.11a supports multiple topologies, i.e., star, mesh, star-mesh or combined topology, and WIA-PA supports hybrid mesh and star topology.

C. TRANSMISSION MEDIA

WirelessHART, ISA100.11a and WIA-PA all implement the IEEE 802.15.4 Physical Layer, with a few modifications. All the three standards operate in the 2.4 GHz Industrial, Scientific and Medical (ISM) band and use Channels 11-25. Channel 26 is not allowed in WirelessHART, since it is not legal for use in some countries, whereas in ISA100.11a and WIA-PA, Channel 26 is defined as optional. Each channel uses a bandwidth of 2 MHz, and the channels are spaced 5 MHz apart. All three standards adopt frequency hopping technologies; WirelessHART supports channel hopping; ISA100.11a supports three kinds of frequency-hopping technology, i.e., slow, fast or mixed frequency hopping and WIA-PA regulates three types of frequency-hopping technology i.e., Adaptive Frequency Switch (AFS), Adaptive Frequency Hopping (AFH), and Timeslot Hopping (TH).

III. FORMULATION OF A COLLABORATIVE COEXISTENCE MANAGEMENT FRAMEWORK

When those IWSNs are deployed in the same geographical area, although each IWSN can apply its respective frequency-hopping technology to circumvent the interference caused by other networks, unexpected message collisions may still happen if they operate independently without any coordination (e.g., when signals in the frequency, time and space domains all overlap), resulting in packet delay or even packet loss.

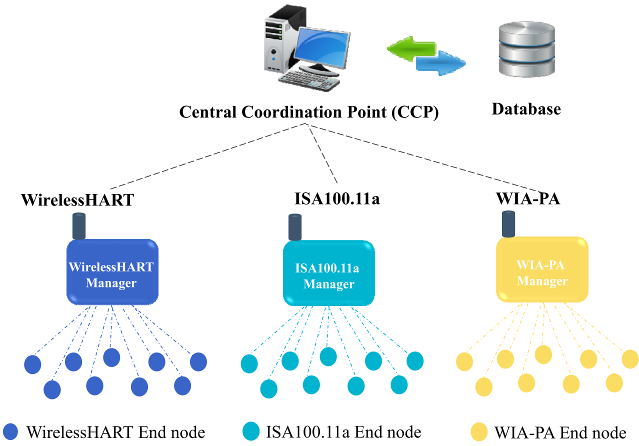

FIGURE 1. **Collaborative coexistence management framework.**

In response to the necessity to maintain coexistence raised by IEC 62657-2, this paper aimed to provide a feasible solution for enabling the coexisted operation of those heterogeneous IWSNs in the time domain. As shown in Figure 1, a collaborative coexistence management framework is established between one CCP and multiple heterogeneous IWSNs, where the communication between CCP and each network manager can be achieved either by wired or wireless access [12]. The sensor nodes residing in different IWSNs are assumed to form a star topology that is common to all three types of IWSNs. Their respective IWSN applications perform various monitoring functionalities (e.g., vibration, temperature, gas, machine condition, etc.) [21] by periodically generating time-sensitive data. Note that, depending on the specific system requirements, IWSN applications usually place different constraints on the allowable message delay towards periodic sensor data (after they are generated); in other words, each periodic dataset must be delivered before the next data are generated. In addition to periodic traffic, some nodes in the network generate aperiodic data such as alarm, system configuration data, file data, etc., which should be transmitted using time slots for aperiodic data. Once these requirements are collected by the CCP from each individual network, a collaborative coexistence management process will be executed to allocate the common medium resource (this paper focuses on the time domain) among heterogeneous IWSNs without violating any constrained delay requirement. Finally, the resource allocation results will be announced to each IWSN manager and utilized for the configuration of the corresponding IWSN.

IV. COLLABORATIVE SCHEDULING ALGORITHM (CSA)

This section presents the details of the collaborative scheduling algorithm (CSA) from the CCP perspective. The notation

TABLE 1. Notation.

Notations	Description
i	Index for node with periodic data generation
k	Index for network, $k \in \mathbf{K}$
$\mathbf{K}$	Set of coordinated networks with number $K = \lvert \mathbf{K} \rvert$
$\mathbf{N}_k$	Set of nodes in network k with number $N_k = \lvert \mathbf{N}_k \rvert$
φ_k^i	Maximum allowable delay of node i (s), $\forall i \in \mathbf{N}_k$
φ_{min}	Minimal φ_k^i among all the nodes (s)
L_k^i	Message length of node i (bytes)
T_k^i	Time slot allocation interval for node i (s)
$T_{\max}$	Hyperperiod of the scheduling (s)
$TSPD_k$	Number of time slots for periodic data in one *ISD* with respect to network k (slots)
$TSAD_k$	Number of timeslots for aperiodic data in one *ISD* with respect to network k (slots)
$TSACP_k$	Number of timeslots of active period in one *ISD* with respect to network k (slots)
$SISD_k^i$	Start *ISD* number for node i, $\forall i \in \mathbf{N}_k$
SSN_k^i	Start slot number for node i, $\forall i \in \mathbf{N}_k$
RTS_k	Remaining timeslots in the current *ISD* (slots)
$FDTI_k^i$	First data transmission instant of node i (s)

