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A Discrete Time Markov Decision Process for Energy Minimization Under Deadline Constraints

Bruno Gaujal, Alain Girault, Stéphan Plassart *

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Abstract: This paper proposes a Discrete Time Markov Decision Process (MDP) approach to compute the optimal on-line speed scaling policy to minimize the energy consumption of a single processor executing a finite or infinite set of jobs with real-time constraints. We provide several qualitative properties of the optimal policy: monotonicity with respect to the jobs parameters, comparison with on-line deterministic algorithms. Numerical experiments in several scenarios show that our proposition performs well when compared with off-line optimal solutions and out-performs on-line solutions oblivious to statistical information on the jobs.

Key-words: Optimization, Real-Time Systems, Markov Decision Process, Dynamic Voltage and Frequency Scaling

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Un processus à décision de Markov en temps discret pour minimiser l'énergie sous des contraintes d'échéances

Résumé : Ce papier propose une approche de processus à décision de Markov (PDM) en temps discret pour calculer la politique de vitesses en-ligne optimale qui minimise la consommation d'énergie d'un seul processeur qui exécute un ensemble de tâches fini ou infini avec des contraintes temps-réel. Plusieurs propriétés de la politique optimale sont présentées: monotonie en fonction des paramètres des tâches et comparaison avec les algorithmes déterministes hors-ligne. Des expérimentations numériques dans le cadre de différents scénarios montrent que notre solution est proche des solutions optimales hors-ligne et est meilleure que les solutions en-ligne qui ne considèrent pas les informations statistiques sur les tâches.

Mots-clés : Optimisation, Système temps-réel, Processus à Décision de Markov, Adaptation en Fréquence et Ajustement Dynamique de Tension.

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1 Introduction

Minimizing the energy consumption of embedded system is becoming more and more important. This is due to the fact that more functionalities and better performances are expected from such systems, together with a need to limit the energy consumption, mainly because batteries are becoming the standard power supplies.

The starting point of this work is the seminal paper of Yao et al. [1] followed by the paper of Bansal et al. [2], both of which solve the following problem.

Let $(r_i, c_i, d_i)_{i \in \mathbb{N}}$ be a set of jobs, where r_i is the release date (or *arrival time*) of job i , c_i is its size (or *WCET*, or *workload*) *i.e.*, the number of processor cycles needed to complete the job, and d_i is its relative *deadline*, *i.e.*, the amount of time given to the processor to execute job i . The problem is to choose the speed $s(t)$ of the processor¹ as a function of the time t , such that the processor can execute all the jobs before their deadlines, and such that the total energy consumption J is minimized. In this problem, J is the *dynamic* energy consumed by the processor: $J = \int_0^T j(s(t))dt$, where T is the time horizon of the problem (in the finite horizon case) and $j(s)$ is the power consumption when the speed is s .

This problem has been solved in Yao et al. [1] when the power function j is a *convex* function of the speed, in the *off-line* case, *i.e.*, when *all* jobs are known in advance. Many variants have been proposed to this off-line solution, for different job and energy models (see e.g., [3]). However, in practice the *exact characteristics* of all the upcoming jobs cannot be known in advance, so the off-line case is unrealistic.

Several solutions have been investigated by Bansal et al. in [2] in the *on-line* case, *i.e.*, when only the jobs released at or before time t can be used to select the speed $s(t)$. Bansal et al. prove that an on-line algorithm introduced in [1], called Optimal Available (OA), has a competitive ratio of α^α when the power dissipated by the processor working at speed s is of the form $j(s) = s^\alpha$. In CMOS circuits, the value of α is typically 3. In such a case, (OA) may spend 27 times more energy than an optimal schedule in the worst case. The principle of (OA) is to choose, at each time t , the *smallest* processor speed such that all jobs released at or before time t meet their deadlines, under the assumption that no more jobs will arrive after time t .

However, this assumption made by (OA) is questionable. Indeed, the speed selected by (OA) at time t will certainly need to be compensated (*i.e.*, increased) in the future due to jobs released after t . This leads to an energetic inefficiency when the j function is convex. In contrast, our intuition is that the best choice is to select a speed *above* the one used by (OA) to *anticipate* on those future job arrivals.

The goal of our paper is to give a precise solution to this intuition by using *statistical knowledge* of the job arrivals (which could be provided by the user) in order to select the processor speed that optimizes the *expected* energy consumption.

Other constructions also based on statistical knowledge have been reported in [4, 5, 6] with a simpler framework, namely for a *single* job whose execution time is uncertain but whose release time and deadline are given, or in [7] by using heuristic schemes. Furthermore, [8] solves also an on-line problem, but with a task set of a *fixed* size; jobs have known execution times and deadlines, and their arrival times have known bounds. Moreover the scheduling policy of [8] is limited to the non-preemptive case. In contrast, we address the case of a finite or infinite number of jobs with uncertain release times, but with a known execution time at release time.

¹Different communities use the term “speed” or “frequency”, which are equivalent for a processor. In this paper, we use the term “speed”.

This is a constrained optimization problem that we are able to model as an unconstrained Markov Decision Process (MDP) by choosing a proper state space that also encodes the constraints of the problem. This is achieved at the expense of the size of the state space (see § 2.4). In particular, this implies that the optimal speed at each time can be computed using a *dynamic programming* algorithm and that the optimal speed at any time t will be a deterministic function of the current state at time t .

In the first part of this paper (§ 2), we present our job model and the problem addressed in the paper. We define the state space of our problem (§ 2.3) and analyze its complexity (§ 2.4). In a second part (§ 3), we construct a Markov Decision Process model of this problem. We propose an explicit *dynamic programming* algorithm to solve it when the number of jobs is finite (§ 3.1), and a *Value Iteration* algorithm [9] for the infinite case (§ 3.2). Finally, we compute numerically the optimal policy in the finite and infinite horizon cases, and compare its performance with off-line policies and “myopic” policies like (OA), oblivious to the arrival of future jobs (§ 4). Moreover we present several useful generalizations: how to account for the cost of processor speed changes, for the cost of task context switches, and for non-convex power functions (§ 5).

This research report is an extended version of [10] in several ways. First we generalize the set of jobs where this approach is possible to simultaneous arrivals and arrival distributions with bounded memory (see Sections 2.3 and 3).

The second addition is the most important one. We provide a proof that discrete decision times are optimal in this framework even when VDD hopping makes a continuous speed range available (see Appendix B).

2 Presentation of the Problem

2.1 Job features, Processor Speed, and Power

We consider a real-time system with one uni-core processor that executes a set \mathcal{J} of real-time jobs, sporadic and independent. In the finite case $\mathcal{J} = \{J_i\}_{1 \leq i \leq N}$ where N is the number of jobs, and in the infinite case $\mathcal{J} = \{J_i\}_{1 \leq i}$. Each job J_i is defined by the triplet (τ_i, c_i, d_i) , where τ_i is the *inter-arrival time* between J_i and J_{i-1} , with $\tau_1 = 0$ by convention, c_i is the WCET, and d_i is the *relative deadline*. From the τ_i values, we can reconstruct the release time r_i of each job J_i as:

$$\begin{cases} r_1 = 0 & \text{by convention} \\ r_i = \sum_{k=1}^i \tau_k & \forall i > 1 \end{cases} \quad (1)$$

Jobs in \mathcal{J} are ordered by their release times r_i , and jobs with the same arrival time are ordered arbitrarily.

We assume that the triplets $(\tau_i, c_i, d_i)_{i \in \mathcal{J}}$ are random variables, defined on a common probability space, whose joint distribution is known (for example by using past observations of the system): $\mathbb{P}(\tau_i = t, c_i = c, d_i = d)$ is supposed to be known for all t, c, d .

We also assume that the relative deadlines of the jobs are bounded by a maximal value, denoted Δ :

$$\Delta = \max_{i \in \mathcal{J}} \Delta_i \quad (2)$$

where Δ_i is the maximal value in the support of the distribution of the relative deadline d_i of job J_i , which is assumed to be finite. The assumption that the deadlines are bounded is classical in real-time systems.

Finally, we assume that the distribution of inter-arrival times has a finite memory bounded by L : For all $i \in \mathcal{J}$ and all t, c, d ,

$$\begin{aligned} \forall G \geq L, \\ \mathbb{P}(\tau_i = t, c_i = c, d_i = d | \tau_i \geq G) = \mathbb{P}(\tau_i = t, c_i = c, d_i = d | \tau_i \geq L). \end{aligned} \quad (3)$$

We further define ℓ_t as the time elapsed between the last job arrival and t .

Regarding the single processor, we assume it can run at any time t at a speed $s(t)$ belonging to a finite set of integer speeds \mathcal{S} :

$$\forall t, s(t) \in \mathcal{S} = \{0, s_1, \dots, s_{k-1}, s_{\max}\}.$$

The processor speeds are usually given as fractional numbers, e.g., $\{0, 1/4, 1/2, 3/4, 1\}$, 1 being the maximal speed by convention. Without loss of generality, we scale the speeds such that $s_1, \dots, s_k, s_{\max}$ are all integer numbers. For instance, the set $\{0, 1/4, 1/2, 3/4, 1\}$ will be scaled to $\{0, 1, 2, 3, 4\}$. This same scaling factor is also applied to the WCETs, e.g., a job of size 1 becomes a job of size 4.

We consider that the power dissipated by the processor working at speed $s(t)$ at time t is $j(s(t))$, so that the energy consumption of the processor from time 0 to time T is computed as $J = \int_0^T j(s(t)) dt$. Usually, the power consumption j is a convex increasing function of the speed (see [1, 2]). This classical case is based on models of the power dissipation of CMOS circuits. Finer models use star-shaped functions [11] to further take into account static leakage. In the present paper, the function j is *arbitrary*. However several structural properties of the optimal speed selection will only hold when the function j is convex. In the numerical experiments (§ 4), several choices of j are used, to take into account different models of power consumption.

For the sake of simplicity, at first we only consider the following simple case: context switching time is null, speed changes are instantaneous and the power consumption function j is convex. However, preemption times, time lags for speed changes, as well as non-convex energy costs can be taken into account with minimal adaptation to the current model. A detailed description of all these generalizations is provided in § 5.

2.2 Problem Statement

The objective is to choose at each time t the speed $s(t) \in \mathcal{S}$ in order to minimize the total energy consumption over the time horizon T , while satisfying the real-time constraints of all the jobs. Furthermore, the choice must be made on-line, *i.e.*, it can only be based on past and current information. In other words, only the jobs released at or before time t are known, while only statistical information is available for all future jobs.

As explained previously, the *statistical information* about the jobs is the distribution of the features: $\mathbb{P}(\tau_i = t, c_i = c, d_i = d)$ is supposed to be known for all t, c, d .

Besides, the *history* at time t is the set $\mathcal{H}(t)$ of all the jobs arrived at or before t , along with all the speeds used at or before t :

$$\mathcal{H}(t) = \{(\tau_i, c_i, d_i) | r_i \leq t\} \cup \{s(u), u \leq t\}. \quad (4)$$

Notice that in this model, unlike in [4, 5], the workload c_i and the deadline d_i are known at the release time of job i ².

We now define the on-line energy minimization problem (\mathcal{P}) as:

²When the actual workload can be smaller than WCET, our approach still applies by modifying the state evolution Eq. (6), to take into account early termination of jobs.

Find on-line speeds $s(t)$ (i.e., $s(t)$ can only depend on the history $\mathcal{H}(t)$) and a scheduling policy $R(t)$ in order to minimize the expected energy consumption under the constraint that no job misses its deadline.

Since all release times and job sizes are integer numbers, the information available to the processor only changes at integer point.

In the following, we will focus on the case where the decision times (instants when the processor can change its speed) are also integers. We show in Appendix B that this can be done without any loss in optimality. Now, if we consider that the speed $s(t)$ can only change at integer points too, we can focus on integer times: $t \in \mathbb{N}$ in the following.

Let (s^*, R^*) be an optimal solution to problem (\mathcal{P}) . Since the energy consumption does not depend on the schedule (preemption is assumed to be energy-free) and since the *Earliest Deadline First* (EDF) scheduling policy is optimal for schedulability even when the speed of the processor changes arbitrarily as proved in Appendix C, then (s^*, EDF) is also an optimal solution to problem (\mathcal{P}) . In the following, we will always assume with no loss of optimality that the processor uses EDF to schedule its jobs. This implies that the only useful information to compute the optimal speed at time t , out of the whole history $\mathcal{H}(t)$, is simply the *remaining work*.

Definition 1 The remaining work at time t is an increasing function $w_t(\cdot)$ defined as follows: $w_t(u)$ is the amount of work arrived before t that must be completed before time $t + u$.

Since all available speeds, job sizes and deadlines are integer numbers, the remaining work $w_t(u)$ is an integer valued *càdlàg*³ staircase function.

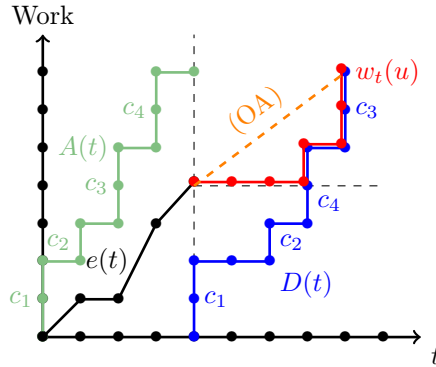


Figure 1: Construction of the remaining work function $w_t(\cdot)$ at $t = 4$, for jobs $J_1 = (0, 2, 4)$, $J_2 = (1, 1, 5)$, $J_3 = (1, 2, 6)$, $J_4 = (1, 2, 4)$, $J_5 = (1, 0, 6)$, and processor speeds $s_0 = 1, s_1 = 0, s_2 = 2, s_3 = 1$. $A(t)$ is the amount of work that has arrived before time t . $D(t)$ is the amount of work that must be executed before time t . $e(t)$ is the amount of work already executed by the processor at time t .

The definition of w_t is essential for the rest of the paper. Let us illustrate it in Figure 1, which shows the set of jobs released just before $t = 4$, namely $J_1 = (0, 2, 4)$, $J_2 = (1, 1, 5)$, $J_3 = (1, 2, 6)$, $J_4 = (1, 2, 4)$, $J_5 = (1, 0, 6)$, as well as the speeds chosen by the processor up to time $t = 4$: $s_0 = 1, s_1 = 0, s_2 = 2, s_3 = 1$. Function $A(t)$ is the amount of work that has arrived before time t . Function $D(t)$ is the amount of work that must be executed before time t . This requires a

³càdlàg = continue à droite, limite à gauche = right continuous with left limits.

detailed explanation: the first step of $D(t)$ is the deadline of J_1 at $t=0+4=4$; the second step is for J_2 at $t=1+5=6$; the third step is for J_4 at $t=3+4=7$; the fourth step is for J_3 at $t=2+6=8$. Hence the step for J_4 occurs *before* the step for J_3 . This is because Figure 1 depicts the situation at $t=4$. At $t=3$ we would only have seen the step for J_3 . Finally, function $e(t)$ is the amount of work already executed by the processor at time t ; in Figure 1, the depicted function $e(t)$ has been obtained with an arbitrary policy (*i.e.*, non optimal). Finally, the remaining work function $w_t(u)$ is exactly the portion of $D(t)$ that remains “above” $e(t)$. In Fig. 1, we have depicted in red the staircase function $w_t(u)$ for $t=4$.

Remark 1 *The on-line algorithm Optimal Available (OA) mentioned in the introduction is also based on the remaining work function: The speed of the processor at time t is the smallest slope of all linear functions above w_t . This is illustrated in Figure 1: the speed that (OA) would choose at time $t=4$ is the slope of the green dotted line marked (OA); in the discrete speeds case (finite number of speeds), the chosen speed would be the smallest available speed just above the green dotted line.*

Out of the whole history $\mathcal{H}(t)$, the remaining work function w_t together with the elapsed time since the latest arrival, ℓ_t , are the only relevant information at time t needed by the processor to choose its next speed. For this reason we call (w_t, ℓ_t) the *state* of the system at time t .

2.3 Description of the State Space

To formally describe the space \mathcal{W} of all the possible remaining work functions and their evolution over time, we introduce several constructors.

