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Abstract

In the paper "Timing Analysis of Fixed Priority Self-Suspending Sporadic Tasks" published in ECRTS 2015, a MILP formulation is provided to compute an upper-bound on the worst-case response time (WCRT) of one self-suspending task running concurrently with a set of higher priority non-self-suspending tasks. Section VI of that paper extends the MILP formulation to the case where the higher priority tasks are also self-suspending. This generalisation is incorrect. We present the problem and its solution in this technical report.

Errata: Timing Analysis of Fixed Priority Self-Suspending Sporadic Tasks

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I. Incorrect Statement

In [1], a MILP formulation is provided to compute an upper bound on the worst-case response time (WCRT) of one self-suspending task running concurently with a set of higher priority non-self-suspending tasks. Section VI of [1] extends the MILP formulation to the case where the higher priority tasks are also self-suspending. It is stated that:

Claim 1 (in [1]). *"[...] each higher priority self-suspending task τ_k can safely be replaced by a non-self-suspending task $\tau'_k \stackrel{\text{def}}{=} \langle (C_k), D_k, T_k, J_k \rangle$ in the response time analysis. The new parameter J_k is the jitter and is given by $J_k \stackrel{\text{def}}{=} \text{WCRT}_k - C_k$. The worst-case execution time C_k of the equivalent task τ'_k is defined as the sum of the worst-case execution times of all τ_k's execution regions, that is, $C_k \stackrel{\text{def}}{=} \sum_{j=1}^{m_k} C_{k,j}$."*

This claim is supported by Theorem 2 repeated below.

Theorem 2 (in [1])**.** *The interference caused by $\tau_k \in \text{hp}(\tau_i)$ on a self-suspending task τ_i is upper bounded by the interference caused by the transformed task $\tau'_k \stackrel{\text{def}}{=} \langle (C_k), D_k, T_k, J_k \rangle$.*

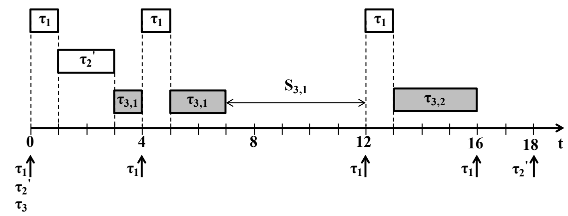
Although Theorem 2 is correct, Claim 1 is not. It is demonstrated with a counter-example below.

Counter-Example 1. *Assume the task set composed of three tasks $\tau_1 = \langle (1), 4, 4, 0 \rangle$, $\tau_2 = \langle (1, 9, 1), 29, 29, 0 \rangle$ and $\tau_3 = \langle (3, 5, 3), 100, 100, 0 \rangle$. τ_1 has the highest priority and τ_3 the lowest. We are interested in computing the WCRT of τ_3.*

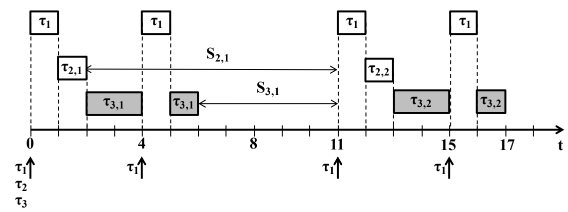
Since τ_1 does not self-suspend we get $\tau'_1 = \tau_1$ and using the definition provided in Claim 1, we get $\tau'_2 = \langle (2), 29, 29, J_2 \rangle$ where $J_2 = \text{WCRT}_2 - C_2 = \text{WCRT}_2 - 2$. Since the minimum inter-arrival time of τ_1 is smaller than the suspension time of τ_2, task τ_1 generates the worst-case interference when it is released synchronously with each execution region of τ_2 (see Figure 1(b)). In which case, we get $\text{WCRT}_2 = 13$ and thus $J_2 = 13 - 2 = 11$.

Figure 1(a) depicts one of the release patterns that generates the WCRT of τ_3 when executed concurrently with the modified tasks τ'_1 and τ'_2. In that execution scenario, the WCRT of τ_3 is 16. Indeed, due to its large inter-arrival time, task τ'_2 can interfere at most once with τ_3 since, even considering its release jitter, the earliest possible release for its second job is at time $T_2 - J_2 = 18$ (see Figure 1(a)).