used in this paper is provided in Table 1. The inputs of the scheduling algorithm are the necessary information that CCP collects from different IWSN managers; the outputs from the algorithm are the corresponding IWSN configuration parameters or, namely, the resource allocation plan.

Inputs to the algorithms:

- Set of nodes ($\mathbf{N}_k$): The set of periodic nodes (with number $N_k = |\mathbf{N}_k|$) that need to be scheduled for its periodic data generation in network k ($\forall k \in \mathbf{K}, K = |\mathbf{K}|$).
- Maximum allowable message delay (φ_k^i): For node $i(\forall i \in \mathbf{N}_k)$ with periodic data generation, it must transmit a message no later than φ_k^i after the data are generated. Denote $\mathbf{\Phi}_k$ ($\forall k \in \mathbf{K}$) as the corresponding vector involving all the nodes, wherein the elements in each vector are sorted in ascending order, as indicated in (2). Accordingly, the vector of periodic message length ($\mathbf{L}_k$) of each node in network k is shown in (3).

$$\mathbf{\Phi}_k = [\varphi_k^1, \ldots, \varphi_k^i, \ldots, \varphi_k^{N_k}] \quad (\varphi_k^i \le \varphi_k^{i+1}) \quad \forall i \in \mathbf{N}_k, \quad \forall k \in \mathbf{K} \tag{2}$$

$$\mathbf{L}_k = [L_k^1, \ldots, L_k^i, \ldots, L_k^{N_k}] \quad \forall i \in \mathbf{N}_k, \ \forall k \in \mathbf{K} \tag{3}$$

- Number of time slots allocated for aperiodic data ($TSAD_k$): It denotes the time slots reserved for transmitting aperiodic data based on request.

Outputs from the algorithm:

- *ISD*: The length of the Integrated Superframe Duration (*ISD*) that acts as the basic scheduling unit of the CCP.
- T_{max}: The hyperperiod of the proposed centralized network coordination, upon which the CCP will repeat the whole network scheduling.
- $FDTI_k^i$: The first data transmission instant of each node.

Next, the principles of the algorithm will be introduced by specifying five steps, upon which, the coexisted heterogeneous IWSNs will be scheduled in a collaborative way.

Step 1: Determine the duration of a time slot (*TS*) and the length of the Integrated Superframe Duration (*ISD*).

As a basic time unit of a superframe, the duration of a time slot (*TS*) is unified first. As discussed in Section II, the *TS* of ISA100.11a (i.e., 10 ms to 12 ms) and WIA-PA is configurable, whereas for WirelessHART the *TS* is fixed as 10 ms. To accommodate the three networks, the *TS* of the coexistence management system is defined to be 10 ms, as shown in (4).

$$TS = 10 \text{ ms} \tag{4}$$

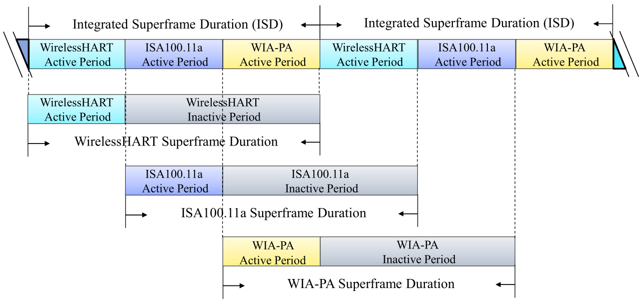

FIGURE 2. The structure of the integrated superframe duration (ISD).

In this paper, a novel superframe structure called Integrated Superframe Duration (*ISD*) is proposed, as shown in Figure 2. The *ISD* consists of three active periods with respect to WirelessHART, ISA100.11a and WIA-PA. Within one *ISD*, one network can only be activated in another networks' inactive period (or sleeping period). In accordance with this, from the perspective of any network, an *ISD* can be deemed as its individual superframe composing two periods (i.e., active and inactive), as shown at the bottom of Figure 2. In this way, various networks under the centralized coordination will be active in an exchangeable way.

