Towards Practical Multiprocessor EDF with Affinities

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Abstract—A gap exists between the theory of EDF scheduling on identical multiprocessors with arbitrary processor affinities (APA) and practical EDF scheduling as embodied by the SCHED_DEADLINE (SD) scheduler in Linux. This is because the EDF variant proposed in theory for APA, called Strong APA EDF (SAPA-EDF) \cite{6}, introduces affinity-related complexities that are not applicable under global EDF, the original target of SD. SD instead treats affinities as a secondary concern. It is shown herein that this treatment comes at the price of causing SD to be fundamentally broken with regard to soft real-time (SRT)-optimality with APA. This result resolves a longstanding open question regarding this matter. It also suggests that Strong APA EDF, which has been proven to be SRT-optimal, is necessary for practical EDF scheduling with APA. However, non-preemptive sections are typically required in practice, and prior work on Strong APA EDF is limited to fully preemptive systems. In this paper, this prior work is extended for the first time to deal with non-preemptivity, which introduces non-trivial nuances with APA. As a byproduct of considering non-preemptivity, it is shown that the SRT-optimality of EDF in this context carries over to a significantly expanded class of schedulers.

I. INTRODUCTION

Variants of earliest-deadline-first (EDF) scheduling have been proven to be soft real-time (SRT)-optimal on various processor models \cite{6,11,13}, meaning that EDF can guarantee bounded deadline tardiness for any (sporadic) task system that does not over-utilize the underlying multiprocessor platform. This property makes EDF an attractive scheduler for systems where some tardiness is permissible.

The SRT-optimality of EDF is significant enough to have warranted mentioning in the documentation of SCHED_DEADLINE (SD) \cite{1}, Linux’s EDF implementation. This documentation specifically references work of Devi and Anderson \cite{6}, who were the first to establish the SRT-optimality of global EDF scheduling on identical multiprocessors. As this documentation suggests, the design of SD reflects an initial focus on global EDF (and by extension, clustered EDF, where global scheduling is used within each cluster of processors), with arbitrary processor affinities (APA) being treated as a secondary concern. This is unfortunate because setting processor affinities (cpusets in Linux) is useful for load balancing and cache locality. While SD may not crash under APA, its SRT-optimality under APA has never been established. The question of whether SD is SRT-optimal was listed among major open problems facing Linux by Peter Zijlstra in his ECRTS’17 keynote \cite{14}.

This open problem was partially addressed by our prior work \cite{11}, in which we proved that an EDF variant (distinct from SD) introduced by Cerqueira et al. called Strong APA EDF (SAPA-EDF) \cite{5} is SRT-optimal under APA. While both SD and SAPA-EDF prioritize tasks on an EDF basis, SAPA-EDF migrates tasks more aggressively so that the maximum number of high-priority tasks is scheduled at any time. At runtime, computing which migrations to enact involves executing graph searches. The increased overheads of such searches and implementation complexities of SAPA-EDF are unnecessary under global scheduling, the main target of SD. Perhaps because of this, the maintainers of SD have not modified it to implement SAPA-EDF, even though it is SRT-optimal.

While SAPA-EDF is SRT-optimal in theory, other theoretical issues must be resolved before a practical implementation of it is possible. One key issue is that its proof of SRT-optimality requires tasks to always be preemptive \cite{11}. This is unrealistic because actual workloads require some degree of non-preemptivity (for system calls, using locking protocols, etc.). Non-preemptivity has not been a problem under global scheduling because non-preemptive (NP) global EDF is also SRT-optimal \cite{6}. In contrast, no work to date on tardiness under APA has considered non-preemptivity.

To summarize, SD and SAPA-EDF are the two natural potential starting points for designing an EDF scheduler that is practical under APA. However, given the aforementioned issues with both schedulers, it is not immediately clear which, if either, can realistically serve as a starting point.

Contributions. Towards clarifying which scheduler should be the starting point, this paper makes four major contributions.

First, we answer Zijlstra’s open question (in the negative) by showing that the current SD implementation is fundamentally broken with respect to tardiness under APA. We do this by presenting counterexamples where feasible task systems have unbounded tardiness under an idealized version of SD without overheads. This suggests that an aggressive migration strategy similar to that of SAPA-EDF is necessary for SRT-optimality under APA, leading us to argue that SAPA-EDF is a preferable starting point for a practical EDF scheduler under APA.

Second, we demonstrate that the reliance on tasks being fully preemptive in the proof of SAPA-EDF’s SRT-optimality \cite{11} is not a limitation of this proof, but rather, is

\footnote{We did not realize that Strong APA EDF had already been discovered under a hard real-time context and unfortunately presented it as IA-GEDF in \cite{11}.}
an intrinsic requirement of any work-conserving EDF variant under APA. We show this by presenting an example task system similar to that used to demonstrate Dhall’s effect [7], where NP execution under APA causes tardiness to increase unboundedly even though total utilization is just above 1.0. Similarly to how Dhall’s effect has not rendered EDF unusable with global scheduling, we argue that our counterexample does not render EDF unusable under APA. Specifically, we define a weaker notion of NP execution called progression, and argue that progression can replace NP sections in many use cases. We prove that SAPA-EDF fortunately can be modified to support progression while maintaining SRT-optimality.

Third, as a byproduct of establishing the above result about progression, we prove that variants of window-constrained schedulers, which have been proven to be SRT-optimal under global scheduling [9], are also SRT-optimal under APA. The class of window-constrained schedulers includes common schedulers such as first-in-first-out (FIFO), least-laxity-first (LLF), and EDF-until-zero-laxity (EDZL), so this result greatly expands the class of known SRT-optimal schedulers under APA. While our proof of this result leverages that pertaining to SAPA-EDF [11], a number of non-trivial extensions were required in our case, because certain properties of SAPA-EDF that were instrumental in [11] are not true generally under window-constrained schedulers.

Fourth, we present the first ever (to our knowledge) NP-blocking analysis under APA. Real workloads will need such analysis, as not all instances of NP execution can be replaced with progression. Unfortunately, NP-blocking analysis under APA introduces nuances that make constructing blocking terms more pessimistic than under global scheduling.

**Organization.** The rest of this paper is organized as follows. After covering needed background in Sec. II, we demonstrate in Sec. III that, under APA, SD is not SRT-optimal, nor is any EDF variant with NP sections. Next, in Sec. IV, we establish the SRT-optimality of window-constrained schedulers under APA. We then use this result in weakening non-preemptivity to progression in EDF in Sec. V. We conclude in Sec. VI.

### II. Background

In this section, we cover notation and necessary background. For ease of reading, tables of notation and abbreviations used in this work are presented in Tbls. I and II, respectively.

#### A. Task Model

We consider a system of \( n \) implicit-deadline sporadic tasks \( \tau = \{\tau_1, \tau_2, \ldots, \tau_n\} \) running on \( m \) unit-speed processors \( \pi = \{\pi_1, \pi_2, \ldots, \pi_m\} \). We assume basic familiarity with the sporadic task model and focus on introducing notation here. We denote the \( j^{th} \) job released by task \( \tau_i \) as \( \tau_{i,j} \) and index jobs starting at \( j = 1 \). Job \( \tau_{i,j} \) must be completed before job \( \tau_{i,j+1} \) is allowed to execute. We let \( C_{i,j} \) denote the required execution time of \( \tau_{i,j} \), and let \( C_i \) denote the worst-case execution time (WCET) of \( \tau_i \) over all its jobs. We let \( T_i \) denote the period of task \( \tau_i \). We denote the release time, deadline, and completion time of job \( \tau_{i,j} \) by \( r_{i,j} \), \( d_{i,j} \), and \( t_{i,j} \), respectively.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>( \tau )</td>
<td>Task system</td>
</tr>
<tr>
<td>( \tau_i )</td>
<td>( i^{th} ) task of ( \tau )</td>
</tr>
<tr>
<td>( \tau' )</td>
<td>Task subset</td>
</tr>
<tr>
<td>( n )</td>
<td>Number of tasks</td>
</tr>
<tr>
<td>( \pi )</td>
<td>Multiprocessor</td>
</tr>
<tr>
<td>( \pi_i )</td>
<td>( i^{th} ) processor of ( \pi )</td>
</tr>
<tr>
<td>( m )</td>
<td>Number of processors</td>
</tr>
<tr>
<td>( \tau_{i,j} )</td>
<td>( j^{th} ) job of ( \tau_i )</td>
</tr>
<tr>
<td>( C_{i,j} )</td>
<td>Execution cost of ( \tau_{i,j} )</td>
</tr>
<tr>
<td>( C_i )</td>
<td>WCET of ( \tau_i )</td>
</tr>
<tr>
<td>( T_i )</td>
<td>Period of ( \tau_i )</td>
</tr>
<tr>
<td>( T_{\max} )</td>
<td>Largest period</td>
</tr>
<tr>
<td>( r_{i,j} )</td>
<td>Release time of ( \tau_{i,j} )</td>
</tr>
<tr>
<td>( d_{i,j} )</td>
<td>Deadline of ( \tau_{i,j} ); ( r_{i,j} + T_i )</td>
</tr>
<tr>
<td>( I_{i,j} )</td>
<td>Completion time of ( \tau_{i,j} )</td>
</tr>
<tr>
<td>( T_{i,j} )</td>
<td>( T_{i,j+1} - r_{i,j} )</td>
</tr>
<tr>
<td>( u_i )</td>
<td>Utilization of ( \tau_i ); ( C_i/T_i )</td>
</tr>
<tr>
<td>( u_{\min} )</td>
<td>Smallest utilization</td>
</tr>
<tr>
<td>( u_{\max} )</td>
<td>Largest utilization</td>
</tr>
<tr>
<td>( U(\tau') )</td>
<td>Sum total utilization over ( \tau' )</td>
</tr>
<tr>
<td>( C_{i}(t) )</td>
<td>Execution cost of ( \tau_i )'s ready job at ( t )</td>
</tr>
<tr>
<td>( r_i(t) )</td>
<td>Release time of ( \tau_i )'s ready job at ( t )</td>
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<tr>
<td>( d_i(t) )</td>
<td>Deadline of ( \tau_i )'s ready job at ( t )</td>
</tr>
<tr>
<td>( c_i(t) )</td>
<td>Remaining execution of ( \tau_i )'s ready job at ( t )</td>
</tr>
<tr>
<td>( D_i(t) )</td>
<td>Deadline of most recently completed job of ( \tau_i ) by ( t )</td>
</tr>
<tr>
<td>( \chi_{i,j}(t) )</td>
<td>Priority of ( \tau_{i,j} ) at ( t )</td>
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<tr>
<td>( \phi )</td>
<td>Window size of a window-constrained scheduler</td>
</tr>
<tr>
<td>( \alpha(\tau_i) )</td>
<td>Processor affinity mask of ( \tau_i )</td>
</tr>
<tr>
<td>( \gamma^G )</td>
<td>Set of migrating tasks of ( \tau )</td>
</tr>
<tr>
<td>( \nu(t) )</td>
<td>Virtual time of ( \tau_i ) at ( t ); Def. 4</td>
</tr>
<tr>
<td>( \text{Dev}(\tau_i, t) )</td>
<td>Deviation of ( \tau_i ) at ( t ); Def. 5</td>
</tr>
<tr>
<td>( \text{Dev}(\tau', t) )</td>
<td>Sum total deviation over ( \tau' ); Def. 6</td>
</tr>
<tr>
<td>( L )</td>
<td>Constant, usually compared against Dev</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Quantifier variable</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>Quantifier variable</td>
</tr>
<tr>
<td>( M )</td>
<td>Maximal number of processors for some ( \tau' )</td>
</tr>
<tr>
<td>( K )</td>
<td>((T_{\max} + 2\phi)/2u_{\min})</td>
</tr>
<tr>
<td>( B_i )</td>
<td>Blocking term of ( \tau_i )</td>
</tr>
<tr>
<td>( I_i )</td>
<td>Largest interval over which ( \tau_i ) may be NP blocked</td>
</tr>
<tr>
<td>( \text{npdbf}(t, \Delta) )</td>
<td>NP demand bound function of ( \tau_i ) over ([t, t + \Delta])</td>
</tr>
<tr>
<td>( \gamma_i )</td>
<td>Worst-case NP execution time of any job of ( \tau_i )</td>
</tr>
<tr>
<td>( \omega_i )</td>
<td>NP utilization of ( \tau_i ); ( \gamma_i/T_i )</td>
</tr>
<tr>
<td>( \Gamma_i )</td>
<td>Sum total worst-case NP execution time over ( \tau/{\tau_i} )</td>
</tr>
<tr>
<td>( \Omega_i )</td>
<td>Sum total NP utilization over ( \tau/{\tau_i} )</td>
</tr>
<tr>
<td>( R_i )</td>
<td>Response time bound of ( \tau_i )</td>
</tr>
<tr>
<td>( R_{\max} )</td>
<td>Largest response time bound over ( \tau/{\tau_i} )</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full</th>
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<tbody>
<tr>
<td>SRT</td>
<td>Soft Real-Time</td>
</tr>
<tr>
<td>APA</td>
<td>Arbitrary Processor Affinities</td>
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<tr>
<td>NP</td>
<td>Non-Preemptive</td>
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<tr>
<td>SD</td>
<td>SCHED DEADLINE</td>
</tr>
<tr>
<td>SAPA-EDF</td>
<td>Strong APA EDF</td>
</tr>
<tr>
<td>WAPA-EDF</td>
<td>Weak APA EDF</td>
</tr>
<tr>
<td>SAPA-EF</td>
<td>Strong APA EDF-FIFO</td>
</tr>
<tr>
<td>L-SAPA-EF</td>
<td>Link-based Strong APA EDF-FIFO</td>
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</table>
we define the functions $C$ of the utilizations of tasks in $\tau$. The utilization $u_i$ of task $\tau_i$ is given by $C_i/T_i$. We denote the smallest (resp., largest) utilization over all tasks as $u_{\text{min}}$ (resp., $u_{\text{max}}$). For a set of tasks $\tau' \subseteq \tau$, we let $U(\tau')$ denote the sum of the utilizations of tasks in $\tau'$.

