FF-DBF-WIN: On the Forced-Forward Demand-Bound Function Analysis for Wireless Industrial Networks

Miguel Gutiérrez-Gaitán and Patrick Meumeu Yomsi
CISTER/INESC-TEC, ISEP, Polytechnic Institute of Porto, Portugal
Email: {mjggt, pamyo}@isep.ipp.pt

***Abstract*—Wireless Industrial Networks (WINs) have brought to the forefront the need for real-time strategies to ensure network schedulability. The Demand Bound Function (DBF) has recently been borrowed from the multicore scheduling theory and adapted to the wireless industrial domain to compute the network demand. However, a more precise estimation can be obtained by using alternative supply/demand analyses. This paper proposes the forced-forward demand bound function to estimate the network demand and better determine the schedulability of WINs.**

1. Application domain

Wireless Industrial Networks (WINs) have become one of the enabling technologies of Industry 4.0. Advantages such as flexibility, easy deployment and low cost devices have led to its gradual incorporation into smart factories, intelligent manufacturing systems, among other industrial contexts. Nevertheless, from a communication and network viewpoint, WINs still pose significant technical challenges compared to traditional wireless sensor networks (WSNs). WirelessHART, ISA100.11a, WIA-PA and IEEE 802.15.4e are a few examples of standards developed during the last two decades to specifically address some of these industrial requirements. Here, techniques such as interference minimization, redundancy, frequency hopping and power efficiency are combined together with recommendations in the standards to satisfy reliability and real-time requirements. Along the same line, with the advent of recent Cyber-Physical Systems and Internet of Things, protocols such as 6LowPAN (IPv6 over Low-Power Wireless Personal Area Networks), RPL (Routing Protocol for Low-Power and Lossy Networks), CoAP (Constrained Application Protocol) and 6TiSCH (IP over the TSCH mode of IEEE 802.15.4e) [1] have focused their standardization efforts on aspects such as the integration of smart devices into the Internet.

Despite all the attempts so far and the entire body of knowledge available in the literature (see [1] for a comprehensive survey) to address common wireless industrial requirements, important hurdles such as real-time schedulability analysis, i.e., the ability of each flow to meet all its timing requirements, have received very little attention in the context of WINs.

2. Motivation

Willig et al. [2] recognize both reliability and timing guarantees as two of the most desirable characteristics of WINs. Because wireless channels are usually prone to transmission errors, a cornerstone on the way to guarantee these features for such a system is the schedulability of the network flows. To this end purpose, channel contention and transmission conflicts are the two common delays that affect the end-to-end transmission of each network flow and thus its schedulability. Recently, Xia et. al [3] have studied these two components and factored the contribution of each in the end-to-end transmission delay of each flow by borrowing analysis techniques from the multicore scheduling theory. Specifically, the authors focused on the relationship between the network supply and demand of the flows in any time interval. However, the proposed analysis was based on the "Demand Bound Function" (DBF) [4] concept to determine the schedulability of the flow set, which does not consider all flows that can potentially contribute to the network demand, unfortunately.

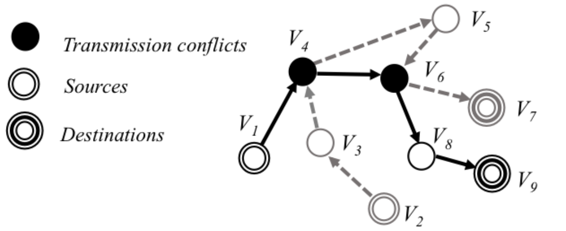
In the literature on multicore scheduling theory, the forced-forward demand bound function (FF-DBF) [5] offers a tighter alternative to estimate the workload demand of a system as it includes potential contributions that are left aside by DBF.

