Multi-core real-time scheduling

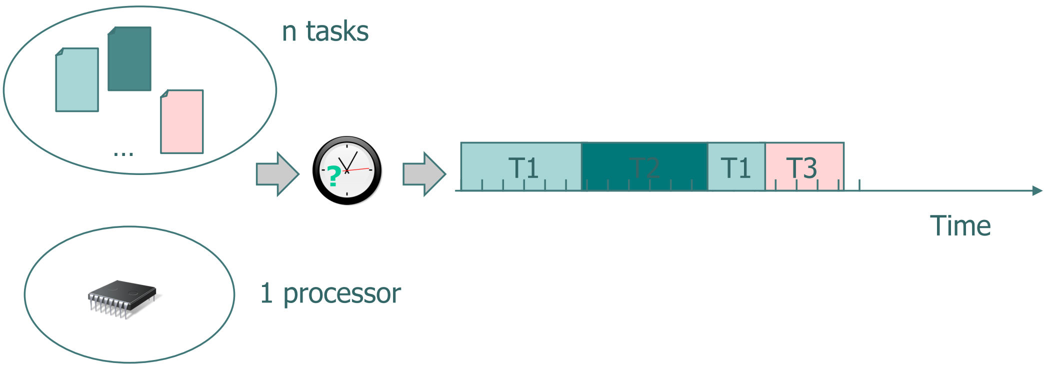
Credits: Anne-Marie Déplanche, Irccyn, Nantes (many slides come from her presentation at ETR, Brest, September 2011)

Multi-core real-time scheduling

- Introduction: problem definition and classification
- Some anomalies of multiprocessor scheduling
- Model and assumptions
- Extension of uni-processor scheduling strategies
- Pfair approaches

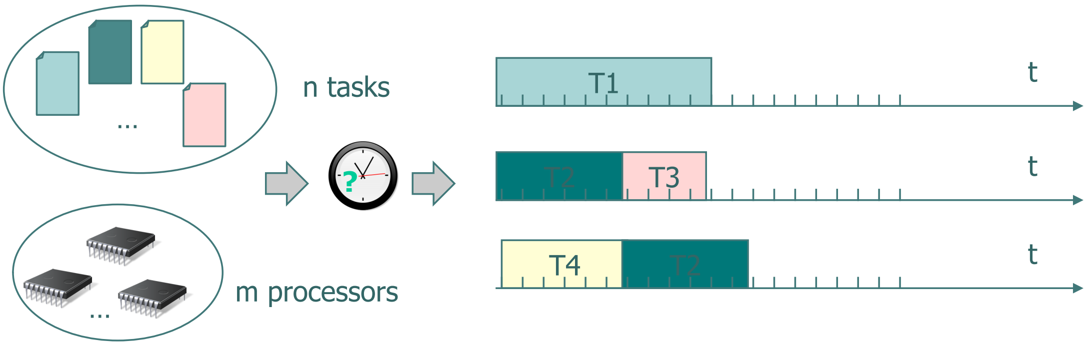
Introduction

- Mono-processor scheduling: one-dimension problem
  - Temporal organization
    - When to start, interrupt, resume every task?



Introduction

- Multi-processor (multi-core) scheduling: two-dimension problem
  - Temporal organization +
  - Spatial organization
    - On which processor execute every task?

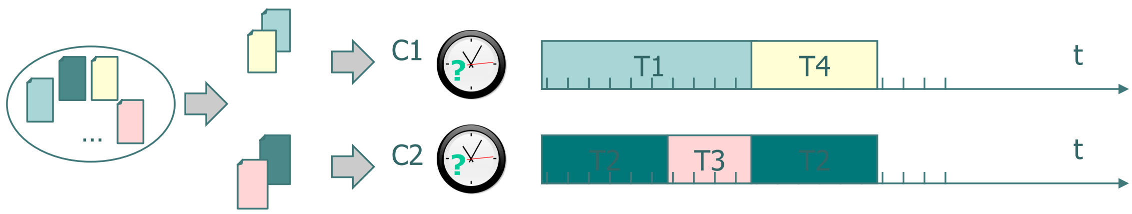


Classification

- Partitioned scheduling
  - Each of the two dimensions is dealt with separately
- Global scheduling
  - Temporal and spatial dimensions are deal with jointly
- Semi-partitioned scheduling
  - Hybrid

