Embedded Systems

6. Aperiodic and Periodic Scheduling

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Computer Engineering and Networks Laboratory
Where we are ...

1. Introduction to Embedded Systems
2. Software Development
3. Hardware-Software Interface
4. Programming Paradigms
5. Embedded Operating Systems
6. Real-time Scheduling
7. Shared Resources
8. Hardware Components
9. Power and Energy
10. Architecture Synthesis

Software

Hardware

Hardware-Software
Basic Terms and Models
Basic Terms

Real-time systems

- **Hard**: A real-time task is said to be hard, if missing its deadline may cause catastrophic consequences on the environment under control. Examples are sensory data acquisition, detection of critical conditions, actuator servoing.

- **Soft**: A real-time task is called soft, if meeting its deadline is desirable for performance reasons, but missing its deadline does not cause serious damage to the environment and does not jeopardize correct system behavior. Examples are command interpreter of the user interface, displaying messages on the screen.
**Schedule**

Given a *set of tasks* $J = \{J_1, J_2, \ldots\}$:

- A *schedule* is an assignment of tasks to the processor, such that each task is executed until completion.
- A schedule can be defined as an *integer step function* $\sigma : \mathbb{R} \to \mathbb{N}$ where $\sigma(t)$ denotes the task which is executed at time $t$. If $\sigma(t) = 0$ then the processor is called idle.
- If $\sigma(t)$ changes its value at some time, then the processor performs a *context switch*.
- Each interval, in which $\sigma(t)$ is constant is called a *time slice*.
- A *preemptive schedule* is a schedule in which the running task can be arbitrarily suspended at any time, to assign the CPU to another task according to a predefined scheduling policy.
Schedule and Timing

- A schedule is said to be **feasible**, if all task can be completed according to a set of specified constraints.

- A set of tasks is said to be **schedulable**, if there exists at least one algorithm that can produce a feasible schedule.

- **Arrival time** \( a_i \) or **release time** \( r_i \) is the time at which a task becomes ready for execution.

- **Computation time** \( C_i \) is the time necessary to the processor for executing the task without interruption.

- **Deadline** \( d_i \) is the time at which a task should be completed.

- **Start time** \( s_i \) is the time at which a task starts its execution.

- **Finishing time** \( f_i \) is the time at which a task finishes its execution.
Schedule and Timing

- Using the above definitions, we have $d_i \geq r_i + C_i$
- **Lateness** $L_i = f_i - d_i$ represents the delay of a task completion with respect to its deadline; note that if a task completes before the deadline, its lateness is negative.
- **Tardiness or exceeding time** $E_i = \max(0, L_i)$ is the time a task stays active after its deadline.
- **Laxity or slack time** $X_i = d_i - a_i - C_i$ is the maximum time a task can be delayed on its activation to complete within its deadline.
Schedule and Timing

- **Periodic task** $\tau_i$: infinite sequence of identical activities, called *instances or jobs*, that are regularly activated at a constant rate with *period* $T_i$. The activation time of the first instance is called *phase* $\Phi_i$.

![Diagram showing schedule and timing for periodic tasks and jobs.](image)

- Relative deadline
- First instance
- Period $T_i$
- Initial phase $\phi_i$
- Deadline of period $k$ $\phi_i + (k-1)T_i$
- Arrival time of instance $k$ $a_{i1} \rightarrow d_{i1}$
- Instance 1
- Instance 2
- Deadline $D_i$
Example for Real-Time Model

Computation times: $C_1 = 9, C_2 = 12$
Start times: $s_1 = 0, s_2 = 6$
Finishing times: $f_1 = 18, f_2 = 28$
Lateness: $L_1 = -4, L_2 = 1$
Tardiness: $E_1 = 0, E_2 = 1$
Laxity: $X_1 = 13, X_2 = 11$
Precedence Constraints

- *Precedence relations* between tasks can be described through an *acyclic directed graph* $G$ where tasks are represented by nodes and precedence relations by arrows. $G$ induces a partial order on the task set.

- There are different *interpretations* possible:
  - All successors of a task are activated (*concurrent task execution*). We will use this interpretation in the lecture.
  - One successor of a task is activated: *non-deterministic choice.*
Precedence Constraints

Example for concurrent activation:

- Image acquisition  \( \text{acq1} \)  \( \text{acq2} \)
- Low level image processing  \( \text{edge1} \)  \( \text{edge2} \)
- Feature/contour extraction  \( \text{shape} \)
- Pixel disparities  \( \text{disp} \)
- Object size  \( H \)
- Object recognition  \( \text{rec} \)
Classification of Scheduling Algorithms

- With **preemptive algorithms**, the running task can be interrupted at any time to assign the processor to another active task, according to a predefined scheduling policy.