3. Problem statement

We consider the model of execution proposed in [3] where a wireless industrial network is represented as a graph $G = (V, E, m)$. Here, V denotes the set of network devices (or nodes), E represents the set of edges between the nodes and m is the number of channels. For implementation purpose, we assume that a number $x \geq 2$ of nodes can communicate if they are not more than d meters apart in an area A such that the following equation holds true:

$$\frac{x}{A} = \frac{2\pi}{d^2\sqrt{27}} \quad (1)$$

Given this setting, we consider a set of n network flows $F \stackrel{\text{def}}{=} \{F_1, F_2, \ldots, F_n\}$ to be transmitted from their respective source to their respective destination by following an Earliest Deadline First (EDF) scheduling algorithm [6]. Each flow F_i, with $i \in [1, n]$, is modeled by using a periodic end-to-end communication scheme between its source and its destination through a 4-tuple $\langle C_i, D_i, T_i, \phi_i \rangle$, where C_i is the number of hops between source and destination; D_i is the relative deadline; T_i is the period; and ϕ_i is the routing path of the flow. These parameters are given with the interpretation that: each flow releases a potentially infinite number of instances (or jobs). The k^{th} job (with $k \geq 1$) of flow F_i is denoted as $F_{i,k}$ and is released at time $r_{i,k}$ such that $r_{i,k+1} - r_{i,k} \stackrel{\text{def}}{=} T_i$. Job $F_{i,k}$ has to be completely transmitted to its destination node by its absolute deadline, i.e., $d_{i,k} \stackrel{\text{def}}{=} r_{i,k} + D_i$. We assume that $D_i \leq T_i$, i.e., only a single job of flow F_i is being/can be transmitted at any time instant. The number of hops between the source and the destination of flow F_i, denoted as C_i, represents its transmission time when it does not suffer any external interference whatsoever from the other flows. The last parameter, ϕ_i, represents the actual route of all jobs issued from flow F_i. Figure 1 depicts an example of a WIN with two flows F_1 and F_2 together with their associated parameters according to this model. In this figure, flow F_1 is transmitted from node V_1 to V_9 via nodes V_4, V_6 and V_8; and flow F_2 is transmitted from node V_2 to V_7 via nodes V_3, V_4, V_5 and V_6. Note that there are transmission conflicts at nodes V_4 and V_6.



	C_i	D_i	T_i	φ_i
F_1 ———	4	15	20	V_1, $\mathbf{V_4}$, $\mathbf{V_6}$, V_8, V_9
F_2 - - -	5	20	30	V_2, V_3, $\mathbf{V_4}$, V_5, $\mathbf{V_6}$, V_7

Figure 1. An example of a wireless industrial network.

The objective is to provide an accurate network supply/demand analysis by using the forced-forward demand bound function, in order to guarantee the schedulability of all the flows in the system. A simulation experiment will be carried out to compare the performance for both the DBF and FF-DBF-based analyses. Finally, a rigorous per flow analysis will be conducted and the gain in terms of accuracy of the analysis will be evaluated.

4. Observations and preliminary results

As mentioned in Section 2, channel contention and transmission conflicts are the two common delays affecting the end-to-end transmission time of network flows in WINs.

1) **Channel contention:** refers to the delay produced by a high priority job occupying all channels at a time instant.
2) **Transmission conflict:** refers to a job transmission delayed by the transmission of a higher priority job.

Xia et al. [3] factored these two delays in their proposed supply/demand bound analysis method.
▷ About Point 1), the authors assume that the flows are executed on a multi-processor platform and each channel of the WIN is mapped as one processor. They bound the supply bound function (sbf)[1] of an industrial network as follows.

$$\text{sbf}(0) = 0 \;\wedge\; \forall \ell, k \geq 0 : \text{sbf}(\ell + k) - \text{sbf}(\ell) \leq \text{Ch} \times k \quad (2)$$

where Ch is the number of channels in the network and they derive the network demand caused by channel contention in any time interval of length ℓ as

$$\text{DBF}(\ell)^{\text{Ch}} = \frac{1}{m} \sum_{i=1}^{n} \max \left\{ \left(\left\lfloor \frac{\ell - D_i}{T_i} \right\rfloor + 1 \right) \cdot C_i, 0 \right\} \quad (3)$$