Classification: partitioned scheduling

- Each of the two dimensions is dealt with separately
  - Spatial organization: the n tasks are partitioned onto the m cores. No task migration at run-time
  - Temporal organization: Mono-processor scheduling is used on each core



Classification: partitioned scheduling

- Two points of view
  - Number of processors to be determined: optimization problem (bin-packing problem)
    - Bin = task, size = utilization (or other expression obtained from the task temporal parameters)
    - Boxes = processors, size = ability to host tasks
  - Fixed number of processors: search problem (knapsack problem)

- Both problems are NP-hard

Classification: partitioned scheduling

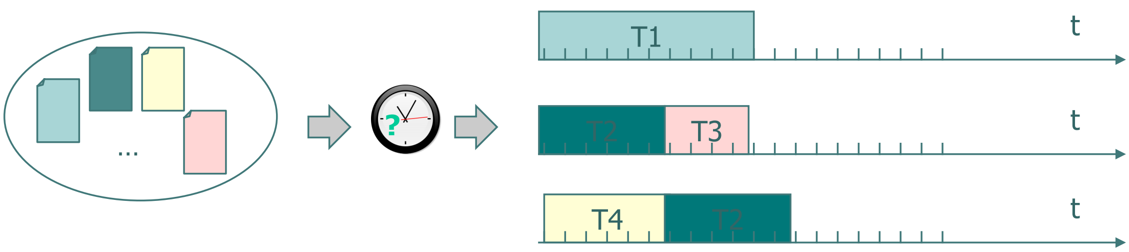
- Optimal mono-processor scheduling strategies: XX
  - RM, DM
  - EDF, LLF (see uni-processor scheduling chapter)
- Bin-packing heuristics: YY
  - FF: First-Fit
  - BF: Best-Fit
  - WF: Worst-Fit, NF: Next-Fit
  - FFD, BFD, WFD: First/Best/Worst-Fit Decreasing
- Partitioning algorithms XX-YY

Classification: partitioned scheduling

- Benefits
  - Implementation: local schedulers are independent
  - No migration costs
  - Direct reuse of mono-processor schedulability tests
  - Isolation between processors in case of overload
- Limits
  - Rigid: suited to static configurations
  - NP-hard task partitioning
  - Largest utilization bound for any partitioning algorithm [Andersson, 2001] $\frac{m+1}{2}$
    (m+1 tasks of execution time 1+ε and period 2)

Classification: global scheduling

- Temporal and spatial dimensions are dealt with jointly
  - Global unique scheduler and run queue
  - At each scheduling point, the scheduler decides when and where schedule at most m tasks
  - Task migration allowed



Classification: global scheduling

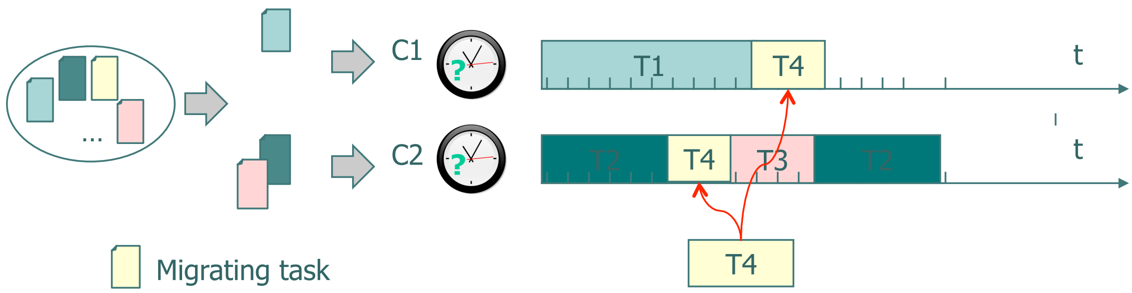
- Benefits
  - Suited to dynamic configurations
  - Dominates all other scheduling policies
    - (if unconstrained migrations + dyn. priorities – see later)
  - Optimal schedulers exist
  - Overloads/underloads spread on all processors
- Drawbacks
  - System overheads: migrations, mutual exclusion for sharing the run queue

