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# Timing Analysis of Mixed-Criticality Hard Real-Time Applications Implemented on Distributed Partitioned Architectures

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## Abstract

*In this paper we are interested in the timing analysis of mixed-criticality embedded real-time applications mapped on distributed heterogeneous architectures. Mixed-criticality tasks can be integrated onto the same architecture only if there is enough spatial and temporal separation among them. We consider that the separation is provided by partitioning, such that applications run in separate partitions, and each partition is allocated several time slots on a processor. Each partition can have its own scheduling policy. We are interested to determine the worst-case response times of tasks scheduled in partitions using fixed-priority preemptive scheduling. We have extended the state-of-the-art algorithms for schedulability analysis to take into account the partitions. The proposed algorithm has been evaluated using several synthetic and real-life benchmarks.*

## 1 Introduction

The current trend in mixed-criticality systems is towards “partitioned architectures”, where several safety-critical functions, of different criticalities, are integrated into the same platform. Safety-Integrity Levels (SILs) capture the criticality level, and will dictate the development and certification procedures that have to be followed. In avionics, the proposed partitioning solution is based on “Integrated Modular Avionics” (IMA) [13], which allows the integration of mixed-criticality functions as long as there is enough spatial and temporal partitioning [13].

There are two basic approaches for handling hard real-time applications [7]. In the Event-Triggered (ET) approach, activities are initiated whenever a particular event is noted. In the Time-Triggered (TT) approach, activities are initiated at predetermined points in time. There has been a long debate in the real-time and embedded systems communities concerning the advantages of each approach, and the consensus is that the right approach depends on the particularities of the application [8]. Hence, in this paper, we assume that applications can be scheduled either using a TT approach, e.g., static-cyclic scheduling (SCS) or an ET approach, such as fixed-priority preemptive scheduling (FPS).

There is a large amount of research on hard real-time systems [7]. Researchers have addressed systems with mixed time-criticality requirements, showing how TT/ET tasks [10] can be integrated onto the same platform. Researchers have also started to address the integration of mixed safety-criticality tasks onto the same architecture [2, 14]. In [14], we have proposed an optimization approach to determine the

mapping of tasks to PEs, the assignment of tasks to partitions, the sequence and size of the time slots on each PE and the schedule tables, such that all the applications are schedulable and the development costs are minimized.

In this paper we are interested in the timing analysis of applications which are running in partitions that use FPS. There is a large amount of research on scheduling and schedulability analysis [7, 3]. In this paper we use a response-time analysis [3] to calculate the worst-case response time  $R_i$  of every task  $\tau_i$ , which is then compared to its deadline  $D_i$ . The basic response-time analysis presented in [3] has been extended over the years [5]. For example, the state-of-the-art analysis from [9] considers arbitrary arrival times and deadlines, offsets and synchronous inter-task communication (where a receiving task has to wait for the input of the sender task).

Audsley and Wellings [1] have proposed a schedulability analysis for FPS tasks in the context of temporal partitioning (let us denote this analysis with “SA”, from Schedulability Analysis), which, when analyzing a FPS task in a certain partition, considers the other time-partitions as higher priority tasks. This analysis assumes that the deadlines are smaller or equal to the periods, that the tasks are independent, and that the start times of partition slices within a major frame are periodic. Pop et al. [10] have proposed a schedulability analysis for ET tasks, which extends the schedulability analysis in [9] to consider the influence of the TT tasks on the worst-case response times of the ET tasks. Such an analysis can be extended to consider that the TT tasks are “partitions” which can interfere with the ET tasks.

In this paper we have decided to extend the WCDOPS+ algorithm from [12], which extends the Worst Case Dynamic Offsets with Priority Schemes (WCDOPS) schedulability analysis algorithm from [9]. Our proposed analysis, denoted with “SA+”, takes into account the influence of time-partitions on the schedulability of the FPS tasks, and does not assume that the partition slices have to be periodic, as in [1]. Section 5 presents WCDOPS+, and our approach is presented in Section 5.1. The proposed schedulability analysis algorithm has been evaluated using several synthetic and real-life benchmarks, and has been compared to the analysis from [1].

## 2 Application Model

We consider a set of mixed-criticality applications. Each application has a SIL-level, from  $SIL_4$  (most critical) to  $SIL_0$  (non-critical) and is developed according to the certification requirements for the particular SIL. This section presents the application model of applications scheduled with FPS. For the full model the reader is referred to [14].