Definition 2 *We define the following operators:*

- The time shift operator $\mathbb{T}f$ is the shift on the time axis of function f , defined as:

$$\forall t \in \mathbb{R}, \quad \mathbb{T}f(t) = f(t+1).$$

- The positive part of a function f is $f^+ = \max(f, 0)$.
- The unit step function (Heaviside function), denoted $H_t(\cdot)$, is the discontinuous step function such that $\forall u \in \mathbb{R}$:

$$H_t(u) = \begin{cases} 0 & \text{if } u < t \\ 1 & \text{if } u \geq t. \end{cases}$$

Definition 3 *The set \mathcal{E}_t of the newly arrived jobs, released exactly at time t , is defined as:*

$$\mathcal{E}_t = \{J_i = (\tau_i, c_i, d_i), i \in \mathbb{N} \mid r_i = t\}. \quad (5)$$

where r_i is the release time of job J_i , defined in Eq. (1).

Furthermore, to take into account the deadlines of the new jobs, we define in Def. 4 the function $a_t(u)$ that represents the work quantity arriving exactly at time t and that must be executed before time $t+u$. Formerly,

Definition 4 *The new work arriving at t with absolute deadline before $t+u$ is given by the function $a_t(u) = \sum_{i \in \mathcal{E}_t} c_i H_{r_i+d_i}(t+u)$.*

Lemma 1 Let s_{t-1} be the processor speed at time $t-1$. Then at time t the remaining work function becomes:

$$w_t(\cdot) = \mathbb{T} [(w_{t-1}(\cdot) - s_{t-1})^+] + a_t(\cdot) \quad (6)$$

and the relationship between ℓ_t and ℓ_{t-1} is as follow:

$$\ell_t = \begin{cases} 0 & \text{if } \mathcal{E}_{t-1} \neq \emptyset \\ (\ell_{t-1} + 1) \wedge L & \text{otherwise.} \end{cases} \quad (7)$$

Proof 1 Between $t-1$ and t , the processor working at speed s_{t-1} executes s_{t-1} amount of work, so the remaining work decreases by s_{t-1} . The remaining work cannot be negative by definition, hence the term $(w_{t-1}(\cdot) - s_{t-1})^+$. After a time shift by one unit, new jobs (belong to the set \mathcal{E}_t) are released at time t , bringing additional work, hence the additional term $a_t(\cdot)$.

Concerning ℓ_t , the time between the last job arrival and t , either there are some jobs that have arrived at $t-1$, i.e. $\mathcal{E}_{t-1} \neq \emptyset$, and in this case the last job arrival is at $t-1$, which implies $\ell_t = 1$, or no jobs have arrived at $t-1$, i.e. $\mathcal{E}_{t-1} = \emptyset$, and in this case the time delay increases, hence $\ell_t = \ell_{t-1} + 1$ until ℓ_t reaches L , at which point, the exact value of ℓ_t becomes irrelevant. The only important information to assess the probability of future arrivals is the fact that ℓ_t is larger than L . □

We illustrate in Fig. 2 the state change over an example, in the particular case where a single job arrives. The red line depicts the previous remaining work function $w_{r_{n-1}}$ at time r_{n-1} , while the blue line depicts the new remaining work function w_{r_n} following the arrival of the job $(1, c_n, d_n)$ at time r_n . The quantity of work executed by the processor is s_{n-1} .

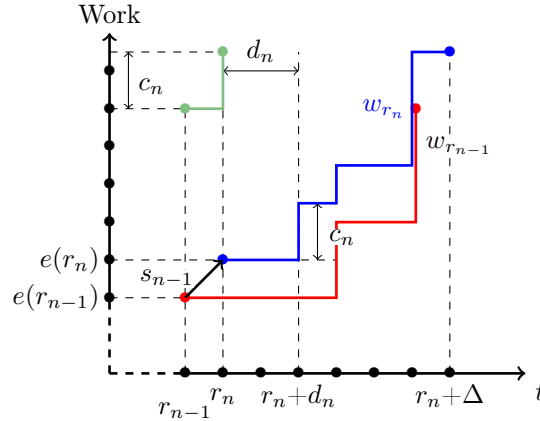


Figure 2: State change following a job arrival at time r_n . The red line corresponds to the previous remaining work function. The blue line corresponds to the new remaining work function.

2.4 Size of \mathcal{W}

2.4.1 Feasible Jobs

Definition 5 (Feasibility) A set of jobs $\mathcal{S} = \{(\tau_i, c_i, d_i)\}_i$ is feasible if no deadline is missed when the processor always uses its maximal speed and the EDF schedule.

The processor can execute at most ts_{\max} amount of work during a sliding time interval of size t . Since Δ is the maximal job deadline, all work arrived between t and $t + \Delta$ must be finished before $t + 2\Delta$. The feasibility of jobs therefore requires that $2s_{\max}\Delta$ be an upper bound on the work quantity that can arrive between t and $t + \Delta$.

Let M be the maximal work quantity that can arrive during any sliding time interval of size Δ . According to the discussion above, the feasibility requirement implies that M must satisfy the following inequality:

$$M \leq 2s_{\max}\Delta \quad (8)$$

Therefore, feasibility implies that the size of the state space (equivalently, the number of remaining work functions) is finite. We compute precisely this state space in the next section.

2.4.2 Bound on the Size of \mathcal{W}

Proposition 1 *Let Δ be the maximal deadline of a job and s_{\max} be the maximal speed. The size $Q(\Delta)$ of the set of remaining work functions \mathcal{W} is bounded by:*

$$Q(\Delta) \leq \binom{\Delta s_{\max} + \Delta - 1}{\Delta - 1} \quad (9)$$

where the notation $\binom{n}{k}$ is the binomial coefficient.

Proof 2 *A state is an increasing integer functions $w_i(\cdot)$. As discussed before, in the worst case, the total remaining work at time t cannot exceed Δs_{\max} , and this remaining work is due before $t + \Delta$. Therefore, each remaining work function can be seen, in the two-dimension integer grid, as an increasing path that connects the point $(0, 0)$ to a point (Δ, K) , $K \leq \Delta s_{\max}$. Hence the size of the space \mathcal{W} is smaller than the total number of increasing paths from $(0, 0)$ to $(\Delta, \Delta s_{\max})$ (by extending paths ending in (Δ, K) , with $K \leq \Delta s_{\max}$), that is:*

$$Q(\Delta) \leq \binom{\Delta s_{\max} + \Delta - 1}{\Delta - 1}$$

□

2.4.3 Jobs with Bounded Sizes

Here we consider the particular case where the amount of work arriving at any time t is bounded (the bound is denoted by C). This leads to a smaller state space size, which is given in Prop. 2.

Proposition 2 *Let C be the maximal amount of work that can arrive at each time t . Then the size $Q(\Delta, C)$ of the space \mathcal{W} is bounded by:*

$$Q(\Delta, C) = \sum_{y_1=0}^C \sum_{y_2=y_1}^{2C} \sum_{y_3=y_2}^{3C} \cdots \sum_{y_{\Delta}=y_{\Delta-1}}^{\Delta C} 1 \quad (10)$$

It can be computed in closed form as:

$$Q(\Delta, C) = \frac{1}{1 + C(\Delta + 1)} \binom{(C + 1)(\Delta + 1)}{\Delta + 1} \quad (11)$$

$$\approx \frac{e}{\sqrt{2\pi}} \frac{1}{(\Delta + 1)^{3/2}} (eC)^\Delta \quad (12)$$

Proof 3 *The proof is postponed to Appendix A.*

The size of \mathcal{W} will play a major role in the complexity of our dynamic programming algorithm to compute the optimal speeds.

3 Markov Decision Process (MDP) Solution

We denote by $\mathbf{x} = (w(\cdot), \ell)$ a *state* of the MDP, defined below. It is composed by a remaining work function denoted $w(\cdot)$, and the time elapsed since the latest job arrival denoted ℓ . We denote by \mathcal{X} the state space (the set of all possible states).

As explained in § 2.4, the space \mathcal{W} is finite and ℓ is bounded by L , so the set \mathcal{X} is also finite. As a consequence, one can effectively compute the optimal speed in each possible state \mathbf{x} using dynamic programming over \mathcal{X} .

In this section, we provide algorithms to compute the optimal speed selection in two cases: when the time horizon is finite and when it is infinite. In the finite case, we minimize the *total* energy consumption, while in infinite case we minimize the *long term average* energy consumed per time unit.

In both cases, we compute off-line the optimal *policy* σ_t^* that gives the speed the processor should use at time t in all its possible states. At runtime, the processor chooses at time t the speed $s(t)$ that corresponds to its current state $\mathbf{x}_t = (w_t, \ell_t)$, that is $s(t) := \sigma_t^*(\mathbf{x}_t)$.

The algorithms to compute the policy σ^* are based on a *Markovian evolution* of the jobs. From the distribution of jobs (τ_i, c_i, d_i) , one can build, under state \mathbf{x} and at time t , the distribution $(\phi_{\mathbf{x}})_{\mathbf{x} \in \mathcal{X}}$ of the work that arrives at t . For any (c_1, \dots, c_{Δ}) :

$$\phi_{\mathbf{x}}(t, c_1, \dots, c_{\Delta}) = \mathbb{P} \left(a_t = \sum_{k=1}^{\Delta} c_k H_{k+t} \mid \mathbf{x}_t = \mathbf{x} \right) \quad (13)$$

Once ϕ is given, the transition matrix $P_t(\mathbf{x}, s, \mathbf{x}')$ from state $\mathbf{x} = (w, \ell)$ to $\mathbf{x}' = (w', \ell')$ when the speed chosen by the processor is s is:

$$P_t(\mathbf{x}, s, \mathbf{x}') = \begin{cases} \phi_{\mathbf{x}}(t, c_1, \dots, c_{\Delta}) & \text{if } w' = \mathbb{T}[(w - s)^+] + \sum_k c_k H_{k+t} \\ \text{and } \ell' = \begin{cases} 0 & \text{if } (c_1 \cdots c_{\Delta}) \neq (0 \cdots 0) \\ (\ell + 1) \wedge L & \text{otherwise} \end{cases} & \\ 0 & \text{otherwise} \end{cases}$$

This shows that the transition probability can be expressed as a function of the probability distributions of the jobs, through the distribution ϕ . If jobs are independent, then ϕ can be computed using a convolution of the job distributions.

3.1 Finite Case: Dynamic Programming

We suppose in this section that the time horizon is finite and equal to T . This implies that we only consider a finite number of jobs. The goal is to minimize the total expected energy consumption J^* over the time interval $[0, T]$. If the initial state is \mathbf{x}_0 , then

$$J^*(\mathbf{x}_0) = \min_{\sigma} \left(\mathbb{E} \left(\sum_{t=0}^T j(\sigma_t(\mathbf{x}_t)) \right) \right) \quad (14)$$

where the expectation is taken over all possible job arriving sequences following the probability distribution of the features and where σ is taken over all possible *policies* of the processor: $\sigma_t(\mathbf{x})$ is the speed used at time t if the state is \mathbf{x} . The only constraint on $\sigma_t(\mathbf{x})$ is that it must belong to

the set of available speeds, *i.e.*, $\sigma_t(\mathbf{x}) \in \mathcal{S}$, and it must be large enough to execute the remaining work at the next time step:

$$\forall t, \sigma_t(\mathbf{x}) \geq w(1) \quad (15)$$

The set of *admissible speeds* in state \mathbf{x} is denoted $\mathcal{A}(\mathbf{x})$ and is therefore defined as:

$$\mathcal{A}(\mathbf{x}) = \{s \in \mathcal{S} \text{ s.t. } s \geq w(1)\} \quad (16)$$

J^* can be computed using a backward induction. Let $J_t^*(\mathbf{x})$ be the minimal expected energy consumption from time t to T , if the state at time t is \mathbf{x} ($\mathbf{x}_t = \mathbf{x}$). We present in the next section an algorithm to compute J^* .

3.1.1 Dynamic Programming Algorithm (DP)

We use a backward induction (Dynamic Programming) to recursively compute the expected energy consumption J^* and the optimal speed policy σ^* . We use the finite Horizon-Policy Evaluation Algorithm from [9] (p. 80). We obtain an *optimal policy* that gives the processor speed that one must apply in order to minimize the energy consumption (Algorithm 1).

Algorithm 1 Dynamic Programming Algorithm (DP) to compute the optimal speed for each state and each time.

```

t ← T                                     % time horizon
for all  $\mathbf{x} \in \mathcal{X}$  do  $J_t^*(\mathbf{x}) \leftarrow 0$  end for
while  $t \geq 1$  do
  for all  $\mathbf{x} \in \mathcal{X}$  do
     $J_{t-1}^*(\mathbf{x}) \leftarrow \min_{s \in \mathcal{A}(\mathbf{x})} \left( j(s) + \sum_{\mathbf{x}' \in \mathcal{W}} P_t(\mathbf{x}, s, \mathbf{x}') J_t^*(\mathbf{x}') \right)$ 
     $\sigma_{t-1}^*[\mathbf{x}] \leftarrow \arg \min_{s \in \mathcal{A}(\mathbf{x})} \left( j(s) + \sum_{\mathbf{x}' \in \mathcal{W}} P_t(\mathbf{x}, s, \mathbf{x}') J_t^*(\mathbf{x}') \right)$ 
  end for
  t ← t - 1                               % backward computation
end while
return all tables  $\sigma_t^*[\cdot] \quad \forall t = 0 \dots T - 1$ .

```

The complexity to compute the optimal policy $\sigma_t^*(\mathbf{x})$ for all possible states and time steps is $\mathcal{O}(T|\mathcal{S}|Q(\Delta)^2)$. The combinatorial explosion of the state space makes it very large when the maximum deadline is large. Note however that this computation is done *off-line*. At runtime, the processor simply considers the current state \mathbf{x}_t at time t and uses the pre-computed speed $\sigma_t^*(\mathbf{x}_t)$ to execute the job with the earliest deadline.

3.1.2 Runtime Process: Table Look-UP (TLU_{DP})

At runtime, the processor computes the current state \mathbf{x}_t and simply uses a Table Look-Up algorithm (TLU) to obtain its optimal speed $\sigma_t^*[\mathbf{x}_t]$, the speed tables having been computed off-line by (DP). This algorithm, called (TLU_{DP}), is shown in Algorithm 2. The size of the table is $T \times Q(\Delta)$ and the runtime cost for (TLU_{DP}) is $\mathcal{O}(1)$.

Algorithm 2 Runtime process (TLU_{DP}) used by the processor to apply the optimal speed

For Each $t = 0 \dots T - 1$
 Update \mathbf{x}_t using Eq. (6)
 Set $s := \sigma_t^*[\mathbf{x}_t]$
 Execute the job(s) with earliest deadline
 at speed s for one time unit
End

3.2 Infinite Case: Value Iteration

When the time horizon is infinite, the total energy consumption is also infinite whatever the speed policy. Instead of minimizing the total energy consumption, we minimize the *long term average* energy consumption per time-unit, denoted g . We therefore look for the optimal policy σ^* that minimizes g . In mathematical terms, we want to solve the following problem. Compute

$$g^* = \min_{\sigma} \mathbb{E} \left(\lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T j(\sigma(\mathbf{x}_t)) \right) \quad (17)$$

under the constraint that no job misses its deadline.

3.2.1 Stationary Assumptions

In the following we will make the following additional assumption on the jobs: The size and the deadline of the next job have *stationary distributions* (*i.e.*, they do not depend on time). We further assume that the probability that no job arrives in the next time slot is strictly positive.

Under these two assumptions, the state space transition matrix is *unichain* (see [9] for a precise definition). Basically, the unichain property is true because, starting from an empty system (state $w_0 = (0, \dots, 0)$), it is possible to go back to state w_0 no matter what speed choices have been made and what jobs have occurred. This is possible indeed because, with positive probability, no job will arrive for long enough a time so that all past deadlines have been met and the state goes back to w_0 .

When the state space is unichain, the limit in Eq. (17) always exists (see [9]) and can be computed with an arbitrary precision using a *value iteration* algorithm (VI), presented in the next section.

3.2.2 Value Iteration Algorithm (VI)

The goal of Algorithm (VI) is to find a *stationary* policy σ (*i.e.*, σ will not depend on t), which is optimal, and to provide an approximation of the gain (*i.e.*, the average reward value g^*) with an arbitrary precision ε .

In Algorithm 3, the quantity u^n can be seen as the total energy up to iteration n . Moreover, the *span* of a vector z is the difference between its maximal value and its minimal value: $span(z) = \max_i(z_i) - \min_i(z_i)$. A vector with a span equal to 0 has all its coordinates equal.

Algorithm 3 computes both the optimal average energy consumption per time unit (g^*) with a precision ε as well as an ε -optimal speed to be selected in each state ($\sigma^*[\mathbf{x}]$).

