ISSN: 2183-6493
DOI: 10.24840/2183-6493_005.001_0005
Revised: 10 January, 2019
Published: 26 April, 2019

Multiprocessor Scheduling meets the Industrial Wireless: A Brief Review

Miguel Gutiérrez-Gaitán[1], Patrick Meumeu Yomsi[2]

[1]Facultad de Ingeniería, Universidad Andres Bello, 8370146 SANTIAGO, Chile (miguel.gutierrez@unab.cl); CISTER Research Centre, ISEP, Polytechnic Institute of Porto (IPP), Rua Alfredo Allen, 535, 4200-135 PORTO, Portugal (mjggt@isep.ipp.pt) ORCID 0000-0002-3307-8731; Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto, PORTO, Portugal (up201809171@fe.up.pt); [2]CISTER Research Centre, ISEP, Polytechnic Institute of Porto (IPP), Rua Alfredo Allen, 535, 4200-135 PORTO, Portugal (pamyo@isep.ipp.pt) ORCID 0000-0003-0473-1559

Abstract

This survey covers the schedulability analysis approaches that have recently been proposed for multi-hop and multi-channel wireless sensor and actuator networks in the industrial control process domain. It reviews the noticeable results with a focus on IEC 62591 (WirelessHART) and ANSI/ISA100.11a-2011 (ISA100.11a), the two major wireless standards in the process automation industry. The paper addresses the mapping of multi-channel transmission scheduling to multiprocessor scheduling theory, and recognizes this mapping as a key research direction. It also provides a taxonomy of the existing approaches and discusses the main features and recent evolutions. The survey identifies a number of open issues, key research challenges, and promising future directions.

Author Keywords. Industrial Internet of Things, Wireless Sensor and Actuator Networks (WSAN), WirelessHART, ISA100.11a, Schedulability Analysis.

Type: Research Article

1. Introduction

Multiprocessor real-time scheduling theory concerns the techniques and methodologies developed in order to enable correct and efficient implementation of real-time systems upon multiprocessor platforms (Baruah, Bertogna, and Buttazzo 2015). Here, the classical resource allocation problem of scheduling is augmented by both the stringent timing requirements of real-time systems and the complexity of multicore platforms. To circumvent this challenge, most of the fundamental techniques and outcomes related to the uniprocessor scheduling theory have found a place to be extended into multiprocessors. That is the case for the state-of-the-art schedulability assessment techniques such as response-time analysis (RTA), demand-based analysis (DBA), and utilization-based analysis (UBA), that have exploited the opportunities arising from the move toward multiprocessors. Automotive, avionics, telecommunications, medical imaging, and space are some of the target industries with highly complex and computationally demanding applications that expect benefits from the advancement in this area (Davis and Burns 2011).

In a similar fashion, the industrial-strength advancements in wireless sensor and actuator networks (WSAN) are also promising a new generation of industrial applications. Indeed, Cyber-Physical Systems (CPS) and the Industrial Internet of Things (IIoT) have recently caught significant attention from both industry and academia on the way to the realization of the Industry 4.0. vision (Sisinni et al. 2018). Here, CPS plays its role by enabling the interaction between the real-world physical objects and its digital counterpart, whereas IIoT does its part by bringing the information and communication technologies into the operational technology domain. Although these definitions may have their nuances in the literature, a common concern in industrial wireless communications is given by the necessity to satisfy all the end-to-end timing requirements in such a challenging arena.

In this direction, WirelessHART and ISA100.11a are the two major standards offering timing and reliable wireless communications for the process automation industry (Wang and Jiang 2016). Although there are other applicable technologies, these two standards present some common technological features that are central to analyze the schedulability of network flows, i.e. the ability of each flow to meet all its timing constraints. Based on the observation that the schedulability is a cornerstone to satisfy the stringent real-time and reliability requirements in the industrial wireless, this paper covers the recent trend of research exploiting the existing results of the multiprocessor scheduling theory into the wireless industrial domain. The idea was first proposed by Saifullah et. al (2010), by introducing this key insight into the scheduling problem domain of WirelessHART networks. Later, since there is a substantial amount of research dedicated to the theoretical scheduling analysis upon multiprocessors, other approaches also emerged. Although Lu et al. (2016) reviewed some of the early works following this line and discussed the implications on the design considerations for industrial CPS, no other articles have comprehensively reviewed all the significant research efforts in this direction.

In a nutshell, this paper recognizes the *multiprocessor scheduling theory applied to the industrial wireless* as a new branch of research aiming to exploit the existing theoretical analyses for multiprocessors by incorporating the wireless characteristics. Then, since there is no other work covering thoroughly the related literature under this perspective, the objective is to fill this gap by carrying out a brief review on the main schedulability analysis techniques that have been applied in WirelessHART and ISA100.11a networks. The result of this state-of-the-art will be classified from the point of view of the real-time scheduling theory, by identifying the scheduling algorithms, basic principles, and evaluation methods used for each approach. Finally, by delineating the evolution of this subject, a common understanding of the assumptions, distinctive aspects, and considerations will be provided. Figure 1 summarizes the key insights behind the research direction covered by this survey.

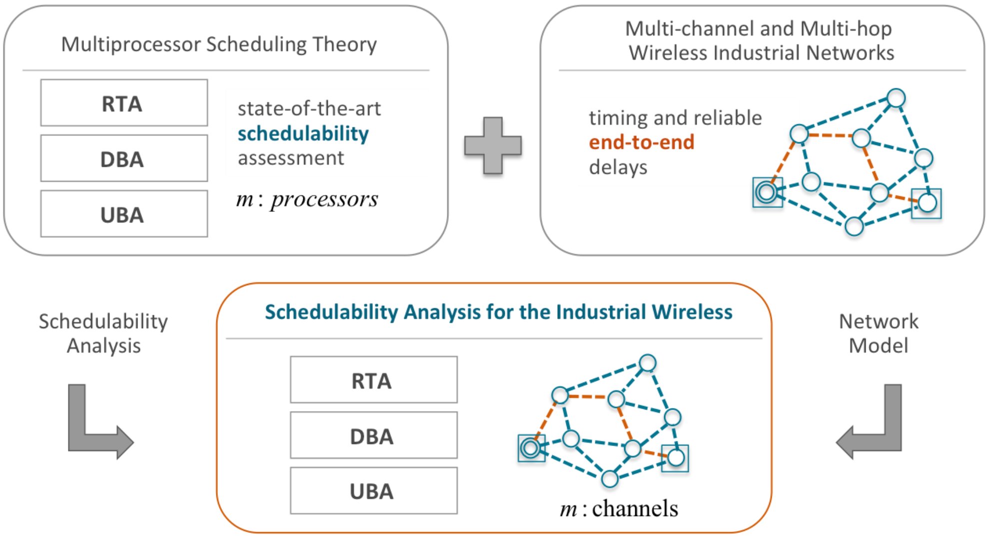

Figure 1: Motivations behind the mapping of the multiprocessor scheduling and multi-channel transmission scheduling

The remainder of the paper is organized as follows: Section 2 outlines the related background on real-time scheduling theory and wireless sensor-actuator networks that is relevant for the aim of this article. Section 3 discusses the evolution of research around the subject and classifies it into a taxonomy. Section 4 concludes the paper by identifying the current state of the research, the impact, and its future directions.