The *ISD* is the basic scheduling unit in the algorithm presented. The coexistence management system in CCP will repeat *ISD* periodically. On the one hand, the *ISD* is expected to be as large as possible to have a longer inactive period [5], such that the power consumption can be reduced. On the other hand, in order to satisfy the requirement of real-time service, the defined *ISD* should be constrained to not exceed the minimum allowable message delay (φ_{min}) of any end node as illustrated in (5) and (6).

$$\varphi_{min} = \min\{\varphi_k^1, \forall k \in \mathbf{K}\} \tag{5}$$

$$ISD \le \varphi_{min} \tag{6}$$

In addition, the *ISD* should also coincide with the regulations of superframe duration in the three standard specifications as discussed in Section II. Because WIA-PA has specific regulation for superframe length compared to the others [as defined in (1)], the length of the *ISD* is identical to that of the superframe and collaboratively determined based on (5), (6) and (7)

$$ISD = SD_{wp} = 32 \times 2^M \times TS \tag{7}$$

Step 2: This step determines the time slot allocation interval (T_k^i) for a node with periodic data generation.

In the context of collaborative coexistence management, a central network controller is responsible for configuring the available network resources on behalf of each application under consideration. For each node with periodic data generation, the CCP needs to allocate a time slot for each node appropriately to avoid collision among IWSNs and concomitant message transmission delay. To achieve this, first the CCP needs to determine the time slot allocation interval (T_k^i) for each node under consideration.

Let $\mathbf{T}_k$ denote the vector of time slot allocation interval for nodes in network k. The elements in $\mathbf{T}_k$ are assumed to be sorted in ascending order.

$$\mathbf{T}_k = [T_k^1, \ldots, T_k^i, \ldots, T_k^{N_k}] \quad (T_k^i \le T_k^{i+1}) \tag{8}$$

For the CCP to schedule all the $\sum_{k \in \mathbf{K}} N_k$ nodes in a feasible way, it is essential that the values of each interval T_k^i ($\forall i \in \mathbf{N}_k, \forall k \in \mathbf{K}$) are integer *multiples* of each other [22], such that all the nodes can be accommodated under a uniform scheduling framework. Next, an effective mechanism will be introduced for determining the value of each interval T_k^i.

As mentioned in Step 1, the *ISD* is the basic scheduling unit in the presented algorithm. Accordingly, the first element (T_k^1) in $\mathbf{T}_k$, which is the minimal time slot allocation interval for network k, should be equal to the *ISD* as follows:

$$T_k^1 = ISD \quad (\forall k \in \mathbf{K}) \tag{9}$$

The definition in (9) naturally guarantees that the most time sensitive data (i.e., generated by a node with minimal maximum allowable delay) can be transmitted in time due to (5) - (7).

For any other node with a different maximum allowable delay φ_k^i ($i > 1$), the CCP will regulate the time slot allocation interval (T_k^i) while meeting the following two conditions [23]:

a) The length of T_k^i should not exceed φ_k^i.

b) The values of T_k^i must be integer multiples of each other.

Equation (10) is defined to meet *a*) and *b*).

$$T_k^i = \alpha_k^i T_k^1, \quad \alpha_k^i = 2^{\left\lfloor \log_2 \frac{\varphi_k^i}{T_k^1} \right\rfloor}, \quad \forall i = 2, \ldots, N_k, \ \forall k \in \mathbf{K} \tag{10}$$

The first term of (10) indicates that each T_k^i is obtained by multiplying an integer α_k^i with the minimum interval T_k^1, wherein α_k^i is the ratio (with respect to T_k^1) defined as a power of two, i.e., 2^n, and n is determined by the floor function $n(x) = \lfloor x \rfloor$. Equation (10) guarantees that T_k^i does not exceed the maximum allowable delay φ_k^i.

Based on the definition in (10), it can be observed that the maximum interval $T_{\max}$ [denoted by (11)] is the least common multiple of the intervals of all the nodes, which is named the "hyperperiod" hereafter [24], [25], upon which the CCP will repeat the whole scheduling every $T_{\max}$ seconds.

$$T_{\max} := \max\{T_k^{N_k} = \alpha_k^{N_k} T_k^1, \quad \forall k \in \mathbf{K}\} \tag{11}$$

Step 3: This step determines the number of time slots ($TSPD_k$) allocated for periodic data transmission in one *ISD* with respect to each network k.

The interval defined in Step 2 indicates how frequently the CCP will allocate a time slot for a node with periodic data generation. In addition, if focusing on the active period of a single *ISD*, we are concerned with how many time slots ($TSPD_k$) should be allocated for periodic data transmission within one *ISD*.