- With a **non-preemptive algorithm**, a task, once started, is executed by the processor until completion.

- **Static algorithms** are those in which scheduling decisions are based on fixed parameters, assigned to tasks before their activation.

- **Dynamic algorithms** are those in which scheduling decisions are based on dynamic parameters that may change during system execution.
Classification of Scheduling Algorithms

- An algorithm is said *optimal* if it minimizes some given cost function defined over the task set.
- An algorithm is said to be *heuristic* if it tends toward but does not guarantee to find the optimal schedule.
- **Acceptance Test:** The runtime system decides whenever a task is added to the system, whether it can schedule the whole task set without deadline violations.

Example for the "domino effect", if an acceptance test wrongly accepted a new task.
Metrics to Compare Schedules

- Average response time:
  \[ t_r = \frac{1}{n} \sum_{i=1}^{n} (f_i - r_i) \]

- Total completion time:
  \[ t_c = \max_i (f_i) - \min_i (r_i) \]

- Weighted sum of response time:
  \[ t_w = \frac{\sum_{i=1}^{n} w_i (f_i - r_i)}{\sum_{i=1}^{n} w_i} \]

- Maximum lateness:
  \[ L_{\text{max}} = \max_i (f_i - d_i) \]

- Number of late tasks:
  \[ N_{\text{late}} = \sum_{i=1}^{n} \text{miss}(f_i) \]
  \[ \text{miss}(f_i) = \begin{cases} 0 & \text{if } f_i \leq d_i \\ 1 & \text{otherwise} \end{cases} \]
### Metrics Example

**Average response time:**
\[
\overline{t_r} = \frac{1}{2} (18 + 24) = 21
\]

**Total completion time:**
\[
t_c = 28 - 0 = 28
\]

**Weighted sum of response times:**
\[
\begin{align*}
    w_1 &= 2, \quad w_2 = 1: \\
    t_w &= \frac{2 \cdot 18 + 24}{3} = 20
\end{align*}
\]

**Number of late tasks:**
\[
N_{\text{late}} = 1
\]

**Maximum lateness:**
\[
L_{\text{max}} = 1
\]
Metrics and Scheduling Example

In schedule (a), the *maximum lateness is minimized*, but all tasks miss their deadlines. In schedule (b), the maximal lateness is larger, but only one *task misses* its deadline.
Real-Time Scheduling of Aperiodic Tasks
Overview Aperiodic Task Scheduling

Scheduling of *aperiodic tasks* with real-time constraints:

- Table with some known algorithms:

<table>
<thead>
<tr>
<th>Independent tasks</th>
<th>Equal arrival times non preemptive</th>
<th>Arbitrary arrival times preemptive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EDD (Jackson)</td>
<td>EDF (Horn)</td>
</tr>
<tr>
<td>Dependent tasks</td>
<td>LDF (Lawler)</td>
<td>EDF* (Chetto)</td>
</tr>
</tbody>
</table>
Earliest Deadline Due (EDD)

Jackson’s rule: Given a set of $n$ tasks. Processing in order of non-decreasing deadlines is optimal with respect to minimizing the maximum lateness.
Earliest Deadline Due (EDD)

Example 1:

<table>
<thead>
<tr>
<th></th>
<th>J_1</th>
<th>J_2</th>
<th>J_3</th>
<th>J_4</th>
<th>J_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_i</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>d_i</td>
<td>3</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

L_{max} = L_4 = -1
Earliest Deadline Due (EDD)

**Jackson’s rule:** Given a set of $n$ tasks. Processing in order of non-decreasing deadlines is optimal with respect to minimizing the maximum lateness.

