Work-in-Progress: Assessing supply/demand-bound based schedulability tests for wireless sensor-actuator networks

Miguel Gutiérrez Gaitán *†, Patrick M. Yomsi‡, Pedro M. Santos‡, and Luis Almeida†
*Facultad de Ingeniería, Universidad Andres Bello, 8370146 Santiago, Chile – miguel.gutierrez@unab.cl
†CISTER/FEUP, Universidade do Porto, Portugal – {mgg, lda}fe.up.pt
‡CISTER/ISEP, Politécnico do Porto, Portugal – {pmy, pss}isep.ipp.pt

***Abstract*—The rising adoption of wireless technologies in the Industry 4.0, including the Industrial Internet of Things (IIoT), has stressed the need for traffic schedulability validation at system design-time. In this context, the demand-based schedulability tests have recently been proposed in the literature. This work revisits two well-established techniques borrowed from the multi-processor scheduling theory, namely the demand-bound-function (DBF) and the forced-forward-demand-bound-function (FFDBF), and evaluates their performances when adapted to the field of wireless sensor-actuator networks. Simulation experiments when varying network configurations confirm the equal or better accuracy of FFDBF over DBF to estimate both network demand and schedulability. In future work, we aim at building upon these promising results in order to design novel admission control and adaptation strategies that improve network schedulability under varying workload conditions.**

***Index Terms*—EDF, TDMA, TSCH, WirelessHART, WSAN**

I. Introduction

In recent years, industrial communications have increasingly adopted wireless sensor-actuator networks (WSANs) as communication infrastructure for industrial automation and process control [1], [2]. Industrial wireless standards based on both time-synchronized channel hopping (TSCH) and centralized network management (e.g., WirelessHART, WIA-PA and 6TiSCH) are currently among the most popular [3]. Both are based on Time-Division Multiple-Access (TDMA) and frequency-channel diversity, key features to provide real-time and reliable communications.

In this class of systems we find network flows involved in control loops, exchanging periodic time-sensitive packets between controllers and sensors and actuators [4]. The estimation of the schedulability of these flows, i.e., the ability to fulfil all their timing constraints, is a long-standing concern in industrial communications.

In this paper, we recall and compare the performance of two demand-based schedulability tests discussed in [5], which are based on the so-called demand-bound function (DBF) [6], [7], and the forced-forward demand-bound function (FFDBF) [8]. Although equivalent studies have already been performed for multi-processor platforms, to the best of our knowledge, this is the first study of this kind in the context of industrial WSANs. We confirm the dominance of FFDBF over DBF since it is more accurate estimating network demand and thus network schedulability, too. This dominance is validated with simulation experiments using varying network configurations.

II. Related Work

The schedulability analysis for real-time networks derives in part from real-time CPU scheduling theory. For example, borrowing techniques from multi-processor scheduling theory [9] we can map the number of cores on the number of radio channels and analyse the impact of *channel contention* and *transmission conflicts*. The works in [5], [10]–[16] explicitly express this mapping while proposing tailored schedulability analyses for WSANs. The work in [15] firstly introduced in this domain the idea of supply/demand-based analysis using DBF. Then, Gaitán and Yomsi [5] demonstrated that for a given assessment time interval this function may not consider all the actual contributions to network demand, thus they rather supported the adoption of FFDBF for a more accurate estimation (Fig. 1).

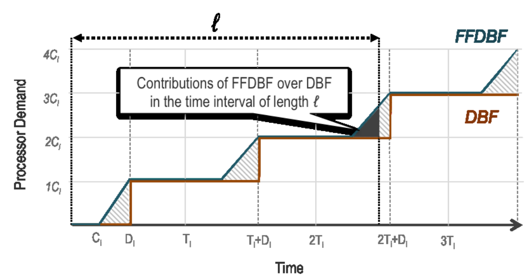

Fig. 1. The cumulative demand estimation of DBF versus FF-DBF.