Classification: global scheduling

- (Preemptive) global RM/DM/EDF: definition
  - Task priorities assigned according to RM/DM/EDF
  - Scheduling algorithm: the m higher priority tasks are executed on the m processors

Classification: semi-partitioned scheduling

- Partitioned scheduling as far as possible
- Some statically determined tasks may migrate
  - Constraint: migrating tasks (T4 on the example) must execute on a single processor at a time



Terminology

- A task set is schedulable if there exists a scheduling policy such that all deadlines are met
- A task set is schedulable by a scheduling policy if under that scheduling policy all deadlines are met
- A scheduling policy is optimal if it is able to correctly schedule all schedulable task sets
  - Different from the optimality defined before
- Utilization bound of a scheduling policy: utilization U_{lim} below which all task sets meet their deadline

Terminology

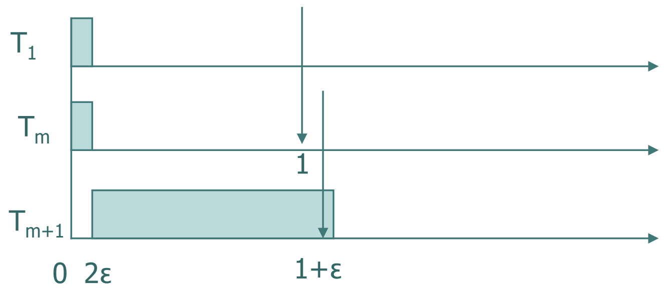
- Priorities
  - Fixed per task (FTP)
  - Fixed per job (FJP)
  - Dynamic per job (DJP)

Overview of global scheduling policies

- Assumptions
  - Tasks
    - Periodic tasks (Pi)
    - Implicit deadlines (Di=Pi)
    - Synchronous tasks (Oi=0 for all i)
    - Independent tasks
    - A single job of a task can be active at a time
  - Architecture
    - Identical processors
    - System costs are neglected (preemption, migration, scheduling policy)

Scheduling anomalies (1/3)

- Dhall's effect [Dhall & Liu, 1978]
  - Periodic task sets with utilization close to 1 are unschedulable using global RM / EDF
  - $n = m+1$, $P_i = 1$, $C_i = 2\varepsilon$, $u_i=2\varepsilon$ for all $1 \le i \le m$
  - $P_{m+1}=1+\varepsilon$, $C_{m+1}=1$, $u_{m+1}=1/(1+\varepsilon)$
  - Task m+1 misses its deadline although U very close to 1

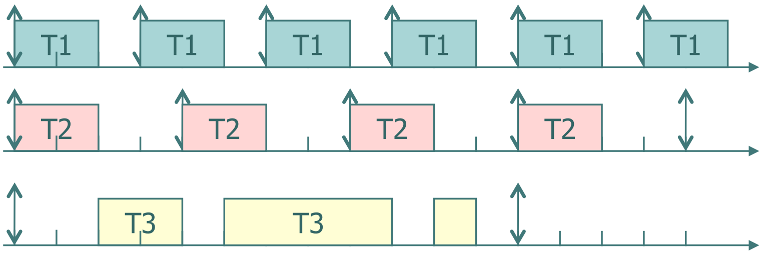


Scheduling anomalies (2/3)