**Proof concept:**

\[
\begin{align*}
\sigma & \quad J_b \quad J_a \\
\sigma' & \quad J_a \quad J_b
\end{align*}
\]

\[
L_{\text{max}}^{ab} = f_a - d_a \quad \quad \quad L_{\text{max}}^{\prime ab} = \max (L_{\prime a}^{\prime}, L_{\prime b}^{\prime})
\]

if $(L_{\prime a}^{\prime} \geq L_{\prime b}^{\prime})$ then \(L_{\text{max}}^{\prime ab} = f_a - d_a < f_a - d_a\)

if $(L_{\prime a}^{\prime} \leq L_{\prime b}^{\prime})$ then \(L_{\text{max}}^{\prime ab} = f_b - d_b < f_a - d_a\)

in both cases: \(L_{\text{max}}^{\prime ab} < L_{\text{max}}^{ab}\)
Earliest Deadline Due (EDD)

Example 2:

<table>
<thead>
<tr>
<th>Ci</th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>di</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

$L_{\text{max}} = L_4 = 2$
Earliest Deadline First (EDF)

**Horn’s rule:** Given a set of \( n \) independent tasks with arbitrary arrival times, any algorithm that at any instant executes a task with the earliest absolute deadline among the ready tasks is optimal with respect to minimizing the maximum lateness.
Earliest Deadline First (EDF)

Example:

<table>
<thead>
<tr>
<th></th>
<th>J₁</th>
<th>J₂</th>
<th>J₃</th>
<th>J₄</th>
<th>J₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>aᵢ</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Cᵢ</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>dᵢ</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>
Earliest Deadline First (EDF)

**Horn’s rule:** Given a set of n independent tasks with arbitrary arrival times, any algorithm that at any instant executes the task with the earliest absolute deadline among the ready tasks is optimal with respect to minimizing the maximum lateness.

**Concept of proof:**
For each time interval \([t, t + 1)\) it is verified, whether the actual running task is the one with the earliest absolute deadline. If this is not the case, the task with the earliest absolute deadline is executed in this interval instead. This operation cannot increase the maximum lateness.
Earliest Deadline First (EDF)

which task is executing?

which task has earliest deadline?

time slice

slice for interchange

situation after interchange
Earliest Deadline First (EDF)

**Acceptance test:**
- worst case finishing time of task i:
- EDF guarantee condition:
- algorithm:

\[
f_i = t + \sum_{k=1}^{i} c_k(t)\]

\[
\forall i = 1, ..., n \ t + \sum_{k=1}^{i} c_k(t) \leq d_i
\]

---

Algorithm: EDF\_guarantee (J, J\_new)

\[
\begin{align*}
J' &= J \cup \{J_{\text{new}}\}; \quad /* \text{ordered by deadline} */ \\
t &= \text{current\_time}(); \\
f_0 &= t; \\
\text{for (each } J_i \in J') \{ \text{ for (each } J_i \in J') \{ \\
\quad f_i &= f_{i-1} + c_i(t); \\
\quad \text{if (} f_i > d_i) \text{ return(INFEASIBLE);} \\
\} \\
\} \\
\text{return(FEASIBLE);} \\
\end{align*}
\]
Earliest Deadline First (EDF*)

- The problem of *scheduling a set of n tasks with precedence constraints* (concurrent activation) can be solved in polynomial time complexity if tasks are preemptable.

- The *EDF* algorithm determines a *feasible schedule* in the case of tasks with precedence constraints if there exists one.

- By the modification it is guaranteed that if *there exists a valid schedule* at all then
  - a task starts execution not earlier than its release time and not earlier than the finishing times of its predecessors (a task cannot preempt any predecessor)
  - all tasks finish their execution within their deadlines
Earliest Deadline First (EDF*)

Modification of deadlines:

- Task must finish the execution time within its deadline.
- Task must not finish the execution later than the maximum start time of its successor.

Solution:

\[
d_i^* = \min(d_i, \min(d_j^* - C_j : J_i \rightarrow J_j))
\]
Early Deadline First (EDF*)

Modification of release times:
- Task must start the execution not earlier than its release time.
- Task must not start the execution earlier than the minimum finishing time of its predecessor.

Solution: 
\[ r_j^* = \max\{r_j, \max(r_i^* + C_i : J_i \rightarrow J_j)\} \]
Earliest Deadline First (EDF*)

Algorithm for modification of release times:
1. For any initial node of the precedence graph set \( r_i^* = r_i \)
2. Select a task \( j \) such that its release time has not been modified but the release times of all immediate predecessors \( i \) have been modified. If no such task exists, exit.
3. Set \( r_j^* = \max(r_j, \max(r_i^* + C_i : J_i \rightarrow J_j)) \)
4. Return to step 2

Algorithm for modification of deadlines:
1. For any terminal node of the precedence graph set \( d_i^* = d_i \)
2. Select a task \( i \) such that its deadline has not been modified but the deadlines of all immediate successors \( j \) have been modified. If no such task exists, exit.
3. Set \( d_i^* = \min(d_i, \min(d_j^* - C_j : J_i \rightarrow J_j)) \)
4. Return to step 2
### Earliest Deadline First (EDF*)