III. System Model

This section revisits the network model and flow specifications detailed in [5]. We also introduce relevant notations and parameters used in our performance evaluation.

A. Network Model

We model a WSAN as an undirected graph $G = (V, E)$, where the vertices V are the nodes and the edges E the links between nodes. V implies a finite number of field devices linked together in a multi-hop fashion and connected

978-1-7281-5297-4/20/$31.00 ©2020 IEEE

to the gateway through multiple access points (APs). The gateway, in turn, enables the bidirectional communication with entities outside the network, e.g., with the host application, the network manager and/or the remote process controller (Fig. 2).

The network manager collects the topological information and is responsible for both routing and scheduling functions. The network assumes a multi-channel TDMA protocol with global synchronization. The length of the time slot is assumed fixed (to 10ms), and allowing exactly one transmission and one acknowledgement within the slot. The multi-channel features enable concurrent per-slot transmissions based on a random channel hopping technique over a number of m IEEE 802.15.4 available channels. The radio transceivers are assumed as omnidirectional and half-duplex, thus preventing simultaneous transmission/reception operations.

B. Flow model

We denote $F \stackrel{\text{def}}{=} \{f_1, f_2, \ldots, f_N\}$ as the set of n network flows to be transmitted from their respective source to their respective destination by following an earliest-deadline-first (EDF) scheduling policy [17]. Each flow f_i (with $i \in [1, n]$) represents a periodic time-constrained end-to-end communication characterized by a 4-tuple (C_i, D_i, T_i, ϕ_i). C_i is the effective transmission time between source and destination, T_i the period, D_i its relative deadline, and ϕ_i the flow routing path. These parameters are given with the interpretation that each network flow f_i releases a potentially infinite number of transmissions. The k^{th} of these instances (with $k \geq 1$) is denoted as $f_{i,k}$ and is released at the time $r_{i,k}$ such that $r_{i,k+1} - r_{i,k} \stackrel{\text{def}}{=} T_i$. This transmission has to reach its destination before its absolute deadline, i.e., $d_{i,k} \stackrel{\text{def}}{=} r_{i,k} + D_i$. Here, we assume that $D_i \leq T_i$, i.e., only a single transmission of f_i is being or can be transmitted at any time slot. In addition, C_i is interpreted as the effective transmission time a flow f_i requires to be completely transmitted from source to destination, when it does not suffer any interference from other flows. The last parameter, ϕ_i, represents the actual route of all transmissions issued from flow f_i.

IV. Problem Formulation

Given this setting, our objective is to assess the performance of the two state-of-the-art supply/demand-bound based schedulability tests for industrial WSANs. Here we reproduce the analytical results from [5] and [15] concerning the relationship between the (time) supply and demand of network flows scheduled under EDF.

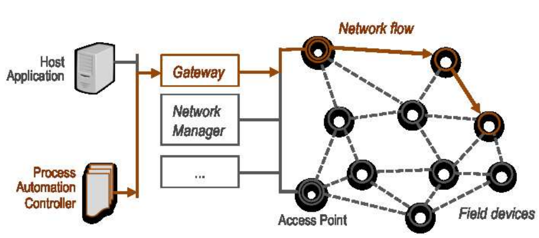

Fig. 2. Pictorial representation of an industrial WSAN.

Supply-Bound Function (SBF): is defined as the minimal transmission capacity offered by a network within a given time interval of length ℓ. The mathematical expression of this definition for a network with m available channels is derived from the work in [15] and reproduced here as follows:

$$\mathrm{sbf}(0) = 0 \ \wedge \ \forall \ell, k \geq 0 : \mathrm{sbf}(\ell + k) - \mathrm{sbf}(\ell) \leq \mathrm{m} \times k \quad (1)$$