At time $t$, a job $\tau_{i,j}$ is either unreleased ($t < r_{i,j}$), pending ($r_{i,j} \leq t < f_{i,j}$), or complete ($t \geq f_{i,j}$). If a task $\tau_i$ has pending jobs at $t$, then its ready job at $t$ is its earliest-released pending job at $t$. If task $\tau_i$ has a ready job $\tau_{i,j}$ at time $t$, then we define the functions $C_i(t)$, $r_i(t)$, and $d_i(t)$ to equate to $C_{i,j}$, $r_{i,j}$, and $d_{i,j}$, respectively. We define the function $c_i(t)$ to equate to the remaining execution required by the ready job $\tau_{i,j}$ at $t$. We define the function $D_i(t)$ to equate to the deadline of the latest completed job of $\tau_i$ by time $t$, or $0$ if no jobs of $\tau_i$ have completed. If task $\tau_i$ has a ready job at time $t$, then its priority is defined by the priority of its ready job. We define the latter using prioritization functions later in Def. 1.

The response time of a job $\tau_{i,j}$ is defined as $f_{i,j} - r_{i,j}$. The tardiness of $\tau_{i,j}$ is defined as $\max\{0, f_{i,j} - d_{i,j}\}$. The tardiness of task $\tau_i$ is the supremum of the tardiness of its jobs. If the tardiness of all tasks is bounded under a given scheduler, then the task system is SRT-schedulable under the scheduler. A task system is SRT-feasible if it is SRT-schedulable under some scheduler. A scheduler is SRT-optimal if any SRT-feasible task system is SRT-schedulable under it.

We assume that $\tau$ executes on $\pi$ without overheads (e.g., scheduling code and context switches execute in zero time). We also assume that time is continuous. This assumption does not invalidate our results on systems where time is integral so long as WCETs and periods are also integral. We limit attention to non-fluid schedulers, i.e., if a job $\tau_{i,j}$ is scheduled (resp., unscheduled) at time $t$, then there exists $\epsilon > 0$ such that $\tau_{i,j}$ is scheduled (resp., unscheduled) over $[t, t + \epsilon]$.

### B. Window-Constrained Schedulers

Leontyev and Anderson considered a class of schedulers called “window-constrained schedulers,” showed that many common schedulers such as EDF, FIFO, and LLF are in this class, and proved that all schedulers in this class are SRT-optimal under global scheduling [9]. This result is relevant to NP scheduling because NP variants of window-constrained schedulers are themselves window-constrained under global scheduling. In this work, we will prove a weaker version of this result concerning NP scheduling under APA.

The class of window-constrained schedulers is defined by introducing the notion of a prioritization function.

**Def. 1.** (Def. 1 of [9]) Associated with each job $\tau_{i,j}$ is a function of time $\chi_{i,j}(t)$, called its prioritization function. If, at time $t$, $\chi_{i,j}(t) < \chi_{h,k}(t)$ holds, then the priority of job $\tau_{i,j}$ is higher than that of job $\tau_{h,k}$ at $t$. We assume consistent tie-breaking if $\chi_{i,j}(t) = \chi_{h,k}(t)$.

Under global scheduling, prioritization functions can serve as abstractions of schedulers. For example, EDF is represented by $\chi_{i,j}(t) = d_{i,j}$, and FIFO by $\chi_{i,j}(t) = r_{i,j}$. Likewise, fixed-priority (FP) scheduling can be abstracted by setting $\chi_{i,j}(t)$ to be task $\tau_i$’s priority level.

**Def. 2.** (Def. 5 of [9]) A scheduling algorithm’s prioritization functions are window-constrained if there exists finite $\phi$ such that for any job $\tau_{i,j}$ and time $t$, $|d_{i,j} - \chi_{i,j}(t)| \leq \phi$ holds.

For example, the EDF and FIFO prioritization functions above are window-constrained with $\phi = 0$ and $\phi = \max_{i,j}(d_{i,j} - r_{i,j}) = T_{\text{max}}$, respectively. On the other hand, the FP prioritization function is not window-constrained because $d_{i,j}$ is unbounded for any given task $\tau_i$ as $j \to \infty$ (assuming jobs are released indefinitely), while $\chi_{i,j}(t)$ is constant.

### C. APA Scheduling

We denote the processor affinity mask of task $\tau_i$ as $\alpha(\tau_i) \subseteq \pi$. Common migration schemes such as global, partitioned, and clustered scheduling can be represented using affinities. For example, under global scheduling, $\alpha(\tau_i) = \pi$ for every task $\tau_i$, and under partitioned scheduling, $\alpha(\tau_i) = \{\pi_j\}$, where $\pi_j$ denotes the processor assigned to task $\tau_i$. A task $\tau_i$ is migrating if $|\alpha(\tau_i)| > 1$, and fixed otherwise.

Processor affinities are often illustrated using affinity graphs. These are undirected bipartite graphs where the nodes represent tasks and processors, and each edge is between a task $\tau_i$ and a processor $\pi_j$, denoting that $\pi_j$ is in $\tau_i$’s affinity mask.

**Ex. 1.** Consider a task system $\tau = \{\tau_1, \tau_2, \ldots, \tau_5\}$ on $\pi = \{\pi_1, \pi_2, \pi_3\}$. Let $\alpha(\tau_1) = \{\pi_1\}$, $\alpha(\tau_2) = \{\pi_1, \pi_2\}$, $\alpha(\tau_3) = \{\pi_2\}$, $\alpha(\tau_4) = \{\pi_2, \pi_3\}$, and $\alpha(\tau_5) = \{\pi_3\}$. The corresponding affinity graph is shown in Fig. 1(a) $\tau_2$ and $\tau_4$ are migrating while all other tasks are fixed.

**Weak vs. Strong APA.** A guarantee that should be made by any priority-based scheduler is that no preemption not taken by the scheduler can result in scheduling a higher-priority task. Ignoring the specifics of which task is assigned which processor, scheduling the $m$ highest-priority tasks is the only way to meet this guarantee under global scheduling. Under APA, distinct scheduling decisions may meet this guarantee.

**Ex. 2.** Suppose that the system in Ex. 1 is scheduled under EDF and that at time $t$, all tasks have ready jobs such that $d_2(t) < d_4(t) < d_5(t) < d_1(t) < d_3(t)$. Consider the scheduling decisions made in Fig. 1(b) where a highlighted edge denotes a task being scheduled on a processor. Because task $\tau_5$ (resp., $\tau_3$) cannot preempt $\tau_4$ (resp., $\tau_2$) on $\pi_3$ (resp., $\pi_2$) as $d_4(t) < d_5(t)$ (resp., $d_2(t) < d_3(t)$), this processor assignment meets our aforementioned guarantee. Likewise, because tasks $\tau_1$ and $\tau_3$ cannot preempt higher-priority tasks in Fig. 1(c), this assignment also meets the guarantee.

\[1\]We have modified this definition to simplify our reasoning in Sec. IV. Any window-constrained prioritization functions as defined in [9] are also window-constrained as defined in this work and vice versa, though the size of windows may be larger under our definition.
In this section, we highlight three sources of non-SRT-optimality in SD under APA. The first two sources are due to specific design choices within SD, while the third pertains to any EDF variant. We consider an idealized version of SD in which scheduling decisions occur atomically and instantly. Note that sporadic releases must be exploited for tardiness to be unbounded as in these counterexamples. Extended versions of these counterexamples are available in App. C.

The first source of non-optimality is that SD does not comply with Weak APA. This is due to an optimization made to speed up SD under global scheduling that prevents certain preemptions under APA. Explaining how this occurs requires a high-level description of the SD implementation. For consistency, we refer to processes under Linux as tasks.

The design of SD is influenced by Linux’s use of per-processor runqueues. It is required by Linux that tasks only ever execute on the processor that owns the runqueue that contains said task. Thus, to implement schedulers that require migration, processors must exchange tasks between their runqueues at runtime through operations called push (processor sends an unscheduled task to another processor) and pull (processor takes an unscheduled task from another processor). Generally, pushes (resp., pulls) are triggered by job releases (resp., completions). For example, consider a task $\tau_h$ that lacks the priority to execute on its runqueue’s processor while having sufficient priority to preempt the running task $\tau_l$ on another processor. For $\tau_h$ to preempt $\tau_l$, it must first be pushed from its current runqueue to the runqueue of the target processor.

The problem arises in how SD chooses which processor to send to in a push. When all processors in a pushed task’s affinity mask are running other tasks, SD selects the processor whose running task has the latest deadline among all processors as the target for the push, regardless of affinity masks. This is because the data structure (a heap called cpu_dl) that returns the target processor with latest deadline is oblivious to affinities. Note that this heap does not cause problems under global scheduling, where all tasks have affinity for all processors. Under global scheduling, usage of this heap is faster than iterating over all processors to determine which is running the task with the latest deadline.

If the processor chosen by a push is not in the pushed task’s affinity mask, SD detects this and does not complete the push. Unfortunately, it does not retry the push, so the task remains unscheduled even if processors in its affinity mask are running tasks with later deadlines, thereby breaking Weak APA. The pushed task remains unscheduled until its runqueue’s processor completes its running job or another processor in its affinity mask completes its running job and pulls the unscheduled task. In the worst-case, tasks may be starved as in the following example.

\[\text{We did not discover this. This issue was recognized by the SD maintainers in 2017} \] but has not been patched in the Linux kernel. To our knowledge, no one has considered this issue from a tardiness perspective.\[\text{In truth, only the processors in the same root domain are considered; however, all processors share the same root domain in our examples.}\]
Ex. 3. Consider the task system illustrated in Fig. 1(a). Let \((C_1, T_1) = (C_3, T_3) = (3, 6)\) and \((C_2, T_2) = (2, 2)\). For simplicity, assume that \(T_4\) does not release jobs in this example. This task system has bounded tardiness under any Weak APA EDF (WAPA-EDF) scheduler but may have unbounded tardiness under SD, as shown in Fig. 2(a).