The time complexity to compute the optimal policy depends exponentially on the precision $\frac{1}{\varepsilon}$. The numerical experiments show that convergence is reasonably fast (see § 4).

Algorithm 3 Value Iteration Algorithm (VI) to compute the optimal speeds in each state and the average energy cost per time unit.

```

 $u^0 \leftarrow (0, 0, \dots, 0), u^1 \leftarrow (1, 0, \dots, 0)$ 
 $n \leftarrow 1$ 
 $\varepsilon > 0$                                      % stopping criterion
while  $\text{span}(u^n - u^{n-1}) \geq \varepsilon$  do
  for all  $\mathbf{x} \in \mathcal{W}$  do
     $u^{n+1}(\mathbf{x}) \leftarrow \min_{s \in \mathcal{A}(\mathbf{x})} \left( j(s) + \sum_{\mathbf{x}' \in \mathcal{W}} P(\mathbf{x}, s, \mathbf{x}') u^n(\mathbf{x}') \right)$ 
  end for
   $n \leftarrow n + 1$ 
end while
Choose any  $\mathbf{x} \in \mathcal{W}$  and let  $g^* \leftarrow u^n(\mathbf{x}) - u^{n-1}(\mathbf{x})$ 
for all  $\mathbf{x} \in \mathcal{W}$  do
   $\sigma^*[\mathbf{x}] \leftarrow \arg \min_{s \in \mathcal{A}(\mathbf{x})} \left( j(s) + \sum_{\mathbf{x}' \in \mathcal{W}} P(\mathbf{x}, s, \mathbf{x}') u^n(\mathbf{x}') \right)$ 
end for
return  $\sigma^*$ 

```

3.2.3 Runtime Process: Table Look-Up (TLU_{VI})

As for (TLU_{DP}), at each integer time $t \in \mathbb{N}$, the processor computes its current state \mathbf{x}_t and retrieves its optimal speed $s := \sigma^*[\mathbf{x}]$ by looking-up in the table σ^* that was pre-computed by (VI). This algorithm is identical to Algorithm 2, except for the size of the table, which is $Q(\Delta)$.

3.3 Schedulability Issues

Let us recall that, according to Definition 5, a set of jobs is *feasible* if using the maximal speed s_{\max} all the time, no job misses its deadline.

Notice that this is a condition on the jobs, unrelated to the speed policy of the processor.

Definition 6 (Schedulability) *A set of jobs is schedulable under speed policy σ if, using speed $\sigma(\cdot)$, the processor executes all jobs without missing a deadline.*

The goal of this section is to show the following result.

Proposition 3 *A finite (resp. infinite) set of jobs is feasible if and only if it is schedulable under policy (DP) (resp. (VI)).*

Proof 4 *We will first show that for all states \mathbf{x} reached under (DP) (resp. (VI)) by executing a feasible set of jobs, the set of admissible speeds $\mathcal{A}(\mathbf{x})$ (defined in Eq. (16)) is never empty.*

To show this, let us first modify the processor by allowing unbounded speeds, and let us introduce a new energy function $j(\cdot)$ such that $\forall s \geq s_{\max}$ we have $j(s) = \infty$. For speed values smaller than s_{\max} , the function $j(\cdot)$ remains unchanged. This modification is valid because one can assign an arbitrary energy consumption to unattainable speeds as one pleases: such speeds will never be used by valid speed policies. In this new framework, the processor can now use unbounded speeds:

$$\mathcal{S}' = \mathcal{S} \cup \{s_{\max} + 1, s_{\max} + 2, \dots\}$$

but when it uses speeds higher than s_{\max} , its energy consumption becomes infinite.

Now, let us consider a set of feasible jobs executed by this extended processor model. Let us also define a simple policy, denoted σ^{\max} , that uses speed s_{\max} at any time t :

$$\forall t, \sigma^{\max}(t) = s_{\max} \quad (18)$$

Under policy σ^{\max} , the expected (resp. long run average) energy consumption is $Tj(s_{\max})$ (resp. $j(s_{\max})$) and no job misses its deadline, by the definition of feasibility.

Since the optimal policy (DP) (resp. (VI)) is optimal in energy, it has a better expected (resp. long term) consumption than σ^{\max} . Hence, $J^*(\mathbf{x}_0)$ for (DP), as defined in § 3.1, (resp. g^* for (VI) in § 3.2) are finite. This implies that speeds higher than s_{\max} , that would have given an infinite energy consumption, were never used by the optimal policy.

To sum up, for any feasible set of jobs, the optimal policy never misses a deadline by construction of $\mathcal{A}(\mathbf{x}_t)$, and, according to the discussion above, it never uses a speed higher than s_{\max} . Therefore the optimal policy, as defined in Algorithm (1) for the finite case or Algorithm (3) for the infinite horizon case, will never miss a deadline if and only if the set of jobs is feasible. \square

As a final remark, not all on-line policies will execute all jobs in a feasible set without missing deadlines when using speeds smaller than s_{\max} . For example, optimal available (OA), presented in § 3.5, requires additional constraints on a feasible set of jobs to guarantee schedulability (see [10]).

3.4 Bounded Job Sizes

As in § 2.4, let us assume that the amount of work that can arrive at any time t is bounded by C . In this case, one can assess more explicitly the feasibility condition of a set of jobs.

The necessary and sufficient feasibility condition of a set of jobs is:

$$s_{\max} \geq C \quad (19)$$

Indeed, if $s_{\max} < C$, then no speed policy can guarantee schedulability: a single job of size C and relative deadline 1 cannot be executed before its deadline. The case where $s_{\max} = C$ is borderline because there exists a unique speed policy guaranteeing that no job will miss its deadline: at any time t , choose $s(t) = a_t(\Delta) \leq C$, where $a_t(\cdot)$ is the work quantity arrived at time t (see Def. 4).

If $s_{\max} > C$, then the previous policy never misses its deadline, hence using the discussion in the previous section, the optimal policy σ_t^* will also schedule all jobs before their deadline. This yields the following property.

Proposition 4 *Starting from an empty system, if the amount of work arriving at any time step is bounded by C , then schedulability with (DP) or (VI) is guaranteed if and only if $s_{\max} \geq C$.*

3.5 Properties of the Optimal Policy

In this section, we show several structural properties of the optimal policy σ^* , which are true for both the finite and infinite horizons.

3.5.1 Comparison with Optimal Available (OA)

Optimal Available (OA) is an on-line speed policy introduced in [1], which chooses the speed $s^{(\text{OA})}(\mathbf{x}_t)$ at time t and in state \mathbf{x}_t to be the minimal speed in order to execute the current

remaining work at time t , should no further jobs arrive in the system. More precisely, at time t and in state \mathbf{x}_t , the (OA) policy uses the speed

$$s^{(\text{OA})}(\mathbf{x}_t) = \max_u \frac{w_t(u)}{u} \quad (20)$$

where $w_t(\cdot)$ is the remaining work function computed by Eq. (6).

We first show that, under any state $\mathbf{x} \in \mathcal{X}$, the optimal speed $\sigma^*(\mathbf{x})$ is always higher than $s^{(\text{OA})}(\mathbf{x})$.

Proposition 5 *Both in the finite or infinite case, the optimal speed policy σ^* satisfies*

$$\sigma^*(\mathbf{x}) \geq s^{(\text{OA})}(\mathbf{x}) \quad (21)$$

for all state $\mathbf{x} \in \mathcal{X}$, if the power consumption j is a convex function of the speed.

Proof 5 *The proof is based on the observation that (OA) uses the optimal speed assuming that no new job will come in the future. Should some job arrive later, then the optimal speed will have to increase. We first prove the result when the set of speeds \mathcal{S} is the whole real interval $[0, s_{\max}]$ (continuous speeds).*

Two cases must be considered. If $s^{(\text{OA})}(\mathbf{x}_t) = \max_u \frac{w_t(u)}{u}$ is reached for $u = 1$ (i.e., $s^{(\text{OA})}(\mathbf{x}_t) = w_t(1)$), then $\sigma^(\mathbf{x}_t) \geq s^{(\text{OA})}(\mathbf{x}_t)$ by definition because the set of admissible speeds $\mathcal{A}(\mathbf{x}_t)$ only contains speeds higher than $w_t(1)$ (see Eq. (20)).*

If the maximum is reached for $u > 1$, then $\mathcal{A}(\mathbf{x}_t)$ may enable the use of speeds below $w_t(1)$.

Between time t and $t + u$, some new jobs may arrive. Therefore, the optimal policy should satisfy $\sum_{i=0}^{u-1} \sigma^(\mathbf{x}_{t+i}) \geq w_t(u)$.*

The convexity of the power function j implies⁴ that all the speeds in the optimal sequence $\sigma^(\mathbf{x}_t), \dots, \sigma^*(\mathbf{x}_{t+u-1})$ must all be above the average value $w_t(u)/u = s^{(\text{OA})}(\mathbf{x}_t)$. In particular, for the first term, $\sigma^*(\mathbf{x}_t) \geq s^{(\text{OA})}(\mathbf{x}_t)$.*

Now, if the set of speeds is finite, then the optimal value of $\sigma^(\mathbf{x}_t)$ must be one of the two available speeds in \mathcal{S} surrounding $s^{(\text{OA})}(\mathbf{x}_t)$. Let s_1 and s_2 in \mathcal{S} be these two speeds, i.e., $s_1 < s^{(\text{OA})}(\mathbf{x}_t) \leq s_2$, and assume again that the max in Eq. (20) is not reached for $t = 1$. If the smallest speed s_1 is chosen as the optimal speed, this implies that further choices for $\sigma^*(\mathbf{x}_{t+i})$ will have to be greater or equal to s_2 , to compensate for the work surplus resulting from choosing a speed below $\sigma^*(\mathbf{x}_t)$. This implies that it is never sub-optimal to choose s_2 in the first place (by convexity of the j function).*

This trajectorial argument is true almost surely, so that the inequality $\sigma^(\mathbf{x}_t) \geq s^{(\text{OA})}(\mathbf{x}_t)$ will also hold for the expected energy over both a finite or infinite time horizon. \square*

3.5.2 Monotonicity Properties

Let us consider two sets of jobs \mathcal{T}_1 and \mathcal{T}_2 for which we want to apply our speed scaling procedure. We wonder which of the two sets uses more energy than the other when optimal speed scaling is used for both.

Of course, since jobs have random features, we cannot compare them directly, but instead we can compare their distributions. We assume in the following that the sizes and deadlines of the jobs in \mathcal{T}_1 (resp. \mathcal{T}_2) follow a distribution ϕ_1 (resp. ϕ_2) independent of the current state \mathbf{x} .

⁴Actually, we use the fact that the sum $\sum_{i=0}^{u-1} j(s)$ is Schur-convex when j is convex (see [12]).

Definition 7 Let us define a stochastic order (denoted \leq_s) between the two sets of jobs \mathcal{T}_1 and \mathcal{T}_2 as follows. $\mathcal{T}_2 \leq_s \mathcal{T}_1$ if the respective distributions ϕ_1 and ϕ_2 are comparable. Formally, for any job (τ_1, c_1, d_1) with distribution ϕ_1 and any job (τ_2, c_2, d_2) with distribution ϕ_2 , we must have:

$$\begin{aligned} \forall \gamma, \delta, \quad & \mathbb{P}(c_2 \geq \gamma, d_2 \leq \delta) \leq \mathbb{P}(c_1 \geq \gamma, d_1 \leq \delta) \\ \forall t \in \mathbb{N}, \quad & \mathbb{P}(\tau_1 = t) = \mathbb{P}(\tau_2 = t). \end{aligned} \quad (22)$$

Moreover, by denoting $(i_1^1, \dots, i_\Delta^1)$ the work quantity that arrives at time t for \mathcal{P}_1 , and $(i_1^2, \dots, i_\Delta^2)$ the work quantity that arrives at time t for \mathcal{P}_2 , we have:

$$\begin{aligned} \forall t, i_1^1, \dots, i_\Delta^1, \quad & i_1^2, \dots, i_\Delta^2, \\ \mathbb{P}(t, w_{t+1} & \geq i_1^1, \dots, w_{t+\Delta} \geq i_\Delta^1) \\ & \leq \mathbb{P}(t, w_{t+1} \geq i_1^2, \dots, w_{t+\Delta} \geq i_\Delta^2) \end{aligned}$$

Proposition 6 If $\mathcal{T}_2 \leq_s \mathcal{T}_1$, then:

1. over a finite time horizon T , the total energy consumption satisfies $J^{(2)} \leq J^{(1)}$ (computed with Eq. (14));
2. in the infinite time horizon case, the average energy consumption per time unit satisfies $g^{(2)} \leq g^{(1)}$ (computed with Eq. (17)).

Proof 6

Case 1 (finite horizon): The definition of $\mathcal{T}_2 \leq_s \mathcal{T}_1$ implies that we can couple the set of jobs \mathcal{T}_1 with the set of jobs \mathcal{T}_2 , such that at each time $t \leq T$, $J_t^{(1)} = (\tau_t^1, c_t^1, d_t^1)$ and $J_t^{(2)} = (\tau_t^2, c_t^2, d_t^2)$ with $t = \tau_t^1 = \tau_t^2$, $c_t^2 \leq c_t^1$ and $d_t^2 \geq d_t^1$ (see [13]). It follows that the optimal sequence of speeds selected for \mathcal{T}_1 is admissible for \mathcal{T}_2 , hence the optimal sequence for \mathcal{T}_2 should have a better performance. Since this is true for any set of jobs generated using ϕ_1 , it is also true in expectation, hence $J^{(2)} \leq J^{(1)}$.

Case 2 (infinite horizon): We just use the fact that the optimal sequence for \mathcal{T}_2 is better than the optimal sequence for \mathcal{T}_1 over any finite horizon T . Letting T go to infinity shows that the average energy cost per time unit will also be better for \mathcal{T}_2 . \square

4 Numerical Experiments

4.1 Application Scenarios

Our approach is usable in several applicative contexts.

The first one concerns real-time systems whose tasks are *sporadic*, with no *a priori* structure on the job release times, sizes, and deadlines. In such a case, a long observation of the job features can be used to estimate the statistical properties of the jobs: distribution of the inter-release times, distribution of the job sizes, and deadlines.

Another case where our approach is efficient is for real-time systems consisting of several *periodic* tasks, each one with some randomly missing jobs. The uncertainty on the missing jobs may be due, for example, to faulty sensors and/or electromagnetic interference causing transmission losses in embedded systems.

A third situation is the case where jobs come from a high number of *periodic* tasks and each of them has an unknown jitter. If we suppose that we have a probabilistic knowledge of the jitter

values, then we can use our model to improve the energy consumption by determining more quickly all the jitters of each task.

The last example is the case where jobs are produced by event-triggered sensors: This case is also a superimposition of *sporadic* tasks, where the job probabilities represents the occurrence probability of events.

These examples are explored in this experimental section where our solution is compared with other on-line solutions. Our numerical simulations report a 5% improvement over (OA) in the sporadic tasks case, and 30% to 50% improvement in the periodic tasks case.

The numerical experiments are divided in two cases: In § 4.3.1 and § 4.3.2, we consider a real-time system with a single periodic task of period 1 with jobs that have randomness on their sizes⁵.

The second set of experiments deals with another type of real-time systems made of several periodic tasks. Each task is characterized by its offset, period, size, and deadline. There is a randomness on the job size, that is due to sensor perturbation.

All the experiments reported below are based on these two scenarios.

4.2 Implementation Issues

The state space \mathcal{X} has a rather complex structure and is very large. Therefore, the data structure used in the implementations of Algorithms 1 and 3 must be very efficient to traverse the state space as well as to address each particular state when state changes occur. This is done by using a hashing table to retrieve states according to a multi-dimensional *key* that represents the state, that is, the vector $[w(1), w(2) - w(1), \dots, w(\Delta) - \sum_{k=1}^{\Delta-1} w(k)]$, and a recursive procedure based on Eq. (10) to traverse the state space.

The implementation of Algorithms 1 and 3 has been done in R to take advantage of the possibility to manipulate linear algebraic operation easily, and in C when the state space was too large to be efficiently handled in R .

4.3 Experimental Set-up, Finite Case

Our experiments are done in two steps:

- Firstly, we compute the optimal speeds for each possible state $\mathbf{x} \in \mathcal{X}$. For this, we use Algorithm 1 (DP) or 3 (VI), and we store in the σ^* table the optimal speed for each possible state of the system.
- Secondly, to compare different speed policies, we simulate a sequence of jobs (produced by our real-time tasks, see § 4.1) over which we use our (TLU_{DP}) solution or other solutions (*e.g.*, off-line or (OA)) and we compute the corresponding energy consumption.

