Flexible Maximum Urgency First Scheduling for Distributed Real-Time Systems

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Type of Report: Other
In the rest of this report, we first describe the design of the FMUF scheduling strategy. Then, we present simulation results to demonstrate that FMUF can provide performance isolation for mission-critical tasks.

2 FMUF Scheduling

The following are some definitions for FMUF Scheduling strategy:
- Two types of tasks: mission-critical tasks and best effort tasks, categorized by its importance specified by users.
- All real-time priorities are divided into two classes: a high priority class and a low priority class. A task whose priority is in the high priority class is in the high group. The other tasks are in the low group. That is, a task in the high group always has a higher priority than any tasks in the low group. Inside each group, all tasks are ordered by their end-to-end deadline, and end-to-end Deadline Monotonic scheduling algorithm is applied to assign subpriorities.

The basic idea of FMUF is to utilize an adaptive mechanism to dynamically adjust the priority of best effort tasks (i.e., move some best effort tasks into or out of the high group) according to the current conditions at runtime. In the rest of this section, we present two approaches to implement this strategy.

2.1 End-to-end Task Model

A system has \( m \) end-to-end periodic tasks \( \{ T_i | 1 \leq i \leq m \} \) executing on \( n \) processors \( \{ P_i | 1 \leq i \leq n \} \). Task \( T_i \) is composed of a chain of subtasks \( \{ T_{ij} | 1 \leq j \leq n_i \} \) that may be allocated to multiple processors. A subtask \( T_{ij} (1 \leq j \leq n_i) \) cannot be released for execution until its predecessor \( T_{i,j-1} \) is completed. A non-greedy synchronization protocol (e.g., release guard [1]) is used to enforce the precedence constraints between subsequent subtasks. Hence, each subtask \( T_{ij} \) of a periodic task \( T_i \) is also periodic and shares the same rate as \( T_i \). Each task \( T_i \) is subject to an end-to-end relative deadline related to its period.

2.2 FMUF based on deadline miss ratio

In this approach the priorities of some best effort tasks are adjusted based on the history of deadline miss. We first introduce several notations:
- \( T_0 \): the best effort task whose priority has just been adjusted in the latest adaptation operation
- \( U_{i,k} \): the total utilization of processor \( P_i \) during the \( k^{th} \) sampling period
- \( S_i \): the set of processors that host subtasks of \( T_i \)

The Logic of FMUF

1. At the start time of the system, place all mission-critical tasks into the high group (by assigning high priority to them); and add all best effort tasks into the low group (by assigning low priority to them); set \( T_0 = \text{null} \).
2. In the end of every sampling period, monitor the total utilizations \( \{U_{i,k} | 1 \leq i \leq n \} \) of all processors and check the deadline miss of all tasks
   (a) If there is deadline miss in the high group, move a best effort task \( T_s \) from the high group to the low group (by decreasing its priority), and set \( T_0 = T_s \).
   (b) If (i) there is no deadline miss in the high group for consecutive \( N \) (\( N > 1 \)) sampling periods and (ii) there are deadline misses in the low group, choose one best effort task \( T_s \) from the low group according to some selection policies (e.g., shortest end-to-end deadline first)
      i. If \( T_s \neq T_0 \), then move \( T_s \) to the high group (by increasing its priority), and set \( T_0 = T_s \).
      ii. Else calculate \( \Delta U_i = U_{i,k-1} - U_{i,k} \) for all processors in \( S_s \); if \( \min_{P \in S_s} \Delta U_i \geq \text{threshold} \), then move \( T_s \) to the high group.

In this approach, an adaptation operation can be triggered by several reasons, such as the arrival and departure of mission-critical tasks, and significant variation of execution times. The threshold is defined to avoid oscillation of the system, i.e., one task has been moved into and out of the high group repeatedly. The value of threshold need to be tuned.

Here is one simple example to demonstrate how FMUF works. In this example, we set \( N = 5 \) and threshold = 5%. The workload includes 7 tasks: three mission-critical tasks, \( T_1 \) with end-to-end deadline \( D_1 = 400 \), \( T_2 \) with \( D_2 = 500 \), and \( T_3 \) with \( D_3 = 600 \); four best effort tasks, \( T_4 \) with \( D_4 = 350 \), \( T_5 \) with \( D_5 = 300 \), \( T_6 \) with \( D_6 = 400 \), and \( T_7 \) with \( D_7 = 550 \). There are two processors. Each task has one subtask on each processor. In the beginning of the \((k-1)\)th sampling period, there is no deadline miss for all tasks. All three mission-critical tasks are in the high group, whereas there are two best effort tasks, \( T_4 \) and \( T_5 \), in the high group. Other two best effort tasks are in the low group. During the \((k-1)\)th sampling period, execution time of \( T_1 \) increases significantly, which incurs \( T_3 \) miss deadline. An adaptation operation is triggered at the end of \((k-1)\)th sampling period. The best effort task with the longest end-to-end deadline in the high group, \( T_4 \) here, is moved to the low group. \( T_0 \) is set to \( T_4 \).