\(T_2\) is released periodically and initially executes on \(\pi_1\). Even though fixed task \(T_1\) releases a job at \(t = 1\), \(T_2\) does not migrate until \(T_1\) has higher priority at \(t = 6\). However, prior to \(T_2\)'s attempt to migrate, \(T_3\) and \(T_4\) release jobs such that all processors execute jobs at \(t = 6\). Thus, SD will mistakenly attempt to push \(T_2\) onto \(\pi_3\) because it schedules the job with the latest deadline. Because \(\pi_3\) is not in \(T_2\)'s affinity mask, this push will fail, and \(T_2\) is unscheduled until it is pulled by \(\pi_2\) at \(t = 7\). This occurs again at \(t = 17\), except \(T_5\) forces \(T_2\) to attempt to migrate. This pattern can be repeated infinitely often, and with each occurrence, the maximum tardiness experienced by \(T_2\) increases by 1.0.

We argue that even if the maintainers of SD are not interested in implementing SAPA-EDF, SD should at least be patched to comply with WAPA-EDF when not all tasks migrate globally. It is inconvenient from a theoretical perspective to consider SD when it does not satisfy basic invariants that one would expect from an EDF implementation.

Unfortunately, even if SD were modified such that pushes would only consider processors in the pushed task’s affinity mask (thereby complying with Weak APA), unbounded tardiness would still be possible under feasible task systems. The second source of non-optimality of SD is that naive implementations of WAPA-EDF are not optimal.

Ex. 4. Consider the task system illustrated in Fig. 1(a). Let \((C_1, T_1) = (C_3, T_3) = (2, 6)\), \((C_2, T_2) = (C_4, T_4) = (2, 2)\), and \((C_3, T_3) = (1, 6)\). This task system has bounded tardiness under SAPA-EDF \([11]\), but may have unbounded tardiness under a WAPA-EDF scheduler, as shown in Fig. 2(b).

\(T_2\) and \(T_4\) release jobs periodically. Initially, \(T_2\) and \(T_4\) execute on \(\pi_1\) and \(\pi_3\), respectively. At \(t = 6\), fixed tasks \(T_1\) and \(T_3\) preempt \(T_2\) and \(T_4\), respectively. The only other processor available to both \(T_2\) and \(T_4\) is \(\pi_2\), which they cannot both use. We assume the tiebreak here favors \(T_2\) and it is scheduled, while \(T_4\) does not execute until \(t = 8\) when it resumes execution on \(\pi_3\). \(T_2\) is also forced to migrate off of \(\pi_2\) by fixed task \(T_3\) at \(t = 12\). This repeats at \(t = 18\), except here \(T_2\) is scheduled over \(T_4\) because it is tardy by 2.0 time units due to not being scheduled over \([6, 8]\). As a result, \(T_2\) also becomes tardy by 2.0 time units by \(t = 20\). This pattern can repeat indefinitely, and with each occurrence, the maximum tardiness experienced by either \(T_2\) or \(T_4\) increases by 2.0.

The final source of non-optimality we consider is the presence of NP sections. The next example shows that no work-conserving EDF variant is SRT-optimal under APA when jobs are fully NP. Note that there is no distinction between Strong and Weak APA when jobs do not migrate once scheduled.

Ex. 5. For this example, we only consider \(T_1, \ldots, T_3\) of Fig. 1(a). Let \((C_1, T_1) = (C_3, T_3) = (3, 6)\) and \((C_2, T_2) = (2, 2)\). Any EDF variant may have unbounded tardiness when jobs are fully NP, as seen in Fig. 2(c).

\(T_2\) releases jobs periodically. Initially, \(T_2\) executes on \(\pi_1\). When \(T_2\) finishes its ready job at \(t = 6\), it is preempted by \(T_1\). However, \(T_3\) has already begun its NP execution on \(\pi_2\), and
so \( \tau_2 \) is unscheduled over \([6, 8]\). This occurs again at \( t = 18 \), though this time \( \tau_2 \) is forced to migrate by \( \tau_3 \). This pattern can be repeated infinitely often, and with each occurrence, the maximum tardiness experienced by \( \tau_2 \) increases by 2.0.

This example contains a single global task with utilization 1.0 that is eventually preempted by a task that is fixed on the processor the global task is executing on, and is then briefly unable to execute because all other processors are executing NP fixed tasks. While this example was limited to two processors and two fixed tasks for simplicity, it can be generalized for any \( m \geq 2 \) processors and fixed tasks. Also, increasing the fixed tasks’ periods only increases the time in between intervals where the global task is unable to execute, so such intervals still can occur infinitely often. This means the global task still has unbounded tardiness even when the utilization of every fixed task approaches 0. Thus, when jobs are NP, for any arbitrarily small \( \epsilon > 0 \), there exists task system \( \tau \) with \( U(\tau) = 1 + \epsilon \) such that \( \tau \) has unbounded tardiness. \( \triangleright \)

We believe that SAPA-EDF is a more reasonable starting point for a practical EDF scheduler under APA than WAPA-EDF because under ideal conditions (i.e., no overheads or NP sections), the former is SRT-optimal \([11]\), while the latter has inherent capacity loss (Ex. 4). We believe that such inherent loss will outweigh any capacity loss caused by overheads or NP sections in SAPA-EDF. Unfortunately, justifying this via an overhead-aware schedulability study would require that several theoretical and implementation-related questions be answered. Firstly, though we have demonstrated in Ex. 4 that WAPA-EDF is not SRT-optimal, we lack a sufficient SRT schedulability condition for WAPA-EDF, which such a schedulability study would require. Secondly, we would also need well-maintained implementations of WAPA-EDF (as SD does not comply with it, as shown in Ex. 3) and SAPA-EDF (which, to our knowledge, does not exist) in order to measure overheads under these respective schedulers. Lastly, we would also need analysis techniques for accounting for overheads and NP blocking (which some overheads can induce). Considering all of these issues will entail work that is beyond the scope of a single paper. Here, we begin this work by considering the important issue of NP execution under SAPA-EDF.

IV. SRT-Optimality of Window-Constrained Schedulers

Before discussing non-preemptivity, we prove an interesting sub-result in this section that we will make use of in our NP-blocking analysis. We prove that the analysis in \([11]\) for EDF can be generalized to work for any window-constrained scheduler under fully preemptive Strong APA scheduling. Due to the density of notation presented in this and the following section, we recommend the reader refer to Tbls. II and III.

Our analysis here is similar to that of \([11]\) in that almost every lemma, corollary, and theorem we present has an analogue in \([11]\). The major difference is that in \([11]\) it is assumed that all tasks are periodic and that all jobs execute to their tasks’ WCETs. Relaxing these assumptions to establish the SRT-optimality of SAPA-EDF under the sporadic task model (App. B of \([11]\)) relies heavily on a sustainability property of SAPA-EDF, namely that diminishing the execution cost of any job does not increase the response time of any other job. This may not hold under window-constrained scheduling.

\( \triangleright \) Ex. 6. Consider \( \tau = \{\tau_1, \tau_2, \tau_3\} \) scheduled globally on \( \pi = \{\pi_1, \pi_2\} \) with \( (C_1, T_1) = (C_2, T_2) = (C_3, T_3) = (2, 3) \). For the first job of each task, let \( \chi_{1,1}(t) = 3, \chi_{2,1}(t) = 3, \) and \( \chi_{3,1}(t) = 8 \). For the second job of each task, let \( \chi_{1,2}(t) = 6, \chi_{2,2}(t) = 7, \) and \( \chi_{3,2}(t) = 3 \). Fig. 3(b) shows a potential schedule for this system when jobs are period and execute to their tasks’ WCET. Decreasing \( C_{3,1} \) from 2 to 1 results in the schedule in Fig. 3(a). Because \( C_{3,1} \) was decreased, \( \tau_{3,1} \) completes earlier at time 3. As a result, the ready job of \( \tau_3 \) at time 3 is \( \tau_{3,2} \), which has higher priority than \( \tau_{2,2} \). \( \tau_2 \)’s ready job \( (\chi_{3,2}(3) = 3 < 7 = \chi_{2,2}(3)) \). Thus, \( \tau_{2,2} \) does not begin execution until time 5, increasing its response time. \( \triangleright \)

As the needed sustainability property may not hold in our context, we cannot make the same assumptions as in \([11]\) about execution costs and periodicity. This change percolates down into almost all proofs in this section. In eliminating these assumptions, we actually have streamlined the proof in \([11]\).

A. Deviation

The foundation of our proof is the concept of deviation (Dev), which replaces the traditional notion of Lag used in \([11]\). The definition of deviation depends on virtual time.

Def. 4. The virtual time of task \( \tau_i \) at time \( t \geq 0 \) is

\[
vt_i(t) = \begin{cases} 
  r_i(t) + T_i \frac{C_i(t) - c_i(t)}{C_i(t)} & \text{\( \tau_i \) has ready job (1a)} \\
  \max(t, Delta_i(t)) & \text{else (1b)}
\end{cases}
\]

\( \triangleright \) Ex. 7. Consider a task \( \tau_1 \) with \( (C_1, T_1) = (3, 5) \) that executes as depicted in Fig. 4(a) over the interval \([0, 12]\). Note from Fig. 4(a) that \( C_{1,1} = 3, C_{1,2} = 1, \text{ and } T_{1,1} = T_{1,2} = 6 \). \( vt_1(t) \) over \([0, 12]\) is plotted in Fig. 4(b).

Over the interval \([0, 4]\), \( \tau_{1,1} \) is ready and unscheduled. Here \( r_1(t) = 0, C_1(t) = C_{1,1}, \) and \( c_1(t) = C_{1,1} \), so \( vt_1(t) \) remains at 0. Over \([4, 7]\), \( \tau_{1,1} \) is scheduled, causing \( c_1(t) \) to decrease at a unit rate, and \( vt_1(t) \) to increase at a rate of \( T_1/C_1(t) = 5/3 \).
At time 7, $\tau_{1,1}$ completes and $\tau_{1,2}$ becomes the ready job of $\tau_1$. This causes $r_1(t)$, $C_1(t)$, and $c_1(t)$ to change, causing a discontinuity at time 7. $\tau_{1,2}$ is completed over $[7,8)$, causing $vt_1(t)$ to increase at a rate of $T_1/C_1(t) = 5/1$ over this interval. At time 8, $\tau_1$ no longer has a ready job, and so $vt_1(t)$ remains constant at $D_1(t) = 11$ until time 11. Past time 11, the time $t$ is greater than $D_1(t)$, so $vt_1(t)$ increases at a unit rate with time until $\tau_{1,3}$ is released at time 12.

Dev compares a task’s virtual time against actual time.

**Def. 5.** For task $\tau_1$ at time $t$, $Dev(\tau_1, t) = u_i(t - vt_1(t))$. For the subset of tasks $\tau'$, $Dev(\tau', t) = \sum_{\tau_i \in \tau'} Dev(\tau_i, t)$.

**Lemma 1.** If $Dev(\tau_1, t) > 0$, then $\tau_1$ has a ready job at $t$.

**Proof.** We prove the contrapositive: for every time instant $t$, if task $\tau_1$ does not have a ready job, then $Dev(\tau_1, t) \leq 0$. By Def. 4 $vt_1(t) = $ max$(t, D_1(t))$.