2. Background

In order to make this document self-contained, this section will present both a selection of the most apposite definitions from the multiprocessor scheduling theory and a brief overview of the industrial wireless networks for the industrial automation domain.

2.1. Workload model

The objective of real-time scheduling theory is to handle concurrent workloads executions on a shared hardware platform such that all timing requirements are always met (Guan 2016). The workload is characterized by a finite collection of recurrent *tasks* in which each task consists of basic units of work also known as *jobs*. Each job is often characterized by its arrival time, its worst-case execution time (WCET), and its deadline. Then depending on the regularity of the arrival times, each task can be classified as *periodic* or *sporadic*. For periodic tasks, each job specifies an exact inter-arrival time separation between consecutive jobs called the period, whereas, for sporadic tasks, each job specifies only a lower bound of its inter-arrival time. In the multiprocessor scheduling, the 3-parameter sporadic task model given by the tuple (C_i, D_i, T_i) for task τ_i (also noted $\tau_i = (C_i, D_i, T_i)$) is the most widely used workload model (Baruah, Bertogna, and Buttazzo 2015). Here, C_i denotes the WCET of each job generated by task τ_i, D_i is the deadline that occurs D_i units after the arrival time, and T_i is the minimum inter-arrival time between two consecutive jobs. A pictorial representation of this workload model for an arbitrary task τ_i is shown in Figure 2.

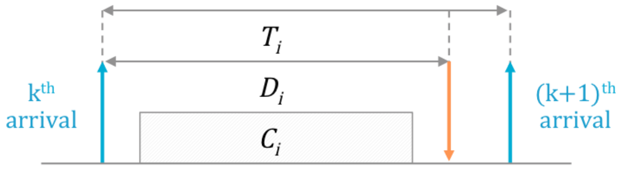

Figure 2: Workload model for an arbitrary task τ_i

By observing the relative distance between deadlines and periods, a sporadic task system can be classified as: (i) *implicit-deadline*, if all deadlines are equal to the periods; (ii) *constrained-deadlines*, if all deadlines are less than or equal to the periods; or (iii) *arbitrary deadlines*, if there are no constraints between the two values. In all of these cases, the *utilization* of task τ_i is defined as the ratio of its WCET with respect to its period and it is denoted as u_i. The sum of all the individual utilizations in a task system is called the *total utilization* and is denoted as U_{sum} (Baruah, Bertogna, and Buttazzo 2015). Equation 1 and Equation 2 formally present these two definitions:

$$u_i = \frac{C_i}{T_i} \quad (1)$$

$$U_{sum} = \sum u_i \quad (2)$$

Although there exist a multitude of other models to represent workloads in multiprocessors, the 3-parameter sporadic task model and its associated definitions are the ones of interesting in the scope of this paper.

2.2. Scheduling on multiprocessor platforms

The multiprocessor scheduling theory focuses primarily on two major problems: *resource allocation* and *priority assignment*. The resource allocation deals essentially with the mapping between tasks and processors, whereas, the priority assignment deals with the order of the job execution with respect to other tasks (Davis and Burns 2011). Although many works have tried to solve both problems by using different scheduling approaches, most of the literature can be categorized into two main paradigms: global scheduling and partitioned scheduling (Guan 2016). The first consists of techniques in which each task can start executing on any core and complete on the same core as or a different core from which the task was assigned. In the latter case, we say that a *migration* has occurred. The second approach promotes the assignment of each task to a core beforehand and migrations are forbidden at runtime. In the last two decades, a new category referred to as semi-partitioned scheduling (Davis and Burns 2011), has also emerged. These schedulers bring together the benefits of both the global and partitioned approaches under the same umbrella by allowing only a subset of tasks to be executed by following a fully partitioned scheme and the remaining tasks to migrate from one core to another during their execution.

Depending on the priority assignment policy used by the scheduling algorithm, the schedulers can be classified as *fixed-task priority* (FTP), *fixed-job priority* (FJP), or *dynamic priority* (DP) algorithms (Davis and Burns 2011). FTP and FJP are fixed-priority approaches (FP), that is the priority assigned to each job for a given task by the algorithm cannot change over time. The difference is that for FTP schedulers all the jobs belonging to a task are assigned the same priority, whereas, for FJP schedulers, two jobs belonging to the same task may be assigned different priorities. In DP algorithms, a job may have different priorities at different time instants (Davis and Burns 2011). Rate Monotonic (RM) and Deadline Monotonic (DM) are two well-known examples of FTP algorithms, whereas Earliest-Deadline-First (EDF) and Least Laxity First (LLF), are the equivalent examples for FJP and DP, respectively.

Another relevant classification for scheduling algorithms is given by their ability to allow *preemption* or not. In *preemptive scheduling*, executing tasks can be interrupted at any time instant and resume its execution later, but in *non-preemptive scheduling*, such an interruption prior to task's completion time is forbidden. A limited preemption capacity is also considered in *cooperative scheduling* algorithms, where preemption is allowed only in predefined points (Davis and Burns 2011).

Although other classifications may exist in the literature, the basic concepts presented until now are enough for the general understanding of following ideas in this paper.

2.3. Schedulability, feasibility and optimality

Feasibility and *optimality* are two fundamentals properties related to the *schedulability* concept. A task set is said to be *feasible* if there exists a schedule able to satisfy all the possible sequence of jobs without missing any deadline. Hence, if there exists a feasible schedule, the task set is also said to be *schedulable*. If a scheduling algorithm is always able to generate a feasible schedule (when there exists one), then it is said to be *optimal*. This means for a given task set that if an optimal scheduling algorithm fails to find a feasible schedule, then the task set cannot be schedulable by any other algorithm (Davis and Burns 2011).

The central point of this review is the schedulability, i.e., the guarantee that all the deadlines will be met under a certain scheduling algorithm. Thereby, to determine if a task (or a task set) is schedulable with respect to a given algorithm, a proper *schedulability test* technique is required. Typically, a schedulability test for a given scheduling algorithm accepts as an input the specifications of the task set upon a given platform, and it offers as an output, the answer whether the task set is schedulable or not (Baruah, Bertogna, and Buttazzo 2015). A schedulability test is defined as *sufficient* with respect to a given algorithm if all the task sets deemed to be schedulable are indeed schedulable. Likewise, a schedulability test is defined to be *necessary* if all the task sets deemed to be *unschedulable* are indeed unschedulable. A schedulability test which is both sufficient and necessary is defined as *exact* (Davis and Burns 2011). Although an exact schedulability test is always desirable, it is often unknown or computationally *intractable*. Therefore, a sufficient but not exact test is more commonly used in practice (Buttazzo 2011). A general classification for the existing schedulability tests is given by the main basic principles of their analyses: response time analysis (RTA), demand-bound analysis (DBA) or utilization-bound analysis (UBA). In the next subsections, the intuition behind these schedulability analysis techniques is presented.

2.3.1. Response Time Analysis

The basic principle of RTA is to compare the deadline of every job in the system against the worst-case response time (WCRT). Then, if for a single job the WCRT is less than or equal to the deadline's job, the job is deemed schedulable. After that, if this condition remains true for all the jobs in the task system, the whole task set is deemed schedulable. However, the analysis of the circumstances in which the WCRT occurs is not trivial and its understanding is essential for the understanding of the RTA technique. As a rule of thumb, the schedulability analysis involves some kind of mathematical proofs and/or simulation validations in order to guarantee the worst-case behavior of a system under a given scheduling algorithm (Davis and Burns 2011). In this regard, the computation of the WCRT of a job is foundational. In essence, the response time of a job is obtained as the difference between its completion time and its arrival time. Since a task system involves many jobs with different arrival and finish times, intuitively the WCRT for each task is given by the maximum response-time exhibited by any of the jobs generated by that task.