Figure 1(b) shows the WCRT of τ_3 when it executes concurrently with the actual tasks τ_1 and τ_2. As it can be seen, the WCRT of τ_3 is in fact 17, thus contradicting the claim that τ_2 can "safely be replaced by" τ'_2 in the WCRT analysis of τ_3.



(a) WCRT of τ_3 with the modified task τ'_2.



(b) WCRT of τ_3 with the original task τ_2.

Fig. 1: Counter-example to Claim 1.

Note that Counter-Example 1 *does not* invalidate Theorem 2. Tasks τ_2 and τ'_2 cause the same amount of interference to τ_3. In fact, Theorem 2 is correct. However, Theorem 2 does not prove Claim 1. Theorem 2 defines an upper bound on the worst-case interference generated by *one* self-suspending task (i.e., either neglecting the impact of the other tasks or assuming that the WCRT is already known). Claim 1 however claims an upper bound on the interference generated by *a set of* self-suspending tasks.

The main issue with Theorem 2 is that it does not tell us how the interference of a task such as τ_2 is distributed between the execution regions of a lower priority task (in this case τ_3). However, as shown in Counter-Example 1, the interference distribution is of prime importance to compute a valid upper bound on the WCRT of τ_3 since it directly impacts the number of jobs of other tasks (τ_1 in this case) that can interfere with τ_3.

II. Solution

The error in Claim 1 is to model the whole self-suspending task τ_k as a single non-self-suspending task τ'_k. In fact, each execution region $\tau_{k,j}$ of τ_k should be modelled by a different non-self-suspending task $\tau'_{k,j}$ with jitter $J_{k,j}$. Such solution was already proposed in [2]. In [2], the jitter $J_{k,j}$ is given by the difference between the WCRT and the best-case response time (BCRT) of the partial self-suspending task composed of the $j-1$ first execution and suspension regions of τ_k. Formally,

Lemma 4. *Let $\tau_{k,j}$ be the j^{th} execution region of τ_k, and let τ_k^j be a self-suspending task composed of the $j-1$ first execution and suspension regions of τ_k, that is, $\tau_k^j \stackrel{\text{def}}{=} \langle (C_{k,1}, S_{k,1}, \ldots, C_{k,j-1}, S_{k,j-1}), D_k, T_k \rangle$. The release jitter of $\tau_{k,j}$ is upper bounded by $J_{k,j} \stackrel{\text{def}}{=} \text{WCRT}_k^j - \text{BCRT}_k^j$, where WCRT_k^j and BCRT_k^j are the worst-case and best-case response time of τ_k^j, respectively.*

Proof. The minimum inter-arrival time of the execution region $\tau_{k,j}$ of task τ_k is inherited from the minimum inter-arrival time of τ_k. However, the execution region $\tau_{k,j}$ can start to execute only when the $(j-1)^{\text{th}}$ suspension region of τ_k completes, that is, when the partial self-suspending task τ_k^j completes its execution. Since the response time of τ_k^j may vary between different jobs released by τ_k, the release of $\tau_{k,j}$ experiences a jitter. This jitter is upper bounded by the difference between the longest and the shortest response time of τ_k^j, i.e., it is upper bounded by the difference between WCRT_k^j and BCRT_k^j. ■

Let $\text{hp}(\tau_{ss})$ be a set of self-suspending tasks with higher priorities than τ_{ss}. And let $\text{hp}(\tau_{ss})'$ be a set of non-self-supending tasks where for each task $\tau_k \in \text{hp}(\tau_{ss})$, the set $\text{hp}(\tau_{ss})'$ contains m_k non-self-suspending tasks $\tau'_{k,j} \stackrel{\text{def}}{=} \langle (C_{k,j}), D_k, T_k, J_{k,j} \rangle$ with $1 \leq j \leq m_k$, where $J_{k,j}$ is defined as in Lemma 4 and each task $\tau'_{k,j}$ ($1 \leq j \leq m_k$) has the same priority than τ_k. We prove below that replacing $\text{hp}(\tau_{ss})$ with $\text{hp}(\tau_{ss})'$ in the WCRT analysis of τ_{ss} provides a response time upper bound which is at least as large as the WCRT when using $\text{hp}(\tau_{ss})$. Therefore, replacing $\text{hp}(\tau_{ss})$ with $\text{hp}(\tau_{ss})'$ is safe.