If $vt_1(t) = D_1(t)$, we have $D_1(t) \geq t$. By Def. 5 we have $Dev(\tau_1, t) = u_i(t - vt_1(t)) = u_i(t - D_1(t)) \leq u_i(t - t) = 0$.

If $vt_1(t) = t$, then by Def. 5 we have $Dev(\tau_1, t) = u_i(t - vt_1(t)) = u_i(t - t) = 0$.

**Lemma 2.** If task $\tau_1$ has a ready job at time $t$, then $t - \frac{Dev(\tau_1, t)}{u_i} \leq d_i(t) \leq t - \frac{Dev(\tau_1, t)}{u_i} + T_i$. (2)

**Proof.** By Def. 4 and because $\tau_1$ has a ready job at $t$, we have $vt_1(t) = r_i(t) + T_i \frac{C_i(t) - c_i(t)}{c_i(t)}$. By the definition of $c_i(t)$, we have $0 < c_i(t) \leq C_i(t)$. Thus, $vt_1(t) + T_i \geq r_i(t) + T_i \frac{C_i(t) - c_i(t)}{C_i(t)} + T_i = r_i(t) + T_i = d_i(t)$. Thus, $vt_1(t) < r_i(t) + T_i \frac{C_i(t) - c_i(t)}{C_i(t)} = r_i(t) + T_i = d_i(t)$. Thus, we have $vt_1(t) < d_i(t) \leq vt_1(t) + T_i$, which by Def. 5 is equivalent to (2).

**Corollary 1.** If for some $L > 0$ we have $\forall t \geq 0 : Dev(\tau_1, t) \leq L$, then the tardiness of any job of $\tau_1$ is at most $L/u_i$.

**Proof.** We prove the contrapositive: if some job of $\tau_1$ has tardiness exceeding $L/u_i$, then $\exists t \geq 0 : Dev(\tau_1, t) > L$ holds.

Let $\tau_{i,j}$ be a job with tardiness exceeding $L/u_i$. Consider time $t = d_{i,j} + L/u_i$. Because the tardiness of $\tau_{i,j}$ exceeds $L/u_i$, job $\tau_{i,j}$ is pending at $t$. Also, because $\tau_{i,j}$’s ready job at $t$ cannot have been released later than $\tau_{i,j}$, we have $d_i(t) \leq d_{i,j}$. Thus, by Lemma 2 $t - Dev(\tau_1, t)/u_i < d_{i,j}$. By the definition of $t$ above, this implies that $Dev(\tau_1, t) > L$ holds.

**Lemma 3.** If at time $t$, tasks $\tau_e$ and $\tau_i$ have ready jobs $\tau_{e,h}$ and $\tau_{i,k}$ and we have

$$\frac{Dev(\tau_e, t)}{u_e} \geq \frac{Dev(\tau_i, t)}{u_i} + T_{max} + 2\phi, \tag{3}$$

then $\chi_{e,h}(t) < \chi_{i,k}(t)$. ($e$ signifies “earlier” and $i$ “later”.)

**Proof.** $\chi_{e,h}(t)$

$$\leq d_{e,h} + \phi \quad \{\text{By Def. 2}\}$$

$$= d_e(t) + \phi \quad \{\text{By the definition of ready job}\}$$

$$\leq t - \frac{Dev(\tau_e, t)}{u_e} + T_e + \phi \quad \{\text{By Lemma 2}\}$$

$$\leq t - \frac{Dev(\tau_i, t)}{u_i} \quad \{\text{By Lemma 3}\}$$

$$< d_{e,h} + \phi \quad \{\text{By Def. 2}\}$$

$$d_{i,k} - \phi \quad \{\text{By the definition of ready job}\}$$

$$\leq \chi_{i,k}(t) \quad \{\text{By Def. 2}\} \tag{3}$$

**Lemma 4.** For $\tau_i$, $\epsilon > 0$, and $t \geq 0$, $vt_i(t + \epsilon) \geq vt_i(t)$.

**Proof.** Assume without loss of generality that $\epsilon$ is arbitrarily small. There are four cases to consider.

**Case 4.1.** $\tau_i$ has a ready job at both $t$ and $t + \epsilon$. For arbitrarily small $\epsilon$, $\tau_i$ has a ready job throughout $[t, t + \epsilon]$ and the ready job of $\tau_i$ changes at most once.

Suppose the ready job of $\tau_i$ does not change over $[t, t + \epsilon]$. Because the remaining execution required by a job does not increase with time, $c_i(t) \geq c_i(t + \epsilon)$. By (1a) of Def. 4 $vt_i(t + \epsilon) = r_i(t + \epsilon) + T_i \frac{C_i(t + \epsilon) - c_i(t + \epsilon)}{c_i(t + \epsilon)}$. Since the ready job of $\tau_i$ does not change, the latter expression equals $r_i(t) + T_i \frac{C_i(t) - c_i(t)}{C_i(t) - c_i(t + \epsilon)}$. By (3) of Def. 4 $vt_i(t) = r_i(t) + T_i \frac{C_i(t) - c_i(t)}{C_i(t) - c_i(t + \epsilon)}$.

Otherwise, suppose $\tau_{i,j}$ is ready at $t$ and $\tau_{i,j+1}$ is ready at $t + \epsilon$. By (1a) of Def. 4 $vt_i(t + \epsilon) = r_i(t + \epsilon) + T_i \frac{C_i(t + \epsilon) - c_i(t + \epsilon)}{c_i(t + \epsilon)}$. Because $c_i(t + \epsilon) \leq C_{i,j+1}$, the latter expression is at least $r_{i,j+1} + T_i \frac{C_{i,j+1} - c_{i,j+1}}{C_{i,j+1} - c_{i,j+1}} = r_{i,j+1} \geq r_{i,j} + T_i = r_{i,j} + T_i \frac{C_i(t) - c_i(t)}{C_i(t) - c_i(t + \epsilon)} = vt_i(t)$, where the last step follows from (1a) of Def. 4.

**Case 4.2.** $\tau_i$ has a ready job at $t$ but not at $t + \epsilon$. As $\tau_i$ transitioned from having a ready job to not having one, the ready job $\tau_{i,j}$ of $\tau_i$ at $t$ completed by $t + \epsilon$. This implies $d_{i,j} \leq D_i(t + \epsilon)$. Also, because $\tau_{i,j}$ is ready at $t$, $d_i(t) = d_{i,j}$. By (1b) of Def. 4 $vt_i(t + \epsilon) = max(t + \epsilon, D_i(t + \epsilon)) \geq D_i(t + \epsilon) \geq d_{i,j} = d_i(t) = r_i(t) + T_i$. Because $c_i(t) > 0$,
Case 4.3. No job of \( \tau_i \) is ready at both \( t \) and \( t+\epsilon \). For arbitrarily small \( \epsilon \), no job of \( \tau_i \) is released or completed within \([t, t+\epsilon] \). Thus, \( \tau_i \) never has a ready job over this interval and \( D_i(t+\epsilon) = D_i(t) \). By (1a) of Def. 4, \( vt_i(t+\epsilon) = \max(t+\epsilon, D_i(t)) \geq \max(t, D_i(t)) = vt_i(t) \).

Case 4.4. \( \tau_i \) has no ready job at \( t \) but does at \( t+\epsilon \). Because \( \tau_i \) transitioned from not having a ready job to having one, the ready job \( \tau_{i,j} \) of \( \tau_i \) at \( t+\epsilon \) is such that \( t < \tau_{i,j} \leq t+\epsilon \). Also, because jobs of \( \tau_i \) are released at least \( T_i \) time units apart, \( D_i(t) \leq \tau_{i,j} \). By (1a) of Def. 4, \( vt_i(t+\epsilon) = rt_i(t+\epsilon) + T_i C_i(\tau_{i,j}+c_i(t+\epsilon)) \geq rt_i(t+\epsilon) + T_i \max(t+\epsilon, D_i(t)) \). The last step follows by (1b) of Def. 4.

For all cases, \( vt_i(t+\epsilon) \geq vt_i(t) \).

Lemma 5. For any task set \( \tau' \subseteq \tau \) and time \( t \), if \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \text{Dev}(\tau', t+\epsilon) > L \) holds, then \( \text{Dev}(\tau', t) \geq L \).

Proof. Assume, to the contrary, that \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \text{Dev}(\tau', t+\epsilon) > L \) holds and \( \text{Dev}(\tau', t) < L \) both hold. Let \( \delta' = (L - \text{Dev}(\tau', t)) / |\tau| \max(\delta, \epsilon) > 0 \). Then, \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \text{Dev}(\tau', t+\epsilon) > L = |\tau| \max(\delta', \epsilon) = \text{Dev}(\tau', t) \).

This implies that \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \text{Dev}(\tau', t+\epsilon) > |\tau| \max(\delta', \epsilon) = \text{Dev}(\tau', t) \). Because the maximum of a finite set must be at least the arithmetic mean of the set, we have \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \exists \tau_i \in \tau' : \text{Dev}(\tau_i, t+\epsilon) - \text{Dev}(\tau_i, t) > |\tau| \max(\delta', \epsilon) = |\tau| \max(\delta, \epsilon) \). Thus, \( \exists \epsilon \in (0, \delta) : \exists \tau_i \in \tau' : \text{Dev}(\tau_i, t+\epsilon) - \text{Dev}(\tau_i, t) > \max(\delta, \epsilon) \).

Lemma 6. For arbitrarily small \( \epsilon > 0 \), if task \( \tau_i \) is scheduled over \([t, t+\epsilon] \), then \( \text{Dev}(\tau_i, t+\epsilon) \leq \text{Dev}(\tau_i, t) + (ui_i - 1) \).

Proof. For small enough \( \epsilon \), the same job of \( \tau_i \) is scheduled over \([t, t+\epsilon] \) and this job does not complete in this interval.

By Def. 5, \( \text{Dev}(\tau_i, t+\epsilon) = ui_i(t+\epsilon - vt_i(t+\epsilon)) \). Because \( \tau_i \) is scheduled, it must have a ready job, therefore only case (1a) of Def. 4 can apply. Thus, \( \text{Dev}(\tau_i, t+\epsilon) = ui_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)} - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

As the ready job of \( \tau_i \) at \( t \) does not change by \( t+\epsilon \), \( rt_i(t+\epsilon) = rt_i(t) \) and \( C_i(t+\epsilon) = C_i(t) \). Since \( \epsilon \) units of execution of this ready job are completed, \( c_i(t+\epsilon) = c_i(t) - \epsilon \). Thus, \( \text{Dev}(\tau_i, t+\epsilon) = ui_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)} + \epsilon) = ui_i(t+\epsilon - vt_i(t+\epsilon) + \epsilon) = \text{Dev}(\tau_i, t+\epsilon) \).

Lemma 7. For arbitrarily small \( \epsilon > 0 \), if task \( \tau_i \) is not scheduled over \([t, t+\epsilon] \), then \( \text{Dev}(\tau_i, t+\epsilon) \leq \text{Dev}(\tau_i, t) + (ui_i - 1) \).

Proof. By Def. 5, \( \text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - vt_i(t+\epsilon)) \). For small enough \( \epsilon \), \( \tau_i \) either has a ready job or does not over all of \([t, t+\epsilon] \).

Case 7.1. \( \tau_i \) has a ready job over \([t, t+\epsilon] \). By (1a), \( \text{Dev}(\tau_i, t+\epsilon) = ui_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)} - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

Because the ready job of \( \tau_i \) does not change while \( \tau_i \) is unscheduled over \([t, t+\epsilon] \), we have \( rt_i(t+\epsilon) = rt_i(t) \), \( C_i(t+\epsilon) = C_i(t) \), and \( c_i(t+\epsilon) = c_i(t) \). Thus, by Defs. 4 and 5, \( \text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - rt_i(t) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) = u_i(t+\epsilon - vt_i(t) + \epsilon) = \text{Dev}(\tau_i, t) + (ui_i - 1) \).