Demand-Bound Function (DBF): is defined as the upper-bound on the maximum possible demand of a flow f_i in any time interval of length ℓ. The mathematical expression for this definition when considering a set of n network flows is derived from the work in [15] and reproduced here as follows:

$$\frac{1}{m} \sum_{i=1}^{n} \max \left\{ \left(\left\lfloor \frac{\ell - D_i}{T_i} \right\rfloor + 1 \right) \cdot C_i, 0 \right\} \quad (2)$$

This equation is based on the multiprocessor DBF concept [7] which consider that flows have all their transmissions (jobs) completed within the time interval of length ℓ. Here, the expression represents the upper-bound on the network demand due to *channel contention*, which is equivalent to the contention phenomenon in multiprocessors, i.e., flows cannot be scheduled simultaneously on different processors/channels.

Unfortunately, and as pointed out in [11], this is not the only source of scheduling interference in industrial WSANs. The so-called *transmission conflicts* [11] caused by the effect of multiple flows possibly encountering on a common node should also be taken into account. Equation 3 expresses this additional factor for a set of n network flows as follows:

$$\sum_{i,j=1}^{n} \left(\Delta(ij) \max \left\{ \left\lceil \frac{\ell}{T_i} \right\rceil, \left\lceil \frac{\ell}{T_j} \right\rceil \right\} \right) \quad (3)$$

where $\Delta(ij)$ represents the total transmission conflicts between two flows f_i and f_j, and is calculated based on the number of path overlaps shared between the flows [13], [15].

As a result, the total demand estimation for the network due to the contributions of *channel contention* and *transmission conflicts* can be obtained summing Eq. 2 and 3. The relationship between this result and the SBF led to the following supply/demand-bound based schedulability test [15]:

$$\sum_{F_i \in F} \mathrm{DBF}(F_i, \ell) \leq \mathrm{sbf}(\ell), \ \forall \ell \geq 0 \quad (4)$$

Similarly to multiprocessor real-time scheduling, this DBF-based test can be further refined considering the principles of FFDBF instead. The dominance of FFDBF over DBF to estimate the processor demand more accurately was already shown in Fig. 1. In [5] we proposed to leverage this observation refining the network demand estimation due to *channel contention*[1].

The analytical expression proposed in [5] to better estimate the contribution of a single flow f_i is presented as follows:

$$\mathrm{FFDBF}(F_i, \ell) \stackrel{\text{def}}{=} q_i C_i + \begin{cases} C_i & \text{if} \quad \gamma_i \geq D_i \\ C_i - (D_i - \gamma_i) & \text{if} \quad D_i > \gamma_i \geq D_i - C_i \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

[1]Note that the contribution of *transmission conflicts* to network demand is independent of the DBF and cannot be further improved by FFDBF.

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

The consideration of a set of n flows in the network in any time interval of length ℓ led to the upper-bound estimation of network demand due to *channel contention*:

$$\text{FFDBF}(\ell)^{\text{Ch}} = \frac{1}{m}\sum_{i=1}^{n} \text{FFDBF}(F_i, \ell) \quad (6)$$

Consequently, the total demand estimation due to both *channel contention* and *transmission conflicts* can be obtained summing Eq. 6 and 3. The corresponding supply/demand-bound based schedulability test is as follows:

$$\sum_{F_i \in F} \text{FFDBF}(F_i, \ell) \leq \text{sbf}(\ell),\ \forall \ell \geq 0 \quad (7)$$