We first define what is a legal release pattern for a task set.

Definition 1 (Legal release pattern for a task set τ)**.** *A release pattern $\mathcal{R}$ defines all the instants at which each execution region of the tasks in τ releases jobs. A release pattern $\mathcal{R}$ is legal if all the constraints defined by the tasks in τ (i.e., minimum inter-arrival time, precedence constraints and release jitter) are respected in $\mathcal{R}$.*

Now, we prove that the release pattern of the task set $\text{hp}(\tau_{ss})$ that generates the WCRT of τ_{ss} can be transformed in a legal release pattern for the tasks in $\text{hp}(\tau_{ss})'$.

Lemma 5. *Let $\overline{\mathcal{R}}$ be any legal release pattern of the execution regions of the tasks in $\text{hp}(\tau_{ss})$ such that the tasks in $\text{hp}(\tau_{ss})$ generate the worst-case interference on τ_{ss}. Let $\overline{\mathcal{R}}'$ be a release pattern for the tasks in $\text{hp}(\tau_{ss})'$ such that whenever an execution region $\tau_{k,j} \in \text{hp}(\tau_{ss})$ releases a job in $\overline{\mathcal{R}}$, the corresponding task $\tau'_{k,j}$ releases a job at the same instant in $\overline{\mathcal{R}}'$. The release pattern $\overline{\mathcal{R}}'$ is a legal release pattern for the tasks in $\text{hp}(\tau_{ss})'$.*

Proof. We have to prove that the minimum inter-arrival times, release jitters and precedence constraints defined for the task in $\text{hp}(\tau_{ss})'$ are all respected in $\overline{\mathcal{R}}'$.

1) The minimum inter-arrival time of $\tau_{k,j}$ is T_k and its release jitter is smaller than or equal to $J_{k,j}$ (from Lemma 4). Let $\tau_{k,j}^{\ell}$ be the ℓ^{th} instance (job) released by $\tau_{k,j}$. Since $\overline{\mathcal{R}}$ is legal, the time between any two jobs $\tau_{k,j}^{\ell}$ and $\tau_{k,j}^{\ell+p}$ released by $\tau_{k,j}$ is at least $(p \times T_k) - J_{k,j}$. Therefore, the time between any two jobs $\tau_{k,j}^{\ell'}$ and $\tau_{k,j}^{\ell+p'}$ released by $\tau'_{k,j}$ is at least $(p \times T_k) - J_{k,j}$ in the release pattern $\overline{\mathcal{R}}'$. Since by definition, the minimum inter-arrival time and the release jitter of $\tau'_{k,j}$ are T_k and $J_{k,j}$ respectively, the release pattern $\overline{\mathcal{R}}'$ respects the minimum inter-arrival time and the release jitter constraints on $\tau'_{k,j}$.
2) Since the tasks in $\text{hp}(\tau_{ss})'$ do not have any precedence constraints, the release pattern $\overline{\mathcal{R}}'$ trivially respects those constraints.

By 1. and 2., the release pattern $\overline{\mathcal{R}}'$ is legal for $\text{hp}(\tau_{ss})'$. ■

We finally prove that replacing $\text{hp}(\tau_{ss})$ by $\text{hp}(\tau_{ss})'$ in the WCRT analysis of τ_{ss} is safe.

Theorem 3. *The worst-case interference generated by the tasks in $\text{hp}(\tau_{ss})'$ is lower bounded by the worst-case interference generated by the tasks in $\text{hp}(\tau_{ss})$.*

Proof. The proof is based on the following facts:

F1. If a job of $\tau_{k,j}$ or $\tau'_{k,j}$ interferes with the execution region $\tau_{ss,p}$ of τ_{ss} than it does not interfere with any other execution region of τ_{ss}. This statement is true because (i) both $\tau_{k,j}$ and $\tau'_{k,j}$ have a higher priority than τ_{ss}, and (ii) they do not self-suspend. Therefore, when they start to interfere with one execution region of τ_{ss}, that execution region cannot resume its execution before $\tau_{k,j}$ or $\tau'_{k,j}$ complete their own execution.