**Proof concept:**

- Show that if there exists a feasible schedule for the modified task set under EDF then the original task set is also schedulable (ignoring precedence relations). To this end, show that the original task set meets the timing constraints also. This can be done by using \( d_i^* \leq d_i \), \( r_i^* \geq r_i \).
- Show the reverse also.
- In addition, show that the precedence relations in the original task set are not violated. In particular, show that
  - a task cannot start before its predecessor and
  - a task cannot preempt its predecessor.
Real-Time Scheduling of Periodic Tasks
### Overview

Table of some known *preemptive scheduling algorithms for periodic tasks*:

<table>
<thead>
<tr>
<th></th>
<th>Deadline equals period</th>
<th>Deadline smaller than period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>static priority</strong></td>
<td>RM (rate-monotonic)</td>
<td>DM (deadline-monotonic)</td>
</tr>
<tr>
<td><strong>dynamic priority</strong></td>
<td>EDF</td>
<td>EDF*</td>
</tr>
</tbody>
</table>
Model of Periodic Tasks

- **Examples:** sensory data acquisition, low-level servoing, control loops, action planning and system monitoring.

- When an *application* consists of several concurrent periodic tasks with individual timing constraints, the OS has to guarantee that each periodic instance is regularly activated at its proper rate and is completed within its deadline.

- **Definitions:**
  
  \[ \Gamma \] : denotes a set of periodic tasks  
  \[ \tau_i \] : denotes a periodic task  
  \[ \tau_{i,j} \] : denotes the \( j \)th instance of task \( i \)  
  \[ r_{i,j}, s_{i,j}, f_{i,j}, d_{i,j} \] : denote the release time, start time, finishing time, absolute deadline of the \( j \)th instance of task \( i \)  
  \[ \Phi_i \] : denotes the phase of task \( i \) (release time of its first instance)  
  \[ D_i \] : denotes the relative deadline of task \( i \)  
  \[ T_i \] : denotes the period of task \( i \)
Model of Periodic Tasks

The following hypotheses are assumed on the tasks:

- The instances of a periodic task are regularly activated at a constant rate. The interval \( T_i \) between two consecutive activations is called period. The release times satisfy
  \[
  r_{i,j} = \Phi_i + (j - 1)T_i
  \]

- All instances have the same worst case execution time \( C_i \)

- All instances of a periodic task have the same relative deadline \( D_i \). Therefore, the absolute deadlines satisfy
  \[
  d_{i,j} = \Phi_i + (j - 1)T_i + D_i
  \]

- Often, the relative deadline equals the period \( D_i = T_i \) (implicit deadline), and therefore
  \[
  d_{i,j} = \Phi_i + jT_i
  \]
The following hypotheses are assumed on the tasks (continued):

- All periodic tasks are independent; that is, there are no precedence relations and no resource constraints.
- No task can suspend itself, for example on I/O operations.
- All tasks are released as soon as they arrive.
- All overheads in the OS kernel are assumed to be zero.

Example:
Rate Monotonic Scheduling (RM)

- **Assumptions:**
  - Task priorities are assigned to tasks before execution and do not change over time (static priority assignment).
  - RM is intrinsically preemptive: the currently executing job is preempted by a job of a task with higher priority.
  - Deadlines equal the periods \( D_i = T_i \).

Rate-Monotonic Scheduling Algorithm: Each task is assigned a priority. Tasks with higher request rates (that is with shorter periods) will have higher priorities. Jobs of tasks with higher priority interrupt jobs of tasks with lower priority.
Periodic Tasks

**Example:** 2 tasks, deadlines = periods, utilization = 97%
Rate Monotonic Scheduling (RM)

**Optimality:** RM is optimal among all fixed-priority assignments in the sense that no other fixed-priority algorithm can schedule a task set that cannot be scheduled by RM.

- The *proof* is done by considering several cases that may occur, but the main ideas are as follows:
  - A *critical instant* for any task occurs whenever the task is released simultaneously with all higher priority tasks. The tasks schedulability can easily be checked at their critical instants. If all tasks are feasible at their critical instant, then the task set is schedulable in any other condition.
  - Show that, given two periodic tasks, if the schedule is feasible by an arbitrary priority assignment, then it is also feasible by RM.
  - Extend the result to a set of \( n \) periodic tasks.
**Proof of Critical Instance**

*Definition:* A critical instant of a task is the time at which the release of a job will produce the largest response time.