▷ About Point 2), the authors provided an estimation of the network demand caused by the transmission conflicts under the EDF scheduling algorithm by tuning the result proposed by Saifullah et al. in [7]. Here, the transmission of two flows are in conflict when their paths overlap, i.e., if we consider two flows F_i and F_j such that F_i has a higher priority than F_j, then at a given node, say V_x, the progress of the jobs generated from F_i cannot be delayed by jobs generated from F_j, but jobs generated from F_j may be delayed by jobs generated from F_i at node V_x and at all subsequent nodes shared by the transmission paths of F_i and F_j. Based on this observation, Xia et al. [3] estimated the network demand caused by the transmission conflicts as follows

$$\sum_{i,j=1}^{n} \left(\Delta(ij) \max\left\{ \left\lceil \frac{\ell}{T_i} \right\rceil, \left\lceil \frac{\ell}{T_j} \right\rceil \right\} \right) \quad (4)$$

In Equation 4, $\Delta(ij) \stackrel{\text{def}}{=} \sum_{k=1}^{\delta(ij)} Len_k(ij) - \sum_{k'=1}^{\delta'(ij)} (Len_{k'}(ij) - 3)$. Here, $Len_k(ij)$ denotes the length of the k^{th} path overlap and $\delta(ij)$ is the number of path overlaps; and $Len_{k'}(ij)$ and $\delta'(ij)$ refer to the delay caused by path overlaps with length as least 4. Finally, Xia et al. computed an upper bound on the network demand in any time interval of length ℓ by summing Equations 3 and 4. They concluded on the schedulability of the flow set F by checking if Equation 5 is satisfied.

$$\sum_{F_i \in F} \text{DBF}(F_i, \ell) \leq \text{sbf}(\ell), \; \forall \ell \geq 0 \quad (5)$$

Since Equation 3 is using the DBF function to estimate the network demand, the contributions of some jobs arriving and/or having deadlines outside the interval of interest are not taken into account, unfortunately. This would lead to an underestimation of the network demand, which in turn may result in a less accurate supply/demand bound analysis. In order to circumvent this issue, we propose to borrow the FF-DBF function[2] from the multi-core scheduling theory, instead. This function is defined for a single flow F_i as follows.

$$\text{FF-DBF}(F_i, \ell) \stackrel{\text{def}}{=} q_i \cdot C_i + \begin{cases} C_i & \text{if} \quad \gamma_i \geq D_i \\ C_i - (D_i - \gamma_i) & \text{if} \quad D_i > \gamma_i \geq D_i - C_i \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

In Equation 6, $q_i \stackrel{\text{def}}{=} \left\lfloor \frac{\ell}{T_i} \right\rfloor$ and $\gamma_i = \ell \mod T_i$. Figure 2 illustrates a comparison between the demand evaluated by using FF-DBF and the demand evaluated by using the classical DBF in an interval of length ℓ for an arbitrary task (or flow).

1. The supply bound function - sbf(ℓ) - of a network is the minimal transmission capacity provided within a time interval of length ℓ.

2. The FF-DBF refines the DBF and allows us to include the potential missing contributions into the cumulative computational demand.

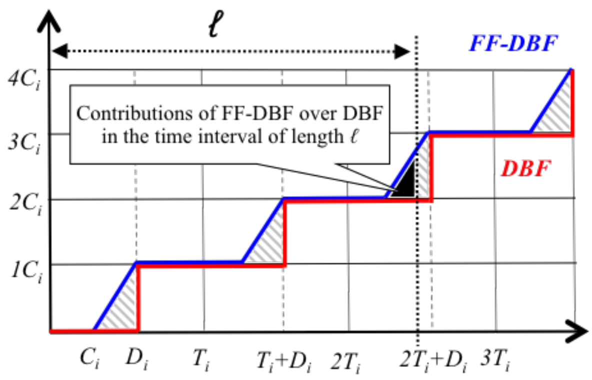


Figure 2. Pictorial representation of FF-DBF vs. DBF.

