Design of an Efficient Ready Queue for Earliest-Deadline-First (EDF) Scheduler

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Abstract—Although dynamic-priority-based EDF algorithm is known to be theoretically optimal for scheduling sporadic real-time tasks on uniprocessor, fixed-priority (FP) scheduling is mostly used in practice. One of the main reasons for FP scheduling being popular in the industry is its efficient implementation: operations on the ready queue can be done in constant time. On the other hand, ready queue of EDF scheduler is generally implemented as a priority queue, for example, using a binary min-heap data structure in which (insertion/deletion) operation cannot be done in constant time.

This paper proposes a new design of ready queue for EDF scheduler: a simple data structure for the ready queue and efficient operations to insert and remove task control blocks (TCBs) to and from the ready queue are proposed. Insertion of a TCB of a newly released job (that cannot preempt the currently-executing job) is done in non-constant time. However, insertion of a TCB of a preempted job or the removal of the TCB of job having the highest EDF priority from the ready queue can be done in constant time. Simulation using randomly generated task sets shows that the overhead of managing jobs in our proposed ready queue for EDF scheduler is significantly lower than that of other approaches. We believe that theoretically optimal EDF algorithm implemented based on our proposed ready-queue data structure will make EDF popular in industry.

I. INTRODUCTION

Meeting hard deadlines while utilizing the CPU capacity as much as possible is a major challenge in real-time tasks scheduling problem. In this paper, preemptive EDF scheduling of a collection of sporadic real-time tasks on uniprocessor is considered. In addition to the execution time of the tasks, scheduling overhead must be taken into account during the design of the system so that no deadline is missed due to such overhead at run-time. One such source of scheduling overhead that we consider in this paper is management of tasks in the ready queue.

An EDF scheduler at each time instant executes the job with the earliest deadline. When the processor is busy executing a job and another job with relatively shorter deadline (i.e., higher EDF priority) is released, the currently-executing job is preempted by the new job. Active jobs that cannot be executed due to having relatively lower EDF priorities wait in a ready queue. A ready-queue manager inserts and removes the task control blocks (TCBs) of such active jobs to and from the ready queue. Unfortunately, such management of jobs in the ready queue of EDF scheduler is more complex and has higher overhead in comparison to that of FP scheduler (please see the discussion by Buttazzo [2]). Although EDF being optimal [3] can (theoretically) better utilize the CPU, many practical systems implement FP scheduling [5] due to its efficient (i.e., low overhead) run-time support in managing jobs in the ready queue.

To minimize overhead of managing jobs in EDF scheduler, Short [9] proposed different ready-queue data structure considering small systems and may have higher overhead for systems that require larger time representation. Pathan [8] proposed a mechanism to efficiently manage jobs in the ready queue of priority-promotion-based scheduling in which jobs are essentially executed in EDF priority order. This work is extended in [7] by proposing new technique to manage jobs in the ready queue. However, the techniques in [8], [7] require promotion of the priority of each job and each such promotion causes the TCB of that job (if it is in ready queue) to be remapped to a new position in the ready queue. Such remapping incurs overhead. The main endeavor of this paper is to reduce such overhead to exploit full schedulability power of EDF.

Building upon the data structure proposed in [8], efficient (insertion/removal) operations to manage ready jobs for EDF scheduler are proposed. Tasks are scheduled based on EDF priorities and do not require any priority promotion. The ready-queue management using the proposed scheme has the following features: insertion of a TCB of a newly released job cannot be done in constant time but the insertion of a TCB of a preempted job to the ready queue and removal of the TCB of the highest EDF priority job from the ready queue can be done in constant time.

To measure the effectiveness of the proposed ready-queue management scheme, the execution of randomly generated task sets is simulated. The ready queue of EDF is simulated using three alternatives: (i) our proposed scheme (presented in this paper), (ii) the approach proposed in [8] for priority-promotion-based scheduling, and (iii) a priority queue implemented as a binary min-heap. The simulation result shows that ready-queue management of our proposed scheme suffers significantly less overhead in comparison to that of the other two alternatives. Although this paper considers uniprocessor scheduling, the proposed scheme also applies to global EDF scheduling [1] for multiprocessors.

