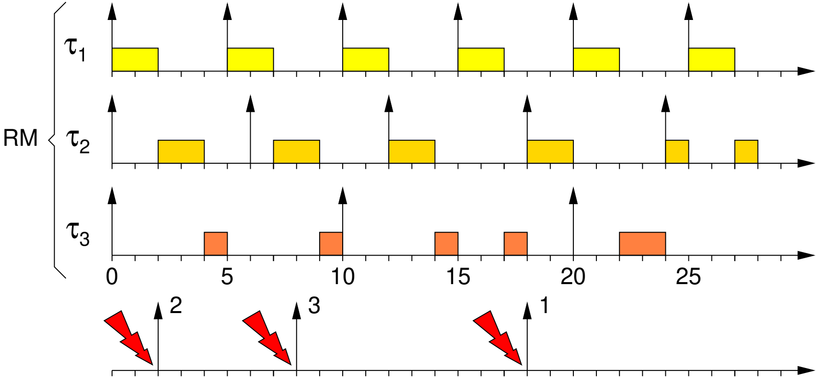
# Real-Time Scheduling
# Aperiodic tasks

Tullio Facchinetti
<tullio.facchinetti@unipv.it>

6 dicembre 2023

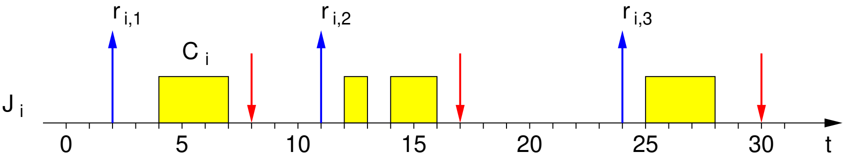
http://robot.unipv.it/toolleeo

# Aperiodic tasks: task model




- when aperiodic requests need to be scheduled
- guarantees on periodic tasks

# Aperiodic tasks



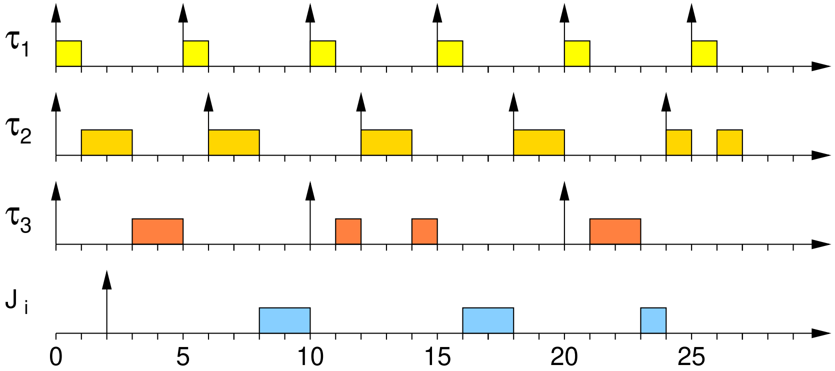

aperiodic tasks

$$r_{i,k+1} > r_{i,k}$$

sporadic tasks

$$r_{i,k+1} \geq r_{i,k} + T_i$$

## Background scheduling




- aperiodic tasks are scheduled when the processor is idle
- simple and easy-to-implement technique

# Dedicated methods

different methods have been proposed, distinguishing between **static** and **dynamic** priority assignment

considered algorithms:

## Static priorities

- Polling Server
- Sporadic Server

## Dynamic priorities

- Total Bandwidth Server
- Constant Bandwidth Server

# Polling Server

scheduling of soft aperiodic tasks concurrently with hard periodic tasks

**assumptions:**

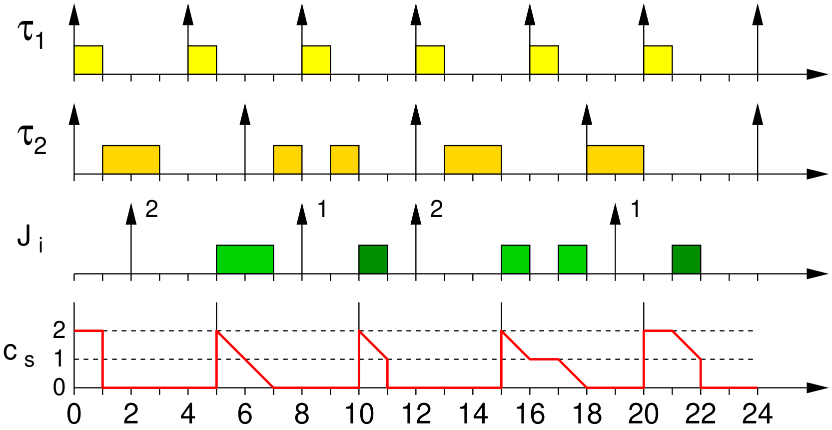
- full-preemption
- periodic tasks are scheduled by RM
- implicit deadlines
- aperiodic tasks have
  - unknown arrival time
  - known worst-case computation time

## Polling Server

1. **period** $T_s$, **nominal capacity** $C_s$ and **current capacity** $c_s$
2. every $T_s$ time units the current capacity is recharged up to the nominal value $C_s$ (i.e., $c_s = C_s$)
3. one unit of $c_s$ is consumed for each slot served to an aperiodic task
4. if there are no aperiodic tasks ready for execution, the server self-suspends and flushes its current capacity (i.e., $c_s = 0$)

> the flushing of the capacity may cause the presence of idle times that is not exploitable by aperiodic tasks ready for execution

# Polling Server




$\tau_1 = (1, 4)$ $\tau_2 = (2, 6)$ $C_s = 2$ e $T_s = 5$

## Schedulability analysis

from the schedulability viewpoint, a Pollig Server behaves like a periodic task having period $T_s$ and WCET $C_s$

$$U_p + U_s \leq U_{lub}(n+1)$$

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

in case there are $m$ Polling Servers:

$$U_p + \sum_{j=1}^{m} U_{s_j} \leq U_{lub}(n+m)$$

## Sporadic Server

parameters for its definition:

- period $T_s$
- maximum budget $C_s$
- static priority $P_s$ (e.g., set according to RM)

parameters used for its functioning:

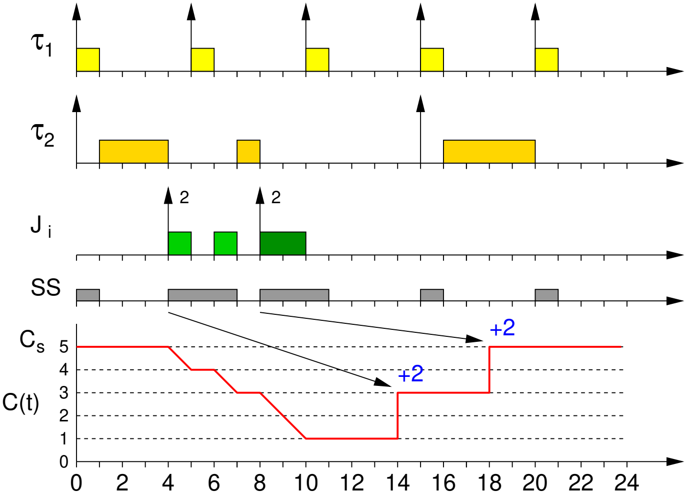
- $C(t)$ : current server capacity
- $P_{exe}$ : priority of the running task

## Sporadic Server: operating rules

the Sporadic Server works according to the following rules:

1. the server is said active at time $t$ if $P_{exe} \geq P_s$ and $C(t) > 0$
2. the server is said idle at time $t$ if $P_{exe} < P_s$ or $C(t) = 0$
3. at time $t = 0$ the server is idle and $C(0) = C_s$
4. when the server becomes active at time $t_1$ a corresponding recharging time is set at time $t_r = (t_1 + T_s)$
5. when the server becomes idle at time $t_2 > t_1$ a recharge budget is set equal to the budget $C_r$ consumed during the interval $[t_1, t_2)$
6. at time $t_r$ the capacity $C_r$ is added to the current budget