Case 7.2. \( \tau_i \) has no ready job over \([t, t+\epsilon] \). \( D_i(t+\epsilon) = D_i(t) \) because \( \tau_i \) is not scheduled over \([t, t+\epsilon] \). Thus, \( \text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

Either \( D_i(t) \leq t \), \( t < D_i(t) \leq t+\epsilon \), or \( D_i(t) > t+\epsilon \).

If \( D_i(t) \leq t \), then \( \text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

If \( t < D_i(t) \leq t+\epsilon \), then \( \text{Dev}(\tau_i, t+\epsilon) = ui_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

If \( D_i(t) > t+\epsilon \), then \( \text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - rt_i(t+\epsilon) - T_i C_i(t+\epsilon) - \frac{c_i(t+\epsilon)}{C_i(t+\epsilon)}) \).

For all cases, \( \text{Dev}(\tau_i, t+\epsilon) \leq \text{Dev}(\tau_i, t) + (ui_i - 1) \).

Lemma 8. (Lemma 35 of [11]) If a task system \( \tau \) is feasible, then for any set of tasks \( \tau' \subseteq \tau \), the maximum number of processors \( M \) that tasks of \( \tau' \) may be simultaneously scheduled upon is such that \( M \geq U(\tau') \).

Corollary 2. Let \( \tau \) be a feasible task system. Under a Strong APA scheduler, at any time instant \( t \), for any set of tasks \( \tau' \subseteq \tau \) with ready jobs such that the tasks of \( \tau' \) have highest priority out of all tasks with ready jobs, \( \forall \delta > 0 : \exists \epsilon \in (0, \delta) : \text{Dev}(\tau', t) \geq \text{Dev}(\tau', t+\epsilon) \) holds.

Proof. Let \( M \) be the number of processors scheduling tasks of \( \tau' \) at \( t \). \( M \) is maximal due to Strong APA. Let \( \delta \) be arbitrarily small such that any task scheduled (resp., unscheduled) at \( t \) is scheduled (resp., unscheduled) over \([t, t+\delta] \). Let \( \tau^* \subseteq \tau' \) be the subset of tasks in \( \tau' \) that are scheduled over \([t, t+\delta] \).
Because $\epsilon \in (0, \delta]$, these tasks are also the tasks scheduled over $[t, t + \epsilon]$. Thus,

\[
\begin{align*}
\text{Dev}(\tau', t + \epsilon) &= \text{Dev}(\tau', t + \epsilon) + \text{Dev}(\tau' \setminus \tau^\delta, t + \epsilon) \\
&\leq \text{Dev}(\tau', t) + \epsilon(U(\tau') - |\tau^\delta|) + \text{Dev}(\tau' \setminus \tau^\delta, t) \\
&\quad + U(\tau') \\
&= \epsilon(U(\tau') - M) + \text{Dev}(\tau', t) \quad \{\text{Def. of } M \text{ and } U(\tau')\} \\
&\leq \text{Dev}(\tau', t) \quad \{\text{By Lemma 3}\}. \quad \blacksquare
\end{align*}
\]

B. Modified Invariant

The rest of the proof entails proving that the vector-valued function $(\text{Dev}(\tau_1, t), \text{Dev}(\tau_2, t), \ldots, \text{Dev}(\tau_n, t))$ stays in a bounded region of $\mathbb{R}^n$ for all $t \geq 0$. The same approach is used in [11], though we have used Dev instead of Lag. The proof in [11] relied on the fact that Lag is continuous, which is not true of Dev. We show that continuity is not necessary; that Dev satisfies Lemma 5 is sufficient for our proof. Our bounded region is also larger than in [11] since we consider window-constrained prioritizations instead of only EDF.

Lemma 9. For any feasible task system and Strong APA window-constrained scheduler, $\forall t \geq 0$,

\[
\forall \tau' \subseteq \tau : \text{Dev}(\tau', t) \leq \beta(\tau') \tag{4}
\]

where $\beta(\tau')$ is defined as

\[
\forall \tau' \subseteq \tau : \beta(\tau') = \frac{T_{\max} + 2\phi}{2U_{\min}} U(\tau')(2U(\tau) - U(\tau')). \tag{5}
\]

Proof. As a shorthand, let $K = (T_{\max} + 2\phi)/(2U_{\min}) > 0$. By Def. 3 and 5, 4 is true at $t = 0$. Assuming 4 is falsified, let $t_0$ (for “boundary”) be the last time instant such that 4 is true over $[0, t_0)$. We prove the lemma by contradicting the definition of $t_0$.

Claim 9.1. 4 is true over $[0, t_0]$.

Proof. We will prove by contradiction that 4 holds at $t_0$. Assume, to the contrary, that 4 does not hold at $t_0$. Let $\epsilon = (\text{Dev}(\tau', t_0) - \beta(\tau'))/(|\tau'|_{\max}) > 0$ and $t' \in (\max(t_0 - \epsilon, 0), t_0)$. Then $t' \in [0, t_0)$. Thus, $\text{Dev}(\tau', t') \leq \beta(\tau')$, and so $\text{Dev}(\tau', t_0) - \text{Dev}(\tau', t') \geq \text{Dev}(\tau', t_0) - \beta(\tau')$.

By the definition of $\beta$, $\text{Dev}(\tau', t_0) - \text{Dev}(\tau', t') \geq |\tau'|_{\max}$. By Def. 3, $\sum_{\tau_i \in \tau} u_i(t_0 - vt_i(t_0) - t') = |\tau'|_{\max}$. Because the maximum of a finite set must be at least the arithmetic mean of the set, we have $\exists \tau_i \in \tau' : u_i(t_0 - vt_i(t_0) - t') > |\tau'|_{\max}/|\tau'| = \epsilon |\tau'|_{\max}$. Because $u_{\max} \geq u_i$, $t_0 - vt_i(t_0) - t' + vt_i(t') \geq \epsilon$. Repeating yields $vt_i(t') - vt_i(t_0) \geq \epsilon - t_0 + t'$. Because $t' > \max(t_0 - \epsilon, 0) \geq t_0 - \epsilon$, $vt_i(t') - vt_i(t_0) - t_0 + t' = \epsilon$. Thus, $vt_i(t') > vt_i(t_0)$. As $t' < t_0$, this contradicts Lemma 4.

Claim 9.2. At time $t_0$,

\[
\forall \tau' \subset \tau : \text{Dev}(\tau', t_0) \leq \beta(\tau'), \tag{6}
\]

\[
\exists \tau^\delta \subseteq \tau : \forall \delta > 0 : \exists \epsilon \in (0, \delta] : \text{Dev}(\tau^b, t_0 + \epsilon) \leq \beta(\tau^b) \tag{7}
\]

\[\land \text{Dev}(\tau^b, t_0) = \beta(\tau^b). \tag{8}\]

Proof. (6) follows from Claim 9.1.

If (7) is false, then $\forall \tau^b \subseteq \tau : \exists \delta > 0 : \exists \epsilon \in (0, \delta] : \text{Dev}(\tau^b, t_0 + \epsilon) \leq \beta(\tau^b)$. This means that (7) is true over $(t_0, t_0 + \delta]$, which contradicts the definition of $t_0$.

(8) follows from (6), (7), and Lemma 5.

Let $\tau^b$ be any of the task subsets known to exist by (7).

Claim 9.3. For any task $\tau_e \in \tau^b$,

\[
\text{Dev}(\tau_e, t_0) \geq K(2U(\tau) - 2U(\tau^b) + u_e)u_e > 0. \tag{9}
\]

Proof. Dev($\tau_e, t_0$)

\[
\begin{align*}
&= \text{Dev}(\tau_e, t_0) - \text{Dev}(\tau_e \setminus \{\tau_e\}, t_0) \\
&\geq \beta(\tau_e) - \beta(\tau_e \setminus \{\tau_e\}) \quad \{\text{By (6) and (8)}\} \\
&= KU(\tau_e)(2U(\tau) - U(\tau^b)) - \quad \{\text{By (5)}\} \\
&= K(2U(\tau) - 2U(\tau^b) + u_e)u_e > 0 \quad \{\text{By (5)}\}.
\end{align*}
\]

Claim 9.4. Any task $\tau_e \in \tau^b$ has a ready job at $t_0$.

Proof. Follows from Lemma 1 and Claim 9.3.

Claim 9.5. For any task $\tau_i \notin \tau^b$,

\[
\text{Dev}(\tau_i, t_0) \leq K(2U(\tau) - 2U(\tau^b) - u_e)u_e. \tag{10}
\]

Proof. Dev($\tau_i, t_0$)

\[
\begin{align*}
&= \text{Dev}(\tau_i \cup \{\tau_e\}, t_0) - \text{Dev}(\tau_i, t_0) \\
&\leq \beta(\tau_i \cup \{\tau_e\}) - \beta(\tau_i) \quad \{\text{By (6) and (8)}\} \\
&= KU(\tau_i)(2U(\tau) - U(\tau^b) \cup \{\tau_i\}) - \quad \{\text{By (6)}\} \\
&= K(2U(\tau) - 2U(\tau^b) - u_e)u_e \quad \{\text{By (5)}\}.
\end{align*}
\]

Claim 9.6. For any tasks $\tau_e \in \tau^b$ and $\tau_i \notin \tau^b$, if $\tau_e$ has a ready job at $t_0$, then $\tau_e$ has higher priority than $\tau_i$ at $t_0$.

Proof. Dev($\tau_e, t_0$) - Dev($\tau_i, t_0$)

\[
\begin{align*}
&\geq K(u_e + u_e) \quad \{\text{By Claims 9.3 and 9.4}\} \\
&\geq T_{\max} + 2\phi \quad \{\text{By Claims 9.3 and 9.4}\}.
\end{align*}
\]

The claim follows from Claim 9.4 and Lemma 5.

By Claim 9.6 Corollary 2 and (8), there exists $\delta > 0$ such that for all $\epsilon \in (0, \delta]$, $\text{Dev}(\tau_i, t_0 + \epsilon) \leq \text{Dev}(\tau^b, t_0) = \beta(\tau^b)$.

This contradicts (7). Thus, $t_0$ does not exist, implying that 4 is true over $[0, \infty)$.

Theorem 1. For any feasible task system $\tau$, the tardiness of any task $\tau_i$ under any Strong APA window-constrained scheduler is at most

\[
\frac{T_{\max} + 2\phi}{2U_{\min}}(2U(\tau) - u_i). \tag{9}
\]

Proof. By Lemma 5, Dev($\tau_i, t$) $\leq \frac{T_{\max} + 2\phi}{2U_{\min}}(2U(\tau) - u_i)$ for all $t \geq 0$. By Corollary 1 the bound in (9) follows.
Corollary 3. For any system as in Thm. 1 the tardiness of any task is at most
\[ m(T_{\text{max}} + 2\phi)/u_{\text{min}}. \] (10)

Proof. Because \( m \geq U(\tau) \) (by Lemma 8), \( m > (2U(\tau) - u_i)/2 \) for any task \( \tau_i \). Thus, the expression in (10) is greater than that in (9) from Thm. 1.

Using (10) over (9) will simplify the NP-blocking analysis presented later.

As a brief aside, much like how [11] considered identical multiprocessors under APA and uniform multiprocessors, our proof of Thm. 1 also applies to uniform multiprocessors with minor modifications. These modifications are detailed in App. A.

V. NON-PREEMPTIVITY

In this section, we define progression, a notion that can replace NP execution in some instances. We use Thm. 1 to show that, unlike NP execution, progression does not lead to capacity loss. For instances where NP execution is required in its strictest sense, we present modifications to SAPA-EDF under which we can compute blocking terms.