*Lemma:* For any task, the critical instant occurs if a job is simultaneously released with all higher priority jobs.

*Proof sketch:* Start with 2 tasks \( \tau_1 \) and \( \tau_2 \).

Response time of a job of \( \tau_2 \) is delayed by jobs of \( \tau_1 \) of higher priority:

\[
\text{Response time of } \tau_2 \text{ is delayed by jobs of } \tau_1 \text{ of higher priority:}
\]

![Diagram showing the response time of \( \tau_2 \) delayed by \( \tau_1 \) jobs]
Proof of Critical Instance

Delay may increase if $\tau_1$ starts earlier:

Maximum delay achieved if $\tau_2$ and $\tau_1$ start simultaneously.

Repeating the argument for all higher priority tasks of some task $\tau_2$: The worst case response time of a job occurs when it is released simultaneously with all higher-priority jobs.
Proof of RM Optimality (2 Tasks)

We have two tasks $\tau_1, \tau_2$ with periods $T_1 < T_2$.

Define $F = \left\lfloor \frac{T_2}{T_1} \right\rfloor$: the number of periods of $\tau_1$ fully contained in $T_2$.

Consider two cases A and B:

**Case A:** Assume RM is not used $\Rightarrow$ prio($\tau_2$) is highest:

Schedule is feasible if $C_1 + C_2 \leq T_1$ and $C_2 \leq T_2$ \hspace{1cm} (A)
Proof of RM Optimality (2 Tasks)

Case B: Assume RM is used \( \rightarrow \) prio\((\tau_1)\) is highest:

Schedulable is feasible if

\[
FC_1 + C_2 + \min(T_2 - FT_1, C_1) \leq T_2 \text{ and } C_1 \leq T_1
\]  

We need to show that (A) \( \Rightarrow \) (B):

\[
C_1 + C_2 \leq T_1 \Rightarrow C_1 \leq T_1
\]

\[
C_1 + C_2 \leq T_1 \Rightarrow FC_1 + C_2 \leq FC_1 + FC_2 \leq FT_1 \Rightarrow
\]

\[
FC_1 + C_2 + \min(T_2 - FT_1, C_1) \leq FT_1 + \min(T_2 - FT_1, C_1) \leq \min(T_2, C_1 + FT_1) \leq T_2
\]

Given tasks \( \tau_1 \) and \( \tau_2 \) with \( T_1 < T_2 \), then if the schedule is feasible by an arbitrary fixed priority assignment, it is also feasible by RM.
Rate Monotonic Scheduling (RM)

*Schedulability analysis:* A set of periodic tasks is schedulable with RM if

\[ \sum_{i=1}^{n} \frac{C_i}{T_i} \leq n \left( \frac{2}{n} - 1 \right) \]

This condition is sufficient but not necessary.

The term \( U = \sum_{i=1}^{n} \frac{C_i}{T_i} \) denotes the *processor utilization factor* \( U \) which is the fraction of processor time spent in the execution of the task set.
Proof of Utilization Bound (2 Tasks)

We have two tasks $\tau_1$, $\tau_2$ with periods $T_1 < T_2$. Define $F = \left\lfloor \frac{T_2}{T_1} \right\rfloor$: number of periods of $\tau_1$ fully contained in $T_2$.

**Proof Concept:** Compute upper bound on utilization $U$ such that the task set is still schedulable:

- assign priorities according to RM;
- compute upper bound $U_{up}$ by increasing the computation time $C_2$ to just meet the deadline of $\tau_2$; we will determine this limit of $C_2$ using the results of the RM optimality proof.
- minimize upper bound with respect to other task parameters in order to find the utilization below which the system is definitely schedulable.
Proof of Utilization Bound (2 Tasks)

As before:

\[ \tau_1 \quad \tau_2 \]

\[ C_1 \quad C_2 \quad T_2 - FT_1 \]

Schedulable if \( FC_1 + C_2 + \min(T_2 - FT_1, C_1) \leq T_2 \) and \( C_1 \leq T_1 \)

**Utilization:**

\[
U = \frac{C_1}{T_1} + \frac{C_2}{T_2} = \frac{C_1}{T_1} + \frac{T_2 - FC_1 - \min\{T_2 - FT_1, C_1\}}{T_2}
\]

\[
= 1 + \frac{C_1(T_2 - FT_1) - T_1 \min\{T_2 - FT_1, C_1\}}{T_1 T_2}
\]
Proof of Utilization Bound (2 Tasks)