Take network k as an example, $TSPD_k$ is calculated as a sum of reciprocals of the interval ratios with respect to N_k nodes. Moreover, to maintain an integer number for $TSPD_k$ as well as guarantee the nodes generating periodic data can be scheduled sufficiently, $TSPD_k$ is defined to be the smallest integer greater than or equal to the sum of reciprocals, as shown in (12) [23].

$$TSPD_k = \left\lceil \sum\nolimits_{i \in \mathbf{N}_k} \left(\frac{1}{\alpha_k^i} \right) \right\rceil \tag{12}$$

Afterwards, in order to validate the feasibility of achieving collaborative scheduling of all the networks, the total time slots allocated for the periodic data generation ($TSPD_k$) as well as reserved for aperiodic data ($TSAD_k$) should not exceed the length of the *ISD*, as constrained by condition (13):

$$\left(\sum\nolimits_{k \in \mathbf{K}} TSPD_k + \sum\nolimits_{k \in \mathbf{K}} TSAD_k \right) \times TS \le ISD \tag{13}$$

Note that in case (13) is violated, it indicates that the current network configuration is overloaded (in other words, there is no feasible solution for the CCP to schedule a total number of $\sum_{k \in \mathbf{K}} N_k$ nodes with periodic data generation). Because the network traffic is overloaded, the number of nodes that generates periodic data should be reduced (e.g. divide the networks covered by one CCP to more than one CCP groups), so that they can be accommodated within the CCP capacity, and the algorithm goes back to Step 1.

Once condition (13) is satisfied, the algorithm will move to Step 4 to execute the final time slot allocation.

Step 4: This step allocates the unique time slot for each node and determines its first data transmission instant (*FDTI*) accordingly.

In Steps 3, the number of time slots to be allocated for nodes with periodic data generation has been determined. In this step, the specific time slot during which a certain node can transmit data will be allocated. As mentioned in Step 2, the scheduling of all the nodes *repeats* with the cycle of the hyperperiod (T_{max}) as defined in (11). Therefore, in the following, only the allocation process for the first T_{max} will be introduced specifically.

The time slot allocation for each node can be uniquely determined by identifying *the start ISD number* ($SISD_k^i$) and *the corresponding start slot number* (SSN_k^i) in that *ISD*. The time slot allocation of the first hyperperiod (T_{max}) is shown in Figure 3.

The sequence of choosing nodes for allocating time slots is assumed to be consistent with the order in (8), i.e., starting from the node with the smallest interval.

To determine the start *ISD* number ($SISD_k^i$) for node i in network k, it is necessary to check the number of remaining

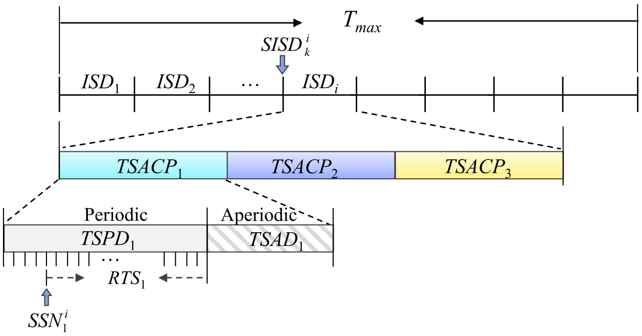

FIGURE 3. Illustration of the time slot allocation for the first hyperperiod.

time slots (RTS_k) in the current ISD that have not been allocated. If RTS_k satisfies (14), then the start slot number (SSN_k^i) for node i is determined, which is the first unallocated slot; otherwise, the allocation should move to the next ISD and repeat the same process.

$$1 \le RTS_k \le TSPD_k \tag{14}$$

After $SISD_k^i$ and SSN_k^i are determined, the first data transmission instant ($FDTI_k^i$) for each node $i \in \mathbf{N}_k$ ($\forall k \in \mathbf{K}$) can be determined using (15) [22], [23].

$$FDTI_k^i = \begin{cases} (SISD_k^i - 1) \times ISD + (SSN_k^i - 1) \times TS & k = 1 \quad (15a) \\ (SISD_k^i - 1) \times ISD + \sum_{m=1}^{k-1} (TSPD_m + TSAD_m) & \\ \quad \times TS + (SSN_k^i - 1) \times TS & k > 1 \quad (15b) \end{cases}$$

Note that equation (15) differentiates, through the index k, between any node belonging to networks other than $k = 1$, and the calculation of $FDTI_k^i$ should consider the time slots that have been allocated (and reserved) for $k - 1$ protocol(s). Once $FDTI_k^i$ is determined for node i, it will transmit its periodic data repeatedly according to its interval T_k^i determined in Step 2.

To better understand the principles of the proposed CSA, a pseudo code is provided in Table 2 which illustrates the procedure of how Step 1 to Step 4 are coordinated in order to derive the final resource allocation plan.