A. Progression

We begin by formally defining progression.

Def. 6. A portion of a job is guaranteed progression if, once the portion is first scheduled, it is always scheduled on some processor until the portion ends.

We do not consider time spent migrating as unscheduled time. Thus, progression is weaker than true NP execution because the considered job may migrate.

Though progression is weaker than NP execution, it is sufficient in many use cases. Locking protocols are a good example. An NP FIFO spin-lock ensures \( O(m) \) blocking on \( m \) processors because NP execution guarantees that the lock’s spin queue may contain at most \( m \) tasks. Progression provides this same guarantee. Of course, other use cases, such as NP execution that occurs within certain OS system calls, may be intolerant of the migrations permitted by progression.

Code sections that require progression can be realized under SAPA-EDF by prioritizing a job by its release time instead of its deadline while within such a section. We call this new scheduler Strong APA EDF-FIFO (SAPA-EDF) because it uses a combination of EDF and FIFO priorities. These priorities are window-constrained, with \( \phi = T_{\text{max}} \), so by Thm 1, SAPA-EDF is SRT-optimal with tardiness at most \( 3mT_{\text{max}}/u_{\text{min}} \).

SAPA-EDF guarantees progression for the same reason that global FIFO ensures NP execution. It is impossible for any newly released job to preempt an executing job under global FIFO because the newly released job must have a later release time than any executing job. Recall that under Strong APA, a job is unscheduled when it is at the end of a shifting path that begins with a higher-priority job. Similarly to global FIFO, it is impossible for any newly released job to have an earlier deadline than the release time of any job already executing. Thus, no job release can cause an executing job whose priority is its release time to be unscheduled via shifting. Such an executing job can, however, be caused to migrate, a behavior that true NP execution would disallow.

B. Link-Based Scheduling

As noted above, true NP execution may be required in some use cases. Unfortunately, SAPA-EDF does not guarantee progression if NP sections exist.

Ex. 8. Consider \( \tau_1, \ldots, \tau_3 \) in Fig. 1(a) executing on \( \pi_1 \) and \( \pi_2 \). Let \( (C_1, T_1) = (1, 2), (C_2, T_2) = (6, 20), \) and \( (C_3, T_3) = (2, 10) \). Consider the schedule in Fig. 5. Initially, \( \tau_2 \) releases a job at \( t = 0 \) and is scheduled upon \( \pi_1 \). \( \tau_2 \) immediately begins executing an NP section. \( \tau_2 \) also immediately requests progression for the entire duration of its job, changing its priority from 20 to 0. Fixed task \( \tau_1 \) releases a job at \( t = 1 \), but is unable to execute because \( \tau_2 \) is in an NP section on \( \pi_1 \). Meanwhile, \( \tau_3 \) releases a job at \( t = 4 \), and immediately begins executing on \( \pi_2 \), which was idle. \( \tau_2 \) requests progression at \( t = 4 \), changing its priority from 14 to 4. However, at \( t = 5 \), \( \tau_2 \) completes its NP section. Because it requested progression for its entire job, \( \tau_1 \) and \( \tau_2 \) have the highest-priority jobs (with priorities of 0 and 3, compared to 4 for \( \tau_3 \)). Moreover, \( \tau_1 \) can now execute on \( \pi_1 \). Thus, at \( t = 5 \), \( \tau_1 \) shifts via path \{\( \tau_1, \tau_1, \tau_2, \pi_2, \tau_3 \)\} and \( \tau_3 \) is unscheduled, violating its progression guarantee.

There is little value in trying to replace some instances of non-preemptiveness with progression if the remaining NP sections break progression. To support NP sections and progression simultaneously, we adapt link-based scheduling [3] for SAPA-EDF. Under link-based scheduling, a distinction is made between what task is actually scheduled on a processor (the scheduled task) and what task would have been scheduled on this processor (the linked task) if NP sections were ignored. The linked task of every processor is updated whenever a task changes its priority (e.g., job releases or completions or via a prioritization function) and is based purely on these priorities, while actual scheduling decisions will only match linked tasks if doing so will not migrate a job in an NP section.

We assume that every job requires progression throughout its execution. This will be necessary to guarantee that any job is NP-blocked at most once, which is desirable because NP-blocking is fundamentally more pessimistic under APA than under global scheduling, as will be demonstrated in Ex. 10.

Formally, our link-based SAPA-EDF (L-SAPA-EDF) scheduler is defined by the following rules.

R1 The priority of job \( \tau_{i,j} \) is initially \( d_{i,j} \), and permanently changes to \( r_{i,j} \) the instant it is first linked.
R2 Tasks are linked onto processors such that if every processor scheduled its linked task, the scheduler would maintain Strong APA.

R3 A processor executing a job continues executing said job until it either completes or is scheduled by another processor, at which point the processor becomes idle.

R4 An idle processor with a linked task schedules the ready job of its linked task and ceases to be idle, unless said task is executing an NP section on another processor.

Our assumption that every job requires progression is reflected in R4. This assumption is guaranteed by R3.

Ex. 9. We find it easier to demonstrate linking by examining affinity graphs rather than schedules. Consider Fig. 6. Initially, $\tau_3$ is the first to release a job. $\tau_3$ becomes linked to $\pi_2$. By R3, $\pi_2$ begins executing $\tau_3$'s job. $\tau_3$ then enters a NP section, which reflects the first affinity graph in Fig. 6.

After this, $\tau_2$ releases a job. Because $\tau_3$ is already linked on $\pi_2$, $\tau_2$ is linked to $\pi_1$. By R4, $\pi_1$ begins executing $\tau_2$'s job. This job also enters an NP section.

Next, $\tau_1$ releases a job. As $\tau_2$ is linked on $\pi_1$ and $\tau_3$ is linked on $\pi_2$, there is a path $\{\tau_1, \pi_1, \tau_2, \pi_2, \tau_3, \pi_3, \tau_0\}$ over which a shift in links may occur. By R2, this shift is taken such that $\tau_0$ is linked on $\pi_1$, $\tau_1$ is linked on $\pi_2$, and $\tau_3$ is linked on $\pi_3$. However, as $\pi_1$ and $\pi_2$ are still executing non-preemptively, no migrations occur. This reflects the third graph.

Next, $\tau_2$ finishes its NP section. By R3, $\pi_1$ continues executing $\tau_2$ even though its linked task is now $\tau_1$. Note that since $\tau_3$ is executing an NP section on $\pi_2$, having $\pi_1$ schedule $\tau_1$ at this time would have broken progression for $\tau_2$. This reflects the fourth graph.

Lastly, $\tau_3$ completes its NP section. By R4, $\pi_3$ schedules its linked task $\tau_3$, thereby making $\pi_2$ idle. Thus, $\pi_2$ schedules its linked task $\tau_2$, thereby making $\pi_1$ idle. This makes $\pi_1$ schedule its linked task $\tau_1$. This reflects the fifth graph.

Besides R1 and R2, which are specific to EDF-FIFO and APA scheduling, respectively, link-based scheduling under R3 and R4 differs slightly from how it is defined in R1. Under R3 and R4, a processor may continue executing a task besides the one it is linked to, even if neither it nor its linked task are executing NP sections. Additionally, under R4, processors only attempt to schedule their linked tasks when they become idle.

Under global scheduling, linking ensures that a job is blocked for at most one NP section. In our context, each job is similarly blocked at most once. However, in our case, the length of blocking may be due to a sequence of NP sections.

Ex. 10. Consider the assignments in Fig. 7. Assume that tasks are prioritized on an EDF basis and for any time $t$ considered in this example, $d_2(t) < d_3(t) < d_4(t) < d_5(t) < d_1(t)$. Initially, $\tau_5$ is unable to shift over the path $\{\tau_5, \pi_3, \tau_4, \pi_2, \tau_2, \pi_1, \tau_1\}$ because $\tau_4$ is executing an NP section on $\pi_3$. Thus, $\tau_5$ is NP blocked for the length of $\tau_4$'s NP section, but before this NP section completes, $\tau_2$ begins an NP section on $\pi_2$. Thus, even after $\tau_4$ completes its NP section, $\tau_5$ cannot execute on $\pi_3$ without unscheduling $\tau_4$, which has higher priority. This pattern may continue to the end of the shifting path, forcing $\tau_5$ to wait for a sequence of NP sections.

C. Blocking Analysis

We now present blocking analysis for L-SAPA-EF. Due to space constraints and our usage of fairly standard blocking-analysis techniques, we cover this analysis at a high level and defer formal details to App. B.

It is common practice to account for NP blocking by adding a blocking term $B_i$ to the WCET of every task $\tau_i$, where $B_i$ upper bounds the duration that task $\tau_i$ can be NP blocked. Because links reflect tasks' priorities, NP blocking occurs when a task is linked while unscheduled.

Observe in the rightmost affinity graph in Fig. 6 that whenever no jobs are executing NP sections, every linked task is scheduled. This is true generally due to R1 and R4 and the fact that APA-EF guarantees progression, any linked task continues to be linked on some processor until its ready job completes. Additionally, by R4, only linked tasks are ever scheduled for execution, and, by R4, any scheduled task executes until its ready jobs complete. Thus, all scheduled task are also linked tasks. Now suppose some linked task is unscheduled while no job is executing an NP section. By R4, the processor the task is linked on must be executing some other task that, because all scheduled tasks are linked, must be linked on some other processor that, by R4, must also be executing some other linked task, and so forth. As the task system is not infinite, it must be that all linked tasks are scheduled when no job is executing an NP section.

Let $I_i$ denote the largest interval in which, at any time, some job not from $\tau_i$ (a task does not NP block itself) is executing an NP section. Because all linked tasks are scheduled when no jobs are executing an NP section, the duration a task $\tau_i$ can be continuously linked and unscheduled is upper bounded by $|I_i|$. Furthermore, because L-SAPA-EF guarantees progression for all jobs, any job can be linked and unscheduled (and hence, NP blocked) at most once. Thus, it is sufficient if $B_i \geq |I_i|$.

For $\tau_i$, let the NP demand bound function $\text{npdbf}_i(t, \Delta)$ be the maximum amount of NP execution required by jobs not from $\tau_i$ that are pending at some point in $[t, t + \Delta]$. Note that $\max_{t 
abla \Delta, \tau_i} (\text{npdbf}_i(t, |I_i|)) \leq |I_i|$, else it is impossible for some job to be executing an NP section at every time instant in $I_i$.

If a function $g(\Delta)$ and $\Delta' \geq 0$ exist such that $g(\Delta)$ upper bounds $\text{npdbf}_i(t, \Delta)$ and $\forall \Delta \geq \Delta' : g(\Delta') < \Delta$, then $|I_i| \leq \Delta'$. The set of jobs of task $\tau_i \neq \tau_i$ considered by $\text{npdbf}_i(t, \Delta)$ includes jobs released in $[t, t + \Delta]$ and jobs released prior to $t$ that are incomplete at $t$. The former is upper bounded by $|\Delta/T_k|$. Assuming the response time of any job is at most
\[ R_k = T_k + 3m T_{\text{max}} / u_{\text{min}} \]

The latter is bounded by \( \lceil R_k / T_k \rceil \).

Let \( \gamma_k \) denote the maximum amount of time any job of \( \tau_k \) will execute non-preemptively and let \( \omega_k = \gamma_k / T_k \). Let

\[ R^i_{\text{max}} = \max_{\tau_i \in \tau \setminus \{\tau_i\}} (R_k), \quad \Gamma_i = \sum_{\tau_i \in \tau \setminus \{\tau_i\}} \gamma_k, \quad \Omega_i = \sum_{\tau_i \in \tau} \omega_k. \tag{11} \]

npdbf\((t, \Delta)\) can be upper bounded by a linear function

\[ g(\Delta) = \Omega_i \Delta + \Omega_i R^i_{\text{max}} + 2 \Gamma_i. \]

If \( \Omega_i < 1 \), then \( \Delta' = (\Omega_i R^i_{\text{max}} + 2 \Gamma_i) / (1 - \Omega_i) \).