In a nutshell, the experiments show that our MDP solution performs very well in practice, almost as well as the optimal *off-line* solution (see § 4.3.1). Regarding the comparison with (OA), in most of our experiments, (TLU_{DP}) outperforms (OA) by 5% on average in the sporadic case when job inter-arrival times are i.i.d.⁶ (see § 4.3.2). In the periodic case, where jobs are more predictable, the gap with (OA) grows to about 50% (see § 4.3.3).

⁵An estimation of the distribution of their size can be obtained through the measurement of many traces of the real-time system.

⁶i.i.d. = independent and identically distributed random variables.

4.3.1 Comparison with the Off-line Solution

To evaluate our on-line algorithm, we compare it with the off-line solution computed on a simulated set of jobs, characteristics of which are described in Example 1. We draw the aggregated work done by the processor (the respective speeds are the slopes) in two cases:

- The optimal off-line solution that only uses speeds in the finite set \mathcal{S} .
- The (TLU_{DP}) solution.

Example 1 One periodic task \mathbf{T}_1 of period 1 with jobs of variable size $c_1 = \{0, 2\}$ with respective probabilities (w.r.p.) $\{0.4, 0.6\}$ and deadline $d_1 = 5$. The processor can use 4 speeds $\mathcal{S} = \{0, 1, 2, 5\}$ and its energy consumption per time unit is given by the function $j(s) = s^3$.

A job of size 0 at some time instant t is the same as no job at all at time t . In Example 1, the variable size $c_1 = \{0, 2\}$ actually models a *sporadic* task: with probability 0.4 no job arrives, while with probability 0.6 a job of size $c_1 = 2$ arrives.

In Example 1, the maximal speed is large enough so that schedulability is not an issue: $5 = s_{\max} > C = 2$ (§3.3). Note that, in contrast with (TLU_{DP}), some jobs created by task \mathbf{T}_1 might not be schedulable under (OA).

The result over one typical simulation of run for Example 1 is displayed in Figure 3. As expected, (TLU_{DP}) consumes more energy than the off-line case. The differences in the chosen speeds are the following: (i) speed 0 is used once by (TLU_{DP}) but is never used by the off-line solution; (ii) speed 2 is used 5 times by (TLU_{DP}) and only 4 times in the off-line case. The energy consumption gap between the two is $2^3 + 0^3 - 1^3 - 1^3 = 6 J$. The total energy consumption under the off-line solution is 46 J , while the total energy consumption under the (TLU_{DP}) solution is 52 J , the difference being 13% of the total energy consumption.

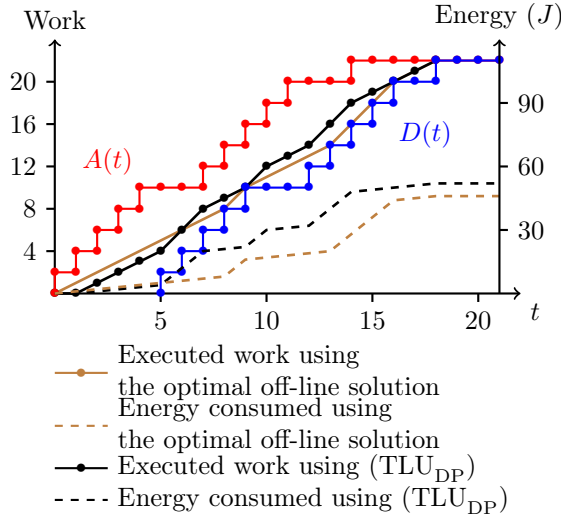


Figure 3: Comparison of the executed work of off-line and (TLU_{DP}) solution on one simulation of Example 1. As defined before, $A(t)$, the red curve, is the workload arrived between 0 and T , and $D(t)$, the blue curve, is the workload deadlines from 0 to T ; Brown curve: work executed using the optimal off-line speeds; Black curve: work executed using the speed selection computed by (TLU_{DP}).

4.3.2 Comparison with (OA), Sporadic Tasks

Recall that, under (OA), the processor speed at time t in state \mathbf{x}_t is set to $\max_u \frac{w_t(u)}{u}$. However, when the number of speeds is finite, the speed computed by (OA) might not be available. Hence, the speed $s^{(\text{OA})}(\mathbf{x}_t)$ chosen by (OA) must be set to the smallest speed in \mathcal{S} greater than $\max_u \frac{w_t(u)}{u}$.

As a consequence, to compare (OA) and (DP), the number of possible speeds must be large enough to get a chance to see a difference between the two. We do so with Example 2, which consists of two sporadic tasks, using the same modelling technique as in Example 1 by fixing $c_2 = \{0, 3, 6\}$.

Example 2 One periodic task \mathbf{T}_2 of period 1, variable job size $c_2 = \{0, 3, 6\}$ w.r.p. $\{0.2, 0.6, 0.2\}$, and fixed deadline $d_2 = 3$. The processor can use 5 processor speeds $\mathcal{S} = \{0, 1, 2, 3, 4\}$ and its energy consumption per time unit follows the function $j(s) = s^3$.

We ran an exhaustive experiment consisting of 10,000 simulations of sequences of jobs generated by this periodic task, over which we computed the relative energy gain of (TLU_{DP}) over (OA) in percentage. The gain percentage of (TLU_{DP}) was in the range $[5.17, 5.39]$ with a 95% confidence interval and an average value of 5.28%.

Even if this gain is not very high, one should keep in mind that it comes for free once the (DP) solution has been computed. Indeed, using (TLU_{DP}) on-line takes a constant time to select the speed (table look-up) while using (OA) on-line takes $\mathcal{O}(\Delta)$ to compute the value $\max_u \frac{w_t(u)}{u}$.

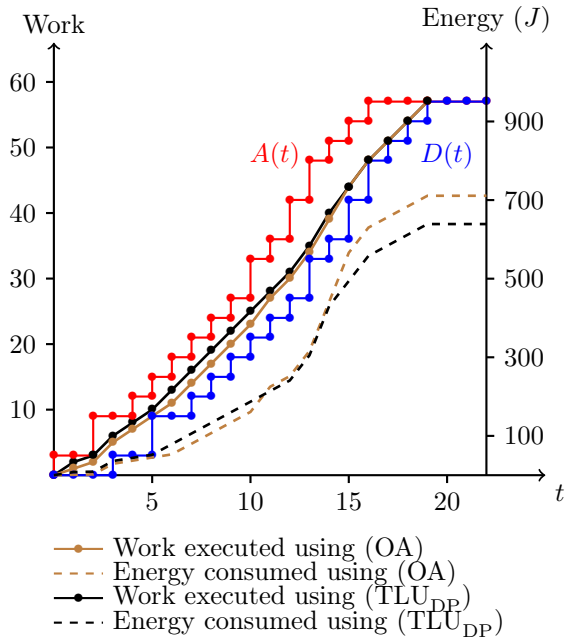


Figure 4: Comparison of the executed work between (OA) and (TLU_{DP}) solutions, with fixed deadlines $d_n = 3$, size $c_n = \{0, 2, 4\}$ w.r.p. $\{0.2, 0.6, 0.2\}$, and processor speeds in $\{0, 1, 2, 3, 4\}$. As defined before, $A(t)$ (red curve) is the workload arrived between 0 and T , while $D(t)$ (blue curve) is the workload deadlines from 0 to T .

Figure 4 shows a comparison between (OA) and (TLU_{DP}). The total work executed by the (TLU_{DP}) solution is always above the total work executed by (OA), as stated in Proposition 5. Moreover, the consumed energy is more important at the beginning with (TLU_{DP}) than with (OA), because we anticipate the work that will arrive in the future. The processor executes more work so it consumes more energy with (TLU_{DP}) before time $t = 11$; but after this time, it's the opposite, the energy consumed by (TLU_{DP}) is lower than the energy consumed by (OA). Over the whole period, (TLU_{DP}) outperforms (OA): The total energy consumption for (OA) is 711 J (dashed brown curve) while that for (TLU_{DP}) is 639 J (dashed black curve). As a result, (TLU_{DP}) outperforms (OA) by a margin of around 10%. Even if this gain is not very high, one should keep in mind that, again, it comes for free once the (DP) solution has been computed off-line.

4.3.3 Comparison with (OA), Periodic Tasks

We now consider several examples consisting of two or more periodic tasks. The fact that the probability matrix, which represents the state change, depends on the time is important in this section. Indeed, at each time step, the probability of the job arrival depends on the time and in particular on the modulo of the number of the considered task. For instance in Example 3 (see below), we have a probability that depends of the time instant modulo 2: at even time steps ($t = 0 \pmod{2}$), we have some probability p_1 that the job J_1 produced by task \mathbf{T}_1 arrives and the job J_2 produced by task \mathbf{T}_2 arrives with a probability equal to zero. In contrast, at odd time steps ($t = 1 \pmod{2}$), we have some probability p_2 that the job J_2 arrives and the job J_1 arrive with a probability equal to zero. On the other examples (Examples 4 and 5), we can perform the same analysis as above to show that the probability matrix depends on the time.

This Section displays three examples, Examples 3, 4, and 5, which consider different cases where we have several periodic tasks that have not necessarily the same offset and the same periodicity.

Example 3 *Two periodic tasks \mathbf{T}_1 and \mathbf{T}_2 . For task \mathbf{T}_1 , the period is 2, the offset is 0, with jobs of variable size $c_1 = \{0, 2\}$ w.r.p. $\{0.2, 0.8\}$, and the deadline is $d_1 = 2$. For task \mathbf{T}_2 , the period is 2, the offset is 0, with jobs of variable size $c_1 = \{0, 4\}$ w.r.p. $\{0.25, 0.75\}$, and the deadline is $d_1 = 1$.*

The total energy consumption over the 20 units of time is of 513 J for (TLU_{DP}), and 825 J for (OA), so more than 60% bigger. Here (TLU_{DP}) has a clear advantage because the job characteristics are highly predictable.

Example 4 *Four periodic tasks $\mathbf{T}_1, \mathbf{T}_2, \mathbf{T}_3, \mathbf{T}_4$ with the same period equal to 4 and respective offsets 0, 1, 2, 3. For each task \mathbf{T}_i , the job size is variable and deadline is fixed, with $c_1 = \{0, 2\}$ w.r.p. $\{0.2, 0.8\}$, and $d_1 = 2$; $c_2 = \{0, 1\}$ w.r.p. $\{0.2, 0.8\}$, and $d_2 = 3$; $c_3 = \{0, 4\}$ w.r.p. $\{0.2, 0.8\}$, and $d_3 = 2$; $c_4 = \{0, 2\}$ w.r.p. $\{0.2, 0.8\}$, and $d_4 = 1$.*

With Example 4, the energy consumed by (TLU_{DP}) is on average 30% lower than the energy consumed by (OA). We performed 10,000 simulations over 40 time steps: the average gain is 29.04% with the following confidence interval at 95%: [28.84, 29.24].

Example 5 *Seven periodic tasks \mathbf{T}_1 to \mathbf{T}_7 . Task \mathbf{T}_4 has period 4, offset 3, and variable job size $c_4 = \{0, 4\}$ w.r.p. $\{0.2, 0.8\}$, and $d_4 = 2$. All the other tasks $\mathbf{T}_1, \dots, \mathbf{T}_3$ and $\mathbf{T}_5, \dots, \mathbf{T}_7$ have period 8, respective offsets 0, 1, 2, 4, 5, 6, 7 (8 being for the second job of \mathbf{T}_4), and respective parameters $c_1 = \{0, 2\}$ w.r.p. $\{0.2, 0.8\}$, and $d_1 = 1$; $c_2 = \{0, 1\}$ w.r.p. $\{0.2, 0.8\}$, and $d_2 = 2$; $c_3 = \{0, 1\}$ w.r.p. $\{0.2, 0.8\}$, and $d_3 = 3$; $c_5 = \{0, 4\}$ w.r.p. $\{0.2, 0.8\}$, and $d_5 = 1$; $c_6 = \{0, 2\}$ w.r.p. $\{0.2, 0.8\}$, and $d_6 = 2$; $c_7 = \{0, 4\}$ w.r.p. $\{0.2, 0.8\}$, and $d_7 = 3$.*

With Example 5, the energy consumed by (TLU_{DP}) is on average 47% lower than the energy consumed by (OA). We performed 10,000 simulations over 80 time steps, the average gain was 46.88% with the following confidence interval at 95%: [46.71, 47.04].

The other simulation parameters for Examples 3 to 5 are $T = 20$, $\mathcal{S} = \{0, 1, 2, 3, 4, 5\}$ and $j(s) = s^3$.

Table 1 summarizes these results.

Table 1: Comparisons between (OA) and (TLU_{DP}) .

example	gain over (OA)	95% confidence interval
Ex. 3 (2 tasks)	56.44%	[56.21, 56.68]
Ex. 4 (4 tasks)	29.04%	[28.84, 29.24]
Ex. 5 (7 tasks)	46.88%	[46.71, 47.04]

In all these cases, (TLU_{DP}) outperforms (OA) by a greater margin than with sporadic tasks. The reason is that the job sequence is more predictable, so the statistical knowledge over which (TLU_{DP}) is based is more useful here than in the sporadic case.

4.4 Computation Experiments, Infinite Case

In this section, we run algorithm (VI) (Algorithm 3) to compute the optimal speed to be used at each time step over an infinite horizon. We fix the stopping criterion in Algorithm 3 to $\varepsilon = 1.0 * 10^{-5}$, so our computation of the average energy consumption is precise by at least 5 digits. We ran the program in the following two cases:

Example 6 *One periodic task of period 1 with jobs of variable size $c_6 = \{0, 2\}$ w.r.p. $\{1 - p, p\}$, and fixed deadline $d_6 = 3$, with p varying from 0 to 1.*

Example 7 *One periodic task of period 1 with jobs of variable size $c_7 = \{0, 2\}$ w.r.p. $\{1 - p, p\}$, and fixed deadline $d_7 = 5$, with p varying from 0 to 1.*

In both examples, the available processor speeds are in the set $\mathcal{S} = \{0, 1, 2\}$ and the energy consumption function is $j(s) = s^2$. The only difference between Examples 6 and 7 are the deadlines.

The results of our computations are displayed in Figure 5. The three curves depict respectively the average energy consumption per time unit as a function of the probability p (which varies from 0 to 1) for Examples 6 and 7, together with the theoretical lower bound.

The different curves in Figure 5 have the following meaning:

- The black and blue curves correspond to the (VI) solution with three processor speeds $\mathcal{S} = \{0, 1, 2\}$. These curves display g^* (computed by Algorithm 3) as a function of p , the probability that a job of size $c = 2$ and deadline $d = 3$ (black curve) or deadline $d = 5$ (blue curve) arrives in the next instant.
- The red curve is the theoretical lower bound on g^* , oblivious of the jobs distribution and deadlines, only based on the average amount of work arriving at each time slot.

As expected according to Proposition 6, the higher the arrival rate, the higher the average energy consumption: both curves are increasing.

Proposition 6 also implies that larger deadlines improve the energy consumption. This is in accordance with the fact that the black curve (deadline 5) is below the blue curve (deadline 3).

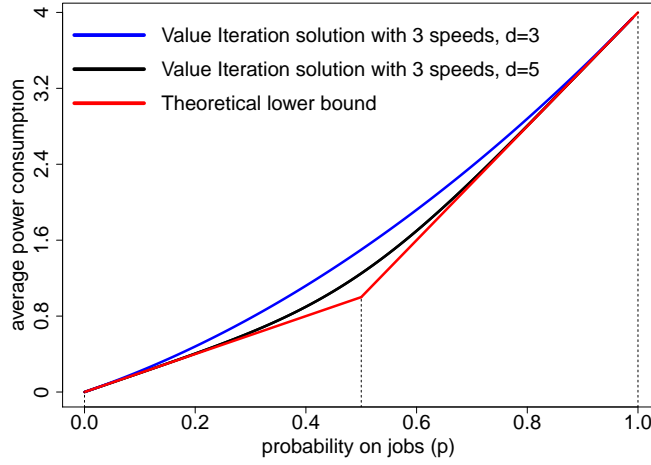


Figure 5: Average energy consumption per time unit for (TLU_{VI}) : theoretical lower bound (red curve), deadlines equal to 3 (black curve, Example 6), and deadline equal to 5 (blue curve, Example 7).