Given the model defined in Section 3, we adapt the FF-DBF function to the wireless industrial networks domain by revisiting Equations 3 and 4 as follows.
▷ *About Equation 3:* We recall that this equation provides us with the network demand caused by channel contention in any time interval of length ℓ. By using the FF-DBF function instead to this end, that estimation is given by:

$$\text{FF-DBF}(\ell)^{\text{Ch}} = \frac{1}{m} \sum_{i=1}^{n} \text{FF-DBF}(F_i, \ell) \tag{7}$$

▷ *About Equation 4:* This equation allowed us to estimate the network demand caused by the transmission conflicts. Since these conflicts are agnostic to the network topology, there is no need to alterate this contribution, therefore this factor remains the same as previously.

As a result of these two observations, a more precise upper-bound of network demand is obtained by using the FF-DBF(ℓ) function defined as follows:

FF-DBF-WIN. A forced-forward demand bound function FF-DBF(ℓ) of a given WIN in any time interval of length ℓ is defined by summing Equations 4 and 7. Formally,

$$\begin{aligned}\text{FF-DBF}(\ell) = &\frac{1}{m} \sum_{i=1}^{n} \text{FF-DBF}(F_i, \ell) + \\ &\sum_{i,j=1}^{n} \Delta(ij) \max\left\{\left\lceil \frac{\ell}{T_i} \right\rceil, \left\lceil \frac{\ell}{T_j} \right\rceil\right\}\end{aligned} \tag{8}$$

A pseudo-code for the computation of this function is presented in Algorithm 1.

5. Envisioned Solution and Conclusion

In this ongoing research, we proposed the forced-forward demand bound function (FF-DBF) as a refinement of the demand bound function (DBF) to charactize the network demand in wireless industrial networks. We believe that Equation 8 is more accurate for the estimation of an upper bound on the network demand as it allows us to take into account potential missing contributions, left aside by the classical DBF function, into the cumulative computational demand in any time interval (see Figure 2). Also, we are confident that it will outperform the analysis proposed by Xia et al. [3] for the schedulability of periodic flows in WINs and will lead us to a more accurate supply/demand bound analysis. Now we seek to: (i) formally demonstrate this claim; (ii) conduct simulation experiments to compare the performances for both DBF and FF-DBF-based analyses and (iii) thus validate the efficiency of the proposed approach. Finally, we will also derive a rigorous per flow analysis and evaluate the gain in terms of computational complexity.

Algorithm 1 FF-DBF Algorithm for WINs

Input: $m; F_i(C_i, D_i, T_i, \phi_i); \ell; \Delta(ij); n;$
Output: FF-DBF(ℓ)
Initialisation : FF-DBF(ℓ) $\leftarrow 0; q_i \leftarrow 0; \gamma_i \leftarrow 0;$
for $i = 1$ to n **do**
  $q_i \leftarrow \left\lfloor \frac{\ell}{T_i} \right\rfloor;$
  $\gamma_i \leftarrow \ell \mod T_i;$
  if $(\gamma_i \geq D_i)$ **then**
    FF-DBF(ℓ) += $q_i \times C_i + C_i;$
  else
    if $(\gamma_i \geq D_i - C_i)$ **then**
      FF-DBF(ℓ) += $q_i \times C_i + C_i - (D_i - \gamma_i);$
    else
      FF-DBF(ℓ) += $q_i \times C_i;$
    end if;
  end if
end for
FF-DBF(ℓ) $\leftarrow \frac{1}{m} \times$ FF-DBF(ℓ);
for $i = 1$ to n **do**
  aux $\leftarrow \max\left\{\left\lceil \frac{\ell}{T_i} \right\rceil, \left\lceil \frac{\ell}{T_j} \right\rceil\right\};$
  FF-DBF(ℓ) += $\Delta(ij) \times$ aux;
end for
return FF-DBF(ℓ)

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