For the next 10 sampling periods, there is no deadline miss in the high group while deadline miss occurs in the low group. Adaption operation is triggered in the end of each sampling period. However, as \( T_4 \) is always equal to \( T_0 \) and the utilization deviations of two processors are both less than the threshold 5%, no task will be moved to the high group according to the algorithm. At the end of \((k+10)\)th sampling period, \( T_2 \) departs from the system. The utilization of either \( T_{21} \) or \( T_{22} \) is greater than 5%. Then after the adaption operation, \( T_4 \) will be moved back to the high group. In this example, we select the best effort task to adjust priority according to the end-to-end deadline in order to decrease the priority inversion. We can easily replace this with other selection policies.

### 2.3 FMUF based on AUB condition

In this algorithm, we try to adjust the priority of some best effort tasks based on Aperiodic Utilization Bound (AUB) for end-to-end tasks [2]. We use AUB
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to guarantee all tasks in high group meet their deadlines. The schedulability condition of Aperiodic Utilization Bound is computed by:

\[ \sum_{j=1}^{N} \frac{U_j(1 - U_j/2)}{1 - U_j} \leq 1 \]  
(1)

\( N \) is the number of processors; \( U_j \) is the estimated utilization of subtasks in high group on processor \( j \), \( U_j = \sum_{T_i \in G_j} C_{ij}/D_i \). For simplicity, in the rest of this section, we call inequation 1 AUB Condition.

Before we describe the logic of the algorithm, we first introduce two notations:

- \( B_h \): set of best effort tasks in the high group
- \( B_l \): set of best effort tasks in the low group

The Logic of FMUF

1. At the start time of the system, place all mission-critical tasks into the high group (by assigning high priority to them), and add all best effort tasks into the low group (by assigning low priority to them);

2. In the end of every sampling period, check the AUB condition
   (a) If AUB condition is satisfied: select one task \( T \) from \( B_l \) and check the new AUB condition for the high group after including \( T \); if new AUB condition is not violated, move \( T \) into the high group; select another task from \( B_l \) and repeat this test until all tasks in \( B_l \) have been tested
   (b) Else AUB condition is violated: move one task \( T' \) from \( B_h \) to the low group and check the new AUB condition for the high group after excluding \( T' \); if new AUB condition is not satisfied yet, select another task from \( B_h \) and repeat this process until the new AUB condition is satisfied or \( B_h \) is empty

3 Simulation Results

In this section, we evaluate the performance of the first approach presented in Section 2.2. The simulation runs on the EUCON simulator with a medium-sized workload that comprises of 11 end-to-end tasks. The task set includes 4 mission-critical tasks and 7 best-effort ones. Each task has 6 subtasks, which are deployed on 6 different processors (for simplicity, subtask \( i \) on processor \( i \), \( 1 \leq i \leq 6 \)). The workload parameters are shown in Table 1. ET1-ET6 are corresponding to the execution times of subtask1-subtask6. There are only 6 different execution times: 35, 40, 55, 65, 70, and 90. Criticality = 1 means miss-critical task; criticality = 0 is corresponding to best-effort task. The time unit of execution time and period is millisecond. We assume each task’s end-to-end deadline is equal to its period. In the beginning, only first 10 tasks run. Task 11 will arrive later. The control period \( T_s = 100s \). Other two parameters for FMUF are chosen like this: \( N = 5 \), threshold = 5%.
In the experiment, the system runs for 10000 seconds. We create three scenarios to evaluate the performance of FMUF: 1) at 2500 seconds, execution times of all subtasks are decreased by 10%; 2) at 5000 seconds, task 11 arrives; 3) at 7500 seconds, execution times of all subtasks are increased by 10%. In order to evaluate the performance of FMUF, we compare it with two baselines: MUF and DMS. We plot the results in Figure 1. The FMUF control operation is trig-
Table 1. workload parameters(ms)

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<th>ET3</th>
<th>ET4</th>
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</table>

gerated four times: in the initial stage, three best-effort tasks are moved into high group; after scenario 1, two more best-effort tasks are moved into high group; after scenario 2, two best-effort tasks are move back to low group; after scenario 3, another two best-effort tasks are degraded into low group. The results shows that FMUF can provide performance isolation for mission-critical tasks.

References