What is more surprising here is how well our solution behaves when the deadline is 5. Its performance is almost indistinguishable from the theoretical lower bound (valid for all deadlines) over a large range of the rate p . More precisely, the gap between our solution with deadline equal to 5 and the theoretical lower bound is less than 10^{-3} for $p \in [0, 0.20] \cup [0.80, 1]$.

4.4.1 Lower Bound

The theoretical lower bound has been obtained by solving the optimization problem without taking into account the distribution of the jobs features nor the constraint on the deadlines. Without constraints, and since the power is a convex function of the speed (here $j(s) = s^2$), the best choice is to keep the speed constant. The ideal constant speed needed to execute the jobs over a finite interval $[0, T]$ is $A(T)/T$, where $A(T)$ is the workload arrived before T . When T goes to infinity, the quantity $A(T)/T$ converges to $2p$ by the strong law of large numbers. Therefore, the optimal constant speed is $s^\infty = 2p$.

Now, if we consider the fact that only 3 processor speeds, namely $\{0, 1, 2\}$, are available, then the ideal constant speed $s^\infty = 2p$ cannot be used. In this case, the computation of the lower bound is based on the following construction.

On the one hand, if $0 \leq p \leq \frac{1}{2}$, then the ideal constant processor speed, $s^\infty = 2p$, belongs to the interval $[0, 1]$. In that case, only speeds $\{0, 1\}$ will be used. To obtain an average speed equal to $2p$, the processor must use speed 1 during a fraction $2p$ of the time and the speed 0 the rest of the time. The corresponding average energy per time unit has therefore the following form:

$$g^\infty = 2p \times 1^2 + (1 - 2p) \times 0^2 = 2p \quad (23)$$

On the other hand, if $p \geq \frac{1}{2}$, then the ideal constant processor speed, $s^\infty = 2p$, belongs to the interval $[1, 2]$. In that case, the processor only uses speeds 1 or 2. To get an average speed of $2p$, the processor must use the speed 2 during a fraction $2p - 1$ of the time and the speed 1

the rest of the time. The corresponding average energy per time unit in this case is:

$$g^\infty = (2p - 1) \times 2^2 + (2 - 2p) \times 1^2 = 6p - 2 \quad (24)$$

By combining Eqs. (23) and (24), we obtain the lower bound on g :

$$g^\infty(p) = \begin{cases} 2p & \text{if } p \leq 1/2 \\ 6p - 2 & \text{if } p \geq 1/2 \end{cases} \quad (25)$$

This is the red curve in Figure 5.

4.4.2 Comparison of (TLU_{DP}) and (TLU_{VI})

We performed a comparison between the two algorithms (TLU_{DP}) and (TLU_{VI}) over different time horizons T in order to study the impact of this parameter. The gain in energy of (TLU_{DP}) vs (TLU_{VI}), represented in blue in Figure 6, is computed as follow:

$$\frac{\text{Energy}_{(\text{VI})} - \text{Energy}_{(\text{DP})}}{\text{Energy}_{(\text{DP})}} \quad (26)$$

This fraction computes the relative difference between the infinite horizon case algorithm (Algorithm 3) and the the finite horizon case algorithm (Algorithm 1). Besides, the cost of (OA) versus (TLU_{DP}), also represented in Figure 6 as a dashed red curve, is defined as follows:

$$\frac{\text{Energy}_{(\text{OA})} - \text{Energy}_{(\text{DP})}}{\text{Energy}_{(\text{DP})}} \quad (27)$$

Computations were done on Example 2 with 10,000 simulations. They are summarized in Table 2.

Table 2: Influence of the time horizon T on (TLU_{DP}) in comparison with (TLU_{VI}).

T	10	15	20	25
(VI) vs (DP)	4.3%	1.7%	0.95%	0.62%
(OA) vs (DP)	4.8%	5.3%	5.3%	5.2%
T	30	40	100	150
(VI) vs (DP)	0.45%	0.29%	0.099%	0.064%
(OA) vs (DP)	5.0%	4.9%	4.6%	4.5%
T	200	250	1000	
(VI) vs (DP)	0.046%	0.031%	$6.19 \cdot 10^{-5}\%$	
(OA) vs (DP)	4.3%	4.3%	4.2%	

One can notice in Table 2 as well as on the blue curve in Figure 6 that, as soon as the time horizon is greater than 20 time units, the energy difference between (TLU_{DP}) and (TLU_{VI}) is smaller than 1%, and is negligible in comparison with the energy difference between (TLU_{DP}) and (OA). We conclude that using (VI) instead of (DP) is a good approximation even over rather short time horizons, because the results are almost as good, and computing the optimal processor speeds is faster for (VI) than for (DP). This result is rather intuitive because the only important difference between (DP) and (VI) concerns the last steps. Indeed, during these last steps, (VI) behaves as if jobs will continue to arrive in the future (after $T - \Delta$), whereas (DP) considers that there is no job arrival after $T - \Delta$. (DP) can therefore adapt the chosen speeds

in the last steps, whereas (VI) cannot. Thanks to this, the energy consumption of (DP) during the last steps is, on average, better than that of (VI).

Finally, the red curve shows that the energy difference between (OA) and (DP) is almost constant, whatever the value of the horizon time T . The horizon time has a limited impact on the energy difference: As for (VI), (OA) does not take into account the finite time horizon (except on the last Δ steps). This is why the red curve is also decreasing with the time horizon, but very slightly. Data in Table 6 confirm the results obtained in Example 2 before, because whatever the considered time horizon, the gain of (DP) in comparison with (OA) ranges between 4% and 5.5%.

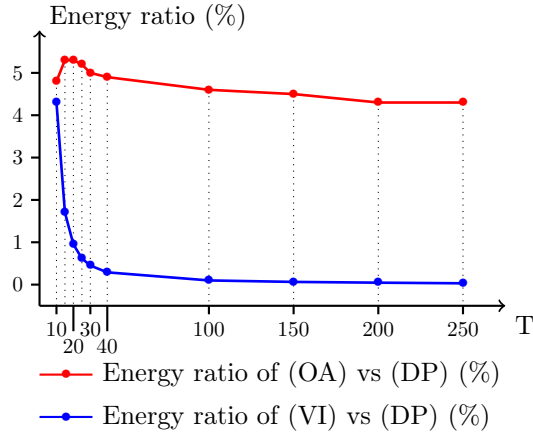


Figure 6: Influence of the time horizon T on the energy difference between (OA) and (DP), and between (VI) and (DP), with Example 2.

5 Generalization of the Model

In the next three parts, we develop several extensions to make our model more realistic. To achieve this, we assume that the processor can change speeds at any time. This assumption is not very strong because there is no technical reason to change processor speed only at task arrival. These generalizations are the following:

1. Convexification of the power consumption function: Any non-convex power function can be advantageously replaced by its convex hull.
2. Taking into account the time penalty required to change the processor speed: This time penalty can be replaced by an additional cost on the energy consumption.
3. Taking into account the context switching time between one task to another: This switching time can also be included in the cost function.

5.1 Convexification of the Power Consumption Function

Our general approach does not make any assumption on the power function $j(\cdot)$. Our algorithms (DP) and (VI) will compute the optimal speed selection for any function $j(\cdot)$. However structural

properties (including the comparison with (OA) and the monotonicity) require the convexity assumption. It is therefore desirable to convexify the power function.

Let us consider a processor, whose speeds belong to the set $\mathcal{S} = \{s_0, s_1, s_2, s_{\max}\}$ and the power function of the processor $j(\cdot) : \mathcal{S} \rightarrow \mathbb{R}$.

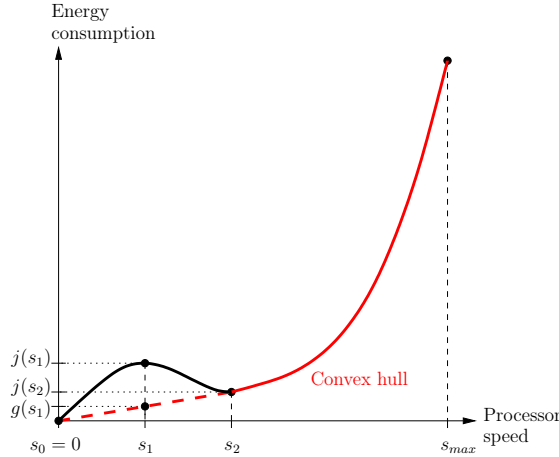


Figure 7: Convexification of the power consumption function.

If the power function is not convex, some speeds are not relevant, because using these speeds is more expensive in terms of energy than using a combination of other speeds. Figure 7 depicts a non-convex power function j in black, and its convex hull g in red. In terms of energy consumption, it is better to choose speeds s_0 and s_2 (actually a linear combination of s_0 and s_2), rather than speed s_1 . In fact, all points of the power function curve, that are above the convex hull, should never be taken into consideration. It is always better to only select the speeds whose power consumption belongs to the convex hull of the power function. Indeed if $g(s_1) < j(s_1)$ (see Figure 7), instead of selecting speed s_1 during any time interval $[t, t+1)$, the processor can select speed s_2 during a fraction of time α_2 , and then speed s_0 during a fraction of time α_0 , such that $\alpha_0 s_0 + \alpha_2 s_2 = s_1$. The total quantity of work executed during the time interval $[t, t+1)$ will be the same as with s_1 , but the energy consumption will instead be $g(s_1) = \alpha_0 j(s_0) + \alpha_2 j(s_2)$, which is less than $j(s_1)$ because of the convexity of function j . This approach uses the V_{dd} hopping technique.

As a result, we can always consider that the power function is convex. This is very useful in practice. Indeed, the actual power consumption of a CMOS circuit working at speed s is non-convex function of the form $j(s) = Cs^\alpha + L(s)$, where the constant C depends on the activation of the logical gates, α is between 2 and 3, and $L(s)$ is the leakage, with $L(0) = 0$ and $L(s) \neq 0$ if $s > 0$. In this case, convexification removes the small values of s from the set of useful speeds.

Remark: This idea of replacing one speed by a linear combination of two speeds (*i.e.*, V_{dd} hopping) can also be used to simulate any speed between 0 and s_{\max} . Indeed, if a speed doesn't exist in the set \mathcal{S} , a solution is to simulate it by combining two neighboring speeds. This technique allows the processor to have more speeds to choose from, so that the optimal speed computed by the (DP) algorithm will use less energy with V_{dd} hopping than without it.

5.2 Taking into Account the Cost of Speed Changes

In our initial model, we have assumed that the time needed by the processor to change speeds is null. However, in all synchronous CMOS circuits, changing speeds does consume time and energy. The energy cost comes from the voltage regulator when switching voltage, while the time cost comes from the relocking of the Phase-Locked Loop when switching the frequency [14]. Burd and Brodersen have provided in [15] the equations to compute these two costs. In contrast with many DVFS studies (e.g., [15, 16, 17, 18]), our formulation can accommodate arbitrary energy cost to switch from speed s to s' . In the sequel, we denote this energy cost by $h_e(s, s')$.

As for the time cost, we denote by δ the time needed by the processor to change speeds. For the sake of simplicity we assume that the delay δ is the same for each pair of frequencies, but our formalization can accommodate different values of δ , as computed in [15]. During this time, the circuit logical functions are altered so no computation can take place.

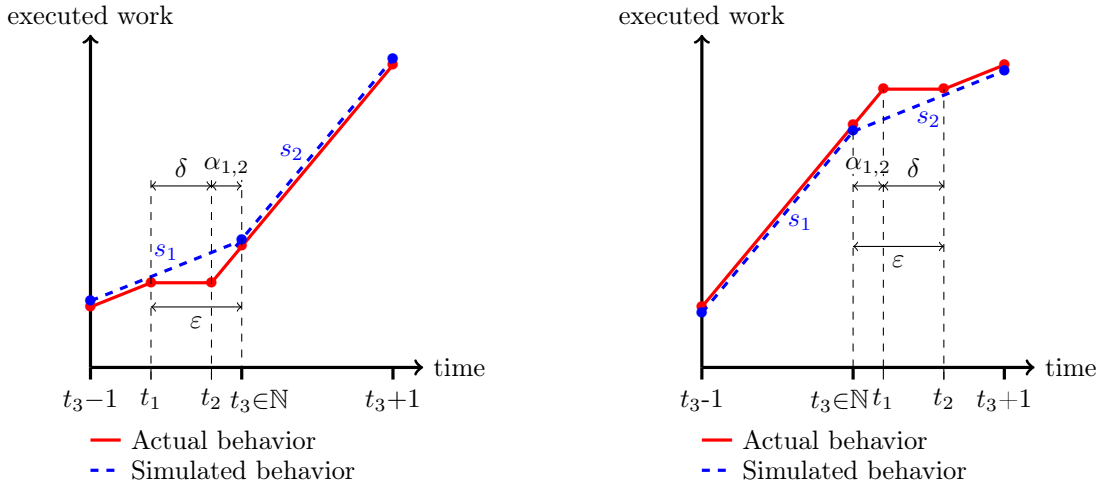


Figure 8: Transformation of the time delay into an energy additional cost by shifting the switching point. The left figure corresponds to the $s_1 < s_2$ case and the right figure to the $s_1 > s_2$ case. The red line represents the actual behavior of the processor with a δ time delay. The blue dashed line represents an equivalent behavior in terms of executed work, with no time delay.

With time delays for speed changes, the executed work by the processor has *two* slope changes, at times t_1 and t_2 , with $t_2 - t_1 = \delta$ (see the red solid line in Figure 8). The problem is that, since in general $\delta \notin \mathbb{N}$, we cannot have both $t_1 \in \mathbb{N}$ and $t_2 \in \mathbb{N}$. As a consequence, one of the remaining work functions w_{t_1} or w_{t_2} of the state states \mathbf{x}_{t_1} or \mathbf{x}_{t_2} will not be integer valued. This is not allowed by our MDP approach.

We propose an original solution that replaces the actual behavior of the processor (represented by the red solid line in Figure 8) by a *simulated* behavior, equivalent in terms of the amount of work performed (represented by the blue dashed line in Figure 8). This simulated behavior exhibits a *single* speed change and is such that the total amount of work done by the processor is identical in both cases at all integer times (*i.e.* at $t_3 - 1$, t_3 , and $t_3 + 1$ in Figure 8). The advantage is that, since there is only one state change, it can be chosen to occur at an integer time. In other words, we *choose* t_1 such that $t_3 \in \mathbb{N}$.

One issue remains, due to the fact that the consumed energy will not be identical with the real behavior and the simulated behavior; it will actually be higher for the real behavior for

convexity reason. This additional energy cost of the real processor behavior must therefore be added to the energy cost of the equivalent simulated behavior.

Finally, in order to trigger the speed change at time t_1 , the processor needs to be “clairvoyant”, *i.e.*, it needs to know in advance (before t_1) the characteristics of the job arriving at time t_3 . This will allow the processor to compute the new speed s_2 and the length ε of the required interval to make sure that the work done by the processor at t_3 in the two cases (real and simulated) is identical.

The value of ε , $\alpha_{1,2}$, and the additional energy cost $h_\delta(s_1, s_2)$ of this speed change are computed as follows. In the case $s_2 > s_1$ (as in Figure 8), we have:

$$\begin{aligned} s_1\varepsilon &= s_2\alpha_{1,2} = s_2(\varepsilon - \delta) \\ \iff (s_2 - s_1)\varepsilon &= \delta s_2 \\ \iff \varepsilon = \delta + \alpha_{1,2} &= \frac{\delta s_2}{s_2 - s_1} \end{aligned} \quad (28)$$

We further assume that, during the time delay δ , the energy is consumed by the processor as if the speed were s_1 . The additional energy cost incurred in the real behavior (red curve) compared with the simulated behavior (blue curve), denoted $h_\delta(s_1, s_2)$, is therefore:

$$h_\delta(s_1, s_2) = \alpha_{1,2}(j(s_2) - j(s_1))$$

Using the value of $\alpha_{1,2}$ from Eq. (28) yields:

$$h_\delta(s_1, s_2) = \delta s_1 \left(\frac{j(s_2) - j(s_1)}{s_2 - s_1} \right) \quad (29)$$

When $s_1 > s_2$, the additional cost becomes:

$$h_\delta(s_1, s_2) = \delta s_2 \left(\frac{j(s_1) - j(s_2)}{s_1 - s_2} \right) \quad (30)$$

This additional energy due to speed changes will be taken in consideration in our model in the cost function, by modifying the state space \mathcal{X} and adding the current speed to the state at $t - 1$. Therefore the new state at time t becomes (\mathbf{x}_t, s_{t-1}) .