In the context of a single core platform, the moment at which such a situation occurs is called the *critical instant* and its analysis is crucial to determine the WCRT and thus the schedulability of the system. Then, the critical instant is well-known, it occurs when all tasks with higher priorities are released at the same instant than the task under analysis. Assuming an FTP and preemptive scheduler, the RTA is based on the concept of *level k-busy period*. Basically, it is defined as the maximum continuous time interval in which the processor is executing tasks with a priority greater than (or equal to) the priority of the task under analysis. By leveraging on these observations, Joseph and Pandya (1986) proposed the following recursive equation to derive a tight upper-bound on the worst-case response time of the task τ_i (R_i) as a solution of the following equation:

$$R_i = C_i + \sum_{\tau_k \in hp(\tau_i)} \left\lceil \frac{R_i}{T_k} \right\rceil C_k \quad (3)$$

In Equation 3 $hp(\tau_i)$ denotes the subset of tasks with higher priorities than τ_i. Further derivations and implications of these results in multiprocessors are discussed in Guan et al. (2009) where the state-of-the-art for FTP schedulers on multiprocessor platforms is reported. In this work, the authors leveraged on the RTA for constrained-deadline task systems. Equation 4 present this basic multiprocessor case where an upper-bound on the response time of a task τ_i upon a multiprocessor platform with m identical processors.

$$R_i = C_i + \frac{1}{m} \sum_{\tau_k \in hp(\tau_i)} \left(\left\lceil \frac{R_i}{T_k} \right\rceil C_k + C_k \right) \quad (4)$$

From this result, Guan et al. (2009) extended the RTA to arbitrary-deadline tasks and improved the precision of previous works. A similar work was conducted by Bertogna, Cirinei, and Lipari (2009), where an iterative test is provided for constrained-deadline task systems under FTP and EDF scheduling algorithms. Although there are other applicable works in the literature, these two results are particularly interesting for the purposes of this paper since both have been adapted to industrial wireless networks.

2.3.2. Demand-bound function analysis

Baruah, Rosier, and Howell (1990) proposed a different approach to analyze the schedulability under the EDF scheduler by assuming the uniprocessor demand criterion. Here, the processor demand of a task in a given interval is defined by the amount of processing time requested by the jobs during the same given interval (Buttazzo 2011). The formal definition also known as the demand bound function (DBF) is presented below in a time interval $[0, \ell[$:

$$\mathrm{DBF}(\tau_i, \ell) \stackrel{\text{def}}{=} \sum_{i=1}^{n} \max\left(0, \left\lfloor \frac{\ell - D_i}{T_i} \right\rfloor + 1\right) \cdot C_i \tag{5}$$

By considering a synchronous set of sporadic tasks with relative deadlines less than or equal to the periods, the associated schedulability test for EDF is as follows:

$$\mathrm{DBF}(\tau_i, \ell) \leq \ell, \qquad \forall \ell > 0 \tag{6}$$

This result was extended to the multiprocessor scheduling of sporadic task systems by Baruah and Fisher (2005). The main result is summarized in Equation 7 which provides a simple necessary condition for the feasibility of a task set upon m processors (Davis and Burns 2011):

$$load(\tau) \leq m \tag{7}$$

Where:

$$load(\tau) = max_{\forall \ell}\left(\frac{\mathrm{DBF}(\ell)}{\ell}\right) \tag{8}$$

Note that the processor load is defined as the maximum value of the demand-bound divided by the length of the time interval (Davis and Burns 2011). An adaptation of these concepts combined with other analytical techniques from the multiprocessor scheduling theory was introduced into the industrial wireless domain by Xia, Jin, and Zeng (2016) and extended into *mixed-criticality* domain by Xia et al. (2017a). Although not the focus of this review, it is worth noting that mixed-criticality started capturing more and more attention only recently in the real-time scheduling sphere. It was firstly introduced by Vestal (2007) and was analyzed from the DBF perspective by Ekberg and Yi (2012). For a comprehensive review on this area, we refer the interested reader to Burns and Davis (2018).

2.3.3. Forced-Forward demand-bound function analysis

A refined version of the DBF-based analysis, referred to as forced-forward demand-bound function (FF-DBF) based analysis, was presented in the context of multiprocessor scheduling by Baruah et al. (2010). The FF-DBF is deemed as a more accurate version of DBF since it considers in the computation of the cumulative demand, potential workload contributions left aside by the DBF. The equation formally describing FF-DBF for a task τ_i in an interval of length ℓ is presented as follows:

$$\mathrm{FF-DBF}(\tau_i, \ell) \stackrel{\text{def}}{=} q_i \cdot C_i + \begin{cases} C_i, & \text{if } \gamma_i \geq C_i \\ C_i - (D_i - \gamma_i)\sigma, & \text{if } D_i \geq \gamma_i \geq D_i - \dfrac{C_i}{\sigma} \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where $q_i \stackrel{\text{def}}{=} \left\lfloor \frac{\ell}{T_i} \right\rfloor$ and $\gamma_i \stackrel{\text{def}}{=} \ell \bmod T_i$.

In this equation, σ represents the speeding factor of the processor, i.e., a resource augmentation factor used for feasibility purposes. Figure 3 clarifies the essential difference between DBF and FF-DBF for a task τ_i assuming a speed factor equal to 1 in a time interval of length ℓ.

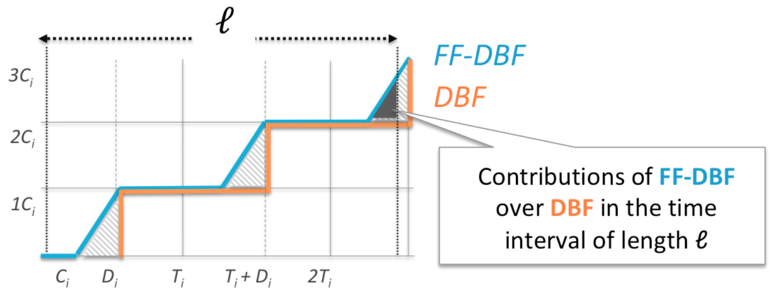

Figure 3: DBF vs FF-DBF

By observing this accuracy of FF-DBF over DBF, Gutiérrez-Gaitán and Yomsi (2018) introduced the FF-DBF concept in the industrial wireless context by proposing a supply/demand analysis based on the work of Xia, Jin, and Zeng (2016).