# Sporadic Server: example




$\tau_1 = (1, 5)$ $\tau_2 = (4, 15)$ $C_s = 5$ e $T_s = 10$

## SS: schedulability analysis

a Sporadic Server does not behave like a periodic task

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

- let $U_p$ be the utilization of all periodic tasks
- the highest utilization of the sporadic server that guarantees the schedulability of periodic tasks is $U^*_{SS}$

$$U^*_{SS} = 2 \left( \frac{U_p}{n} + 1 \right)^{-n} - 1$$

# Scheduling algorithms for dynamic priorities

many algorithms are adaptations of static priority scheduling algorithms

example:

- Dynamic Sporadic Server

some algorithms were born for dynamic priorities:

- Total Bandwidth Server
- Total Bandwidth Server*
- Constant Bandwidth Server

## Assumptions

concurrent scheduling of soft aperiodic tasks and hard periodic tasks

### assuming that

- periodic tasks are scheduled by EDF
- implicit deadlines (deadlines are equal to periods)
- full preemption
- for aperiodic tasks:
  - unknown arrival times
  - known computation times

## Total Bandwidth Server

### server design parameter:

- bandwidth (utilization) $U_s$

### operating rules:

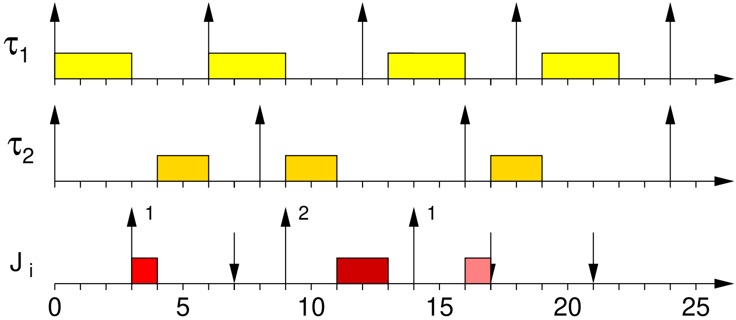
- an aperiodic task $J$ arrives at time $r_k$
- the $J$ task requires $C_k$ time units to execute
- an absolute deadline $d_k$ is calculated for $J$

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

- being $d_0 = 0$ by definition
- $J$ is scheduled by EDF considering the computed deadline $d_k$

# TBS: example

$\tau_1 = (3,6)$ $\tau_2 = (2,8)$ $U_s = 1 - U_p = 0.25$




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

$\max(3,0) + \frac{1}{0.25} = 3 + 4 = 7$

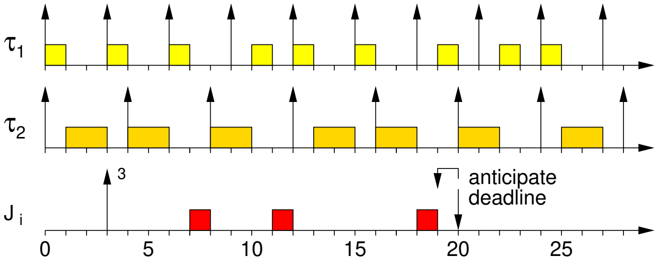
$\max(9,7) + \frac{2}{0.25} = 9 + 8 = 17$