Minimize utilization bound w.r.t $C_1$:

- If $C_1 \leq T_2 - FT_1$ then $U$ decreases with increasing $C_1$
- If $T_2 - FT_1 \leq C_1$ then $U$ decreases with decreasing $C_1$
- Therefore, minimum $U$ is obtained with $C_1 = T_2 - FT_1$:

\[
U = 1 + \frac{(T_2 - FT_1)^2 - T_1(T_2 - FT_1)}{T_1T_2}
\]

\[
= 1 + \frac{T_1}{T_2} \left( \left( \frac{T_2}{T_1} - F \right)^2 - \left( \frac{T_2}{T_1} - F \right) \right)
\]

We now need to minimize w.r.t. $G = T_2 / T_1$ where $F = \lfloor T_2 / T_1 \rfloor$ and $T_1 < T_2$. As $F$ is integer, we first suppose that it is independent of $G = T_2 / T_1$. Then we obtain

\[
U = \frac{T_1}{T_2} \left( \left( \frac{T_2}{T_1} - F \right)^2 + F \right) = \frac{(G-F)^2 + F}{G}
\]
Proof of Utilization Bound (2 Tasks)

Minimizing $U$ with respect to $G$ yields

$$2G(G - F) - (G - F)^2 - F = G^2 - (F^2 + F) = 0$$

If we set $F = 1$, then we obtain

$$G = \frac{T_2}{T_1} = \sqrt{2} \quad U = 2(\sqrt{2} - 1)$$

It can easily be checked, that all other integer values for $F$ lead to a larger upper bound on the utilization.
Deadline Monotonic Scheduling (DM)

- Assumptions are as in rate monotonic scheduling, but *deadlines may be smaller than the period*, i.e.

\[ C_i \leq D_i \leq T_i \]

**Algorithm:** Each task is assigned a priority. Tasks with smaller relative deadlines will have higher priorities. Jobs with higher priority interrupt jobs with lower priority.

**Schedulability Analysis:** A set of periodic tasks is schedulable with DM if

\[ \sum_{i=1}^{n} \frac{C_i}{D_i} \leq n \left(2^{1/n} - 1\right) \]

This condition is sufficient but not necessary (in general).
Deadline Monotonic Scheduling (DM) - Example

\[ U = 0.874 \]
\[ \sum_{i=1}^{n} \frac{C_i}{D_i} = 1.08 > n \left(2^{1/n} - 1\right) = 0.757 \]
Deadline Monotonic Scheduling (DM)

There is also a necessary and sufficient schedulability test which is computationally more involved. It is based on the following observations:

- The worst-case processor demand occurs when all tasks are released simultaneously; that is, at their critical instances.
- For each task $i$, the sum of its processing time and the interference imposed by higher priority tasks must be less than or equal to $D_i$.
- A measure of the worst case interference for task $i$ can be computed as the sum of the processing times of all higher priority tasks released before some time $t$ where tasks are ordered according to $m < n \Leftrightarrow D_m < D_n$:

$$I_i = \sum_{j=1}^{i-1} \left\lfloor \frac{t}{T_j} \right\rfloor C_j$$
Deadline Monotonic Scheduling (DM)

- The **longest response time** $R_i$ of a job of a periodic task $i$ is computed, at the critical instant, as the sum of its computation time and the interference due to preemption by higher priority tasks:

$$R_i = C_i + I_i$$

- Hence, the schedulability test needs to compute the smallest $R_i$ that satisfies

$$R_i = C_i + \sum_{j=1}^{i-1} \left[ \frac{R_i}{T_j} \right] C_j$$

for all tasks $i$. Then, $R_i \leq D_i$ must hold for all tasks $i$.

- It can be shown that this condition is necessary and sufficient.
Deadline Monotonic Scheduling (DM)

The longest response times $R_i$ of the periodic tasks $i$ can be computed iteratively by the following algorithm:

```
Algorithm: DM_guarantee ($\Gamma$)
{
    for (each $\tau_i \in \Gamma$){
        I = 0;
        do {
            R = I + C_i;
            if (R > D_i) return(UNSCHEDULABLE);
            I = \sum_{j=1,...,(i-1)} \left\lceil R/T_j \right\rceil C_j;
        } while (I + C_i > R);
    }
    return(SCHEDULABLE);
}
```
Example:

- Task 1: $C_1 = 1; T_1 = 4; D_1 = 3$
- Task 2: $C_2 = 1; T_2 = 5; D_2 = 4$
- Task 3: $C_3 = 2; T_3 = 6; D_3 = 5$
- Task 4: $C_4 = 1; T_4 = 11; D_4 = 10$