2.3.4. Utilization bound analysis

A different approach based on the system utilization as presented in Section 2.1 has also been extended to multiprocessors. Here, the intuitive idea is to derive a worst-case utilization bound (U_A) and used it as a performance metric to test the schedulability (Davis and Burns 2011). Basically, assuming an implicit-deadline task set and a given scheduling algorithm, U_A provides the maximum utilization that would guarantee the feasibility of any system with utilization U_{sum} below that value. For task sets with a total utilization (U_{sum}) greater than U_A, two sub-cases are considered: (1) if U_A is less than or equal to m (where m is the number of cores), then a schedulability decision by using this approach cannot be taken, i.e., the system may or may not be schedulable; and (2) if $U_{sum} > m$ then the task set is definitely deemed unschedulable. This simple sufficient but not necessary test is applied in terms of schedulability test as follows:

$$u_{sum} \leq \mathrm{U}_A \qquad \textbf{(10)}$$

Assuming a platform with m cores and a set of n sporadic tasks scheduled on this platform by following a fully preemptive DM scheduler (Bertogna, Cirinei, and Lipari 2006), derived the following utilization-based schedulability condition:

$$\sum_{i=1}^{n} \frac{C_i}{D_i} \leq \frac{m}{2}\left(1 - max\left\{\frac{C_i}{D_i} \middle| 1 \leq i \leq n\right\}\right) + max\left\{\frac{C_i}{D_i} \middle| 1 \leq i \leq n\right\} \qquad \textbf{(11)}$$

Comparably, Baruah (2007) provided a complete version of this schedulability test for n real-time sporadic tasks and m processors when using the preemptive EDF scheduling:

$$\sum_{i=1}^{n} \frac{C_i}{D_i} \leq m - (m-1)\left(max\left\{\frac{C_i}{D_i} \middle| 1 \leq i \leq n\right\}\right) \qquad \textbf{(12)}$$

Both of these results have been adapted recently to the industrial wireless domain in Modekurthy et al. (2018) by assuming both DM and EDF schedulers.

These last two approaches complete the UBA-based schedulability analysis category which together with RTA-based and DBA-based represent the three main lines covered in this paper. In the following subsection, a brief overview of the wireless networks for the industrial automation domain is presented.

2.4. An overview of Wireless Industrial Networks

Typically, the WSANs involve several sensors and actuators nodes connected in a wireless manner with or without infrastructure. Due to their advantages associated to wireless over wired, such as flexibility, easy deployment, and low-cost devices, they have been incorporated into a wide variety of applications (e.g., environmental monitoring, agriculture, industrial automation, etc.) (Wang and Jiang 2016). However, the design considerations may change significantly. For example, in the industrial automation sector, WSANs have widely been adopted for monitoring and process-control operations. Such kind of applications poses stringent reliability and timing requirements due to both the inherent noisy property of the wireless medium and the criticality of their industrial labors. Although there are several protocols dealing with this challenge, this paper focuses on the two major standards being adopted by the process-automation industry, WirelessHART and ISA100.11a. Since these two standards share most of the characteristics that make them suitable for the industry (e.g. system architecture, physical-layer, the handle of interference, etc.), in this paper the term WirelessHART-like networks refers to any of both.

2.4.1. WirelessHART-like features

Saifullah et al. (2010), were the first to identify the general features below for WirelessHART-like networks, relevant for their schedulability analysis.

System architecture. WirelessHART-like networks involve three main architectural elements: field devices (usually 80 to 100 sensors and actuators), a gateway, and a network manager. Here, the network topology is implemented in a mesh fashion, where the transmissions are forwarded based on slot-frames and supported by frequency hopping and time-division multiple access (TDMA) techniques. The routes and schedules of all the transmissions are configurated in a centralized manner by the network manager, although no specific scheduling or routing algorithm is proposed in the standards. Figure 4 depicts a basic representation of the system architecture described here.

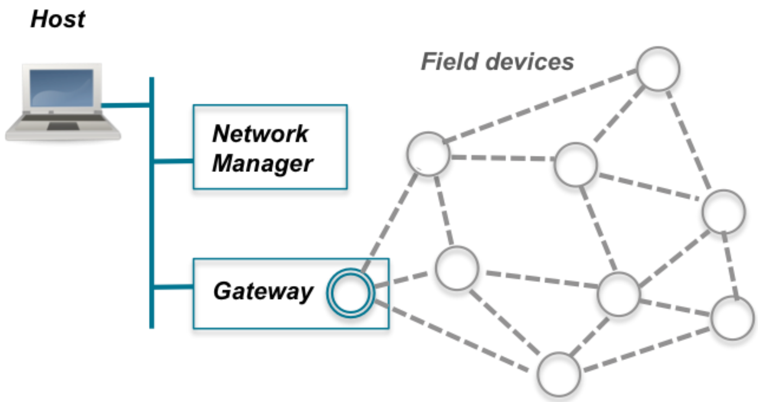

Figure 4: A representation of the basic system architecture for WirelessHART-like networks

Multi-channel TDMA. WirelessHART-like networks are based on the IEEE 802.15.4 physical layer. They use radio interfaces which operate up to 16 channels and 2.4GHz band, which is unlicensed worldwide (Chen, Nixon, and Mok 2010). Here, the TDMA implies a time synchronization mechanism used to synchronize all the devices in the network. The time is slotted in intervals of 10 ms and the device transmissions use one of these slots for their whole transmission process i.e., to transmit and to receive an acknowledgment. Multiple accesses in this context means that multiple transmissions may occur on the same channel.

Spectrum and route diversity. WirelessHART-like networks adopt channel hopping in every time slot in order to provide frequency diversity. This helps in mitigating the interference and to reduce multipath fading (Chen, Nixon, and Mok 2010). Similarly, WirelessHART-like networks enable two different routing approaches: source routing and graph routing. The first provides a single path for routing between two field devices, whereas the second provides a list of different paths for the same purpose. Additionally, in this latter, the end-to-end communications occur in two phases: the sensing phase and the control phase, each of them with different graphs: uplink and downlink, respectively.

Handling of internal interference. WirelessHART-like networks avoid the reuse of channels, i.e., the interference due to concurrent transmissions is avoided by scheduling each of the per-slot transmissions in different channels. As a result, the number of concurrent transmissions in the entire network is never greater than the number of available channels. Notice that in WirelessHART-like networks some channels may be blacklisted (or not used) due for example to the excessive noise in the channel (Chen, Nixon, and Mok 2010).

2.4.2. Network modeling

According to the previous characteristics, the literature studying the schedulability problem of WirelessHART-like networks adopted the network as a graph $\mathrm{G} = (V, E)$, where V represents the set of field devices (a.k.a. nodes) and E the edges between those nodes. The number of channels is denoted as m and sometimes can be specified as an input (Saifullah et al. 2010). Given this setting, a set of n network flows $F \stackrel{\text{def}}{=} \{F_1, F_2, \ldots, F_n\}$ to represent the end-to-end communications between nodes is defined. Each flow F_i traveling from its source to its destination is scheduled under a given policy and typically modeled as a 4-tuple $(C_i, D_i, T_i, \emptyset_i)$. Here, C_i characterizes the time required by each transmission (instance) of the flow when it does not suffer any external interference whatsoever from the other flows, D_i the deadline of each instance, and T_i the period or minimum interarrival time between two consecutive instances. The last parameter $\emptyset_i$ (when it is considered) is used for routing decisions. All parameters are given with the interpretation that each flow F_i release a potentially infinite number of transmissions in a constrained-deadline fashion. Given such a model, a straightforward one-to-one mapping between industrial wireless modeling nomenclature and multiprocessor scheduling theory terminology is to consider the number of channels m as the number of m identical processors upon a multicore platform, the network flow tuple and its parameters as same than the sporadic task workload model, and finally the existing multiprocessor scheduling techniques as valid for such a setting.