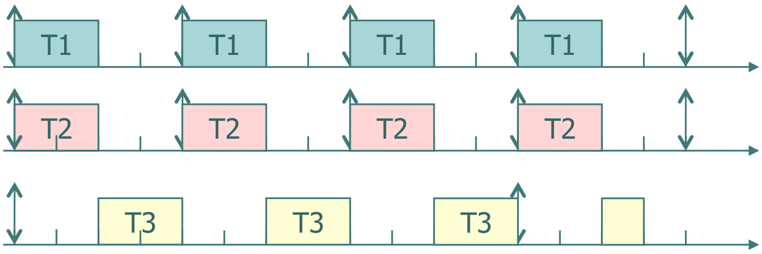
- Period increase for periodic tasks and fixed priorities [Anderson, 2003]
  - $n = 3$, $m=2$, ($P_1= 3$, $C_1=2$), ($P_2=4$,$C_2=2$), ($P_3=12$,$C_3=7$)
  - Schedulable under global RM
  - If P_1 is increased to $P_1=4$ and priorities stay the same, T_3 misses its deadline

Scheduling anomalies (2/3)

- $(P_1 = 3, C_1=2), (P_2=4, C_2=2), (P_3=12, C_3=7)$

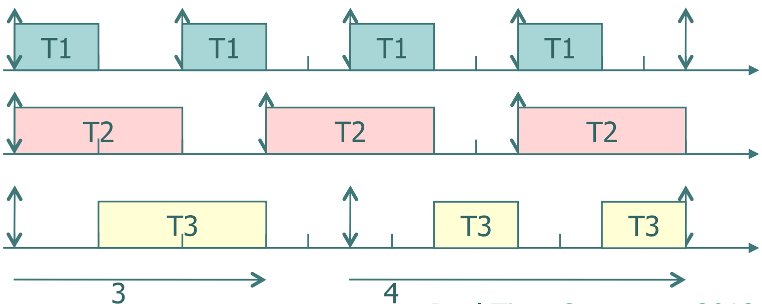


- $(P_1 = 4, C_1=2), (P_2=4, C_2=2), (P_3=12, C_3=7)$



Scheduling anomalies (3/3)

- Critical instant not necessarily the simultaneous release of higher priority tasks
  - n=3, m=2
  - $(P_1=2, C_1=1), (P_2=3, C_2=2), (P_3=4, C_3=2)$
  - Under RM scheduling
    - Response time of T_3 higher at time 4 than at time 0

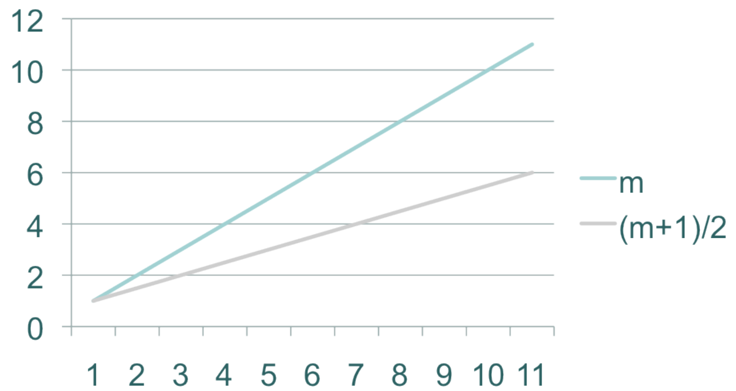


General properties of multiprocessor scheduling (1/2)

- Exact schedulability condition
  - $U \leq m$ and $u_{max} \leq 1$
  - U = total utilization
  - U_{max} = maximum utilization
  - Does not tell for which scheduling algorithm!
- Schedule is cyclic on the hyperperiod H ($PPCM(P_i)$) for:
  - Deterministic
  - Without memory scheduling algorithms

General properties of multiprocessor scheduling (2/2)