Taking into account both the energy cost and the time cost, the new main step of the (DP) Algorithm 1 becomes:

$$\begin{aligned} J_{t-1}^*(\mathbf{x}, s) \leftarrow & \min_{s' \in \mathcal{A}(\mathbf{x})} \left(j(s) + h_\delta(s, s') + h_e(s, s') \right. \\ & \left. + \sum_{\mathbf{x}' \in \mathcal{W}} P_t(\mathbf{x}, s', \mathbf{x}') J_t^*(\mathbf{x}', s') \right) \end{aligned} \quad (31)$$

with $h_\delta(s, s') = 0$ when $s = s'$, and otherwise given by Eq. (30) if $s' < s$ and Eq. (29) if $s < s'$. The rest of the analysis is unchanged.

5.3 Taking into Account the Cost of Context Switches

In the core of our article, we have neglected the context switch delay in EDF incurred by a preemption. This cost is orders of magnitude less than the cost of executing a job [19, 20, 21]. Nevertheless, in the following, we present a solution where we take into account this context switch delay.

5.3.1 Without Processor Sharing

When the processor can only execute one job at a time, one can consider that switching from the execution of one job to another one takes some time delay, denoted γ . This is essentially the time needed to upload or download the content of the execution stack. During this context switch, no useful work is being executed. This time delay is assumed to be identical for the beginning of a new job or the resuming of a job after preemption.

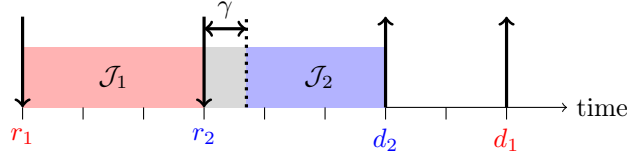


Figure 9: Impact of a context switch on the execution time.

Figure 9 illustrates an example made of 2 jobs with the following characteristics: $\mathcal{J}_1(r_1 = 0, c_1 = 3, d_1 = 7, 5)$ and $\mathcal{J}_2(r_2 = 3, c_2 = 2, d_2 = 3)$. The switching time γ is marked with the barred area.

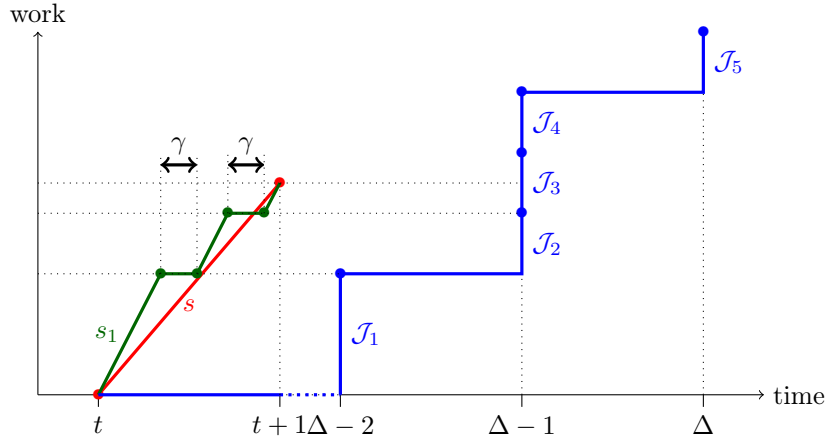


Figure 10: Compensation of the impact of the context switches on the executed work by using a higher speed. The released jobs are $\mathcal{J}_i = (r_i, c_i, d_i)$, for $1 \leq i \leq 5$, with $r_5 + d_5 = \Delta$, $r_4 + d_4 = r_3 + d_3 = r_2 + d_2 = \Delta - 1$, and $r_1 + d_1 = \Delta - 2$.

Figure 10 illustrates the fact that, during one time step, several context switches can occur. In this example, during the time interval $[t, t + 1)$, the processor completes two jobs, \mathcal{J}_1 and \mathcal{J}_2 , and starts the execution of \mathcal{J}_3 (see the red curve). This involves two context switches, both of which occur during one time unit. This leads to a total delay of 2γ . As in Section 5.2, we transform this time delay into an energy cost: In one time unit, the evolution of the executed work under speed s_1 , with K context switches (see the green curve), is the same as the evolution of the executed work under speed $s = s_1(1 - K\gamma)$, with no switching delay (red curve).

The state space of the system must be modified to be able to compute K , the number of context switches in each time interval. We must keep in memory the sizes of the jobs instead of only the total remaining work. Indeed, with the current state space \mathcal{X} , we do not know the number of actual different jobs composing a given amount $w(i), i \in \{0, \dots, \Delta\}$, so we cannot

know the number of context switches. We denote by $\bar{\mathcal{X}}$ the new state space and by $\bar{\mathbf{x}}_t \in \bar{\mathcal{X}}$ the new current state at time t :

$$\bar{\mathbf{x}}_t = (\bar{w}_t, \ell_t) \quad (32)$$

where \bar{w}_t has the following form:

$$\bar{w}_t = \left[\begin{array}{c} (\rho_1^1, \dots, \rho_1^{k_1}), \dots, \underbrace{(\rho_i^1, \dots, \rho_i^{k_i})}_{\substack{\text{remaining work quantity of jobs} \\ \text{with absolute deadline } t+i}}, \\ \dots, (\rho_\Delta^1, \dots, \rho_\Delta^{k_\Delta}) \end{array} \right] \quad (33)$$

where k_i is the number of jobs whose relative deadline is i time units away (hence their absolute deadline is $t+i$), and ρ_i^j is the work quantity of the j -st such job.

For the sake of simplicity, we will consider that there is only one new job at t (instead of a set of jobs). The general case with multiple arrival will be identical, upto an increase of the state space.

To simplify we consider a single new arrival (τ_n, c_n, d_n) at time $t = r_n$ (recall that r_n is computed from the τ_k values with Eq. (1)). The case with several arrivals is a direct adaptation of the following formula.

If the processor speed at time $t-1$ is s_{t-1} , then at time t the next state $\bar{\mathbf{x}}_{t+1}$ becomes $(\bar{w}_{t+1}, \ell_{t+1})$, where \bar{w}_{t+1} is:

$$\begin{aligned} \bar{w}_{t+1} = & \left[\left((\rho_2^1 - f(1, 1))^+, \dots, \right. \right. \\ & \left. \left. (\rho_2^{k_1} - f(1, k_1))^+ \right), \right. \\ & \dots, \\ & \left((\rho_{d_n}^1 - f(d_n, 1))^+, \dots, \right. \\ & \left. (\rho_{d_n}^{k_{d_n}} - f(d_n, k_{d_n}))^+, c_n \right), \\ & \dots, \\ & \left((\rho_\Delta^1 - f(\Delta, 1))^+, \dots, \right. \\ & \left. (\rho_\Delta^{k_\Delta} - f(\Delta, k_\Delta))^+ \right), \\ & \left((\rho_\Delta^1 - f(\Delta, 1))^+, \dots, \right. \\ & \left. (\rho_\Delta^{k_\Delta} - f(\Delta, k_\Delta))^+ \right) \left. \right] \quad (34) \end{aligned}$$

where

$$f(d, k) = \left(s_{t-1} - \sum_{i=1}^{d-1} \sum_{j=1}^{k_i} \rho_i^j - \sum_{j=1}^k \rho_d^j \right)^+$$

The idea of the state change is to set all the ρ_i^j values to 0 when $s \geq \sum_{i,j} \rho_i^j$. One job is executed partially and the others remain unchanged.

We further assume that the energy consumption during a context switch is the same as when some work is executed. The new main step of the Algorithm 1 for (DP) now has the following form:

$$J_{t-1}^*(\bar{\mathbf{x}}) \leftarrow \min_{s \in \mathcal{A}(\bar{\mathbf{x}})} \left(j \left(\frac{s}{1 - K_s \gamma} \right) + \sum_{\bar{\mathbf{x}}' \in \bar{\mathcal{X}}} P_t(\bar{\mathbf{x}}, s, \bar{\mathbf{x}}') J_t^*(\bar{\mathbf{x}}') \right) \quad (35)$$

Note that the speed $\frac{s}{1 - K_s \gamma}$ may not be directly available, but using the remark made in Section 5.1, one can easily simulate this speed with the neighboring available speeds.

Let K_s be the number of job executed if we use the speed s . We have:

$$K_s = \sum_{i=1}^{\alpha-1} k_i + \alpha \quad (36)$$

where $\alpha = \arg \min_{\alpha, k_\beta} \left(s < \sum_{i,j}^{\alpha, k_\beta} \rho_i^j \right)$. The rest of the analysis is unchanged.

5.3.2 With Processor Sharing

If processor sharing is enabled, which is often the case nowadays, the switching time is replaced by the additional delay *per time unit* caused by the permanent context switch. This additional delay is also denoted γ in this section.

In this case, the state space can be simplified. One only needs to keep in memory the number of jobs that are executed in a specific $w_t(i)$ from state \mathbf{x}_t , instead of all their sizes. Therefore, the state becomes

$$\mathbf{x}'_t = [w_t(1), \dots, w_t(\Delta), k_t(1), \dots, k_t(\Delta), \ell_t]$$

where $k_t(i)$ is the number of jobs with relative deadlines i . We have also to modify the change state function accordingly. Again we consider a single arrival (r_n, c_n, d_n) at time $t+1 = r_n$ (the general case is a direct extension). If the processor speed at time t is s_t , then at time $t+1$ the next state $\mathbf{x}'_{t+1} = (w_{t+1}, k_{t+1}, \ell_{t+1})$ is such that:

$$w_{t+1}(\cdot) = \mathbb{T} [(w_t(\cdot) - s_t)^+] + c_n H_{d_n}$$

as before, ℓ_{t+1} also follows the same evolution as in the original case, and for all $i = 1 \dots \Delta$,

$$k_{t+1}(i) = \begin{cases} \mathbf{1}_{\{i=d_n\}} & \text{if } s_t > w_t(i+1) \\ k_t(i+1) + \mathbf{1}_{\{i=d_n\}} & \text{otherwise,} \end{cases}$$

In the processor sharing case, the additional time due to switching is γ per time unit. The Bellman equation is the same as Eq. (35) but replacing K_s by:

$$K'_s = \sum_i \frac{\mathbf{1}_{\{k_i > 1\}}}{s} (s - w(i-1))^+ + \mathbf{1}_{\{k_1 > 1\}} \frac{w(1)}{s} \quad (37)$$

6 Conclusion and Perspectives

In this paper, we showed how to select on-line speeds to execute real-time jobs while minimizing the energy consumption by taking into account statistic information on job features. This information may be collected by using past experiments or simulations, as well as deductions from

the structure of job sources. Our solution provides performances that are close to the optimal off-line solutions on average, and outperforms classical on-line solutions in cases where the job features have distributions with large variances.

While the goal of this study is to propose a better processor speed policy, several points are still open and will be the topic of future investigations.

The first one concerns the scheduling model: In this paper jobs are executed under the *Earliest Deadline First* policy, but this is not always possible in practice. What would be the consequence of using another scheduling policy?

The second one concerns the time and space complexity of our algorithms. These complexities are exponential in the deadlines of the jobs. Although our algorithms (DP) and (VI) are used off-line and can be run on powerful computers, our approach remains limited to a small range of parameters. One potential solution is to simplify the state space and to aim for a sub-optimal solution (but with proven guarantees), using approximate dynamic programming.

Finally, the statistical information gathered on the job features is crucial. When this information is not accurate or even not available, Markov Decision approaches are not possible and one should use reinforcement learning techniques (such as Q-learning [22]) to construct a statistical model of the jobs on-line and select the speeds accordingly, which will converge towards optimal speeds over time.

A Size of the State Space

This appendix is dedicated to the enumeration of the total number of states of the MDP.

Let $w(\cdot)$ be a valid state of the system, at any time t . Since all parameters are integer numbers and the maximum deadline of a task is Δ , the maximal look-ahead at any time is Δ , hence $w(\cdot)$ is characterized by its first Δ integer values (that are non-decreasing by definition): $w(1) \leq \dots \leq w(\Delta)$.

Let us define the step sizes of w , starting from the end: $x_1 = w(\Delta) - w(\Delta - 1)$, and more generally, $x_j = w(\Delta - j + 1) - w(\Delta - j)$, for all $j = 1, \dots, \Delta$, the released work being of maximal size C at any time, $x_1 \leq C$ because x_1 must be bounded by the amount of work that was released at step t . Similarly, $x_1 + x_2$ must be bounded by the amount of work that was released at steps t and $t - 1$, namely $2C$, and so on and so forth up to $x_1 + x_2 + \dots + x_\Delta \leq \Delta C$. This is the only condition for a function w to be a possible state when deadlines and sizes are arbitrary integers bounded by Δ and C respectively.

Therefore $(x_1, x_2, \dots, x_\Delta)$ satisfy the following conditions:

$$\begin{cases} x_1 \leq C \\ x_1 + x_2 \leq 2C \\ x_1 + x_2 + x_3 \leq 3C \\ \vdots \\ x_1 + x_2 + \dots + x_\Delta \leq \Delta C \end{cases}$$

By defining the partial sums $y_j = x_1 + \dots + x_j$, the number of states satisfies:

$$Q(C, \Delta) = \sum_{y_1=0}^C \sum_{y_2=y_1}^{2C} \sum_{y_3=y_2}^{3C} \dots \sum_{y_\Delta=y_{\Delta-1}}^{\Delta C} 1$$

This multiple sum can be seen as a generalized Catalan number. Indeed, notice that a state characterized by its steps (x_1, \dots, x_Δ) is in bijection with a path on the integer grid from $(0, 0)$ to $(\Delta + 1, C(\Delta + 1))$, which remains *below* the diagonal of slope C (see Fig. 11).

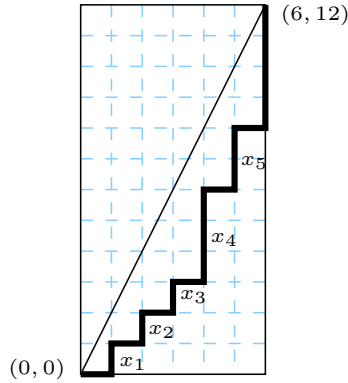


Figure 11: A valid state seen as a path below the diagonal $(0,0)$ — $(6,12)$, for $C = 2$ and $\Delta = 5$.

Counting the number of such paths has been done in [23] and corresponds to the generalized Catalan numbers, $C_n^k = \frac{1}{nk+1} \binom{nk+1}{n}$.

We propose below a direct proof for computing $Q(C, \Delta)$, which is new up to our knowledge. This new proof is inspired by the ordinary Catalan numbers. First, let us count the total number

of paths from $(0, 0)$ to $(\Delta + 1, C(\Delta + 1))$ without the constraint of staying below the diagonal. This is standard combinatorics and this number of paths is equal to $\binom{(C+1)(\Delta+1)}{\Delta+1}$.

Second, this set of paths can be partitioned into *classes* according to the number of vertical steps taken *above* the diagonal. According to this classification, $Q(C, \Delta)$ is the size of class 0 (the paths that take no step over the diagonal).

Third, by using a *shift*, we will show that any path of class k (with $k < C$) can be bijectively transformed into a path of class $k + 1$. This will prove that all the classes have the same size. Here is how to proceed.

Since the path is not of class C , it takes excursions below the diagonal and therefore, its first vertical step that hits the diagonal from below is well defined. The path P can be written xvy where v is this vertical step, and x and y are respectively the prefix and the suffix of P w.r.t. v . This is illustrated in Fig. 12 (left).

We then construct the path P' by swapping the prefix and the suffix of P , i.e., $P' = yvx$, and we claim that P' is in class $k + 1$. The construction of P' from P is illustrated in Fig. 12.