V. Performance Evaluation

A. Simulation Setup

We assessed the performance of DBF and FFDBF based tests using a synthetic generation of flow sets under varying network configurations. We controlled the overall workload of the network using a UUniFast-alike algorithm [18], i.e., a method providing a set of n flows and a specified total target utilization U, with random uniformly distributed individual period and utilization. We set U allowing tolerance of $\pm 20\%$ because of the particular restrictions of our system model. In specific, we are constrained to have both transmission times (C_i) and periods (T_i) as (positive) integers, thus limiting the range of values that individual utilization factors can take, i.e., the $u_i = C_i / T_i$. In our model, C_i is the effective transmission time (in ms) a packet requires to travel an arbitrary path of length $|\phi_i|$ (in number of hops). Then, since for each hop only one per-slot transmission (of 10ms each) is permitted, C_i always result in an integer value. In addition, C_i is further restricted to be in the range of $[1, N-1]$ times slots, since is N is the number of nodes (and the maximum number of hops) in the network. Similarly, T_i is constrained as an integer too, since we assume it as random harmonically generated in the form of 2^i time slots; a common assumption in industrial networks (e.g., see [16]). Additionally, we assumed T_i as significantly greater than C_i to favour fast and light generation of u_i factors. We also choose T_i in the range of $[2^{10}, 2^{12}]$. Moreover, and in order to offer a broader period range, we also evaluate the case of random not-harmonic periods in the same range (i.e., 1024 to 4096), but in this case allowing to take any other integer value in between. Motivations for this latter case can be found in recent literature [19].

Note that we use the length of the evaluation interval $\Delta\ell$ as T_{max}, i.e. the maximum period of the flow set. The difference between both random generations is that in the case of harmonic periods, T_{max} corresponds to the hyperperiod, i.e., the least-common-multiplier between all the flow set periods. In addition, for the network demand estimation purposes, we assume for all cases, constrained or implicit deadlines varying in the range $D_i \in [0.6, 1.0]T_i$

Finally, for the sake of simplicity we assume the network adopts a tree routing (as in [16]). This corresponds to a worst-case factor of $\Delta(ij) = 3$ in our simulations.

B. Simulation Results

For each network configuration, we generated 100 random test cases. Then, we reported the schedulability ratios using: (i) random harmonically generated periods, and (ii) random (not harmonic) generated periods.

(1) Varying number of flows (n). Figure 3 reports the impact of varying the number of flows in the network in the range $n \in [25, 35]$. The sets were generated with a total target utilization of $U = 0.8 \pm 20\%$, and evaluated under $m = 10$ channels.

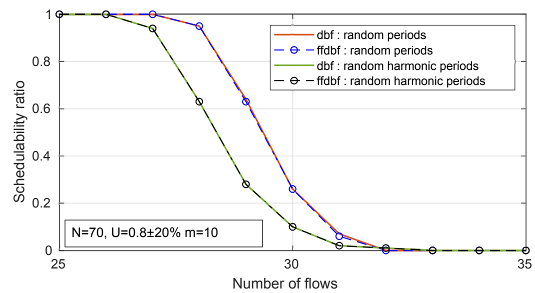

Fig. 3. $n \in [25, 35]$.

(2) Varying utilization (U). Figure 4 reports the impact of varying the total target utilization in the range of $U \in [0.55, 0.85]$ for a number of $n = 30$ simultaneous flows. The sets were evaluated under a number of $m = 5$ channels.

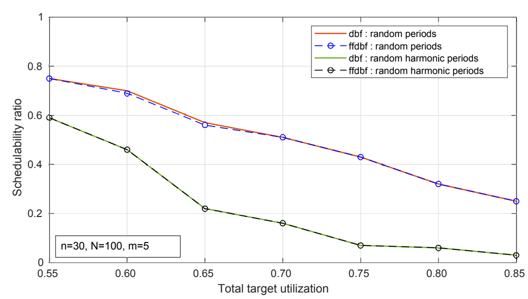

Fig. 4. $U \in [0.55, 0.85]$.

(3) Varying number of nodes (N). Figure 5 reports the impact of varying the number of nodes in the range $N \in [60, 90]$. The test cases consider a workload of $n = 30$ flows with total of utilization of $U = 0.8 \pm 20\%$. The network schedulability was estimated using a number of $m = 5$ channels.