V. PERFORMANCE EVALUATION

To verify the performance of the proposed collaborative algorithm for coexistence management, a simulation model was developed in OPNET based on the IEEE 802.15.4 open source provided by open-ZB [26]. In this work, three example IWSNs were deployed which conformed to the three respective protocols of WirelessHART, ISA100.11a and WIA-PA, wherein the IEEE 802.15.4 MAC layer was modified according to each specification. As shown in Figure 4, three network managers [which are WH_Network_Manager (red), ISA_Network_Manager (yellow) and WP_Network_Manager (green)] lie in the middle, and each sub-network has twenty end nodes. All the three IWSNs were deployed in the same geographical area of 90 m × 40 m by forming star topologies.

TABLE 2. Collaborative scheduling algorithm (CSA).

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Inputs: $\mathbf{N}_k$, $\mathbf{\Phi}_k$, $TSAD_k$, $\mathbf{L}_k$
1:  Step 1: Determine the duration of $TS$ and the length of $ISD$ based on
        (4) and (5)-(7).
2:  Step 2: Determine the time slot allocation interval $T_k^i$ for a node with
        periodic data generation using (9) and (10).
3:  Step 3: Determine the number of time slots for periodic data ($TSPD_k$)
        in one $ISD$ based on (12)
4:      Validate the feasibility of achieving collaborative scheduling:
5:      if $(\sum_{k\in\mathbf{K}} TSPD_k + \sum_{k\in\mathbf{K}} TSAD_k) \times TS \le ISD$, then
6:          Go to Step 4;
7:      Otherwise,
8:          Indicates network configuration is overloaded;
9:          Reduce $N_k$, $(\forall k \in \mathbf{K})$, go back to Step 1.
10: Step 4: Allocate the unique time slot for each node and determine its
        first data transmission instant ($FDTI$) accordingly.
11:   Choose a node ( $\forall i \in \mathbf{N}_k$, $\forall k \in \mathbf{K}$) according to the sequence in (8):
12:   Start from the first $ISD$:
13:     if $1 \le RTS_k \le TSPD_k$
14:       Regard the current $ISD$ as the start ISD number ($SISD_k^i$) .
15:       Assign the first unallocated slot to node $i$ and denote it as $SSN_k^i$ .
16:       Determine the first data transmission instant ($FDTI$):
17:         if $k = 1$,
18:           Determine $FDTI$ using (15a);
19:         else
20:           Determine $FDTI$ using (15b);
21:     else
22:       Move to next $ISD$.
23: Repeat Line 10 to Line 22 until all the nodes are allocated with $FDTI$.
Outputs: $ISD$, $T_{max}$, $FDTI_k^i$
```