Now, since the wireless networks have distinctive characteristics compared to the multiprocessors, they involve both *channel contention* and *transmission conflicts* in the analysis (Saifullah et al. 2011a). The channel contention refers to the delay occurred when a high priority transmission occupies all the channels in a time instant, whereas the transmission conflict refers to a transmission instance delayed by the transmission of a higher priority. Thus, the channel contention derivation problem can be matched with the multiprocessors interference derivation problem, whereas the transmission conflict problem, can be considered as property specific to the wireless schedulability analysis. Given this setting, the overall problem of the schedulability of wireless industrial networks is analyzed from the perspective of multicore scheduling, i.e., by studying the ability of each flow to satisfy its timing requirements.

Since channel contention and transmission conflicts are two components relevant in the schedulability analysis of network flows, Figure 5 depicts both contributions for an arbitrary section of a graph network. Here, the channel contention is represented as a single high-priority flow occupying all the channels at a given time slot, i.e., flows with a lower priority will be delayed until a channel becomes available. Subsequently, transmission conflicts are represented by two flows transmissions (one with higher priority than the other) at a common intermediate node. In this case, the transmission of the low priority flow will be delayed until the transmission of all the flows with a higher priority is completed.

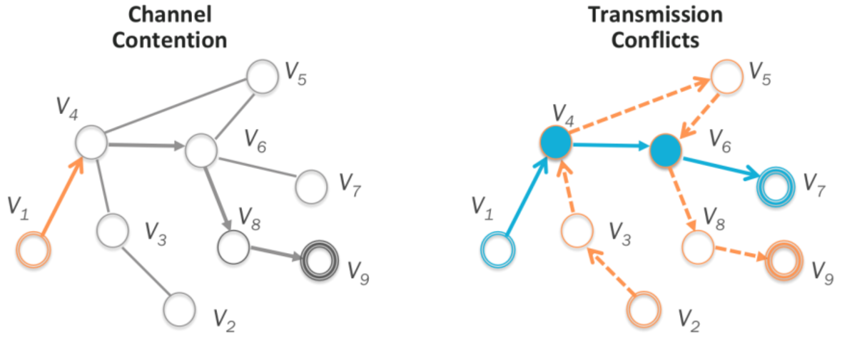

Figure 5: A representation of channel contention and transmission conflicts

Both of these sources of delays have been analyzed in the literature when using different scheduling algorithms and/or routing mechanisms. To name a few, Saifullah et al. (2015a) analyzed both components under FTP algorithms and graph routing, while Wu et al. (2014) did it assuming an EDF scheduler and source routing. In the following section, a literature review of the schedulability analysis techniques used in WirelessHART-like networks is presented.

3. Literature Review on WirelessHART-like Networks

This section discusses the schedulability analysis techniques based on the multiprocessor scheduling theory applied in the context of WirelessHART-like networks. It also provides a taxonomy of the works based on multiprocessor scheduling theory, basic principles, and evaluation methods that have been used to demonstrate their efficiency.

3.1. Schedulability analyses for WirelessHART-like networks

Schedulability analysis techniques of WirelessHART-like networks leveraging on the multiprocessor scheduling theory have been applied in recent years. Saifullah et al. (2010), started formulating the end-to-end real-time transmission scheduling problem based on the characteristics of WirelessHART and proved it is NP-hard. That is, the decision of whether the end-to-end transmissions are schedulable or not is solved in non-deterministic polynomial time (Saifullah et al. 2010). Here, the authors assume a set of flows to be transmitted in a WirelessHART-like network and focused on the proposal of a scheduling algorithm based on a branch-and-bound technique and heuristics. They derived the necessary condition for the schedulability of flows and used this understanding to analyze end-to-end transmission delay of each flow. This approach resulted to be suitable for any fixed priority scheduling policy as the proposed approach was proved to be optimal (Saifullah et al. 2011a). Here the optimality is given with the following interpretation: If any other scheduling algorithm is capable to guarantee that all flows meet their timing requirements, then the proposed scheduling algorithm will also get us to reach the same conclusion. Conversely, if the proposed scheduling algorithm is not successful, then we can guarantee that no other algorithm would be. The key insight of this work was the mapping of real-time data flows between sensors and actuators to the real-time multiprocessor scheduling. This contribution marked a turning point in the way multi-hop and multi-channel transmissions are formulated and analyzed. The same authors extended the work by proposing an optimal priority assignment algorithm (Saifullah et al. 2011b), and claimed that the approach is suitable for online admission control and adaptation, which is relevant to handle dynamic workloads and topology changes in wireless networks. In Saifullah et al. (2012), the authors extended the work proposed in Saifullah et al. (2011a) in order to take into account transmission failures. Wu et al. (2014) presented a delay analysis for periodic real-time flows in WSANs in which transmissions are scheduled based on the EDF policy. We recall that EDF is an FJP scheduler, i.e., here two jobs belonging to the same task may be assigned with different priorities. The authors bound the communication delays in WSANs by analyzing channel contention and transmission conflicts separately. This is yet another key insight along this research direction. Later on, Saifullah et al. (2015a) presented a refined version of their previous contributions assuming fixed priority scheduling and derived a tighter bound on the conflict delay. Along the same line, Saifullah et al. (2015b) presented a worst-case end-to-end delay analysis of flows under graph routing. The authors claimed this was the first analysis of the kind. All of these attempts present similar assumptions and techniques to deal with the schedulability on industrial WSANs, thus delineating a kind of research around the subject. Lu et al. (2016) acknowledged these efforts in a broader review concerning real-time scheduling algorithms, schedulability analysis techniques and wireless-CPS co-design efforts in the industry. However, a few recent and significant advances following the idea of mapping multiprocessor scheduling and multi-channel transmission scheduling were not covered.

Other works followed the same line of research. Jin, Wang, and Zeng (2015) introduced the concept of mixed-criticality into the industrial WSANs and proposed and end-to-end delay analysis based on the work done by Saifullah et al. (2011a). Here, the authors claimed the work is the first assuming mixed criticality WirelessHART network flows, which can be used for the transmission of network flows with two criticality levels. Jin et al. (2016) extended the previous work by proposing a scheduling algorithm and a schedulability analysis. The novelty of the latter contribution is the ability of the scheduling algorithm to deal with both centralized optimizations and adaptive adjustment based on criticality requirements of the network flows. Xia, Jin, and Zeng (2016) paved the same path for the analysis of mixed-criticality industrial WSANs by promoting an alternative approach to determine the schedulability of network flows. Specifically, the authors proposed a supply/demand bound function based analysis assuming an EDF scheduling policy. A similar approach for single-criticality wireless industrial networks was presented by Xia et al. (2017a), still assuming an EDF scheduler. Here, the authors based their analysis on the Demand-Bound Function (DBF) to estimate the demand of the network flows. Although DBF is a widely adopted method in the multiprocessor scheduling sphere, it does not consider all potential contributions to the workload estimation in a given time window (see Figure 3). By, leveraging on this observation, Gutiérrez-Gaitán and Yomsi (2018) introduced a Forced-Forward Demand-Bound Function (FF-DBF) based analysis to the industrial WSANs domain, thus offering a more accurate alternative than DBF for the network workload estimation. This work represented the first analysis of the kind for the Industrial Wireless. In a similar fashion, Ismail et al. (2017) introduced the first utilization-bound based analysis for studying the schedulability of network flows in industrial WSANs when assuming EDF and DM scheduling policies. Modekurthy et al. (2018) completed the work by considering both graph routing and hierarchical networking, and evaluated the performance of the approach through simulations. Both the FF-DBF-based and the utilization-bound based approaches confirm the intuition that recognizes these contributions as a new line of research in terms of applicability of the multiprocessor scheduling theory in the industrial wireless domain. Indeed, the fact that RTA, DBA, and UBA-based approaches, have all been recently applied in the context of WirelessHART-like networks, promises that this kind of analyses can be extended to other related industrial wireless applications.