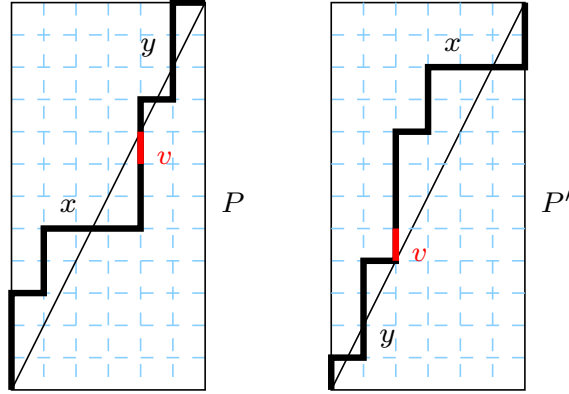
- The number of vertical steps in y is the same in P' and in P because y starts on the diagonal and ends on the diagonal in both cases (see Fig. 12).
- Regarding x , it is *shifted up* by one step up in P' , so all the vertical steps taken by x above the diagonal in P are still taken above the diagonal in P' . As for the vertical steps taken below the diagonal by x in P , they remain below the diagonal in P' . Indeed, suppose that there exists a vertical step in x that is below the diagonal in P but above the diagonal in P' . Since x is shifted up by one step, this means that this step was touching the diagonal from below in P . This is not possible since the first such step is v , hence not in x .

As a result, like y , x also contributes the same number of vertical steps above the diagonal in P and in P' . It follows that the only difference in the number of vertical steps between P and P' comes from v , which is not above the diagonal in P but is above in P' . Hence the class of P' is $k + 1$.

Let us now show that this transformation is bijective. As explained above, the last sub-path x in P' does not contain any vertical step that starts on the diagonal. This means that the step v is the last vertical step that starts from the diagonal in P' . This implies that P can be reconstructed back from P' . Therefore, the transformation of P into P' is reversible, so it is an injection. Since all paths of class $k + 1$ contain a last vertical step starting on the diagonal, the transformation is bijective.

The construction of this bijection means that the size of class k is equal to the size of class $k + 1$, for all $0 \leq k < C$. This means that all the classes have the same size. Therefore, the class 0 has size $Q(C, \Delta) = \frac{1}{1+C(\Delta+1)} \binom{(C+1)(\Delta+1)}{\Delta+1}$.

Using the Stirling formula, we finally get $Q(C, \Delta) \approx \frac{e}{\sqrt{2\pi}} \frac{1}{(\Delta+1)^{3/2}} (eC)^\Delta$.



B Appendix: Decision Times

In the whole paper, we have assumed that the decision times (*i.e.* time instants when the processor can change its speed) are integers. This assumption may seem natural because all job arrivals occur at integer times. However, this overlooks the fact that allowing the processor to change its speed at any time t in \mathbb{R} gives to the processor a new degree of freedom that could be beneficial in terms of energy consumption.

Here is a simple example illustrating this fact: If the processor can use speed $s = 0$ over the sub-interval $[t, t + 1/2]$ and speed $s' = 1$ over the sub-interval $[t + 1/2, t + 1]$, then, in total over the interval $[t, t + 1]$, this can be seen as a processor using speed $s'' = 1/2$, with an energy consumption $P(s)/2 + P(s')/2$. This combination is not possible if the processor can only change its speed at integer times and this new possibility may help to decrease the energy consumption. In this appendix, we will show that this is not the case.

To do so, let us consider a processor using the finite set of speeds \mathcal{S} with respective powers $\{P_{\text{ow}}(s), s \in \mathcal{S}\}$ that may change its speed at any time in \mathbb{R} . Its minimal expected energy consumption when starting in state x is denoted $J^{*,\mathcal{S},\mathbb{R}}(x)$.

A priori such a processor is more capable than a processor using the same finite set of speeds \mathcal{S} that may only change its speed at times in \mathbb{N} , whose minimal expected energy loss when starting in state \mathbf{x} is now denoted $J^{*,\mathcal{S},\mathbb{N}}(\mathbf{x})$ (in the paper, this was simply denoted $J^*(\mathbf{x})$). For all \mathbf{x} ,

$$J^{*,\mathcal{S},\mathbb{R}}(\mathbf{x}) \leq J^{*,\mathcal{S},\mathbb{N}}(\mathbf{x}).$$

We will show in the following that equality always holds when the set of speeds is consecutive.

Theorem 1 *If the set \mathcal{S} is made of consecutive speeds (i.e. $\mathcal{S} = \{0, 1, 2, \dots, s_{\max}\}$), then there is no energy gain for the processor to use non-integer decision times: for all \mathbf{x} , $J^{*,\mathcal{S},\mathbb{R}}(\mathbf{x}) = J^{*,\mathcal{S},\mathbb{N}}(\mathbf{x})$.*

Proof 7 *The proof is done with a simplified case where job arrivals have the same independent distribution at each time step, so that we can consider w as the state instead of the more general state $\mathbf{x} = (\ell, w)$ used in the paper. The proof is essentially the same, as explained at the end of*

the proof. To keep notations simple, we also skip the indices \mathcal{S}, \mathbb{N} in $J^{*, \mathcal{S}, \mathbb{N}}$ in the proof up to the last part of the proof.

Let us consider that the set \mathcal{S} of processor speeds is consecutive and that the processor can change its speed at times $t \in \mathbb{N}$ as well as at times $t + 1/2$. We will show that this does not bring any energy gain.

The time horizon is T and the minimal energy at time t under state w can be decomposed into two actions (taken at times t and $t + 1/2$):

$$J_{t+\frac{1}{2}}^*(w) = \min_{v \in \mathcal{A}_2(w)} \left(\frac{Pow(v)}{2} + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}_2 \left(w - \frac{v}{2} \right)^+ + a \right) \right) \quad (38)$$

$$J_t^*(w) = \min_{u \in \mathcal{A}_1(w)} \left(\frac{Pow(u)}{2} + J_{t+\frac{1}{2}}^* \left(\mathbb{T}_2 \left(w - \frac{u}{2} \right)^+ \right) \right) \quad (39)$$

where $\mathcal{A}_2(w) = \{s \in \mathcal{S} : s \geq 2w(1)\}$, $\mathcal{A}_1(w) = \mathcal{S}$ and the operator $\mathbb{T}_2(f)$ only shifts the function f by $1/2$: $\mathbb{T}_2(f(x)) = f(x + 1/2)$.

This is a similar DP equation as used in Algorithm 1, where we take into account the fact that there are no arrival at time $t + 1/2$, and a modified admissibility condition on the speeds: to meet all deadlines, the speed at time $t + 1/2$ must execute all the work with deadline $t + 1$, hence the speed u must be larger than $2w(1)$ while the speed chosen at time t does not have any constraint: no job has a deadline at time $t + 1/2$. These two equations show that the new state space should also include the step functions with step sizes in $\mathbb{N}/2$.

By replacing the value of $J_{t+1/2}^*$ in the second equation, one gets J_t^* as a function of J_{t+1}^* :

$$\begin{aligned} J_t^*(w) &= \min_{u \in \mathcal{A}_1(w)} \left(\frac{Pow(u)}{2} + \min_{v \in \mathcal{A}_2(w)} \left(\frac{Pow(v)}{2} + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}_2 \left(\mathbb{T}_2 \left(w - \frac{u}{2} \right)^+ - \frac{v}{2} \right)^+ + a \right) \right) \right) \\ &= \min_{u \in \mathcal{A}_1(w), v \in \mathcal{A}_2(w)} \left(\frac{Pow(u)}{2} + \frac{Pow(v)}{2} + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T} \left(w - \frac{u+v}{2} \right)^+ + a \right) \right) \end{aligned}$$

where we have used the distributivity of $+$ over \max to get the second line.

This says precisely what was asserted without proof at the beginning: changing speed at half times is equivalent to choosing half speeds at integer times.

The first property that one can get from the last equation is the following: The speeds u, v achieving the \min are such that $|u - v| \leq 1$. Indeed, if $|u - v| > 1$, then one can choose $u', v' \in \mathcal{A}_1(w), \mathcal{A}_2(w)$ such that $|u' - v'| \leq 1$ and $u + v = u' + v'$. By convexity of Pow , $Pow(v)/2 + Pow(u)/2 \geq Pow(v')/2 + Pow(u')/2$ so that the choice u', v' is better than the choice u, v .

With no loss of generality, we will assume in the following that either $u = v$ (in which case we are back to an integer speed) or $v = u + 1$.

A second property is that both optimal speeds u and $u + 1$ are admissible in state w : If $u + 1 \in \mathcal{A}_2(\mathbb{T}_2(w - u/2)^+)$, then $u + 1 + u \geq 2w(1)$. This implies $u \geq w(1) - 1/2$, so that $u \geq w(1)$ because both u and $w(1)$ are integers (and of course $u + 1 \geq w(1)$).

We are now ready for the proof, that holds by backward induction on t . Let us prove the two following properties simultaneously:

(P1) for all w with integer steps sizes, $J_t^*(w)$ is obtained by using integer speeds only.

(P2) for all w, a and all $u \in \mathcal{A}(w)$, then using $v = u + 1$,

$$J_t^* \left(\left(w - \frac{u+v}{2} \right)^+ + a \right) = \frac{1}{2} J_t^* \left((w-u)^+ + a \right) + \frac{1}{2} J_t^* \left((w-v)^+ + a \right).$$

Both properties are obviously true at time T where there is nothing to prove. Now, let us prove (P1) at time t :

Under state w with integer steps, let us consider the randomized policy that chooses at time t , speed $u \in \mathcal{A}(w)$ with probability $1/2$ and speed $u + 1$ with probability $1/2$ and is optimal from time $t + 1$ on.

The energy of this policy is

$$\begin{aligned} J_t^*(w) &= \frac{1}{2} \left(Pow(u) + \sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w-u)^+ + a) \right) \\ &\quad + \frac{1}{2} \left(Pow(u+1) + \sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w-u-1)^+ + a) \right) \\ &= \frac{Pow(u)}{2} + \frac{Pow(u+1)}{2} + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T} \left(w - \frac{u+u+1}{2} \right)^+ + a \right) \end{aligned}$$

where (P2) at time $t+1$ is used for states $(\mathbb{T}(w-u)^+ + a, \mathbb{T}(w-u-1)^+ + a, \mathbb{T}(w - \frac{u+u+1}{2})^+ + a)$ to get the second inequality.

This says that this randomized policy has the same energy cost as the policy that uses speed $(u+u+1)/2$ at time t . The theory of Markov decision processes says that there exists an optimal policy that does not randomize. Here, this implies that there exists an optimal policy at time t that uses an integer speed. This is exactly (P1).

As for (P2), we first notice that the arrival of jobs a can be included in the state w for simplicity. Therefore, let us consider two states with integer step sizes, $w_2 := (w-u+1)^+$ and $w_1 := (w-u)^+$ at time t . Using (P1), the optimal speed used in both states are integers. Let us denote by σ_1 the optimal speed used in state w_1 .

Since $w_2 \geq w_1$ pointwise, then by monotony of the total energy with respect to the state, by using the same reasoning as in Proposition 6 and an induction on t , the optimal speed σ_2 in state w_2 is higher than σ_1 : $\sigma_2 \geq \sigma_1$. We further claim that $\sigma_2 \leq \sigma_1 + 1$. We show this by contradiction: assume that $\sigma_2 = \sigma_1 + k$, with $k \geq 2$. Convexity of the power implies

$$Pow(\sigma_1 + k) - Pow(\sigma_1 + 1) \geq Pow(\sigma_1 + k - 1) - Pow(\sigma_1).$$

Since $\sigma_2 = \sigma_1 + k$ is optimal for w_2 , we get

$$\begin{aligned} & Pow(\sigma_1 + k) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}(w-u+1-\sigma_1-k)^+ + a \right) \\ & < Pow(\sigma_1 + 1) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}(w-u+1-\sigma_1-1)^+ + a \right). \end{aligned}$$

Together with the previous inequality this implies

$$Pow(\sigma_1 + k - 1) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}(w-u-\sigma_1-k+1)^+ + a \right) \quad (40)$$

$$< Pow(\sigma_1) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T}(w-u-\sigma_1)^+ + a \right). \quad (41)$$

The first term is the energy cost of using speed $\sigma_1 + k - 1$ in state w_1 . The second term is the energy cost of using speed σ_1 in state w_1 . This inequality contradicts the optimality of σ_1 . Therefore, $\sigma_2 \leq \sigma_1 + 1$.

Now, let us compute the optimal speed σ_3 in the “middle” state $w_3 = (w - \frac{u+u-1}{2})^+$. By monotonicity, $\sigma_1 \leq \sigma_3 \leq \sigma_2$. Therefore, there only exists two possibilities:

- If $\sigma_1 = \sigma_2$ then $\sigma_3 = \sigma_1$ and

$$\begin{aligned}
J_t^*(w_3) &= P_{ow}(\sigma_1) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T} \left(w - \frac{u+u-1}{2} - \sigma_1 \right)^+ + a \right) \\
&= P_{ow}(\sigma_1) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T} \left(w - \frac{(u+\sigma_1) + (u+\sigma_1) - 1}{2} \right)^+ + a \right) \\
&= \frac{1}{2} \left(P_{ow}(\sigma_1) + \sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w - u - \sigma_1)^+ + a) \right) \\
&\quad + \frac{1}{2} \left(P_{ow}(\sigma_1) + \sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w + 1 - u - \sigma_1)^+ + a) \right) \\
&= \frac{1}{2} J_t^*(w_1) + \frac{1}{2} J_t^*(w_2)
\end{aligned}$$

where the third equality comes from (P2) at time $t + 1$.

- If $\sigma_2 = \sigma_1 + 1$ then by using the same argument to prove that $\sigma_1 \leq \sigma_2 \leq \sigma_1 + 1$, then the optimal speed in state w_3 is $\sigma_3 = (\sigma_1 + \sigma_2)/2$. In this case,

$$\begin{aligned}
J_t^*(w_3) &= \frac{1}{2} P_{ow}(\sigma_1) + \frac{1}{2} P_{ow}(\sigma_2) + \sum_a P_t(a) J_{t+1}^* \left(\mathbb{T} \left(w - \frac{u+u-1}{2} - \frac{\sigma_1 + \sigma_1 + 1}{2} \right)^+ + a \right) \\
&= \frac{1}{2} P_{ow}(\sigma_1) + \frac{1}{2} P_{ow}(\sigma_2) + \sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w - u - \sigma_1)^+ + a) \\
&= \frac{1}{2} J_t^*(w_1) + \frac{1}{2} J_t^*(w_2).
\end{aligned}$$

This shows that changing speeds at half times does not help. A straightforward generalization says that changing speeds at times $t \in \mathbb{N}/2^i$ will not help either for any i . By continuity of the total energy with respect to the speed function, this shows that changing speeds at times $t \in \mathbb{R}$ will not help either: $J^{*,S,\mathbb{R}}(w) = J^{*,S,\mathbb{N}}(w)$.

Finally, as announced at the beginning of the proof, one can take into account the more detailed state $\mathbf{x} = (\ell, w)$ instead of w . The proof is the same up to one harmless modification: Replace everywhere w by (ℓ, w) and

$$\sum_a P_t(a) J_{t+1}^* (\mathbb{T}(w - v)^+ + a)$$

by

$$P_t(0) J_{t+1}^* (\ell + 1, \mathbb{T}(w - v)^+) + \sum_{a \neq 0} P_t(a) J_{t+1}^* (1, \mathbb{T}(w - v)^+ + a).$$

□

When the available speeds do not form a consecutive set, it is possible that all the optimal speed schedules change speed at non integer times. Here is a simple example. Consider the degenerated case where there is a single arrival at time $t = 0$ with probability one, of a job of size 4 with deadline 3: $w_0 = 0$, $P_0((0, 4, 3)) = 1$ and $P_t(a) = 0$ for all $t > 0$ and all $a \neq 0$.

If $\mathcal{S} = \{0, 1, 3\}$ (non-consecutive), then all optimal speed schedules must use speed $s = 3$ during $1/2$ a unit of time before time 3, speed 1 during $5/2$ units of time before time 3, and then speed 0 from time 3 on. So at least one speed change must occur at a non-integer time.

As a side note, if the set of speeds were consecutive: $\bar{\mathcal{S}} = \{0, 1, 2, 3\}$, then all optimal speed schedules would use speed 2 during one time unit, speed 1 during 2 time units and speed 0 from time 3 on. This is achievable with speed changes occurring at integer times.

In the following, we show that if \mathcal{S} is not consecutive, it is always possible to go back to the consecutive case with integer decision times by interpolating the power function.