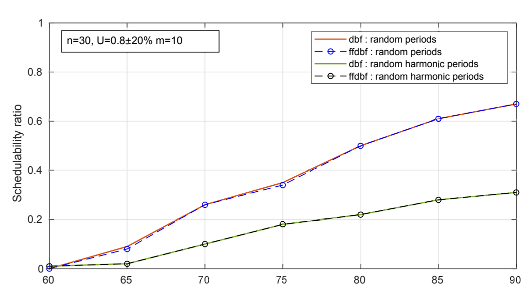

Fig. 5. $N \in [60, 90]$.

(4) Varying number of channels (m). Figure 6 reports the impact of varying the number of channels in the range $m \in [1, 16]$. The flow sets were generated considering a number of $N = 100$ nodes in the network, under a workload of $n = 30$ flows with total of utilization of $U = 0.6 \pm 20\%$.

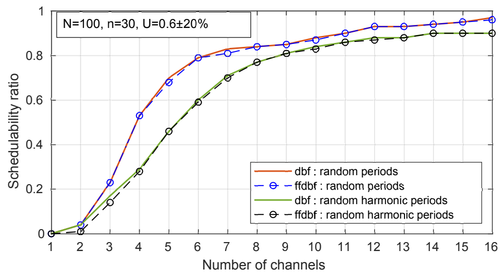

Fig. 6. $m \in [1, 16]$.

(5) Varying interval of evaluation ($\Delta\ell$). Figure 7 reports the impact of varying the length of the interval of evaluation between the minimum and maximum periods in flow set, i.e., $T_i \in [1024, 4096]$. The evaluation was performed assuming a network of $N = 70$ nodes, $m = 16$ available channels, and $n = 30$ network flows of $U = 0.7 \pm 20\%$ utilization.

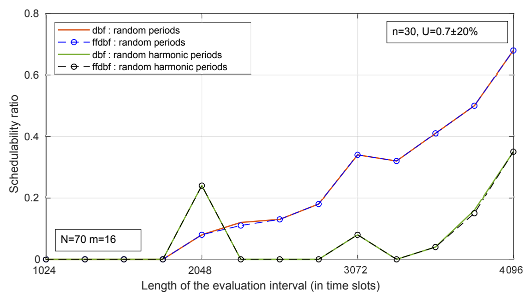

Fig. 7. $\Delta\ell \in [1024, 4096]$.

Discussion. The variety of situations here evaluated offers a broad picture of the real-time performance of both DBF and FFDBF, an effort that had not yet been done in the context of industrial WSANs. The difference between both techniques, although minimal, it exists, and thus it is not to ignore in industrial and/or safety-critical application domains. How to exploit these results, e.g., as a valuable input for the design of novel admission control and adaptation strategies, is part of the aspects of this ongoing research not dealt with in this work but which represent our primary objective.

VI. Conclusion & Future Work

This paper addressed the growing importance of WSANs in industry and provided a comparative assessment of the two state-of-the-art supply/demand-bound based schedulability analysis, confirming the equal or better accuracy of FFDBF over DBF under particular conditions. In future work, we aim at building upon these results in order to design strategies that improve the schedulability under varying workload conditions.

Acknowledgment

This work is a result of the project Safe Cities - Inovação para Construir Cidades Seguras, with the reference POCI-01-0247-FEDER-041435, co-funded by the European Regional Development Fund (ERDF), through the Operational Programme for Competitiveness and Internationalization (COMPETE 2020), under the PORTUGAL 2020 Partnership Agreement. This work is also partially supported by FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (UIDB/04234/2020).

References

[1] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, and M. Gidlund, "Industrial internet of things: Challenges, opportunities, and directions," *IEEE Trans. on Industrial Informatics*, vol. 14, no. 11, pp. 4724–4734, 2018.

[2] F. Tramarin, A. K. Mok, and S. Han, "Real-time and reliable industrial control over wireless lans: Algorithms, protocols, and future directions," *Proceedings of the IEEE*, vol. 107, no. 6, pp. 1027–1052, 2019.

[3] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, "IEEE 802.15.4e in a nutshell: Survey and performance evaluation," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1989–2010, 2018.