The following subsection will organize the literature review discussed here according to the basic principles borrowed from the multiprocessors scheduling theory. It will also report on the scheduling algorithms and the methods used to evaluate each work.

3.2. RTA, DBA and UBA in WirelessHART-like networks

From the multiprocessor real-time scheduling theory perspective, most of the previous analyses have exploited the RTA techniques to deal with the timing guarantees needed in the transmission of network flows. Particularly, assuming a fixed-priority scheduling approach, Saifullah et al. (2011a), Saifullah et al. (2011b), Saifullah et al. (2012), Saifullah et al. (2015a), and Saifullah et al. (2015b), proposed a RTA-based technique based on the results provided by Guan et al. (2009) and Bertogna, Cirinei, and Lipari (2009). Similarly, since Jin, Wang, and Zeng (2015) and Jin et al. (2016) built their contributions on top of the results obtained by Saifullah et al. (2011a) for their single-criticality analysis, these works also adopted the same RTA fundamentals. Their analyses are also based (although not directly), on the classical Vestal model (Vestal 2007), and thus, leveraged on the existence of a fruitful branch of research in the field of mixed-criticality on multiprocessors (see Burns and Davis (2018) for an updated and comprehensive review). Assuming an EDF scheduler, Wu et al. (2014) also used an RTA-based approach by using an iterative technique as presented in Bertogna, Cirinei, and Lipari (2009). Later, Xia, Jin, and Zeng (2016), Xia et al. (2017a), and Gutiérrez-Gaitán and Yomsi (2018) introduced the supply/demand-bound analysis into the discussion. Xia, Jin, and Zeng (2016) proposed the use of the DBF concept (Baruah, Rosier, and Howell 1990) to determine the schedulability of network flows by means of a resource-based approach, borrowing the ideas from the compositional performance analysis of Rox and Ernst (2013), the resource-aware task approach for multiprocessor scheduling from Tillenius et al. (2015), and the derivation of the demand-bound functions for mixed-criticality sporadic tasks (Ekberg and Yi 2012). This last work is used by Xia et al. (2017a) when exploring the resource-based analysis into the mixed-criticality domain. It is worth noticing that both Xia, Jin, and Zeng (2016) and Xia et al. (2017a) are also based on the supply models introduced by Mok, Feng, and Chen (2001) and Shin and Lee (2003). Gutiérrez-Gaitán and Yomsi (2018) enriched the discussion around supply/demand-based schedulability analysis in WirelessHART-like networks by introducing the FF-DBF concept from Baruah et al. (2010). The authors proposed to extend the work by Xia, Jin, and Zeng (2016), by using FF-DBF instead of DBF. In the same manner, Ismail et al. (2017) and Modekurthty et al. (2018) proposed to use a UBA-based analysis for studying the schedulability of network flows in industrial WSANs. Ismail et al. (2017) introduced the idea and (Modekurthty et al. 2018) materialized it by extending the analysis when using graph routing and hierarchical networking. In terms of the techniques borrowed from the multiprocessor scheduling theory, the authors based their UBA based approach on the results obtained by Baruah (2007) and Bertogna, Cirinei, and Lipari (2006).

In summary, all the attempts represent the main line of work supported by the multiprocessor scheduling theory to fill the gap between both the wireless transmission scheduling and the real-time multiprocessor scheduling. A taxonomy organizing these works is presented in Table 1.

Main approach for schedulability analysis	Scheduling algorithm	Basic principles	Evaluation
End-to-end delay analysis (Saifullah et al. 2011a)	FTP	RTA (Guan et al. 2009)	Simulations. DM and proportional deadline-monotonic (PDM) schedulers.
End-to-end delay analysis accounting for failure (Saifullah et al. 2012)	FTP	RTA (Guan et al. 2009), (Bertogna, Cirinei, and Lipari 2009)	Simulations. DM and delay based (DB) schedulers.
End-to-end delay analysis (Wu et al. 2014)	EDF	RTA (Bertogna, Cirinei, and Lipari 2009)	Testbed, Simulation.
End-to-end delay analysis under graph routing (Saifullah et al. 2015a)	FTP	RTA (Saifullah et al. 2011a)	Testbed, Simulations. DM scheduler.
End-to-end delay analysis (Saifullah et al. 2015b)	FTP	RTA (Guan et al. 2009), (Bertogna, Cirinei, and Lipari 2009)	Testbed, Simulations. DM scheduler.
End-to-end delay analysis under mixed-criticality (Jin, Wang, and Zeng 2015)	FTP	RTA (Saifullah et al. 2011a), (Ekberg and Yi 2012), (Vestal 2007)	Testbed, Simulations. DM and proportional deadline-monotonic (PDM) schedulers.
End-to-end delay analysis under mixed-criticality (Jin et al. 2016)	FTP	RTA (Saifullah et al. 2011a), (Ekberg and Yi 2012), (Vestal 2007)	Simulations. RM-based and criticality-based schedulers.
Supply/demand bound analysis (Xia, Jin, and Zeng 2016)	EDF	DBF (Baruah, Rosier, and Howell 1990), (Rox and Ernst 2013), (Tillenius et al. 2015), (Ekberg and Yi 2012), (Mok, Feng, and Chen 2001), (Shin and Lee 2003).	Simulations.
Supply/demand bound analysis under mixed-criticality (Xia et al. 2017a)	EDF	DBF (Baruah, Rosier, and Howell 1990), (Rox and Ernst 2013), (Tillenius et al. 2015), (Ekberg and Yi 2012), (Mok, Feng, and Chen 2001), (Shin and Lee 2003).	Simulations.
Supply/demand bound analysis (Gutiérrez-Gaitán and Yomsi 2018)	EDF	FF-DBF (Baruah et al. 2010), (Xia, Jin, and Zeng 2016)	---
Utilization-bound analysis (Ismail et al. 2017)	EDF, DM	Utilization-Bound (Baruah 2007), (Bertogna, Cirinei, and Lipari 2006)	---
Utilization-bound analysis (Modekurthty et al. 2018)	EDF, DM	Utilization-Bound (Baruah 2007), (Bertogna, Cirinei, and Lipari 2006)	Simulations.

Table 1: Taxonomy of the schedulability analysis techniques for WirelessHART-like networks based on the multiprocessor scheduling theory

The auspicious results in the branch of research considered in this paper have led to apply and/or extend some of the most relevant results from the multiprocessor scheduling theory to other veins of the industrial wireless domain. In the WirelessHART-like networks, besides the results already discussed, other works have been presented in Saifullah et al. (2011b), Wu et al. (2016) and Modekurthy, Saifullah, and Madria (2018). In other domains, the results presented here were applied to other wireless contexts such as heterogeneous industrial networks (Xia et al. 2017b), multi-use multiple-input multiple-output industrial network (Xia et al. 2017c), scheduling of emergency tasks in industrial networks (Xia et al. 2017d) and hierarchical data transmission in industrial WSANs (Jin et al. 2017). Indeed, in its broadest sense, all of the articles covered in this review may have interesting implications in wireless networked control systems (WNCS) and wireless cyber-physical systems (WCPS), where there are other relevant applications such as intra-vehicle wireless networks, wireless avionics intra-communications, and building automation. A comprehensive review of this class of distributed systems was recently presented by Park et al. (2018), and can be used as a reference for the target domains where the schedulability analyses remains a cornerstone.