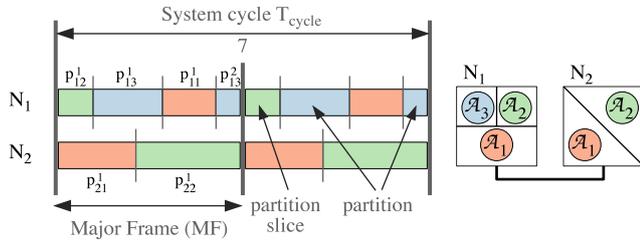


Figure 1: Partitioned architecture

We consider that the mapping of tasks to processing elements (PEs) and the assignment of tasks to partitions is given, and can be determined using our approach from [14]. We model an application  $\mathcal{A}$  as a directed, acyclic graph  $\Gamma(\mathcal{V}, \mathcal{E})$ . Each node  $\tau_i \in \mathcal{V}$  represents one task. An edge  $e_{ij} \in \mathcal{E}$  represents a precedence relationship between  $\tau_i$  and  $\tau_j$ , and indicates that  $\tau_i$  must complete its execution before  $\tau_j$ . Each task  $\tau_i$  is characterized by a worst-case execution time (WCET)  $C_i$  (on the PE that is assigned to for execution), a best-case execution time  $C_i^{min}$ , and in case the task uses shared resources, a maximum blocking time  $B_i$ . Additionally,  $\tau_i$  has a unique priority denoted by  $prio(\tau_i)$ , an offset  $\Phi_i$  and a maximum release time jitter  $J_i$ . Thus, considering that the graph  $\Gamma$  to which  $\tau_i$  belongs is triggered by an external event arriving at  $t_0$ ,  $\tau_i$  arrives at time  $t_0 + \Phi_i$  and is released after an additional maximum delay of  $J_i$ . For each application we have a deadline  $D_{\mathcal{A}}$  and a period  $T_{\mathcal{A}}$ .

### 3 System Model

We consider architectures composed of a set  $\mathcal{N}$  of PEs connected by a broadcast communication channel. We assume that the hardware and software architecture implements a temporal- and space-partitioning scheme similar to IMA [14].

Each application  $\mathcal{A}_i$  is allowed to execute only within its defined partition  $P_j$ . Each partition can use its own scheduling policy. On a processing element  $N_i$ , a partition  $P_j$  is defined as the sequence  $P_{ij}$  of  $k$  partition slices  $p_{ij}^k$ ,  $k \geq 1$ . A partition slice  $p_{ij}^k$  is a predetermined time interval in which the tasks of application  $\mathcal{A}_j$  mapped to  $N_i$  are allowed to use the PE. All the slices on a processor are grouped within a Major Frame (MF), that is repeated periodically. The period  $T_{MF}$  of the major frame is given by the designer and is the same on each node. Several MFs are combined together in a system cycle that is repeated periodically, with a period  $T_{cycle}$ .

In Fig. 1 we have 3 applications,  $\mathcal{A}_1$ ,  $\mathcal{A}_2$  and  $\mathcal{A}_3$ , implemented on 2 PEs,  $N_1$  and  $N_2$ , with  $T_{MF} = 10$  and  $T_{cycle} = 20$ . The tasks of  $\mathcal{A}_1$ , for example, can execute only in partition  $P_1$  on PE  $N_1$ , composed of the partition slice  $p_{1,1}^1$ , and in partition  $P_1$  on PE  $N_2$ , composed of the slice  $p_{2,1}^1$ . The sequence and length of the partition slices in a MF are the same (on a given PE), but the contents of the slices can differ. An application can extend its execution over several MFs.

For simplicity, in this paper we ignore the communication. However, researchers have shown how realistic bus protocols, e.g., FlexRay [11], can be integrated into the analysis.

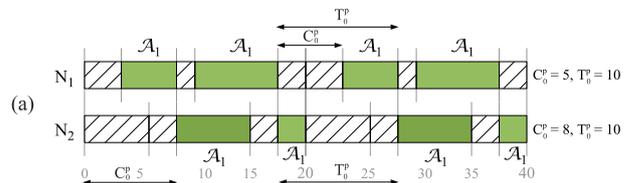


Figure 2: Motivational example

### 4 Motivational Example

Let us illustrate the importance of accurately taking the partitions into account during the analysis using the example in Fig. 2. We consider a system with 2 PEs and 6 tasks. The partition table is given in Fig. 2a, where two consecutive MFs with  $T_{MF} = 20$  are presented. The details of the application are given in Fig. 2b (the tasks are sorted according to their priorities—highest on the top—and the deadlines are equal to the periods).