Theorem 2 *If the set \mathcal{S} is not consecutive, the optimal speed policy can be constructed using integer decision times under an augmented consecutive set of speeds and then using VDD hopping (defined in the proof).*

Proof 8 *Let $\bar{\mathcal{S}}$ be the extended set of speeds to all integer speeds below s_{\max} : $\bar{\mathcal{S}} = \{0, 1, 2, \dots, s_{\max}\}$.*

First, we assign to each non available integer speed a power consumption by using a linear interpolation. More precisely, for each $s < s_{\max}$ and $s \notin \mathcal{S}$, let $s_1, s_2 \in \mathcal{S}$ be the two neighboring available speeds such that $s_1 < s < s_2$. Therefore, s can be seen as a convex combination of s_1 and s_2 :

$$s = \beta s_1 + (1 - \beta) s_2, \text{ with } \beta = \frac{s_2 - s}{s_2 - s_1}. \quad (42)$$

We define the power consumption of s as:

$$P_{ow}(s) = \beta P_{ow}(s_1) + (1 - \beta) P_{ow}(s_2). \quad (43)$$

Once this is done for each non available speed, we can solve the problem over $\bar{\mathcal{S}}$ with integer decision times (the unavailable speeds being seen as available with the power cost defined in Eq. (43)). According to our notation, the optimal energy when starting in x is $J^{, \bar{\mathcal{S}}, \mathbb{N}}(x)$. The optimal speed policy with integer decision times are denoted $\{s^*(t)\}_{t \in \mathbb{N}} \in \{0, 1, 2, \dots, s_{\max}\}$.*

The following transformation is done at each integer time step $t \in \mathbb{N}$ (this is called VDD hopping in the following). In the time interval $[t, t + 1)$, if the optimal speed $s^(t)$ was not originally available ($s^*(t) \notin \mathcal{S}$), then it is replaced by its two neighboring available speeds s_1 and s_2 over sub-intervals $[t, t + \beta)$ and $[t + \beta, t + 1)$ respectively. Since the deadlines are integers, no job will miss its deadline during the interval $(t, t + 1)$.*

This new policy only uses speeds in \mathcal{S} but contains speed changes at non-integer times. We denote by $J^{VDD, \mathcal{S}, \mathbb{R}}(\mathbf{x})$ its energy consumption.

Since the power cost $P_{ow}(s^(t))$ is a linear interpolation of the power cost of the neighboring available speeds s_1 and s_2 , the energy consumption over the interval $[t, t + 1)$ is the same using speed $s^*(t)$ on $[t, t + 1]$ and using the neighboring speeds s_1 and s_2 over the two sub-intervals $[t, t + \beta]$ and $[t + \beta, t + 1]$. This also means that the total energy consumption is the same before and after using VDD hopping:*

$$J^{VDD, \mathcal{S}, \mathbb{R}}(\mathbf{x}) = J^{*, \bar{\mathcal{S}}, \mathbb{N}}(\mathbf{x}).$$

On the one hand, Theorem 1 states that, with consecutive speeds, integer decision times minimize the total energy consumption. In other words, this can be written

$$J^{*, \bar{\mathcal{S}}, \mathbb{R}}(\mathbf{x}) = J^{*, \bar{\mathcal{S}}, \mathbb{N}}(\mathbf{x}).$$

On the other hand, the optimal solution only using the subset composed by the available speeds must use at least as much energy as when all the intermediate speeds are available. This implies

$$J^{*,\bar{\mathcal{S}},\mathbb{R}}(\mathbf{x}) \leq J^{*,\mathcal{S},\mathbb{R}}(\mathbf{x}).$$

Putting everything together yields the following sequence of inequalities:

$$J^{VDD,\mathcal{S},\mathbb{R}}(\mathbf{x}) \geq J^{*,\mathcal{S},\mathbb{R}}(\mathbf{x}) \geq J^{*,\bar{\mathcal{S}},\mathbb{R}}(\mathbf{x}) = J^{*,\bar{\mathcal{S}},\mathbb{N}}(\mathbf{x}) = J^{VDD,\mathcal{S},\mathbb{R}}(\mathbf{x}).$$

This shows that $J^{VDD,\mathcal{S},\mathbb{R}}(\mathbf{x}) = J^{*,\mathcal{S},\mathbb{R}}(\mathbf{x})$. This equality says that the VDD hopping policy is optimal. This optimal policy is an easy patch over the optimal policy with integer decision time, using the extended set of speed. \square

Corollary 1 *The optimal policy with integer decision times and using speeds in the consecutive set $\mathcal{S} = \{0, 1, \dots, s_{\max}\}$ is dominant over all policies with continuous decisions times, continuous speeds in the interval $[0, s_{\max}]$ and interpolated powers. Using our previous notation, this can be written: For all state \mathbf{x} , $J^{*,\{0\dots s_{\max}\},\mathbb{N}}(\mathbf{x}) = J^{*,[0,s_{\max}],\mathbb{R}}(\mathbf{x})$.*

Proof 9 Recall that the interpolated power of any speed $s \in [0, s_{\max}]$ is $Pow(s) = \beta Pow(s_1) + (1 - \beta)Pow(s_2)$, where s_1 and s_2 are the two neighboring speeds of s in \mathcal{S} , as in Equation (43). Under this power function, $J^{*,\{0\dots s_{\max}\},\mathbb{N}}(\mathbf{x}) \leq J^{*,[0,s_{\max}],\mathbb{R}}(\mathbf{x})$ by definition.

Let $s^*(t)$ be the optimal policy in continuous time with continuous speeds in $[0, s_{\max}]$. Then, starting in x ,

$$\begin{aligned} J^{*,[0,s_{\max}],\mathbb{R}}(\mathbf{x}) &= \mathbb{E} \int_0^T Pow(s^*(t)) dt \\ &= \mathbb{E} \sum_{t=0}^{T-1} \int_t^{t+1} Pow(s^*(t)) dt \\ &\geq \mathbb{E} \sum_{t=0}^{T-1} Pow\left(\int_t^{t+1} s^*(t) dt\right) \end{aligned} \tag{44}$$

$$= \mathbb{E} \sum_{t=0}^{T-1} \beta Pow(s_1^*(t)) + (1 - \beta) Pow(s_2^*(t)) \tag{45}$$

$$\geq J^{*,\{0\dots s_{\max}\},\mathbb{R}}(\mathbf{x}) \tag{46}$$

$$= J^{*,\{0\dots s_{\max}\},\mathbb{N}}(\mathbf{x}), \tag{47}$$

where Equation (44) comes from Jensen inequality for the convex function Pow and the fact that there is no random innovation between times t and $t + 1$; where $s_1^*(t), s_2^*(t)$ in (45) are the neighboring speeds in \mathcal{S} of the average speed $\int_t^{t+1} s^*(t) dt$; and Theorem 1 is used to finish the proof in (47). \square

C Optimality of EDF Scheduling

In this appendix, we generalize a known result about the optimality of EDF schedulability [24] to the case where the processor speed varies.

Proposition 7 *For any processor speed profile, the scheduling policy Earliest Deadline First (EDF) minimizes the maximum lateness of any set of jobs as described in section 2.1.*

Optimal schedulability is equivalent to having a maximum of lateness equal to 0. The proof of proposition 7 is done in [24] when the speed is constant ($s = 1$), which is not the case here. Indeed, speed varies over time, is independent of the current job. We use the idea of Horn's proof to demonstrate this property.

Proof 10

Recall that jobs are defined as $J_i = (r_i, c_i, d_i)$. We denote also $s(t)$ the speed function, which is assumed integrable and finite (this is the only assumption on speeds). For any scheduler ρ , we introduce the following definitions:

- The job executed at time t is $\rho(t)$.
- The finishing time of job J_i under ρ , is noted $f_\rho(J_i)$.
- The remaining work, $w_\rho(J_i, t)$, is the quantity of work of job J_i that remains to be done at time t under ρ :

$$w_\rho(J_i, t) = c_i - \int_0^t s(u) \mathbb{1}_{\{\rho(u)=J_i\}} du$$

where $\mathbb{1}_{\{\rho(u)=J_i\}} = 1$ if $\rho(u) = J_i$ and 0 otherwise.

- The lateness of job J_i under ρ is:

$$\lambda_\rho(J_i) = (f_\rho(J_i) - d_i)^+$$

- The maximum of lateness of schedule ρ is:

$$\Lambda(\rho) = \max_{J_i} \lambda_\rho(J_i)$$

From now on, we consider two schedulers, EDF and an arbitrary scheduler ρ . For ρ , let us consider the time instants when the scheduler switches from one job execution to another. For EDF, let us also consider the time instants when EDF switches from one job to another. By combining these two sets of time instants, we denote by $t_1 < \dots < t_m$, all the time instants when either EDF or ρ switches its job.

Let us now focus on the first time t_k when ρ and EDF differ: we denote by J the job (represented in red in Figure 13) executed by ρ and by J' the job (represented in blue in Figure 13) executed by EDF. The fact that EDF chooses J' over J at time t_k implies that the respective deadlines of J and J' are such that

$$d_J \geq d_{J'} \tag{48}$$

We denote by W_k the work quantity executed between t_k and t_{k+1} , i.e., $W_k = \int_{t_k}^{t_{k+1}} s(t) dt$. Since both jobs J and J' are executed between t_k and t_{k+1} , and since EDF and ρ coincide up to time t_k , the remaining work for both of them at time t_k must be larger than W_k :

$$\begin{aligned} w_\rho(J, t_k) &= w_{EDF}(J, t_k) \geq W_k \\ w_\rho(J', t_k) &= w_{EDF}(J', t_k) \geq W_k \end{aligned}$$

Let us define a new scheduler ρ' as follows:

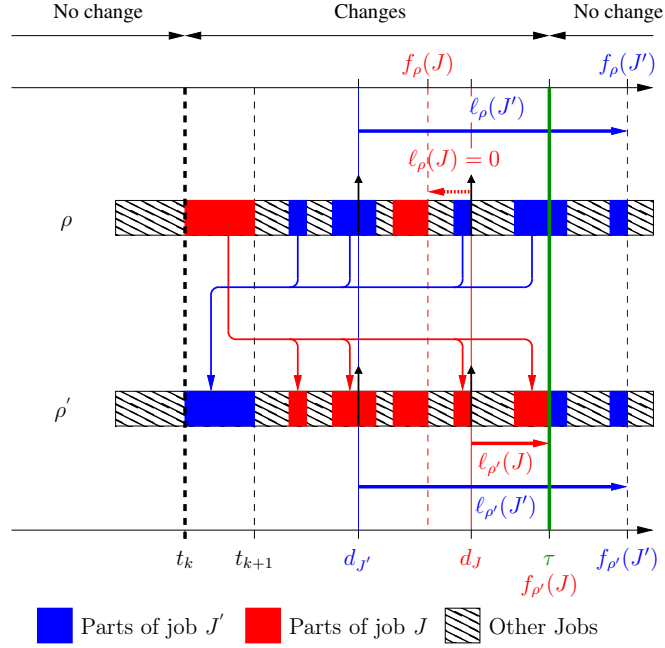


Figure 13: Schedules ρ and ρ' and their respective lateness on $[t_k, \tau]$. The lateness of J' is the same under ρ and ρ' while the lateness of J increases under ρ' , but remains smaller than the lateness of J' under ρ . So the maximum of lateness is the same on ρ and ρ' .

- $\forall t \in [0, t_k], \rho'(t) = \rho(t) = EDF(t)$.
- $\forall t \in [t_k, t_{k+1}], \rho'(t) = J'$. Since the function $g : t, J \rightarrow \int_{t_k}^t s(u) \mathbb{1}_{\{\rho(u)=J\}} du$ is a continuous function of t and because $w_\rho(J', t_{k+1}) \geq W_k$, by the Intermediate Value Theorem, there exists τ such that:

$$\tau = \inf \left\{ t \left| \int_{t_{k+1}}^t s(u) \mathbb{1}_{\{\rho(u)=J'\}} du = W_k \right. \right\} \quad (49)$$

- Between times t_{k+1} and τ , the scheduler ρ' executes J whenever ρ executes J' : $\forall t_{k+1} \leq t \leq \tau, \rho(t) = J' \Rightarrow \rho'(t) = J$ and $\rho(t) \neq J' \Rightarrow \rho'(t) = \rho(t)$.

Now let us show that the maximum lateness of ρ' is smaller or equal than the maximum lateness of ρ . First, the latenesses of all jobs except J and J' do not change under ρ' .

Now, let us analyse the lateness of job J' under ρ' . By construction of ρ' , the remaining work W_k is such that $w_\rho(J', t_k) \geq W_k$. So we are faced with two cases:

- The first one is $w_\rho(J', t_k) > W_k$. Here, all the remaining work due to job J' is not finished at $[t_k, \tau]$, then the finishing time is the same under both schedulers, so $\lambda_{\rho'}(J') = \lambda_\rho(J')$. This case is the case represented in Figure 13.
- The second one is the case where $w_\rho(J', t_k) = W_k$. In this case, in t_{k+1} , the job J' has been entirely executed, so we have:

$$f_{\rho'}(J') = t_{k+1} \leq f_\rho(J') \leq f_\rho(J')$$

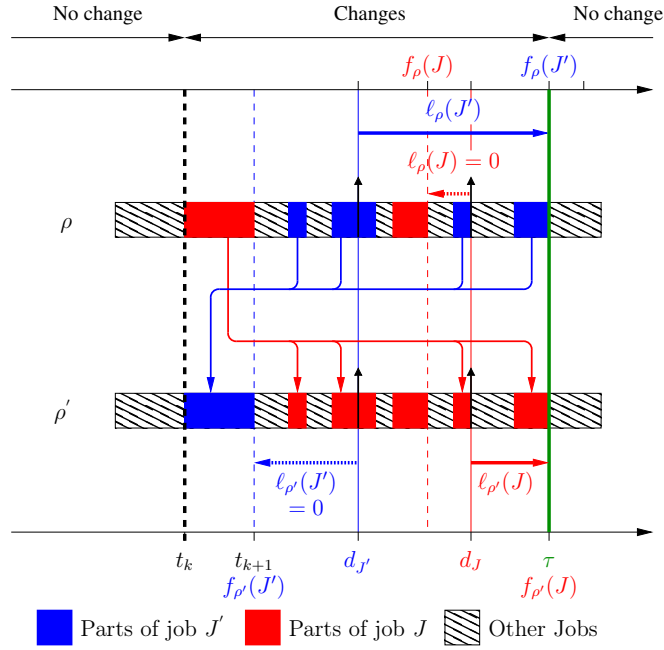


Figure 14: Schedules ρ and ρ' and their respective lateness on $[t_k, \tau]$. The lateness of J' is better under ρ' than under ρ while the lateness of J increases under ρ' , but remains smaller than the lateness of J' under ρ . So the maximum of lateness is smaller under ρ' than under ρ .

The two previous cases imply that we have no lateness increase for job J' , so:

$$\lambda_{\rho'}(J') \leq \lambda_{\rho}(J') \leq \Lambda(\rho). \quad (50)$$

This case is the case represented in Figure 14.

Lastly, let us analyse job J . Again there are two cases for the lateness $\lambda_{\rho'}(J)$ of job J under ρ' :

- $f_{\rho}(J) > \tau$. This means that the execution of job J ends after the time τ . In that case, there is no difference for the finishing time of J whatever the scheduling. Indeed the difference between ρ and ρ' only modifies the order of the execution of parts of job J , which belongs to $[t_k, \tau]$, but not after time τ (see Figure 13), so:

$$f_{\rho'}(J) = f_{\rho}(J)$$

The lateness is also the same:

$$\lambda_{\rho'}(J) = \lambda_{\rho}(J) \leq \Lambda(\rho) \quad (51)$$

- $f_{\rho}(J) \leq \tau$. In that case, the end of the job J under ρ' occurs exactly at τ (see Figure 13):

$$f_{\rho'}(J) = \tau$$

So the lateness of job J under ρ' is:

$$\lambda_{\rho'}(J) = (\tau - d_J)^+$$

On the other hand, we know that at time τ , ρ is executing job J' , therefore, $f_\rho(J') \geq \tau$ and we also know that $d_{J'} \leq d_J$ (see (48)). We can conclude that:

$$\lambda_{\rho'}(J) \leq (f_\rho(J') - d_{J'})^+ = \lambda_\rho(J') \leq \Lambda(\rho) \quad (52)$$

As a consequence, the maximum lateness does not increase under ρ' in comparison with ρ : By Eqs. (50), (51), and (52), we have:

$$\Lambda(\rho') \leq \Lambda(\rho)$$

If we repeat this reasoning starting with ρ' instead of ρ , then the new schedule will coincide with EDF further in time and the maximum lateness will not increase.

This shows that, eventually, EDF too minimizes the maximum lateness:

$$\Lambda(EDF) \leq \Lambda(\rho') \leq \Lambda(\rho)$$

which concludes the proof. □

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