Because \( \Delta' \geq |I_i| \) if \( \Omega_i < 1 \) and it is sufficient that \( B_i \geq |I_i| \), it is sufficient if \( B_i = (\Omega_i R^i_{\text{max}} + 2 \Gamma_i) / (1 - \Omega_i) \). Thus, for the task system \( \tau \), if \( \max_{\tau_i \in \tau} \Omega_i < 1 \) and \( \tau \) is feasible when \( C_i \) is inflated by \( B_i \), then \( \tau \) is SRT-schedulable under L-SAPA-EDF with tardiness at most \( 3m T_{\text{max}} / u_{\text{min}} \).

**D. Refining the Blocking Analysis**

For simplicity, several over-approximations have been made in this section. For example, the tardiness bound of \( 3m T_{\text{max}} / u_{\text{min}} \) shown for preemptive SAPA-EDF can be reduced to \( 2m T_{\text{max}} / u_{\text{min}} \) by specifying unique upper and lower bounds on \( x_{i,j}(t) \) for each \( \tau_i \) (as in \( 9 \)) and modifying the proof of Thm. [1] accordingly. This has the twofold effect of reducing \( R_k \) for each \( \tau_k \) in \( 11 \), which reduces \( B_i \), and reducing the tardiness bound under L-SAPA-EDF. In the same vein, we made use of \( 10 \) as a tardiness bound instead of the tighter \( 9 \). This is because \( 9 \) depends on \( U(\tau) \) while \( 10 \) does not. If tardiness depends on \( U(\tau) \), then it also depends on the WCET inflation caused by \( B_i \), while \( B_i \) in turn also depends on tardiness due to \( R_k \) in \( 11 \). This circular dependence would require that \( B_i \) be deduced via some iterative procedure. In this case, the condition required would no longer be \( \Omega_i < 1 \), but rather that the procedure converges. Such an iterative procedure would yield less pessimistic \( B_i \) terms. It is also not necessary to consider \( R^i_{\text{max}} \) instead of each individual \( R_k \).

A more substantial over-approximation is our assumption that all tasks in \( \tau \) besides \( \tau_i \) contribute to npdbf\((t, \Delta)\), causing the sums in \( 11 \) to be over all such tasks. Fixed tasks do not need to be considered in these sums, as they do not cause NP blocking. This is intuitive, as for them, progression, which does not cause capacity loss, is equivalent to NP execution. In practice, many tasks would likely be fixed as this maximizes cache locality for most tasks. Even if this is not the case, it was proven in \( 12 \) that for any feasible task system, it is possible to remove processors from tasks’ affinity masks until at most \( m - 1 \) tasks are not fixed without affecting feasibility.

**VI. Conclusion**

We have demonstrated fundamental faults in SD regarding bounded tardiness under APA scheduling. The natural alternative is SAPA-EDF, which has attractive theoretical properties, but is hindered by complexities in its implementation and analysis. We have addressed complexities introduced by non-preemptivity and proposed a weaker form of it, progression. In practice, true NP sections (which cause capacity loss) would likely be used only when such sections are short (as in an OS kernel), with progression (which causes no loss) sufficing in other cases. As a side effect of obtaining these results, we greatly expanded the space of SRT-optimal APA schedulers.

Several other issues with SAPA-EDF must be resolved before it can be made into a practical EDF scheduler under APA. From an implementation point of view, we must consider how to balance scheduler efficiency with correctness, else we risk introducing scheduling glitches such as those possible under SD. From an analytical point of view, it remains an open problem how to account for suspensions, as well as how to implement suspension-based locking protocols under APA.

While we have demonstrated that SD may be unsuitable for APA, we believe that small modifications to SD are sufficient to yield SRT-optimality under special cases of processor affinities beyond just global or clustered scheduling. Given that SD is not SRT-optimal, identifying these special cases and the corresponding required modifications is likely the most complete answer we can give for the problem of how to provide real-time guarantees for SD with affinity masks.
We formally de
formulations are also exposed. The only proofs in Sec. IV that change when considering a uniform multiprocessor instead of an identical multiprocessor under APA are those of Lemma 6 (whose proof depends on the rate that \(c_i(t)\) decreases while \(\tau_i\) is scheduled), Corollary 2 (which considers Strong APA scheduling and depends on the feasibility condition under APA given in Lemma 8), and Corollary 3 (which also depends on Lemma 8).

A variant of Lemma 6 can be proven in the context of uniform multiprocessors with minor modifications as follows.

**Lemma 11.** For arbitrarily small \(\epsilon > 0\), if task \(\tau_i\) is scheduled over \([t, t+\epsilon)\) on processor \(\pi_j\), then \(\text{Dev}(\tau_i, t+\epsilon) \leq \text{Dev}(\tau_i, t) + \epsilon(u_i - s_j)\).

**Proof.** For small enough \(\epsilon\), the same job of \(\tau_i\) is scheduled over \([t, t+\epsilon)\) on processor \(\pi_j\), and this job does not complete in this interval.

By Def. 5, \(\text{Dev}(\tau_i, t+\epsilon) = u_i(t+\epsilon - vt_i(t+\epsilon))\). Because \(\tau_i\) is scheduled, it must have a ready job, therefore only case 1a of Def. 4 can apply. Thus, \(\text{Dev}(\tau_i, t+\epsilon) = u_i\left(t+\epsilon - r_i(t+\epsilon) - T_i \frac{C_i(t+\epsilon) - C_i(t)}{C_i(t)}\right)\).

As the ready job of \(\tau_i\) at \(t\) does not change by \(t+\epsilon, r_i(t+\epsilon) = r_i(t)\) and \(C_i(t+\epsilon) = C_i(t)\). Since \(s_j\) units of execution of this ready job are completed, \(c_i(t+\epsilon) = c_i(t) - s_j\). Thus, \(\text{Dev}(\tau_i, t+\epsilon) = u_i\left(t+\epsilon - r_i(t) - T_i \frac{C_i(t) - C_i(t)}{C_i(t)} + \epsilon s_j\right) = u_i(t - vt_i(t)) + u_i\epsilon - u_i \frac{T_i}{C_i(t)} \epsilon s_j \leq \text{Dev}(\tau_i, t) + \epsilon(u_i - s_j)\) by Def. 5 and \(T_i/C_i(t) \geq 1/u_i\).

**Corollary 4.** Under a Strong Uniform scheduler, at any time instant \(t\), for any set of tasks \(\tau'\) with ready jobs such that the tasks of \(\tau'\) have highest priority out of all tasks with ready jobs, \(\exists \delta > 0 : \forall \epsilon \in (0, \delta] : \text{Dev}(\tau', t) \geq \text{Dev}(\tau', t+\epsilon)\) holds.

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**APPENDIX A**

**UNIFORM MULTIPROCESSORS**

As in [17], which proved the SRT-optimality of EDF under both identical multiprocessors with APA and uniform multiprocessors, our proof in Sec. IV of the SRT-optimality of any window-constrained scheduler under APA can also be modified to show that such schedulers are SRT-optimal under uniform multiprocessors. We detail these modifications in this appendix.

**Background on uniform multiprocessors.** We formally define our model of a uniform multiprocessor as follows.

**Def. 7.** A uniform multiprocessor is a multiprocessor \(\pi = \{\pi_1, \pi_2, \ldots, \pi_n\}\) where processor \(\pi_i\) executes jobs at a rate of \(s_i\) units of execution per unit of time. We assume without loss of generality that processors are indexed by non-increasing speed.

The feasibility condition under uniform multiprocessors is as follows [8].

\[ \forall t' \subseteq t : \text{Dev}(\tau', t) \leq \sum_{j=1}^{m} s_j. \]
Proof. Let δ be arbitrarily small such that no task changes its priority over [t, t + δ]. Let $τ^*$ be the subset of $\min(\{|τ|, m\})$ tasks in $τ'$ with highest priority over $[t, t + δ]$. Because of Strong Uniform (Def. 8), these are the tasks scheduled over $[t, t + δ]$.

Because $ε \in (0, δ]$, these tasks are also the tasks scheduled over $[t, t + ε]$. Let $j_i$ denote the index of the processor $π_j$, upon which $τ_i$ $∈$ $τ^*$ is scheduled. Thus,

$$\text{Dev}(τ', t + ε) = \text{Dev}(τ^*, t + ε) + \text{Dev}(τ' \setminus τ^*, t + ε) \leq \text{Dev}(τ^*, t) + \epsilon \left( \sum_{τ_j \in τ^*} u_τ - s_j \right) + \text{Dev}(τ' \setminus τ^*, t + ε) \quad \text{(By Lemma 11)} \leq \text{Dev}(τ^*, t) + \epsilon \left( U(τ^*) - \sum_{j} s_j \right) + \text{Dev}(τ' \setminus τ^*, t + ε) \quad \text{(By Def. 8)} \leq \text{Dev}(τ^*, t) + \epsilon U(τ^*) + \text{Dev}(τ' \setminus τ^*, t + ε) \quad \text{(By Lemma 7)} \leq \text{Dev}(τ^*, t) + \epsilon U(τ^*) + \epsilon U(τ' \setminus τ^*) \quad \text{(Def. of τ^*)} \leq \text{Dev}(τ^*, t) \quad \text{(By Lemma 10).} \quad \Box$$

Once Lemma 11 and Corollary 4 are substituted in for Lemma 9 and Corollary 2 in Sec. IV, respectively, a analogous version of Thm. 1 with the same tardiness bound can be proven for Strong Uniform window-constrained schedulers under uniform multiprocessors.

We have not shown an analogue of Corollary 3 for uniform multiprocessors. This is because we only proved Corollary 5 because its corresponding tardiness bound was more convenient to consider in Sec. V which deals with non-preemptivity. We chose not to consider non-preemptivity under uniform multiprocessors because it is unclear how the duration of a NP section should be affected by differing processor speeds.

APPENDIX B

FORMAL TREATMENT OF NON-PREEMPTIVITY

In this appendix, we present a more formal and refined version of the proof of our NP blocking analysis under L-SAPA-EF in Sec. V-C. Note that due to refining the blocking analysis, $B_i$ and the symbols defined in (11) are defined slightly differently in this appendix than in Sec. V-C.

We begin by defining NP blocking under L-SAPA-EF.

Def. 9. Task $τ_i$ is NP blocked if $τ_i$ is linked and unscheduled.

Lemma 12. Every executing task is linked on some processor.

Proof. By $R1$, $R2$, and the fact that SAPA-EF guarantees progression, every linked task remains linked on some processor until the completion of its current job. By $R4$, the only way a previously unscheduled task may begin executing is if it is linked on some processor. The lemma follows. \quad \Box

Lemma 13. If task $τ_{i1}$ is NP blocked at time $t$, then at time $t$, there is a unique path of tasks and processors $\{τ_{i1}, π_{j1}, τ_{i2}, π_{j2}, \ldots, π_{j, τ_{i1}} \}$ where $π_{j1}$ is idle and $τ_{i1}$ is linked on $π_{j1}$, $π_{j1}$ is executing $τ_{i2}$, $τ_{i2}$ is linked on $π_{j2}$, and so on.

Proof. The method of constructing this path is described in the lemma statement. We prove that this method results in a well-defined path. To this end, we must show that the processor that follows every task in the path is well-defined, the task that follows every processor is well-defined, the elements of the path are distinct, and that the path eventually ends with an idle processor.

The processor that follows every task in the path can always be found because every task in the path is guaranteed to be linked on some processor. This is either because the task is $τ_{i1}$, which is linked by Def. 9 or because the task is executing on the processor that precedes it in the path and every executing task is linked by Lemma 12.