The mapping and the partitioning are given, and we assume they are derived with our approach from [14]. The hashed partition slices represent partitions on which the application  $\mathcal{A}_1$  is not allowed to execute. The partition slices corresponding to the application  $\mathcal{A}_1$  are coloured in green.

We are interested to determine the worst-case response times of the tasks in Fig. 2b considering the partitions in Fig. 2a. We have compared the SA analysis from [1] with our proposed analysis, SA+. To facilitate the comparison, we consider the assumptions from [1], i.e., deadlines are equal to the periods, and we ignore the dependencies. The SA results are presented in column 5 in Fig. 2b, and the SA+ results are in column 6. As we can see, SA is much more pessimistic (the application is considered unschedulable) compared to our proposed analysis, SA+.

The pessimism of SA comes from its limiting assumptions that the partition slices have to be periodic within a MF. This assumption is not true in practice, but it simplifies the analysis. When analyzing the tasks in a partition  $P_j$  on a PE  $N_i$ , SA merges all the other partition slices into a “higher priority task” with WCET  $C_0^p$  (the length of the other slices) and period  $T_0^p$ . In order to apply SA in the general context of Fig. 2a, we have to consider  $C_0^p$  as the longest time-interval of continuous partition slices  $\notin P_j$  on  $N_i$ , and  $T_0^p$  as the shortest inter-arrival time of these intervals. These values are calculated for each PE. For example, the values of  $C_0^p$  and  $T_0^p$  for  $N_1$  and  $N_2$  in Fig. 2a are as depicted in the figure. Our proposed analysis, SA+, does not assume that the partition slices have to be periodic, and thus reduces the pessimism of SA by accurately taking into account the exact position and size of the partition slices.

### 5 Response Time Analysis

WCDOPS+ [12] is an algorithm that performs worst-case response time analysis on fixed priority scheduled tasks disposed in tree-shaped transactions taking into consideration

|          | $C_i$ | $T_i$ | PE    | $R_i^{SA}$ | $R_i^{SA+}$ |
|----------|-------|-------|-------|------------|-------------|
| $\tau_1$ | 2     | 15    | $N_1$ | 12         | 7           |
|          | 8     | 40    | $N_1$ | 20         | 19          |
| $\tau_2$ | 3     | 30    | $N_1$ | 30         | 27          |
|          | 3     | 30    | $N_2$ | 19         | 14          |
| $\tau_3$ | 4     | 40    | $N_2$ | 50         | 18          |
|          | 8     | 100   | $N_1$ | 120        | 59          |

the precedence constraints between them, which later was extended to consider graphs [6].

The WCDOPS+ response time analysis for a certain task  $\tau_{ab}$  is based on finding the contributions from each transaction in the system to a busy period of  $\tau_{ab}$ . The busy period (also called busy window) of  $\tau_{ab}$  is defined as the longest interval of time during which tasks with priority greater or equal than  $\tau_{ab}$  are executed continuously [5].

When studying the contribution of a transaction  $\Gamma_i$  to the worst case response time of a task  $\tau_{ab}$ , it may be useful to somehow group the tasks of  $\Gamma_i$  and treat each group as if it were a single task. The creation of these groups of tasks is accomplished by defining the concepts of  $H$  sections and  $H$  segments. Two tasks of a transaction  $\Gamma_i$  belong to the same  $H$  section for the analysis of  $\tau_{ab}$  if they belong to  $hp_i(\tau_{ab})$  and there is no intermediate task in the transaction that belongs to  $lp_i(ab)$ . Similarly, two tasks of a transaction  $\Gamma_i$  belong to the same  $H$  segment for the analysis of  $\tau_{ab}$  if they belong to  $hp_i(\tau_{ab})$  and there is no intermediate task in the transaction that does not belong to  $hp_i(ab)$ . The set of tasks  $hp_i(ab)$  represents the tasks belonging to a transaction  $\Gamma_i$  that are executed on the same PE as  $\tau_{ab}$  and have a priority greater or equal than  $\tau_{ab}$ . The set  $lp_i(\tau_{ab})$  contains tasks belonging to  $\Gamma_i$  and executed on the same PE as  $\tau_{ab}$  that have lower priorities than  $\tau_{ab}$ .

$H$  segments are more restrictive than  $H$  sections in the sense that if two tasks belong to the same  $H$  section with respect to a task  $\tau_{ab}$ , then they *may* belong to the same  $\tau_{ab}$  busy period, while if two tasks belong to the same  $H$  segment with respect to a task  $\tau_{ab}$ , then they *must* belong to the same  $\tau_{ab}$  busy period.