F2. When they execute for their WCET, one job of $\tau_{k,j}$ generates as much interference as one job of $\tau'_{k,j}$. It is simply due to the fact that $\tau_{k,j}$ and $\tau'_{k,j}$ have the same WCET.

Let $\overline{\mathcal{R}}$ be any legal release pattern of the execution regions of the tasks in $\text{hp}(\tau_{ss})$ such that the tasks in $\text{hp}(\tau_{ss})$ generates the worst-case interference on τ_{ss}. And let $\overline{\mathcal{R}}'$ be the corresponding release pattern for the tasks in $\text{hp}(\tau_{ss})'$ such that whenever an execution region $\tau_{k,j}$ of a task $\tau_k \in \text{hp}(\tau_{ss})$ releases a job in $\overline{\mathcal{R}}$, the corresponding task $\tau'_{k,j}$ releases a job at the same instant in $\overline{\mathcal{R}}'$. By Lemma 5, $\overline{\mathcal{R}}'$ is a legal release pattern for the tasks in $\text{hp}(\tau_{ss})'$. Since by Fact F2., each job released by each task $\tau'_{k,j}$ generates as much interference than each job released by the corresponding execution region $\tau_{k,j}$, and because by Fact F1., this interference is generated in the same execution region of τ_{ss}, the total interference generated by the set of tasks in $\text{hp}(\tau_{ss})'$ under the release pattern $\overline{\mathcal{R}}'$ is equal to the worst-case interference generated by the corresponding self-suspending tasks in $\text{hp}(\tau_{ss})$ under $\overline{\mathcal{R}}$.

Therefore, because we proved that there exists at least one legal release pattern of the tasks in $\text{hp}(\tau_{ss})'$ generating as much interference as the worst-case interference generated by $\text{hp}(\tau_{ss})$, the worst-case interference generated by the tasks in $\text{hp}(\tau_{ss})'$ is lower bounded by the worst-case interference generated by the tasks in $\text{hp}(\tau_{ss})$. ■

Theorem 4. *The WCRT of τ_{ss} running concurrently with $\text{hp}(\tau_{ss})'$ is no smaller than its WCRT when it runs concurrently with $\text{hp}(\tau_{ss})$.*

Proof. Theorem 3 proves that $\text{hp}(\tau_{ss})'$ generates at least as much interference on τ_{ss} than $\text{hp}(\tau_{ss})$. Therefore, the WCRT of τ_{ss} when its runs concurrently with $\text{hp}(\tau_{ss})'$ is no smaller than its WCRT when it runs concurrently with $\text{hp}(\tau_{ss})$. ■

A. Upper Bounding $J_{k,j}$

The solution presented above requires an upper bound on the jitter $J_{k,j}$ experienced by each execution region $\tau_{k,j}$. In this section, we provide three different upper bounds (stated in Lemmas 6, 7 and 8) on the jitter $J_{k,j}$.

Lemma 6. *The release jitter $J_{k,j}$ of $\tau_{k,j}$ is upper bounded by $\text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$.*

Proof. Let a_k and f_k be the release time and the completion time of any job of τ_k, and let $a_{k,j}$ be the release time of the execution region $\tau_{k,j}$ in that job. Instant $a_{k,j}$ also corresponds to the completion time of the partial self-suspending task τ_k^j. We prove that $a_{k,j}$ is no later than $a_k + \text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$.

The proof is by contradiction. Let us assume that the completion of τ_k^j, and hence the release of $\tau_{k,j}$, happens after $a_k + \text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$, that is,

$$a_{k,j} > a_k + \text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p} \tag{1}$$

If every execution region executes for its worst-case execution time and every suspension region suspends for its worst-case suspension time, then τ_k must still execute for $\sum_{p=j}^{m_k} C_{k,p}$ time units and suspend for $\sum_{p=j}^{m_k-1} S_{k,p}$ time units after $a_{k,j}$. Therefore, even without interference from higher priority tasks, task τ_k completes its execution at time

$$f_k \geq a_{k,j} + \sum_{p=j}^{m_k} C_{k,p} + \sum_{p=j}^{m_k-1} S_{k,p}$$

Replacing $a_{k,j}$ with Eq. (1), we get

$$f_k > a_k + \text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p} + \sum_{p=j}^{m_k} C_{k,p} + \sum_{p=j}^{m_k-1} S_{k,p}$$

Simplifying and passing a_k from the right hand side to the left-hand side, we obtain

$$f_k - a_k > \text{WCRT}_k$$

which is a clear contradiction with the fact that WCRT_k is an upper bound on the response time of τ_k. It results that for any job of τ_k, the partial self-suspending task τ_k^j completes at time $a_{k,j} \leq a_k + \text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$. The worst-case response time WCRT_k^j of τ_k^j is therefore upper bounded by $\text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$.