- Theorem [Srinavasan & Baruah, 2002]
  - Non existence of FJP (FJP+FTP) scheduling with utilization bound strictly larger than (m+1)/2 for implicit deadline periodic task sets



Global multiprocessor scheduling: detailed outline

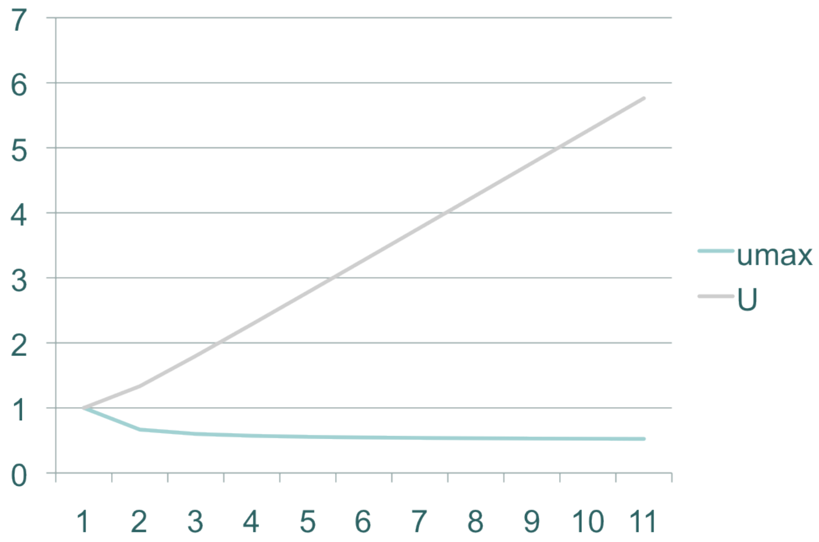
- Transposition of uni-processor algorithms
- Extensions of uni-processor algorithms
  - US (Utilization Threshold)
  - EDF(k)
  - ZL (Zero Laxity)
- Pfair approaches (Proportional Fair)

Transposition of uni-processor algorithms (1/2)

- Main algorithms
  - RM (Rate Monotonic) ➔ G-RM, Global RM
  - EDF (Earliest Deadline First) ➔ G-EDF, Global EDF
- Not optimal anymore
- Sufficient schedulability tests (depend on u_{max})

G-RM	G-EDF
$u_{max} \leq m/(3m-2)$ and $U \leq m^2/(3m-2)$	$u_{max} \leq m/(2m+1)$ and $U \leq m^2/(2m+2)$
$u_{max} \leq 1/3$ and $U \leq m/3$	$u_{max} \leq 1/2$ and $U \leq (m+1)/2$
$U \leq m/2 * (1-u_{max}) + u_{max}$	$U \leq m – (m-1)\, u_{max}$

Transposition of uni-processor algorithms (2/2)



Extensions of global RM/EDF: US (Utilization Threshold) policies

- Priority assignment depend on an utilization threshold ξ
  - If $u_i > \xi$, then T_i is assigned maximal priority
  - Else, T_i's priority assigned as in original algorithm (RM/EDF)
  - Arbitrary deterministic tie resolution
- Remarks
  - Still non optimal,
  - Outperforms the base policy
  - Defies Dhall's effect

Extensions of global RM/EDF: US (Utilization Threshold) policies

- Example: RM-US[ξ=1/2]

	Ci	Pi	Ui	Prio
T1	4	10	2/5	2
T2	3	10	3/10	2
T3	8	12	2/3	∞
T4	5	12	5/12	1
T5	7	12	7/12	∞

Extensions of global RM/EDF: US (Utilization Threshold) policies

- Utilization bounds

RM-US		EDF-US	
ξ=m/(3m-2)	$U \leq m^2/(3m-2)$	ξ=m/(2m-1)	$U \leq m^2/(2m-1)$
ξ=1/3	U ≤ (m+1)/3	ξ=1/2	U ≤ (m+1)/2