II. SYSTEM MODEL AND BACKGROUND

The EDF scheduling of a collection of n sporadic tasks \( \tau_1, \ldots, \tau_n \) is considered. Each task \( \tau_i \) has three parameters \( (C_i, D_i, T_i) \), where \( C_i \) is the worst-case execution time (WCET) of the task, \( D_i \) is the relative deadline, and \( T_i \) is the minimum inter-arrival time of the instances (called, jobs) of task \( \tau_i \). After a job of \( \tau_i \) is released at time \( t \), it requires at
most \(C_t\) units of execution time before its absolute deadline, which is at time \((t + D_t)\). Tasks are indexed in deadline-monotonic order: if \(k < \ell\) for any two tasks \(T_k\) and \(T_\ell\), then \(D_k \leq D_\ell\). A job is called active at time \(t\) if it is released but has not completed its execution. An active job may be in execution or awaiting execution in the ready queue.

**Scheduling Events.** In EDF scheduling, the active job with earliest absolute deadline has the highest priority and is always the one in execution. The ready-queue manager updates the ready queue based on one or more of the following scheduling events that may occur at time \(t\):

- If the processor is busy and a new job (denoted by \(J_{new}\)) with shorter absolute deadline than that of the currently-executing job (denoted by \(J_{exe}\)) is released, then \(J_{new}\) starts execution by preempting \(J_{exe}\). The TCB of the preempted job \(J_{exe}\) is inserted in the ready queue. This insertion event managed by the ready-queue manager is called the “rel_prmt” event.
- If the processor is busy and a new job \(J_{new}\) with absolute deadline higher than or equal to that of the currently-executing job \(J_{exe}\) is released at time \(t\), then \(J_{new}\) does not preempt \(J_{exe}\) and the TCB of \(J_{new}\) is inserted in the ready queue. This insertion event is called “rel_no_prmt” event.
- If the processor is idle while the ready queue is non-empty, then the TCB of the job with earliest absolute deadline (i.e., highest EDF priority) from the ready queue is removed and that job starts execution. This removal event is called “idle_remv” event.

The main contribution of this paper is to propose efficient operations (presented in next section) to manage each of the rel_prmt, rel_no_prmt and idle_remv events.

### III. EFFICIENT READY QUEUE MANAGEMENT

This section presents the data structure of the ready queue and operations to handle the events rel_prmt, rel_no_prmt and idle_remv for EDF scheduler.

We use the same data structure that is proposed in [8]: an array of \(n\) linked lists is used to store the TCBs of the ready jobs of EDF scheduler (see Figure 1). Each linked list has a head and a tail pointer that respectively points the first and last TCB in that particular linked list. The head and tail pointers of the \(k^{th}\) linked list are denoted by head\([k]\) and tail\([k]\) for \(k = 1, 2, \ldots, n\). In order to specify which linked lists are non-empty, we use a bitmap \(B[n.\ldots1]\). We set \(B[k] = 1\), whenever the \(k^{th}\) linked list is non-empty; otherwise, \(B[k] = 0\).

**Function NEXT_LIST\((k, B)\).** Given index \(k\) of some linked list of the ready queue, the index of its immediately next (i.e., higher-indexed) non-empty linked list is computed using functions NEXT_LIST\((k, B)\). For example, consider a bitmap of length \(n = 8\) such that \(B[8.\ldots1] = 11001011\) and we want to find NEXT_LIST\((k, B)\) for \(k = 5\). The next non-empty higher-indexed linked list relative to \(5^{th}\) linked-list has index NEXT_LIST\((5, 11001011) = 7\). Function NEXT_LIST\((k, B)\) will be used later and can be implemented in constant time (please see [6] for details).

![Figure 1. Data structure of EDF ready queue proposed in [8].](image-url)
other job in the ready queue. Notice that property P1 and P2 hold before TCB of \( J_{exe} \) is inserted in the ready queue and all the \((\rho - 1)\) lower-indexed (i.e., \(1^{st}, 2^{nd}, \ldots, (\rho - 1)^{th}\)) linked lists are empty. Since the EDF priority of \( J_{exe} \) is higher than or equal to any other job in the ready queue, inserting the TCB of job \( J_{exe} \) at the front of \( \rho^{th} \) linked list ensures that property P1 and P2 continue to hold at time \( t \).

Property P3 holds for the \( \rho^{th} \) linked list before job \( J_{exe} \) is inserted. This implies that the absolute deadline relative to time \( t \) of each job (if any) in the \( \rho^{th} \) linked list is not larger than \( D_\rho \). Because the EDF priority of job \( J_{exe} \) is higher than or equal to any other job in the ready queue, the absolute deadline of job \( J_{exe} \) is not larger \( D_\rho \) relative to time \( t \) regardless whether \( \rho = \ell \) or \( \rho = k \). Therefore, property P3 continues to hold after the TCB of \( J_{exe} \) is inserted in the \( \rho^{th} \) linked list. If \( B[\rho] = 0 \), we also set \( B[\rho] = 1 \) to specify that there is a TCB awaiting execution in the \( \rho^{th} \) linked list.