The inputs to the CSA are provided herein. The number of time slots for aperiodic data ($TSAD_k$) was set to 4 for each protocol. The maximum allowable message delay (φ_k^i) of each end node was generated using a random number generator within a uniform distribution in the range 0.32s to 5s. The corresponding periodic message length (L_k^i) of nodes from different protocols were generated from random number generators with different uniform distributions: 0∼115 bytes (the maximum allowable MAC upper layer data length defined in WirelessHART), 0∼96 bytes (the maximum allowable MAC upper layer data length defined in ISA100.11a) and 0∼108 bytes (the maximum allowable MAC upper layer data length defined in WIA-PA). The resulting φ_k^i and L_k^i for each node are shown in Table 3.

Based on the inputs above, the proposed CSA was first run by a virtual CCP (as illustrated in Figure 4), to determine the outputs. Following the four steps specified in Section IV, a numerical example is given as follows which illustrated the values obtained from each step of the CSA.

In Step 1, the ISD was first determined to be 320 ms based on (5)-(7).

In Step 2, the time slot allocation interval (T_k^i) for the node with minimal φ_k^i was fixed to be the length of the ISD. For other nodes with different φ_k^i, T_k^i was determined using (10), with the ratio (α_k^i) and T_k^i as presented in Table 4. Accordingly, the hyperperiod $T_{\max}$ was determined to be 2560 ms via (11), which means the CCP will repeat the whole scheduling every eight $ISDs$.

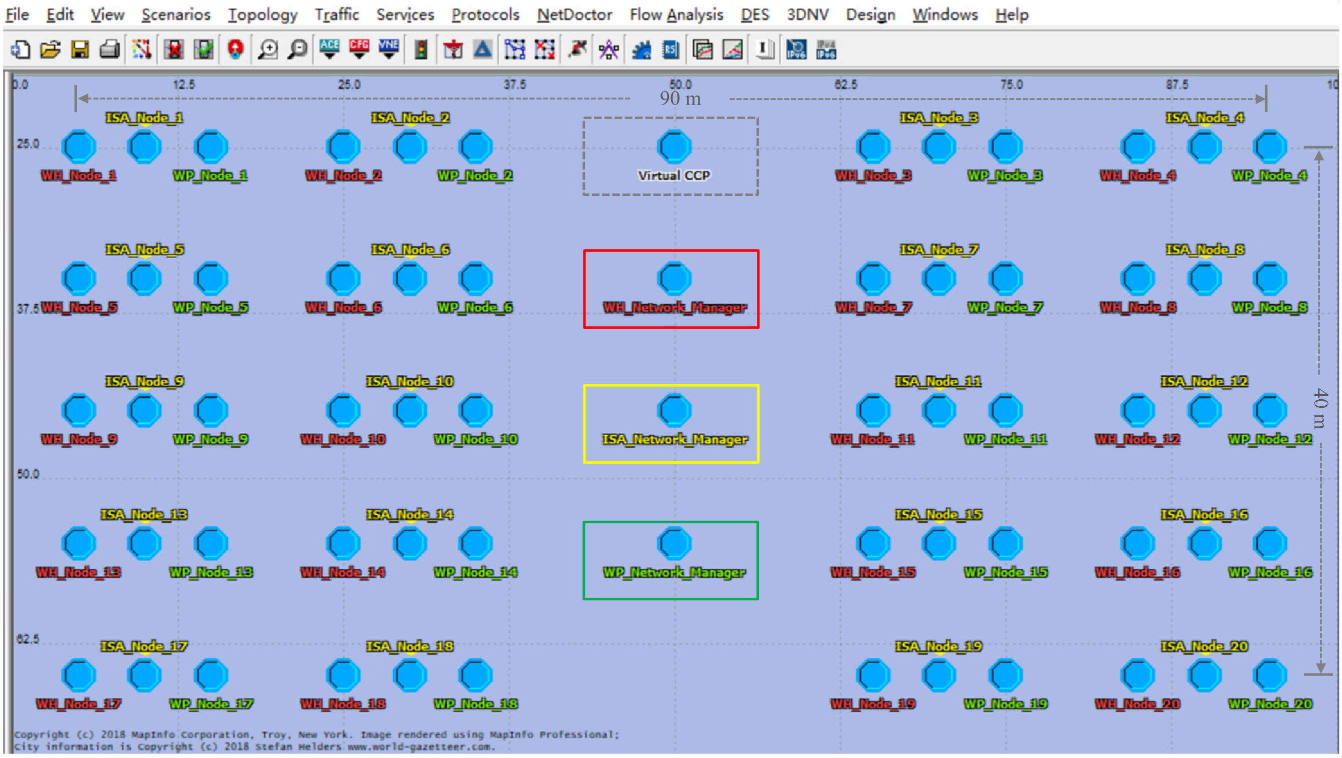

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FIGURE 4. Screen capture of network deployment in the simulation model.

TABLE 3. Input parameters.

	Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
WirelessHART	L_k^i	69	24	27	106	5	16	98	52	27	32	55	4	41	60	29	114	19	81	57	107
	φ_k^i	4.4	2.52	4.95	0.69	2.74	4.34	4.56	0.98	1.73	3.95	1.13	3.81	3.96	0.74	4.41	4.98	0.36	0.48	2.55	3.16
ISA100. 11a	L_k^i	80	53	23	42	72	32	58	55	9	71	91	69	3	22	23	34	74	13	69	76
	φ_k^i	2.56	2.24	4.2	3.09	1.72	1.42	2.15	3.54	3.41	4.81	2.66	2.84	1.1	2.24	0.38	3.29	4.19	3.07	2.76	2.49
WIA-PA	L_k^i	106	90	1	7	95	56	74	93	108	19	105	69	15	39	85	72	15	79	105	36
	φ_k^i	2.65	1.32	1.52	1.85	4.62	3.77	0.99	4.6	4.66	2.81	0.77	1.71	2.93	3.91	0.47	0.42	0.93	1.72	1.33	1.63

TABLE 4. Output parameters obtained from the CSA.

	Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
WirelessHART	α_k^i	8	4	8	2	8	8	8	2	4	8	2	8	8	2	8	8	1	1	4	8
	T_k^i	2.56	1.28	2.56	0.64	2.56	2.56	2.56	0.64	1.28	2.56	0.64	2.56	2.56	0.64	2.56	2.56	0.32	0.32	1.28	2.56
	$SISD_k^i$	2	1	2	1	2	3	4	1	2	4	1	4	4	1	4	6	1	1	2	6
	SSN_k^i	5	7	6	3	7	7	3	4	3	4	5	5	6	6	7	5	1	2	4	6
	$FDTI_k^i$	0.32	0.06	0.33	0.02	0.34	0.62	0.86	0.03	0.30	0.87	0.04	0.88	0.89	0.05	0.9	1.44	0	0.01	0.31	1.45
ISA100. 11a	α_k^i	8	4	8	8	4	4	4	8	8	8	8	8	2	4	1	8	8	8	8	4
	T_k^i	2.56	1.28	2.56	2.56	1.28	1.28	1.28	2.56	2.56	2.56	2.56	2.56	0.64	1.28	0.32	2.56	2.56	2.56	2.56	1.28