Algorithm for the schedulability test for task 4:

- Step 0: $R_4 = 1$
- Step 1: $R_4 = 5$
- Step 2: $R_4 = 6$
- Step 3: $R_4 = 7$
- Step 4: $R_4 = 9$
- Step 5: $R_4 = 10$
DM Example

\[ U = 0.874 \]

\[ \sum_{i=1}^{n} \frac{C_i}{D_i} = 1.08 > n \left( 2^{1/n} - 1 \right) = 0.757 \]
EDF Scheduling (earliest deadline first)

- **Assumptions:**
  - dynamic priority assignment
  - intrinsically preemptive

- **Algorithm:** The currently executing task is preempted whenever another periodic instance with earlier deadline becomes active.

  \[ d_{i,j} = \Phi_i + (j - 1)T_i + D_i \]

- **Optimality:** No other algorithm can schedule a set of periodic tasks if the set that can not be scheduled by EDF.
- The proof is simple and follows that of the aperiodic case.
Periodic Tasks

*Example:* 2 tasks, deadlines = periods, utilization = 97%
A necessary and sufficient schedulability test for $D_i = T_i$:

A set of periodic tasks is schedulable with EDF if and only if

$$\sum_{i=1}^{n} \frac{C_i}{T_i} = U \leq 1$$

The term $U = \sum_{i=1}^{n} \frac{C_i}{T_i}$ denotes the **average processor utilization**.
EDF Scheduling

- If the utilization satisfies $U > 1$, then there is no valid schedule: The total demand of computation time in interval $T = T_1 \cdot T_2 \cdot \ldots \cdot T_n$ is
  \[ \sum_{i=1}^{n} \frac{C_i}{T_i} T = UT > T \]
  and therefore, it exceeds the available processor time in this interval.

- If the utilization satisfies $U \leq 1$, then there is a valid schedule.

  We will proof this fact by contradiction: Assume that deadline is missed at some time $t_2$. Then we will show that the utilization was larger than 1.
EDF Scheduling

- If the deadline was missed at $t_2$ then define $t_1$ as a time before $t_2$ such that (a) the processor is continuously busy in $[t_1, t_2]$ and (b) the processor only executes tasks that have their arrival time AND their deadline in $[t_1, t_2]$.

- Why does such a time $t_1$ exist? We find such a $t_1$ by starting at $t_2$ and going backwards in time, always ensuring that the processor only executed tasks that have their deadline before or at $t_2$:
  - Because of EDF, the processor will be busy shortly before $t_2$ and it executes on the task that has deadline at $t_2$.
  - Suppose that we reach a time when the processor gets idle, then we found $t_1$: There is a task arrival at $t_1$ and the task queue is empty shortly before.
  - Suppose that we reach a time such that shortly before the processor works on a task with deadline after $t_2$, then we also found $t_1$: Because of EDF, all tasks the processor processed in $[t_1, t_2]$ arrived at or after $t_1$ (otherwise, the processor would not have operated before $t_1$ on a task with deadline after $t_2$).
EDF Scheduling

- Within the interval $[t_1, t_2]$ the total *computation time demanded* by the periodic tasks is bounded by

$$C_p(t_1, t_2) = \sum_{i=1}^{n} \left\lfloor \frac{t_2 - t_1}{T_i} \right\rfloor C_i \leq \sum_{i=1}^{n} \frac{t_2 - t_1}{T_i} C_i = (t_2 - t_1)U$$

number of complete periods of task $i$ in the interval

- Since the deadline at time $t_2$ is missed, we must have:

$$t_2 - t_1 < C_p(t_1, t_2) \leq (t_2 - t_1)U \Rightarrow U > 1$$
Periodic Task Scheduling

**Example:** 2 tasks, deadlines = periods, utilization = 97%
Real-Time Scheduling of Mixed Task Sets
Problem of Mixed Task Sets

In many applications, there are aperiodic as well as periodic tasks.