$\max(14,17) + \frac{1}{0.25} = 17 + 4 = 21$

## Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time

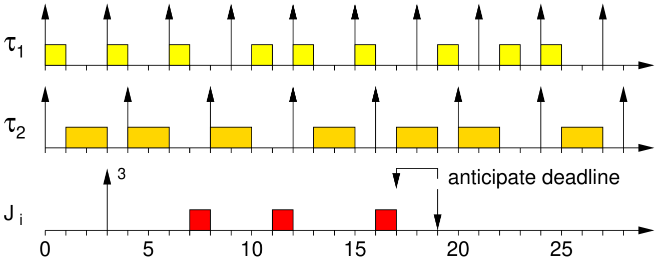



$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

## Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time

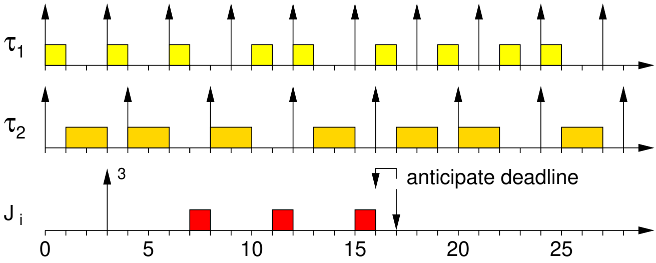



$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

# Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time

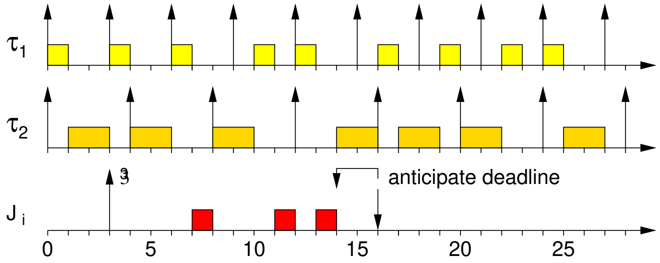



$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

# Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time

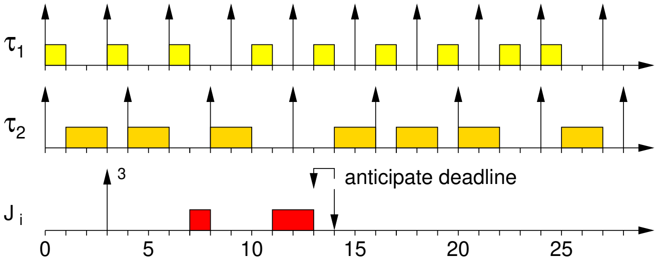



$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

# Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time

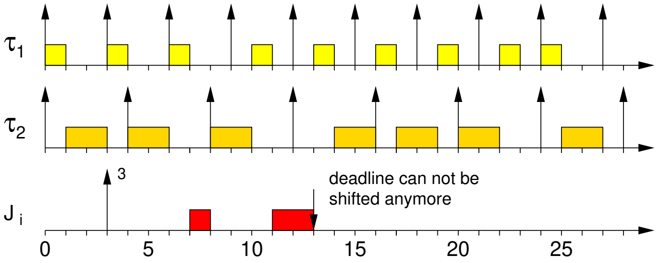



$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

# Total Bandwidth Server*

TBS* shortens the deadline of the aperiodic task $J$ as much as possible

- the first assignment is done as in TBS
- the deadline can be shortened to the actual finishing time




$\tau_1 = (1, 3)$ $\tau_2 = (2, 4)$ $U_s = 1 - U_p = 0.1667$

# Total Bandwidth Server*

the deadline is shortened
using an iterative process

being at iteration $s$:

- $d_k^s$ is the deadline assigned to $J_k$
- $f_k^s$ is the finishing time of $J_k$

the iterative shortening process is:

- at step $s + 1$ it is set $d_k^{s+1} = f_k^s$
- the process stops when $d_k^{s+1} = d_k^s$

# Total Bandwidth Server*

## computational issue

- the calculation of the worst-case finishing time may require to perform the schedule until the desired time
- in many cases (e.g., high utilization of periodic tasks), this may lead to impractical computation times

- the finishing time $f_k^s$ can be approximated
- an upper bound is proved to exist
- its calculation is fast enough to be used online

## TBS*: optimality

**Theorem**

TBS* generates the absolute deadline of an aperiodic task such as its response time is minimized

therefore, TBS* is optimal
(in the sense of response time minimization)

## Constant Bandwidth Server

- the CBS implements a bandwidth reservation scheme
- let $U_s$ be the bandwidth assigned to the CBS
- the CBS never requires more that $U_s$ to work

the server absolute deadline is based on the server bandwidth

- ... even in case of overload (overrun of aperiodic tasks)

the absolute deadline is postponed to achieve the constraint on the bandwidth assigned to the server