Since the best-case response time BCRT_k^j of τ_k^j is trivially lower bounded by 0, the jitter $J_{k,j}$, which by definition is equal to $\text{WCRT}_k^j - \text{BCRT}_k^j$, is upper bounded by $\text{WCRT}_k - \sum_{p=j}^{m_k} C_{k,p} - \sum_{p=j}^{m_k-1} S_{k,p}$. ■

Lemma 7. *The release jitter $J_{k,j}$ of $\tau_{k,j}$ is upper bounded by $\sum_{p=1}^{j-1} (\text{UB}_{k,p} + S_{k,p})$ where $\text{UB}_{k,p}$ is an upper bound on the WCRT of each execution region $\tau_{k,p}$ given by the smallest positive t such that*

$$t = C_{k,p} + \sum_{\tau_\ell \in \text{hp}(\tau_k)} \left\lceil \frac{t + J_\ell}{T_\ell} \right\rceil C_\ell$$

Proof. It was proven in [3] that the WCRT of a self-suspending task τ_k^j is upper bounded by $\sum_{p=1}^{j-1} (\text{UB}_{k,p} + S_{k,p})$. Since $J_{k,j} \stackrel{\text{def}}{=} \text{WCRT}_k^j - \text{BCRT}_k^j$, and because BCRT_k^j is lower bounded by 0, we get that $J_{k,j} \leq \sum_{p=1}^{j-1} (\text{UB}_{k,p} + S_{k,p})$. ■

Lemma 8. *The release jitter $J_{k,j}$ of $\tau_{k,j}$ is upper bounded by $\text{UB}_k^j + S_{k,j-1}$ where UB_k^j is given by the smallest positive t such that*

$$t = \sum_{p=1}^{j-1} C_{k,p} + \sum_{p=1}^{j-2} S_{k,p} + \sum_{\tau_\ell \in \text{hp}(\tau_k)} \left\lceil \frac{t + J_\ell}{T_\ell} \right\rceil C_\ell$$

Proof. It was proven in [3] that the WCRT of a self-suspending task $\langle (C_{k,1}, S_{k,1}, \ldots, C_{k,j-1}), D_k, T_k \rangle$ is upper bounded by UB_k^j. Because the last suspension region $S_{k,j-1}$ of τ_k^j cannot be preempted, the WCRT of τ_k^j is given by $\text{UB}_k^j + S_{k,j-1}$. Since $J_{k,j} \stackrel{\text{def}}{=} \text{WCRT}_k^j - \text{BCRT}_k^j$, and because BCRT_k^j is lower bounded by 0, we get that $J_{k,j}$ is upper bounded by $\text{UB}_k^j + S_{k,j-1}$. ■

III. Discussion

Using Theorem 4, each higher priority self-suspending task can be transformed in a set of non-self-suspending tasks with jitter. One can therefore use the MILP formulation proposed in [1], which computes an upper bound on the WCRT a self-suspending task τ_{ss} running concurrently with a set of non-self-suspending tasks with jitter.

For the convenience of the reader, we reproduce below the MILP formulation.

$$\textbf{Maximize:} \quad \sum_{j=1}^{m_{ss}} R_{ss,j} \tag{2}$$

Subject to:

$$\sum_{j=1}^{m_{ss}} R_{ss,j} + \sum_{j=1}^{m_{ss}-1} S_{ss,j} \leq \mathrm{UB}_{ss} \tag{3}$$

$$\forall \tau_{\mathrm{ss},j} \in \tau_{\mathrm{ss}} \quad : \; R_{ss,j} = C_{ss,j} + \sum_{\tau_p \in \mathrm{hp}(\tau_{ss})'} \mathrm{NI}_{p,j} \times C_p \tag{4}$$