- **Periodic tasks: time-driven**, execute critical control activities with hard timing constraints aimed at guaranteeing regular activation rates.
- **Aperiodic tasks: event-driven**, may have hard, soft, non-real-time requirements depending on the specific application.
- **Sporadic tasks**: Offline guarantee of event-driven aperiodic tasks with critical timing constraints can be done only by making proper assumptions on the environment; that is by assuming a **maximum arrival rate** for each critical event. Aperiodic tasks characterized by a minimum interarrival time are called sporadic.
Background Scheduling

*Background scheduling* is a simple solution for RM and EDF:

- Processing of aperiodic tasks in the background, i.e. execute if there are no pending periodic requests.
- Periodic tasks are not affected.
- Response of aperiodic tasks may be prohibitively long and there is no possibility to assign a higher priority to them.
- Example:

![Diagram of scheduling](image-url)
Background Scheduling

*Example* (rate monotonic periodic schedule):

\[ \tau_1 \]

\[ \tau_2 \]

aperiodic requests

0 2 4 6 8 10 12 14 16 18 20 22 24

1 2
Rate-Monotonic Polling Server

- **Idea:** Introduce an artificial periodic task whose purpose is to service aperiodic requests as soon as possible (therefore, “server”).

- **Function of polling server (PS)**
  - At regular intervals equal to $T_s$, a PS task is instantiated. When it has the highest current priority, it serves any pending aperiodic requests within the limit of its capacity $C_s$.
  - If no aperiodic requests are pending, PS suspends itself until the beginning of the next period and the time originally allocated for aperiodic service is not preserved for aperiodic execution.
  - Its priority (period!) can be chosen to match the response time requirement for the aperiodic tasks.

- **Disadvantage:** If an aperiodic requests arrives just after the server has suspended, it must wait until the beginning of the next polling period.
Rate-Monotonic Polling Server

**Example:**

<table>
<thead>
<tr>
<th>(\tau_1)</th>
<th>(C_i)</th>
<th>(T_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_2)</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

Server

\[C_s = 2\]
\[T_s = 5\]

The server has the current highest priority and checks the queue of tasks. A remaining budget is lost.

The diagram illustrates the scheduling of tasks over time, with shaded bars indicating the allocation of resources.
Rate-Monotonic Polling Server

*schedulability analysis* of periodic tasks:

- The interference by a server task is the same as the one introduced by an equivalent periodic task in rate-monotonic fixed-priority scheduling.
- A set of periodic tasks and a server task can be executed within their deadlines if

\[
\frac{C_s}{T_s} + \sum_{i=1}^{n} \frac{C_i}{T_i} \leq (n+1)\left(2^{1/(n+1)} - 1\right)
\]

- Again, this test is sufficient but not necessary.
Rate-Monotonic Polling Server

**Guarantee the response time of aperiodic requests:**

- **Assumption:** An aperiodic task is finished before a new aperiodic request arrives.
  - Computation time $C_a$, deadline $D_a$
  - Sufficient schedulability test:
    
    $$(1 + \left\lfloor \frac{C_a}{C_s} \right\rfloor) T_s \leq D_a$$

  The aperiodic task arrives shortly after the activation of the server task.

  Maximal number of necessary server periods.

  If the server task has the highest priority there is a necessary test also.
EDF – Total Bandwidth Server

**Total Bandwidth Server:**

- When the kth aperiodic request arrives at time $t = r_k$, it receives a deadline

$$d_k = \max(r_k, d_{k-1}) + \frac{C_k}{U_s}$$

where $C_k$ is the execution time of the request and $U_s$ is the server utilization factor (that is, its bandwidth). By definition, $d_0=0$.

- Once a deadline is assigned, the request is inserted into the ready queue of the system as any other periodic instance.
EDF – Total Bandwidth Server

Example:

$$U_p = 0.75, \ U_s = 0.25, \ U_p + U_s = 1$$
EDF – Total Bandwidth Server

**Schedulability test:**

Given a set of $n$ periodic tasks with processor utilization $U_p$ and a total bandwidth server with utilization $U_s$, the whole set is schedulable by EDF if and only if

$$U_p + U_s \leq 1$$

**Proof:**

- In each interval of time $[t_1, t_2]$, if $C_{ape}$ is the total execution time demanded by aperiodic requests arrived at $t_1$ or later and served with deadlines less or equal to $t_2$, then

$$C_{ape} \leq (t_2 - t_1)U_s$$
If this has been proven, the proof of the schedulability test follows closely that of the periodic case.

**Proof of lemma:**

\[
C_{ape} = \sum_{k=k_1}^{k_2} C_k \\
= U_s \sum_{k=k_1}^{k_2} (d_k - \max(r_k, d_{k-1})) \\
\leq U_s \left( d_{k_2} - \max(r_{k_1}, d_{k_1-1}) \right) \\
\leq U_s (t_2 - t_1)
\]