WCDOPS+ analyzes separately the contributions to the  $\tau_{ab}$  busy period: first, the contributions made by all the transactions to which the task  $\tau_{ab}$  doesn't belong to; secondly, the contribution made by the transaction  $\Gamma_a$  of which  $\tau_{ab}$  is a part of. For each transaction, two types of contributions are considered: a non-blocking interference ( $W_i$ ) and a blocking interference ( $WB_i$ ). Since, as shown in [12] only one blocking  $H$  segment can contribute to the busy period, WCDOPS+ allows this contribution to the transaction with the maximum interference increase ( $\Delta W = WB_i - W_i$ ).

The worst-case response time of an instance of  $\tau_{ab}$  with the index  $p_{ab}$  is determined by WCDOPS+ based on its completion time,  $w_{abc}(p_{ab})$ , which is composed of the following: the maximum blocking time from lower priority tasks, a blocking interference and a non-blocking interference from the transactions in the system. The blocking interference is expressed through the interference increase which has to be maximized for the calculation of worst case completion time. Since there can only be one blocking segment executing in a busy period, the interference increase is chosen to be the maximum from the interference increases calculated separately:

$$\Delta W_{ac}^*(\tau_{ab}, w, p_{ab}) = \text{MAX}(\Delta W_{ac}(\tau_{ab}, w, p_{ab}), \Delta W_i^*(\tau_{ab}, w, p_{ab}, \tau_{ac})) \quad (1)$$

The non blocking interference is obtained by summing up the non blocking interferences from all transactions in the

system, so the completion time  $w_{abc}(p_{ab})$  is

$$w_{abc}(p_{ab}) = B_{ab} + W_{ac}(\tau_{ab}, w, p_{ab}) + \sum_{\forall i \neq a} W_i^*(\tau_{ab}, w, \tau_{ac}) + \Delta W_{ac}^*(\tau_{ab}, w, p_{ab}) \quad (2)$$

This equation is solved iteratively and because the instance  $p_{ab}$  of task  $\tau_{ab}$  arrives at  $\varphi_{abc} + (p_{ab} - 1)T_a$ , its response time is [12]:

$$R_{abc}^w(p_{ab}) = w_{abc}(p_{ab}) - \varphi_{abc} - (p_{ab} - 1)T_a + \phi_{ab} \quad (3)$$

The worst-case response time  $R_{ab}^w$  for the task  $\tau_{ab}$  is the maximum value of the result in Eq. 3, considering all the critical instants initiated by higher priority tasks and by  $\tau_{ab}$  and also all the job instances.

## 5.1 Extending WCDOPS+ with Partitioning

We have extended WCDOPS+ to take into account the partitions by using the concepts of *availability* and *demand*, inspired by the approach presented in [10]. Informally, the *availability* associated to a task  $\tau_{ij}$  during a time interval  $t$ , denoted as  $A_{ij}(t)$ , is equal to the processor time that is not used by other partitions during  $t$ . The *demand* for a task  $\tau_{ij}$  during a time interval  $t$ , denoted as  $H_{ij}(t)$ , is equal to the sum of the processor times required by  $\tau_{ij}$  and all higher priority tasks mapped to the same processor during  $t$ .

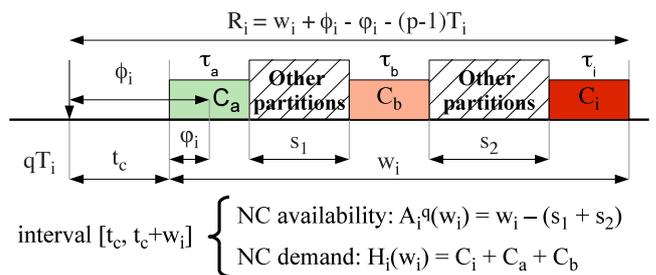


Figure 3: Availability and demand

In more general terms, the demand of a task scheduled in a partition  $P_k$  is equal to the length of its busy period when there wouldn't be any time partitions considered or when  $P_k$  would be the only partition on the processor. Fig. 3 shows that the demand of task  $\tau_i$  during the busy window  $w_i$  is equal to the sum of the worst-case execution time of the higher priority tasks  $C_a$  and  $C_b$  and the worst-case execution time of the task in question,  $C_i$ . In the WCDOPS+ analysis, the length of a  $\tau_{ab}$  busy period is called  $\tau_{ab}$ 's completion time and is expressed in Eq. 2. Thus, the demand  $H_{abc}(p_{ab})$  of an instance  $p_{ab}$  of a task  $\tau_{ab}$  during a busy period initiated by a task  $\tau_{ac}$  is equal to  $p_{ab}$ 's completion time.