- performance in terms of response time for aperiodic tasks is similar to those of TBS

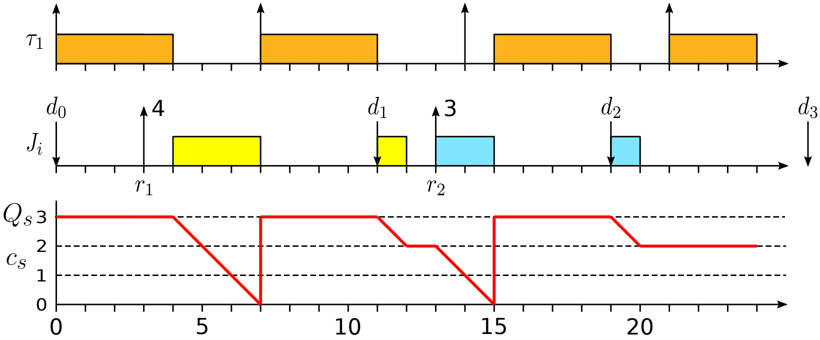
## CBS: operating rules

1. maximum budget $Q_s$, period $T_s$ and current budget $c_s$
2. server bandwidth: $U_s = Q_s / T_s$
3. at every time, the $k$-th calculated absolute deadline $d_{s,k}$ is the current deadline of the CBS
4. by definition $d_{s,0} = 0$
5. at each job $J_{i,j}$ it is assigned the absolute deadline $d_{i,j} = d_{s,k}$
6. the current budget $c_s$ decreases of one unit for each time unit of execution
7. when $c_s = 0$ the budget is refilled (i.e., it is set $c_s = Q_s$), and a new absolute deadline is computed as $d_{s,k+1} = d_{s,k} + T_s$

## CBS: operating rules

1. the server is *active* when there are pending aperiodic jobs, *idle* otherwise
2. when the server is active, a new aperiodic job $J_{i,j}$ is queued with arbitrary policy to the queue of pending requests
3. when the server is idle and a new aperiodic job $J_{i,j}$ is released:
   - if $c_s \geq (d_{s,k} - r_{i,j})U_s \Rightarrow$ compute a new absolute deadline $d_{s,k+1} = r_{i,j} + T_s$ and set $c_s = Q_s$
   - otherwise $\Rightarrow$ schedule $J_{i,j}$ with the current absolute deadline $d_{s,k}$ and budget $c_s$
4. when a job finishes, the next one is served with absolute deadline $d_{s,k}$ and budget $c_s$
5. if no more tasks are present in the queue, the server becomes idle

# CBS: example




$$c_s \geq (d_{s,0} - r_1)U_s \Rightarrow 3 \geq (0 - 3)0.375$$

$$c_s < (d_{s,2} - r_2)U_s \Rightarrow 2 < (19 - 13)0.375 = 2.25$$

$\tau_1 = (7, 4)$ $\quad Q_s = 3 \quad T_s = 8 \quad U_s = 0.375$

## CBS: schedulability analysis

- let $U_p$ be the utilization of periodic tasks
- the utilization of a CBS is always $U_s = Q_s/T_s$ independently from the timing parameters of aperiodic jobs
- the system is schedulable iif $U_p + U_s \leq 1$
- since the budget $c_s$ is never null, the CBS performs an automatic reclaiming of unused computing time in case of earlier termination of an aperiodic job

in case of $m$ CBSs where the $i$-th server has utilization $U_{s_i}$, the system is schedulable iif

$$U_p + U_s \leq 1 \quad U_s = \sum_{i=1}^{m} U_{s_i}$$

# Summary

## TBS

- trivial operating rules
- good performance
- does not tolerate overloads

## TBS*

- optimal response time
- higher complexity w.r.t. TBS
- trade-off can be established between response time and computational overhead

## CBS

- bandwidth reservation in case of overload
- good performance (comparable with TBS)
- simple implementation