4. Conclusion

This paper contributes to recognize the research branch aiming to bridge the gap between the multiprocessor scheduling theory and transmission of data flows in the wireless industrial domain. The background and discussion on the evolutions in both research domains have been discussed and used to understand the basics, the current state and the future directions of the research that is being done around this subject. The taxonomy provided summarizes the primary results on schedulability analysis techniques based on three main techniques borrowed from the multiprocessor scheduling theory, namely RTA, UBA, and supply/demand based. The first is mostly based on evaluating the maximum timespan between the completion time and release of a job for a given task. The second focused on providing an upper bound on the system utilization that would guarantee that all timing requirements are meets. Finally, the last approach evaluates the workload of the entire system and compares it to the supply provided by the underlying computing platform. Although all these techniques are now relatively mature and well-understood, further simulations and testbed experiments are still needed to understand their potentials and particular benefits. Last but not least, since this work focused on WirelessHART-like networks, we conjecture that future work will highlight other relevant intersections between the multiprocessor scheduling theory and the broad wireless industrial domain while considering alternative network topologies. Specifically, the idea is to take a stand towards end-to-end guarantees in the domains of the WCPS and the IIoT.

References

Baruah, Sanjoy K., Louis E. Rosier, and Rodney R. Howell. 1990. "Algorithms and complexity concerning the preemptive scheduling of periodic, real-time tasks on one processor". *Real-Time Systems* 2, no. 4 (november): 301-24. https://doi.org/10.1007/BF01995675.

Baruah, Sanjoy, and Nathan Fisher. 2005. "The partitioned multiprocessor scheduling of sporadic task systems". In *Proceedings of the 26th IEEE International Real-Time Systems Symposium (RTSS'05)*, 329. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2005.40.

Baruah, Sanjoy. 2007. "Techniques for multiprocessor global schedulability analysis". In *Proceedings - RTSS 2007 28th IEEE International Real-Time Systems Symposium*, 119-28. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2007.35.

Baruah, Sanjoy, Vincenzo Bonifaci, Alberto Marchetti-Spaccamela, and Sebastian Stiller. 2010. "Improved multiprocessor global schedulability analysis". *Real-Time Systems* 46, no. 1 (september): 3-24. https://doi.org/10.1007/s11241-010-9096-3.

Baruah, Sanjoy, Marko Bertogna, and Giorgio Buttazzo. 2015. *Multiprocessor scheduling for real-time systems*. Cham: Springer. https://doi.org/10.1007/978-3-319-08696-5.

Bertogna, Marko, Michele Cirinei, and Giuseppe Lipari. 2006. "New schedulability tests for real-time task sets scheduled by deadline monotonic on multiprocessors". In *OPODIS: International Conference on Principles of Distributed Systems*, 306-21. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer. https://doi.org/10.1007/11795490_24.

Bertogna, Marko, Michele Cirinei, and Giuseppe Lipari. 2009. "Schedulability analysis of global scheduling algorithms on multiprocessor platforms". *IEEE Transactions on Parallel and Distributed Systems* 20, no. 4 (april): 553-66. https://doi.org/10.1109/TPDS.2008.129.

Burns, Alan, and Robert Davis. 2018. "Mixed criticality systems - A review". Paper produced as part of the EPSRC funded projects MCC and MCCps. https://www-users.cs.york.ac.uk/burns/review.pdf.

Buttazzo, Giorgio. 2011. *Hard real-time computing systems: predictable scheduling algorithms and applications*. Real-Time Systems Series, vol. 24. Boston, MA: Springer. https://doi.org/10.1007/978-1-4614-0676-1.

Chen, Deji, Mark Nixon, and Aloysius Mok. 2010. "Why WirelessHART". *In WirelessHART™: Real-Time Mesh Network for Industrial Automation*, 195-99. Boston, MA: Springer. https://doi.org/10.1007/978-1-4419-6047-4_15.

Davis, Robert I., and Alan Burns. 2011. "A survey of hard real-time scheduling for multiprocessor systems". *ACM Computing Surveys (CSUR)* 43, no. 4 (october): 1-44. https://doi.org/10.1145/1978802.1978814.

Ekberg, Pontus, and Wang Yi. 2012. "Bounding and shaping the demand of mixed-criticality sporadic tasks". In *Proceedings of the 24th Euromicro Conference on Real-Time Systems*, 135-44. Los Alamitos, CA: IEEE. https://doi.org/10.1109/ECRTS.2012.24.

Guan, Nan, Martin Stigge, Wang Yi, and Ge Yu. 2009. "New response time bounds for fixed priority multiprocessor scheduling". In *Proceedings 2009 30th IEEE Real-Time Systems Symposium*, 387-97. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2009.11.

Guan, Nan. 2016. *Techniques for building timing-predictable embedded systems*. Cham: Springer. https://doi.org/10.1007/978-3-319-27198-9.

Gutiérrez-Gaitán, Miguel, and Patrick Meumeu Yomsi. 2018. "FF-DBF-WIN: On the forced-forward demand-bound function analysis for wireless industrial networks". In *Proceedings of the Work-in-Progress Session (ECRTS 2018)*: 13-15. https://doi.org/10400.22/12321.

Jin, Xi, Jintao Wang, and Peng Zeng. 2015. "End-to-end delay analysis for mixed-criticality WirelessHART networks". *IEEE/CAA Journal of Automatica Sinica* 2, no. 3: 282-89. https://doi.org/10.1109/JAS.2015.7152662.

Jin, Xi, Changqing Xia, Huiting Xu, Jintao Wang and Peng Zeng. 2016. "Mixed criticality scheduling for industrial wireless sensor networks". *Sensors* 16, no. 9: 1376. https://doi.org/10.3390/s16091376.

Jin, Xi, Fanxin Kong, Linghe Kong, Huihui Wang, Changqing Xia, Peng Zeng, and Qingxu Deng. 2017. "A hierarchical data transmission framework for industrial wireless sensor and actuator networks". *IEEE Transactions on Industrial Informatics* 13, no. 4 (august): 2019-29. https://doi.org/10.1109/TII.2017.2685689.

Joseph, Mathai, and Paritosh Pandya. 1986. "Finding response times in a real-time system". *The Computer Journal* 29, no. 5 (october): 390-95. https://doi.org/10.1093/comjnl/29.5.390.

Ismail, Dali, Mahbubur Rahman, Venkata P. Modekurthy, and Abusayeed Saifullah. 2017. "Work-in-progress: Utilization based schedulability analysis for wireless sensor-actuator networks". In *Proceedings of the 23rd IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, 137-40. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTAS.2017.27.

Lu, Chenyang, Abusayeed Saifullah, Bo Li, Mo Sha, Humberto Gonzalez, Dolvara Gunatilaka, Chengjie Wu, Lanshun Nie, and Yixin Chen. 2016. "Real-Time wireless sensor-actuator networks for industrial cyber-physical systems". *Proceedings of the IEEE* 104, no. 5 (may): 1013-24. https://doi.org/10.1109/JPROC.2015.2497161.