$$H_{abc}(p_{ab}) = w_{abc}(p_{ab}) \quad (4)$$

The availability associated to an instance  $p_{ab}$  of a task  $\tau_{ab}$ , scheduled in a partition  $P_k$ , is the processing time available during  $w_{ab}(p_{ab})$  for  $P_k$ . Because of the time partitioning scheme and because task  $\tau_i$  can execute only during its own partition  $P_k$ , the availability is calculated by subtracting from  $w_{ab}(p_{ab})$  the time reserved for the "other" partitions.

In Fig. 3, the availability is shown as what is left after subtracting from  $w_i$  the durations of the other partitions,  $s_1$  and  $s_2$ .

As a consequence of considering the partitioning scheme, the completion time  $w_{abc}(p_{ab})$  of an instance  $p_{ab}$  of task  $\tau_{ab}$  is replaced by an *extended completion time*  $e_{abc}(p_{ab})$ , computed according to Algorithm 1. The purpose of this algorithm is to increase a task’s completion time until the availability is at least as large as the demand during this time interval. The algorithm starts by initializing the extended completion time of  $p_{ab}$  with  $p_{ab}$ ’s original completion time and the availability and demand with 0 (lines 10–12). It then proceeds to iteratively re-compute the availability and demand until the availability is greater or equal to the demand (lines 13–19). At each iteration, the extended completion time of  $p_{ab}$  is increased with the difference between the current values of the availability and demand (lines 16–18). Finally, the obtained extended completion time is returned (line 20).

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**Algorithm 1** EXTENDED\_COMPLETION\_TIME

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1: Inputs:
2:  $\tau_{ab}$  - a task;
3:  $p_{ab}$  - an instance of  $\tau_{ab}$ ;
4:  $\tau_{ac}$  - a task starting a  $p_{ab}$  busy period;
5:  $w_{abc}$  - completion time of  $p_{ab}$ ;
6: Outputs:
7:  $e_{abc}$  - extended completion time of  $p_{ab}$ ;
8:
9: begin
10:  $e_{abc} \leftarrow w_{abc}$ ;
11:  $demand \leftarrow 0$ ;
12:  $availability \leftarrow 0$ ;
13: repeat
14:    $demand \leftarrow COMPUTE\_DEMAND(\tau_{ab}, p_{ab},$ 
      $\tau_{ac}, e_{abc})$ ;
15:    $availability \leftarrow COMPUTE\_AVAILABILITY(w_{abc})$ ;
16:   if  $demand > availability$  then
17:      $e_{abc} \leftarrow e_{abc} + demand - availability$ ;
18:   end if
19: until  $availability \geq demand$ 
20: return  $e_{abc}$ ;
21: end

```

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## 6 Experimental Evaluation and Conclusions

Table 1 presents our experimental evaluation. We have used seven synthetic benchmarks and one real-life example. The synthetic benchmarks were generated similar to [14], and the number of PEs and number of tasks in the FPS applications are presented in columns 2 and 3, respectively, in Table 1. The real-life case study is derived from the “automotive” benchmark in the E3S suite [4]. The partition tables and the mapping have been generated using the “Initial Solution” approach from [14]. We have run both SA and SA+ on these tasks sets. Columns 4 and 5 present the number of tasks found schedulable, i.e.,  $R_i \leq D_i$ , using SA and SA+, respectively. To show the reduction in the pessimism of SA+ over SA, the last column in the table represents the percentage reduction of worst-case response times obtained

with SA+ compared to SA averaged over all tasks.

As we can see from these results, accurately taking into account the partitions during the analysis can significantly reduce the pessimism of the results.

Table 1: Experimental results

| Test Case  | PEs | Tasks | SA | SA+ | %<br>reduction |
|------------|-----|-------|----|-----|----------------|
| 1          | 2   | 4     | 3  | 4   | 59.04          |
| 2          | 3   | 7     | 5  | 7   | 27.95          |
| 3          | 3   | 10    | 6  | 10  | 46.82          |
| 4          | 4   | 16    | 12 | 15  | 41.66          |
| 5          | 4   | 19    | 17 | 19  | 24.91          |
| 6          | 5   | 22    | 20 | 22  | 56.67          |
| 7          | 5   | 25    | 21 | 25  | 30.23          |
| automotive | 3   | 5     | 4  | 4   | 34.18          |

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