Likewise, the task that follows every processor in the path (besides $π_{j1}$) is whatever task the processor executes. If no such task exists, then this processor is $π_{j1}$ and the path ends.

The elements of the path are distinct because both linking and execution are one-to-one relations between tasks and processors. Thus, the path must be finite, as there are only a finite number of distinct tasks and processors. This completes our proof obligation. \quad \Box

Def. 10. If task $τ_{i1}$ is NP blocked at time $t$, its link shift path at $t$ is the unique path known to exist by Lemma 13.

Def. 11. Task $τ_{i2}$ is NP blocked by $τ_j$ at time $t$ if $τ_j$ is in $τ_{i1}$’s link shift path and $τ_j$ is executing an NP section.

Once no tasks in an NP-blocked task’s link shift path are executing NP sections, the NP-blocked task becomes scheduled (by $R4$), and is no longer NP blocked. We assume that this occurs before any jobs enter NP sections that happen to begin at the same time instant.

Lemma 14. No job is ever NP blocked by a fixed task.

Proof. We show that any task that NP blocks another must be migrating. Suppose task $τ_i$ is NP blocked. $τ_i$ can only be NP blocked by tasks in its link shift path. For every task besides $τ_i$ in $τ_i$’s link shift path, the task is preceded in the path by the
processor that executes it and followed by the processor it is linked on. Both the processor that executes it and the processor it is linked on must be in the task’s processor affinity mask.

Thus, every task besides \( t_i \)’s link shift path is migrating. These are the only tasks that can NP block \( t_i \).

**Def. 12.** For blocking term \( B_i \), let the inflated WCET of task \( t_i \) be denoted \( C'_i = C_i + B_i \). Likewise, let the inflated utilization of a task \( t_i \) be \( u'_i = u_i' + B_i \) and of a task set \( \tau \) be \( U'(\tau) = \sum_{t_i \in \tau} u'_i \), and the minimum inflated utilization be \( u'_{\text{min}} = \min_{t_i \in \tau} u'_i \).

**Def. 13.** For task \( t_i \), let

\[ R'_i = T_i + \frac{3T_{\text{max}}}{2u'_{\text{min}}} (U' - u'_i). \]

The task set \( \tau^G \subseteq \tau \) denotes the set of migrating tasks in \( \tau \). As in Sec. [V.C] let \( \gamma_i \) denote the worst-case NP execution required by any job of \( t_i \).

**Lemma 15.** If \( \exists B_1, B_2, \ldots, B_n > 0 \) such that \( \forall t_i \in \tau : B_i \geq \sum_{t_n \in \tau \setminus \{t_i\}} \left( \left\lfloor \frac{R'_n + B_n}{T_n} \right\rfloor + 2 \right) \gamma_n \) (12)

and \( \tau \) is feasible when every task \( t_i \) has its WCET \( C_i \) inflated by \( B_i \) (and hence, utilization \( u'_i \) instead of \( u_i \)), then the response time of task \( t_i \) is bounded by \( R'_i \) under L-SAPA-EF.

**Proof.** For each job \( t_{i,j} \), let the time instant \( \ell_{i,j} \) denote the first time instant where \( t_{i,j} \) is linked on some processor under L-SAPA-EF. Order the jobs released by \( \tau \) by time \( \ell_{i,j} \), assuming some arbitrary tie-breaking. We will prove by induction on the jobs of \( \tau \) under this ordering that any job \( t_{i,j} \) is scheduled on some processor by time \( \ell_{i,j} + B_i \) and thus, is NP blocked for at most \( B_i \).

Let the set \( J_v \) be the set of the first \( v \) jobs under our ordering. In the base case, \( J_0 = \emptyset \), so it is vacuously true that every job \( t_{i,j} \) in \( J_0 \) is scheduled by time \( \ell_{i,j} + B_i \).

We prove the induction step by showing that for the \((v + 1)\)th job \( t_{i,j} \), at some time instant in \([\ell_{i,j}, \ell_{i,j} + B_i] \), \( t_{i,j} \) is not NP blocked by any task. Thus, \( t_{i,j} \) must be scheduled by this time instant.

**Claim 15.1.** Prior to time \( \ell_{i,j} \), no job \( t_{h,k} \) has been NP blocked for more than \( B_h \) time units.

**Proof.** Assume, to the contrary, that \( t_{h,k} \) has been NP blocked (and hence, linked while unblocked) for more than \( B_h \) time units by time \( \ell_{i,j} \). For \( t_{h,k} \) to be linked for more than \( B_h \) by \( \ell_{i,j} \), it must be that \( \ell_{h,k} + B_h < \ell_{i,j} \). As \( B_h > 0 \) by the lemma statement, \( \ell_{h,k} < \ell_{i,j} \), and so \( t_{h,k} \in J_v \). By the induction hypothesis, \( t_{h,k} \) is NP blocked for at most \( B_h \) time units.

**Claim 15.2.** Any job \( t_{h,k} \) with \( r_{h,k} + R_{h}^i < \ell_{i,j} \) completes before time \( \ell_{i,j} \).

**Proof.** Assume, to the contrary, that \( t_{h,k} \) completes later than time \( \ell_{i,j} \). By converting the time any job is spent NP blocked into execution of said job, we obtain a modified schedule where jobs are fully preemptive (this process is detailed in [4]). Prior to time \( \ell_{i,j} \), the WCET of any task \( t_i \) in this modified schedule is at most \( C_p + B_p \) (by Claim 15.1).

This modified system is feasible by the lemma statement. Thus, by Thm. [1] the tardiness of task \( t_h \) prior to \( \ell_{i,j} \) is at worst \((T_{\text{max}} + 2\phi)U'(2u'_h) / (2u'_{\text{min}}) \). Because \( \phi = T_{\text{max}} \) under SAPA-EF and L-SAPA-EF uses the same prioritization functions as SAPA-EF, by Def. [13] this tardiness is at most \( 3T_{\text{max}}U'(2u'_h) / (2u'_{\text{min}}) = R'_h - T_h \). This means the response time of \( t_h \) prior to time \( \ell_{i,j} \) is at most \( R'_h \). As \( \gamma_{h,k} + R'_h < \ell_{i,j}, t_{h,k} \) completes by time \( \ell_{i,j} \).

**Claim 15.3.** At most \( (|R'_h + B_i|/T_h) + 2) \gamma_h \) time units of NP execution from \( t_h \) can be executed during \([\ell_{i,j}, \ell_{i,j} + B_i] \).

**Proof.** Only jobs pending at some point in \([\ell_{i,j}, \ell_{i,j} + B_i] \) can execute in this interval. By Claim 15.2 only jobs released between \([\ell_{i,j} - R'_h, \ell_{i,j} + B_i] \) can be pending at some point in \([\ell_{i,j}, \ell_{i,j} + B_i] \). Because the spacing between job releases of \( t_h \) is at least \( T_h \), there are at most \((R'_h + B_i)/T_h \) + 2 such jobs. Such jobs include at most \((|R'_h + B_i|/T_h) + 2) \gamma_h \) time units of NP execution.

By Lemma [14] and Claim [15.3] the amount of NP execution from tasks that can NP block \( t_{i,j} \) over \([\ell_{i,j}, \ell_{i,j} + B_i] \) is upper bounded by

\[ \sum_{t_n \in \tau \setminus \{t_i\}} \left( \left\lfloor \frac{R'_n + B_n}{T_n} \right\rfloor + 2 \right) \gamma_n. \]

By (12), there is insufficient NP execution from such tasks for \( t_{i,j} \) to be NP blocked throughout \([\ell_{i,j}, \ell_{i,j} + B_i] \). Thus, \( t_{i,j} \) must be scheduled by time \( \ell_{i,j} + B_i \), meaning \( t_{i,j} \) is NP blocked for at most \( B_i \) time units. This completes the induction step of our proof.

Thus, any job \( t_{i,j} \) is NP blocked for at most \( B_i \) time units. That response times are bounded is shown through the same argument as in Claim 15.2 except for all time instead of only prior to \( \ell_{i,j} \).

**Def. 14.** For task \( t_i \), let

\[ R_i = T_i + \frac{3mT_{\text{max}}}{u'_{\text{min}}}, \]

\[ R^i_{\text{max}} = \max_{t_n \in \tau \setminus \{t_i\}} (R_n). \]

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Def. 15. For task \( \tau_i \), let

\[
\omega_i = \frac{\gamma_i}{T_i}, \\
\Omega_i = \sum_{\tau_k \in \mathcal{T} \setminus \{\tau_i\}} \omega_k, \\
\Gamma_i = \sum_{\tau_k \in \mathcal{T} \setminus \{\tau_i\}} \gamma_k.
\]

Corollary 5. If \( \max_i(\Omega_i) < 1 \) and the task system \( \tau \) is feasible when \( C_i \) of every task \( \tau_i \) is inflated by

\[
B_i = \frac{\Omega_i R_{\text{max}}^i + 2\Gamma_i}{1 - \Omega_i},
\]

then the tardiness of \( \tau_i \) under L-SAPA-EF is at most \( 3mT_{\text{max}}/u_{\text{min}} \) time units.

Proof. If the task system is feasible with inflated WCETs, then for task \( \tau_i \),

\[
R_i' = T_i + \frac{3T_{\text{max}}}{2u_{\text{min}}'} (2U'(\tau) - u_i') \quad \{\text{By Def. 15}\}
\]

\[
\leq T_i + \frac{3T_{\text{max}}}{2u_{\text{min}}'} (2U'(\tau)) \quad \{u_i' > 0\}
\]

\[
\leq T_i + \frac{3mT_{\text{max}}}{u_{\text{min}}'} \quad \{m \geq U'(\tau) \text{ by Lemma 8}\}
\]

\[
\leq T_i + \frac{3mT_{\text{max}}}{u_{\text{min}}'} \left\{ \forall \tau_j \in \tau : \frac{1}{u_j'} = \frac{T_j}{C_j} + B_j \leq \frac{T_j}{C_j} = \frac{1}{u_j} \right\}
\]

\[
= R_i \quad \{\text{By Def. 14}\}
\]

Thus,

\[
\sum_{\tau_h \in \mathcal{T} \setminus \{\tau_i\}} \left( \frac{R_i' + B_i}{T_h} \right) + 2 \gamma_h \\
\leq \sum_{\tau_h \in \mathcal{T} \setminus \{\tau_i\}} \left( \frac{R_h + B_i}{T_h} \right) + 2 \gamma_h \quad \{R_i' \leq R_h\}
\]

\[
\leq \sum_{\tau_h \in \mathcal{T} \{\tau_i\}} \left( \frac{R_{\text{max}}^i + B_i}{T_h} \right) + 2 \gamma_h \quad \{R_h \leq R_{\text{max}}^i\}
\]

\[
\leq \sum_{\tau_h \in \mathcal{T} \setminus \{\tau_i\}} \left( \frac{R_{\text{max}}^i + B_i}{T_h} \right) + 2 \gamma_h
\]

\[
= \sum_{\tau_h \in \mathcal{T} \setminus \{\tau_i\}} (R_{\text{max}}^i + B_i)\omega_h + 2\gamma_h \quad \{\text{By Def. 15}\}
\]

\[
= \Omega_i R_{\text{max}}^i + \Omega_i B_i + 2\Gamma_i \quad \{\text{By Def. 15}\}
\]

\[
= B_i \quad \{\text{By (13)}\}
\]

Thus, the definition of \( B_i \) in (13) satisfies the inequality in (12). By Lemma 15, the corollary statement follows. \( \square \)
Fig. 8: Extended counterexamples.
(a) Extended version of Fig. 2(a).
(b) Extended version of Fig. 2(b).
(c) Extended version of Fig. 2(c).