In summary, the TCB of the preempted job is inserted in the ready queue in constant time and properties P1–P3 hold.

**Event rel_no_prmt.** This event occurs if a newly released job \( J_{new} \) cannot preempt the currently-executing job \( J_{exe} \). In such case, the TCB of \( J_{new} \) is inserted in the ready queue. Assume without loss of generality that \( J_{new} \) is an instance of \( \tau_k \). Therefore, the deadline of \( J_{new} \) is exactly equal to \( D_k \) relative to time \( t \) since \( J_{exe} \) is released at \( t \).

Because the deadline of \( J_{new} \) is exactly \( D_k \) relative to time \( t \), the EDF priorities of the jobs in the \( k \) lower-indexed (i.e., \( 1^{st}, \ldots, k^{th} \)) linked lists are not lower than that of \( J_{new} \) follows from property P3). In order to maintain properties P1–P3, the TCB of \( J_{new} \) (which is a job of task \( \tau_k \)) can be inserted at the end of the \( k^{th} \) linked list.

However, inserting the TCB of \( J_{new} \) at the end of the \( k^{th} \) linked list is not sufficient to maintain properties P1–P3. This is because some jobs in the \((n-k)\) higher-indexed linked lists (i.e., \( \nu^{th} \) linked list where \( \nu > k \)) may have higher EDF priorities than that of the newly released job \( J_{new} \). The TCBs of such jobs having higher EDF priorities than that of \( J_{new} \) have to be removed from the \((n-k)\) higher-indexed linked lists and inserted at the end of the \( k^{th} \) linked list before the TCB of \( J_{new} \) is inserted at the end of the \( k^{th} \) linked list. To insert the TCB of \( J_{new} \) at the end of the \( k^{th} \) list, we execute the following steps (Step 1–Step 4).

**Step 1:** We find \( h = NEXT\_LIST(k, B) \), which is the position of the immediately next higher-indexed non-empty linked list of \( k^{th} \) linked list. If \( h \) is an invalid index (i.e., all the higher-indexed list are empty), then go to Step 4; otherwise (i.e., \( h^{th} \) list is non-empty), we follow next steps.

**Step 2:** If the last element of the \( h^{th} \) linked list (pointed by \( \text{tail}[h] \)) has absolute deadline smaller than that of \( J_{new} \), then all the jobs in \( h^{th} \) linked list have higher EDF priorities than that of job \( J_{new} \) due to property P2. In such case, the entire \( h^{th} \) linked list is inserted (i.e., appended) at the end of the \( k^{th} \) linked list in constant time using the \( \text{head}[h] \) and \( \text{tail}[h] \) pointers. We set \( \text{head}[h] = NULL, \text{tail}[h] = NULL \) and \( B[h] = 0 \) to specify that the \( h^{th} \) list is now empty. We repeat the process (for next higher-indexed list) by jumping to Step 1.

**Step 3:** If the last element of the \( h^{th} \) linked list has absolute deadline larger than or equal to that of \( J_{new} \), then the EDF priorities of all the jobs in the \( h^{th} \) linked list are not higher than that of job \( J_{new} \). In such case, we only remove the TCBs of those jobs from \( h^{th} \) list that have their EDF priorities higher than that of \( J_{new} \) and insert these TCBs at the end of the \( k^{th} \) list. These removal and insertion operations are done by testing one-by-one element of \( h^{th} \) list starting from the \( fi^{st} \) element, which ensures that jobs from \( h^{th} \) list are inserted at the end of the \( k^{th} \) list in non-increasing EDF priority order. As soon as a TCB of a job that has absolute deadline larger than or equal to that of \( J_{new} \) is found in \( h^{th} \) linked list, the removal and insertion process stops. At this stage there is no job with higher EDF priority than that of \( J_{new} \) in any of the \((n-k)\) higher-indexed linked lists (follows from property P1 and P2). We go to step 4.

**Step 4:** The TCB of job \( J_{new} \) is inserted at the end of the \( k^{th} \) linked list. If \( B[k] = 0 \), then we set \( B[k] = 1 \) to specify that the \( k^{th} \) linked list is now not empty.

The jobs in the higher-indexed \((k+1)^{th},(k+2)^{th},\ldots,n^{th}\) non-empty linked lists satisfy properties P1–P3 before the TCB of \( J_{new} \) is inserted. Notice that TCBs of the jobs from these higher-indexed linked lists are removed and inserted in the \( k^{th} \) linked list in non-increasing EDF priority order. Because only jobs that have higher EDF priorities than \( J_{new} \) are removed from these higher-indexed lists and inserted in the \( k^{th} \) linked list, it is guaranteed that properties P1–P3 hold after inserting \( J_{new} \) at the end of \( k^{th} \) linked list.