Modekurthy, Venkata Prashant, Dali Ismail, Mahbubur Rahman, and Abusayeed Saifullah. 2018. "A utilization-based approach for schedulability analysis in wireless control systems". In *Proceedings - 2018 IEEE International Conference on Industrial Internet*, 49-58. Los Alamitos, CA: IEEE. https://doi.org/10.1109/ICII.2018.00014.

Modekurthy, Venkata P., Abusayeed Saifullah, and Sanjay Madria. 2018. "Distributed graph routing for wirelessHART networks". In *Proceeding - ICDCN '18 Proceedings of the 19th International Conference on Distributed Computing and Networking*, article no. 24. New York, USA: ACM. https://doi.org/10.1145/3154273.3154335.

Mok, Aloysius K., Xiang Feng, and Deji Chen. 2001. "Resource partition for real-time systems". In *Proceedings - Seventh IEEE Real-Time Technology and Applications Symposium*, 75-84. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTTAS.2001.929867.

Park, Pangun, Sinem Coleri Ergen, Carlo Fischione, Chenyang Lu, and Karl Henrik Johansson. 2018. "Wireless network design for control systems: A survey". *IEEE Communications Surveys & Tutorials* 20, no. 2 (second quarter): 978-1013. https://doi.org/10.1109/COMST.2017.2780114.

Rox, Jonas, and Rolf Ernst. 2013. "Compositional performance analysis with improved analysis techniques for obtaining viable end-to-end latencies in distributed embedded systems". *International Journal on Software Tools for Technology Transfer* 15, no. 3 (june): 171-87. https://doi.org/10.1007/s10009-012-0260-z.

Saifullah, Abusayeed, You Xu, Chenyang Lu, and Yixin Chen. 2010. "Real-time scheduling for WirelessHART networks". In *Proceedings IEEE Real-Time Systems Symposium RTSS 2010*, 150-59. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2010.41.

Saifullah, Abusayeed, You Xu, Chenyang Lu, and Yixin Chen. 2011a. "End-to-end delay analysis for fixed priority scheduling in WirelessHART networks". In *Proceedings of the Seventeenth IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS) 2011*, 13-22. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTAS.2011.10.

Saifullah, Abusayeed, You Xu, Chenyang Lu, and Yixin Chen. 2011b. "Priority assignment for real-time flows in WirelessHART networks". In *Proceedings of the 23rd Euromicro Conference on Real-Time Systems,* 35-44. Los Alamitos, CA: IEEE. https://doi.org/10.1109/ECRTS.2011.12.

Saifullah, Abusayeed, Paras Babu Tiwari, Bo Li, and Chenyang Lu. 2012. *Accounting for failures in delay analysis for WirelessHART networks*. Report Number WUCSE-2012-16. https://doi.org/10.7936/K7X0658J.

Saifullah, Abusayeed, Dolvara Gunatilaka, Paras Tiwari, Mo Sha, Chenyang Lu, Bo Li, Chengjie Wu, and Yixin Chen. 2015a. "Schedulability analysis under graph routing in WirelessHART networks". In *Proceedings - IEEE 36th Real-Time Systems Symposium RTSS 2015*, 165-74. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2015.23.

Saifullah, Abusayeed, You Xu, Chenyang Lu, and Yixin Chen. 2015b. "End-to-end communication delay analysis in industrial wireless networks". *IEEE Transactions on Computers* 64, no. 5 (may): 1361-74. https://doi.org/10.1109/TC.2014.2322609.

Shin, Insik, and Insup Lee. 2003. "Periodic resource model for compositional real-time guarantees". In *Proceedings. 24th IEEE International Real-Time Systems Symposium RTSS 2003*, 2-13. Los Alamitos, CA: IEEE. https:// doi.org/10.1109/REAL.2003.1253249.

Sisinni, Emiliano, Abusayeed Saifullah, Song Han, Ulf Jennehag, and Mikael Gidlund. 2018. "Industrial Internet of Things: Challenges, opportunities, and directions". *IEEE Transactions on Industrial Informatics* 14, no. 11 (november): 4724-34. https://doi.org/10.1109/TII.2018.2852491.

Tillenius, Martin, Elisabeth Larsson, Rosa M. Badia, and Xavier Martorell. 2015. "Resource-aware task scheduling". *ACM Transactions on Embedded Computing Systems (TECS)* 14, no. 1 (january): article no. 5. https://doi.org/10.1145/2638554.

Vestal, Steve. 2007. "Preemptive scheduling of multi-criticality systems with varying degrees of execution time assurance". In *Proceedings - RTSS 2007 28th IEEE International Real-Time Systems Symposium*, 239-43. Los Alamitos, CA: IEEE. https://doi.org/10.1109/RTSS.2007.47.

Wang, Quan, and Jin Jiang. 2016. "Comparative examination on architecture and protocol of industrial wireless sensor network standards". *IEEE Communications Surveys & Tutorials* 18, no. 3 (third quarter): 2197-219. https://doi.org/10.1109/COMST.2016.2548360.

Wu, Chengjie, Mo Sha, Dolvara Gunatilaka, Abusayeed Saifullah, Chenyang Lu, and Yixin Chen. 2014. "Analysis of EDF scheduling for wireless sensor-actuator networks". In *2014 IEEE 22nd International Symposium of Quality of Service (IWQoS)*, 31-40. IEEE. https://doi.org/10.1109/IWQoS.2014.6914298.

Wu, Chengjie, Dolvara Gunatilaka, Abusayeed Saifullah, Mo Sha, Paras Babu Tiwari, Chenyang Lu, and Yixin Chen. 2016. "Maximizing network lifetime of WirelessHART networks under graph routing". In *Proceedings. 2016 IEEE First International Conference on Internet-of-Things Design and Implementation - IoTDI 2016*, 176-86. Los Alamitos, CA: IEEE. https://doi.org/10.1109/IoTDI.2015.43.

Xia, Changqing, Xi Jin, and Peng Zeng. 2016. "Resource analysis for wireless industrial networks". In *Proceedings. 12th International Conference on Mobile Ad-Hoc and Sensor Networks - MSN 2016*, 424-28. Los Alamitos, CA: IEEE. https://doi.org/10.1109/MSN.2016.078.

Xia, Changqin, Xi Jin, Linghe Kong, and Peng Zeng. 2017a. "Bounding the demand of mixed-criticality industrial wireless sensor networks". *IEEE Access* 5: 7505-16. https://doi.org/10.1109/ACCESS.2017.2654483.

Xia, Changqing, Xi Jin, Linghe Kong, Peng Zeng, and Di Guan. 2017b. "Scheduling for heterogeneous industrial networks based on NB-IoT technology". In *Proceedings. IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 3518-23. IEEE. https://doi.org/10.1109/IECON.2017.8216595.

Xia, Changqing, Xi Jin, Linghe Kong, Jintao Wang, and Peng Zeng. 2017c. "Transmission scheduling for mixed-critical multi-user multiple-input and multiple-output industrial cyber-physical systems". *International Journal of Distributed Sensor Networks* 13, no. 12 (december). https://doi.org/10.1177/1550147717748910.

Xia, Changqing, Xi Jin, Linghe Kong, and Peng Zeng. 2017d. "Scheduling for emergency tasks in industrial wireless sensor networks". *Sensors* 17, no. 7 (july): article no. 1674. https://doi.org/10.3390/s17071670.

Acknowledgments

This work was partially supported by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (UID/CEC/04234).