	$SISD_k^i$	2	1	3	3	1	1	2	3	4	4	4	4	1	2	1	6	7	7	7	2
	SSN_k^i	5	3	3	4	4	5	2	5	2	3	4	5	2	3	1	5	3	4	5	4
	$FDTI_k^i$	0.44	0.14	0.7	0.71	0.15	0.16	0.41	0.72	0.97	0.98	0.99	1	0.13	0.38	0.12	1.56	1.82	1.83	1.84	0.39
WIA-PA	α_k^i	8	4	4	4	8	8	2	8	8	8	2	4	8	8	1	1	2	4	4	4
	T_k^i	2.56	1.28	1.28	1.28	2.56	2.56	0.64	2.56	2.56	2.56	0.32	0.64	1.28	1.28	0.32	0.32	0.64	1.28	1.28	1.28
	$SISD_k^i$	3	1	1	2	3	4	1	4	4	4	1	2	4	7	1	1	1	2	2	2
	SSN_k^i	6	6	7	3	7	4	3	5	6	6	4	4	7	6	1	2	5	5	6	7
	$FDTI_k^i$	0.82	0.26	0.27	0.51	0.83	1.07	0.23	1.08	1.09	1.1	0.24	0.52	1.11	1.94	0.21	0.22	0.25	0.53	0.54	0.55

In Step 3, to guarantee the scheduling feasibility, we first calculated the number of required time slots for periodic data ($TSPD_k$) in one ISD with respect to each network k. Based on the ratios determined in Step 2, the values of $TSPD_k$ were calculated to be 7, 5 and 7 using (12). According to (13), the total time slots for periodic ($TSPD_k$) and aperiodic ($TSAD_k$) data generation of all the networks were calculated as $\left(\sum_{k\in\mathbf{K}} TSPD_k + \sum_{k\in\mathbf{K}} TSAD_k\right) \times 10 = 310 < 320$, such that under the current network configuration it is feasible for the CCP to seek a solution that can schedule all the nodes with periodic data generation, which also means the network was not overloaded.

In Step 4, the unique time slot as well as the first data transmission instant *FDTI*(s) for each node were determined ultimately. Following the allocation process indicated by Line 10 to Line 22 in Table 2, the obtained *start ISD number* ($SISD_k^i$) and *the corresponding start slot number* (SSN_k^i) in the first hyperperiod ($T_{\max}$) were provided in Table 4, which were then assigned to each IWSN manager to configure its own IWSN.

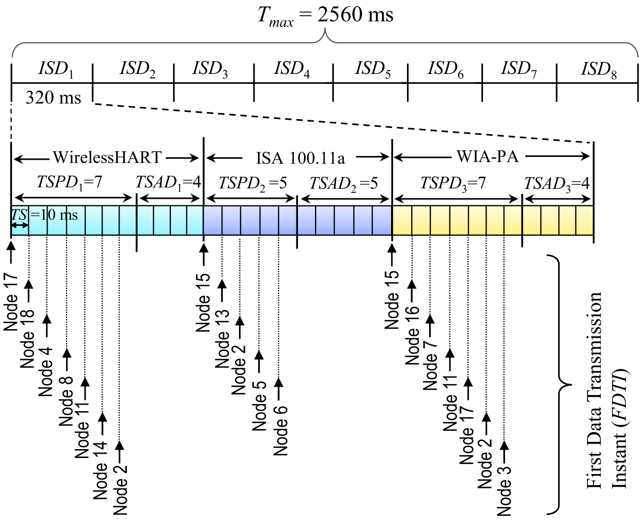

FIGURE 5. **Illustration of the first data transmission instant (*FDTI*) in the first *ISD* of the hyperperiod (T_{max}).**

To facilitate understanding how time slots were uniquely assigned to the nodes in Table 4, we took the first *ISD* as an example to show the time slot allocation with respect to three protocols. As shown in Figure. 5, the nodes that were scheduled to start data transmission in the first *ISD* (i.e., $SISD_k^i = 1$) are assigned with unique time slots according to the values of SSN_k^i in Table 4, and the time instant pointed by each arrow exactly maps with the value of $FDTI_k^i$ in Table 4. In a similar manner, all other nodes will be allocated with unique time slots in remained *ISDs*.