$$R_{ss,j} \leq \mathrm{UB}_{ss,j} \tag{5}$$

$\forall \tau_k \in \mathrm{hp}(\tau_{ss})', \forall \tau_{\mathrm{ss},j} \in \tau_{\mathrm{ss}}$:

$$O_{k,j} \geq -J_k \tag{6}$$

$$O_{k,j+1} \geq O_{k,j} + \mathrm{NI}_{k,j} \times T_k - (R_{ss,j} + S_{ss,j}) - J_k \tag{7}$$

$$\mathrm{NI}_{k,j} \geq 0 \tag{8}$$

$$\mathrm{NI}_{k,j} \leq \left\lceil \frac{R_{ss,j} - O_{k,j}}{T_k} \right\rceil \tag{9}$$

$$R_{ss,j} > \mathrm{rel}_{k,j} + \sum_{\tau_p \in \mathrm{hp}(\tau_{ss})'} \max\{0, \; \left\lfloor \frac{d_{p,j} - \mathrm{rel}_{k,j}}{T_p} \right\rfloor C_p\} \tag{10}$$

where

$$\mathrm{rel}_{k,j} \stackrel{\mathrm{def}}{=} O_{k,j} + (\mathrm{NI}_{k,j} - 1) \times T_k$$
$$d_{p,j} \stackrel{\mathrm{def}}{=} O_{p,j} + \mathrm{NI}_{p,j} \times T_p$$

and where UB_{ss} is an upper bound on the WCRT of τ_{ss} given by the smallest positive t such that

$$t = \sum_{j=1}^{m_{ss}} C_{ss,j} + \sum_{j=1}^{m_{ss}-1} S_{ss,j} + \sum_{\tau_p \in \mathrm{hp}(\tau_{ss})'} \left\lceil \frac{t + J_p}{T_p} \right\rceil C_p$$

and $\mathrm{UB}_{ss,j}$ is an upper bound on the WCRT of each execution region $\tau_{\mathrm{ss},j}$ given by the smallest positive t such that

$$t = C_{ss,j} + \sum_{\tau_p \in \mathrm{hp}(\tau_{ss})'} \left\lceil \frac{t + J_p}{T_p} \right\rceil C_p$$

Finally, an upper bound on the WCRT of τ_{ss} is given by

$$\sum_{j=1}^{m_{ss}} R_{ss,j} + \sum_{j=1}^{m_{ss}-1} S_{ss,j}$$

where $\sum_{j=1}^{m_{ss}} R_{ss,j}$ is the solution to the MILP formulation.

A. Impact on Other Results in [1]

At the exception of Claim 1, none of the other results presented in [1], including the experimental section, are impacted by the error reported in this errata.

B. Impact on Related Work

To the best of the authors' knowledge, three papers [4]–[6] building on top of [1] were published recently. As far as the authors can tell, the results in those papers *were not affected* by the error reported in this technical report.

References

[1] G. Nelissen, J. Fonseca, G. Raravi, and V. Nélis, "Timing analysis of fixed priority self-suspending sporadic tasks," in *27th Euromicro Conference on Real-Time Systems (ECRTS 2015)*. IEEE Computer Society, Jul 2015, pp. 80–89.

[2] J. Palencia and M. Gonzalez Harbour, "Schedulability analysis for tasks with static and dynamic offsets," in *RTSS'98*, Dec 1998, pp. 26–37.

[3] K. Bletsas, "Worst-case and best-case timing analysis for real-time embedded systems with limited parallelism," Ph.D. dissertation, University of York, Department of Computer Science, 2007, pp. 131–141.

[4] J. Fonseca, G. Nelissen, V. Nélis, and L. M. Pinho, "Response time analysis of sporadic dag tasks under partitioned scheduling," in *11th IEEE Symposium on Industrial Embedded Systems (SIES)*, 2016, pp. 1–10.

[5] A. Biondi, A. Balsini, M. Pagani, E. Rossi, M. Marinoni, and G. Buttazzo, "A framework for supporting real-time applications on dynamic reconfigurable fpgas," in *IEEE Real-Time Systems Symposium 2016 (RTSS)*, 2016, pp. 1–12.

[6] M. Mohaqeqi, P. Ekberg, and W. Yi, "On fixed-priority schedulability analysis of sporadic tasks with self-suspension," in *24th International Conference on Real-Time Networks and Systems (RTNS)*, 2016, pp. 109–118.