In contrast to the approach of this paper, the work in [7] handles the rel_no_prmt event by linearly searching each element in the higher-indexed linked list even if all the jobs in that list have higher EDF priorities than that of \( J_{new} \). Therefore, the proposed technique of this paper is more efficient. Although a linear linked-list implementation of the ready queue does not need any remapping of other TCBs but it requires linear search to find the appropriate position of the new job. The number of comparisons for such linear search is larger than the number of remapping required in the proposed approach.

**Event idle_remv.** This event occurs when the processor becomes idle and the ready-queue is not empty. In such case, the TCB of the highest EDF priority job from the ready queue is removed and that job is dispatched for execution. The TCB of the highest EDF priority job is the first element in the lowest-indexed non-empty linked list since P1 and P2 hold at time \( t \). The position of lowest-indexed non-empty linked list is found in constant time using bitmap \( B \). Let the \( \ell^{th} \) linked list is the lowest-indexed non-empty linked list.

The job from the front of the \( \ell^{th} \) linked list is removed and dispatched for execution. The removal from the front
done in constant time using head[ℓ] pointer. If head[ℓ] becomes NULL, then we set the B[ℓ] = 0. Since removal of a job from any linked list of the ready queue cannot violate P1–P3, these properties continue to hold.

### IV. Evaluation

In this section, the results demonstrating the effectiveness of the proposed ready-queue management mechanism using randomly generated task sets are presented. Task sets are randomly generated using the same approach as in [8]. At each utilization level (starting from 0.5 with a step size of 0.025), total 1000 task sets are generated. The randomly-generated task sets that are exclusively schedulable using EDF and not schedulable using FP are considered. Results for task set with utilization larger than 0.5 at which task sets are difficult to schedule using FP are presented.

For each task set, the execution is simulated using EDF scheduling. The ready jobs that need to await execution are stored in the ready queue and remapped to new position when necessary. Three alternatives for EDF ready queue are considered: (i) the approach proposed in this paper, (ii) the approach proposed for priority-promotion-based scheduling in [8], and (iii) binary min-heap based priority queue. We denote Our_avg, Prom_avg, and Heap_avg as the average number of remapping of the TCBs in the ready queue that is implemented respectively using our proposed scheme, the approach proposed in [8], and using binary min-heap.

The binary min-heap-based ready queue is considered as the baseline. The improvement at each utilization level of the proposed approach (denoted as Our_vs_Heap) and the priority-promotion-based approach proposed in [8] (denoted as Prom_vs_Heap) over the min-heap-based ready queue management approach for EDF scheduler is computed as follows:

\[
\text{Our_vs_Heap} = \frac{\text{Our}_{\text{avg}} - \text{Heap}_{\text{avg}}}{\max(\text{Our}_{\text{avg}}, \text{Heap}_{\text{avg}})} \times 100\%
\]

\[
\text{Prom_vs_Heap} = \frac{\text{Prom}_{\text{avg}} - \text{Heap}_{\text{avg}}}{\max(\text{Prom}_{\text{avg}}, \text{Heap}_{\text{avg}})} \times 100\%
\]

The results of simulation using \( n = 10, 20 \) tasks for constrained- and implicit-deadline task sets are presented in Fig. 2 (please see [6] for additional results and details of simulation setup). The x-axis is the utilization level and the y-axis represents Improvement (i.e., value of Our_vs_Heap and Prom_vs_Heap) over the base case. It is evident that both approaches perform better than the base case since most of the values are positive. The value of Our_vs_Heap is significantly larger than that of Prom_vs_Heap. The value of Our_vs_Heap is around 90% at most utilization levels, which implies that about 90% of all remapping of the TCBs in the min-heap-based ready queue can be reduced using our proposed scheme. In other words, the proposed ready-queue management approach outperforms the priority-promotion-based approach proposed in [8].

### V. Conclusion

Building upon an array of linked-lists-based ready queue data structure, this paper presents efficient management of jobs in the ready queue of EDF scheduler. It is shown that insertion and removal operations of jobs to and from our proposed ready queue is very efficient. In particular, almost 90% remapping of the TCBs required in binary min-heap-based ready queue can be eliminated using our proposed scheme. I expect that such low overhead in managing jobs in ready queue — combined with optimal schedulability power — will make EDF popular in industry.

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### REFERENCES