Simulation was then performed based on the aforementioned configurations. It deserves noticing that for a node with periodic data generation, the data must be transmitted within their maximum allowable delay once they are generated, and it is thus necessary to evaluate the real-time message delay measured as the elapsed time *from* the time those data were generated, *to* the time those data were received by their destination. First, the sample nodes with the strictest requirement of allowable delay ($\min\{\varphi_k^i, \forall i \in \mathbf{N}_k\}$) were selected as the representatives from each network, i.e., node 17 from WirelessHART, node 15 from ISA100.11a and node 16 from WIA-PA. Figure 6 shows the real-time message delay of each sample node. Clearly, the message delay was appropriately controlled below the corresponded maximum allowable delay when nodes were scheduled according to the CSA. In addition, we also examined the real-time message delay of all other nodes in each network, and confirmed that all the nodes were able to satisfy their real-time requirements. However, the resulting figures for other nodes were not enumerated here as they exhibited same patterns.

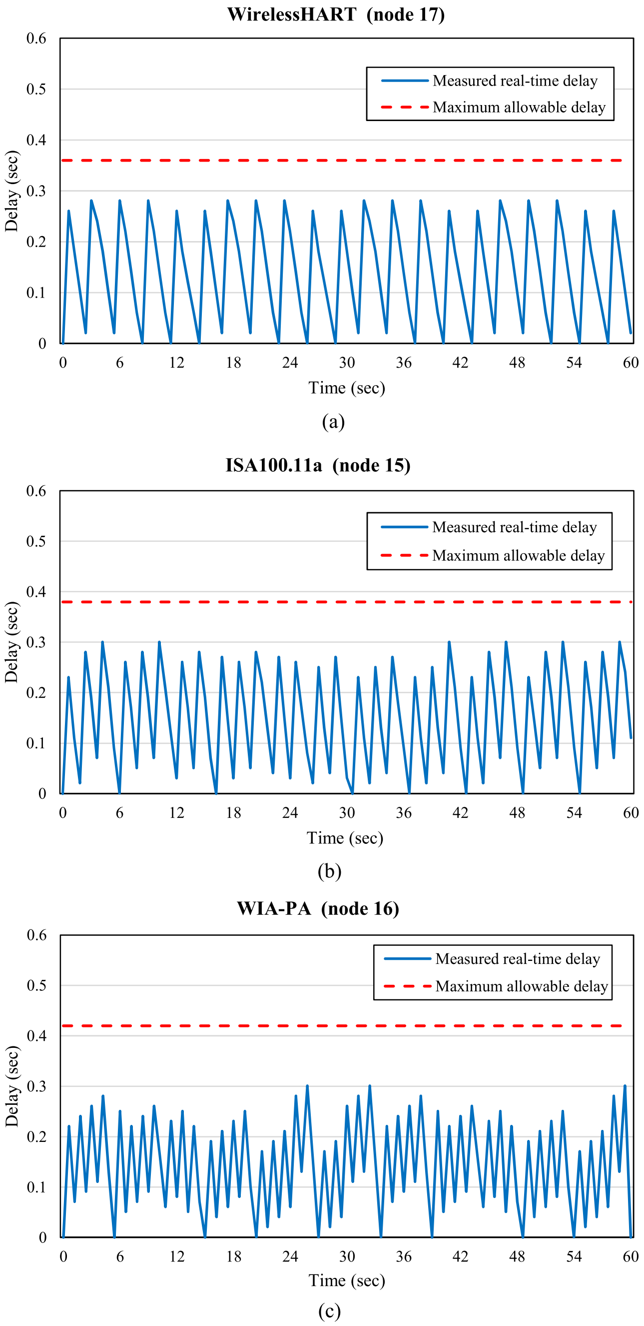

FIGURE 6. **Real-time message delay of three sample nodes: (a) WirelessHART node 17, (b) ISA100.11a node 15, and (c) WIA-PA node 16.**

VI. CONCLUSION AND FUTURE WORKS

Based on the requirements of the future manufacturing environment with heterogeneous IWSNs deployed in the same geographical area, this paper proposed a scheduling algorithm called CSA to coordinate the activation of each IWSN without the interference of each other while taking the end-to-end delay constraint of each periodic node that generates time sensitive data into consideration, which is imperatively required especially for IWSN. Simulation results showed that the CSA could successfully maintain the coexistence of heterogeneous IWSNs, and also guarantee the real-time communication requirement of the whole system under collaborative management. In future, the proposed CSA is expected to be implemented in an industrial facility deployed with heterogeneous IWSNs, in order to test the performance of coexistence management using real industrial data. Moreover, the work presented in this paper can be extended in several directions. First, the coordination framework could be modified to support mesh network topology, e.g., the scheduling algorithm can be updated to take account of the forwarding time considering routing and any redundant path, and afterwards an adaptive resource allocation decision can be made by guaranteeing the end-to-end delay requirement. Second, the scheduling algorithm can be expanded to the frequency domain, e.g., augmented by multiple channel allocation schemes, the coordination framework would accommodate more network nodes while maintaining the same real-time performance.

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