[4] C. Lu, A. Saifullah, B. Li, M. Sha, H. Gonzalez, D. Gunatilaka, C. Wu, L. Nie, and Y. Chen, "Real-time wireless sensor-actuator networks for industrial cyber-physical systems," *Proceedings of the IEEE*, vol. 104, no. 5, pp. 1013–1024, 2015.

[5] M. G. Gaitán and P. M. Yomsi, "FF-DBF-WIN: On the forced-forward demand-bound function analysis for wireless industrial networks," in *30th Euromicro Conference on Real-Time System (ECRTS)*, pp. 13–15, ECRTS (Work-in-Progress Session), 2018.

[6] S. Baruah, L. Rosier, and R. Howell, "Algorithms and complexity concerning the preemptive scheduling of periodic, real-time tasks on one processor," *Real-Time Systems*, vol. 2, no. 4, pp. 301–324, 1990.

[7] S. Baruah and N. Fisher, "The partitioned multiprocessor scheduling of sporadic task systems," in *26th IEEE International Real-Time Systems Symposium (RTSS)*, pp. 321–329, IEEE, 2005.

[8] S. Baruah, V. Bonifaci, A. Marchetti-Spaccamela, and S. Stiller, "Improved multiprocessor global schedulability analysis," *Real-Time Systems*, vol. 46, no. 1, pp. 3–24, 2010.

[9] M. G. Gaitán and P. M. Yomsi, "Multiprocessor scheduling meets the industrial wireless: A brief review," *U. Porto Journal of Engineering*, vol. 5, no. 1, pp. 59–76, 2019.

[10] A. Saifullah, Y. Xu, C. Lu, and Y. Chen, "Real-time scheduling for WirelessHART networks," in *31st IEEE Real-Time Systems Symposium (RTSS)*, pp. 150–159, IEEE, 2010.

[11] A. Saifullah, Y. Xu, C. Lu, and Y. Chen, "End-to-end delay analysis for fixed priority scheduling in WirelessHART networks," in *17th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pp. 13–22, IEEE, 2011.

[12] C. Wu, M. Sha, D. Gunatilaka, A. Saifullah, C. Lu, and Y. Chen, "Analysis of EDF scheduling for wireless sensor-actuator networks," in *22nd International Symposium of Quality of Service (IWQoS)*, pp. 31–40, IEEE, 2014.

[13] A. Saifullah, Y. Xu, C. Lu, and Y. Chen, "End-to-end communication delay analysis in industrial wireless networks," *IEEE Transactions on Computers*, vol. 64, no. 5, pp. 1361–1374, 2014.

[14] A. Saifullah, D. Gunatilaka, P. Tiwari, M. Sha, C. Lu, B. Li, C. Wu, and Y. Chen, "Schedulability analysis under graph routing in WirelessHART networks," in *36th Real-Time Systems Symposium (RTSS)*, pp. 165–174, IEEE, 2015.

[15] C. Xia, X. Jin, and P. Zeng, "Resource analysis for wireless industrial networks," in *Proceedings of the 12th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN)*, pp. 424–428, IEEE, 2016.

[16] V. P. Modekurthy, D. Ismail, M. Rahman, and A. Saifullah, "A utilization-based approach for schedulability analysis in wireless control systems," in *2nd International Conference on Industrial Internet (ICII)*, pp. 49–58, IEEE, 2018.

[17] C. L. Liu and J. W. Layland, "Scheduling algorithms for multiprogramming in a hard-real-time environment," *Journal of the ACM*, vol. 20, no. 1, pp. 46–61, 1973.

[18] E. Bini and G. C. Buttazzo, "Measuring the performance of schedulability tests," *Real-Time Systems*, vol. 30, no. 1-2, pp. 129–154, 2005.

[19] M. Kashef and N. Moayeri, "Real-time scheduling for wireless networks with random deadlines," in *2017 IEEE 13th International Workshop on Factory Communication Systems (WFCS)*, pp. 1–9, IEEE, 2017.