- Remarks
  - Utilization bounds do not depend on u_{max} anymore
  - EDF-US[1/2] attains the best utilization bound possible for FJP

Extensions of global RM/EDF: EDF(k)

- Task indices by decreasing utilization
  - $u_i >= u_i+1$ for all i in [1,n]
- Priority assignment depends on a threshold on task index
  - i < k, then maximum priority
  - Else, priority assignment according to original algorithm

Extensions of global RM/EDF: EDF(k)

- Example, EDF(4)

	Ci	Pi	Ui	Prio
T1	4	10	2/5	EDF
T2	3	10	3/10	EDF
T3	8	12	2/3	∞
T4	5	12	5/12	∞
T5	7	12	7/12	∞

Extensions of global RM/EDF: EDF(k)

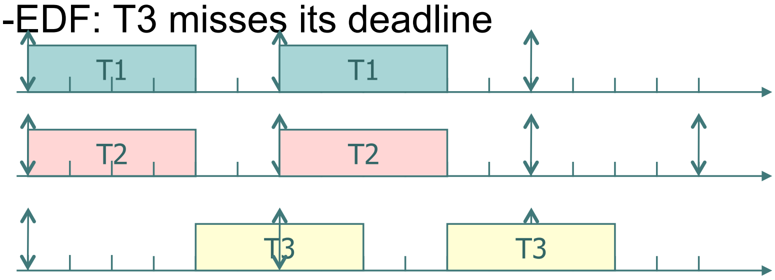
- Sufficient schedulability test $m \geq (k-1) - \left\lceil \dfrac{\sum_{i=k+1}^{n} u_i}{1-u_k} \right\rceil$
  - k_{min} = value minimizing right side of the equation
  - With $k=k_{min}$, utilization bound of (m+1)/2 (best possible for FJP)
  - Comparison with EDF[1/2]
    - Same utilization bound
    - EDF(k_{min}) dominates EDF[1/2]

Extensions of global RM/EDF: ZL (Zero Laxity) policies

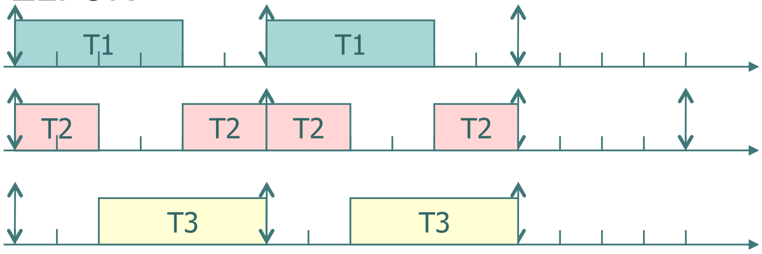
- XX-ZL: apply policy XX until Zero Laxity
  - Maximal priority when laxity reaches zero (regardless of the currently running job), original priority assignment for the others
  - In category DJP (dynamic job scheduling)
- Policies: EDZL [Lee, 1994], RMZL [Kato & al, 2009], FPZL [Davis et al, 2010]
- Utilization bound: (m+1)/2
- Dominates G-EDF

Extensions of global RM/EDF: ZL (Zero Laxity) policies

- Example: m=3,m=2; all Pi to 2, all Ci to 2
  - G-EDF: T3 misses its deadline



  - EDZL: OK



Pfair algorithms

- Principle
- Construction of a Pfair schedule
- Pfair scheduling policies

Pfair algorithms: principle

- Pfair: "Proportionate Fair"
  - [Baruah et al, 1996]
  - Allocate time slots to tasks as close as possible to a "fluid" system, proportional to their utilization factor
- Example
  - $C_1=C_2=3$, $P_1=P_2=6$ ($u_1=u_2=1/2$)
  - Each task will be "approximately" allocated 1 slot out of 2 (whatever the processor)

Pfair algorithms: principle

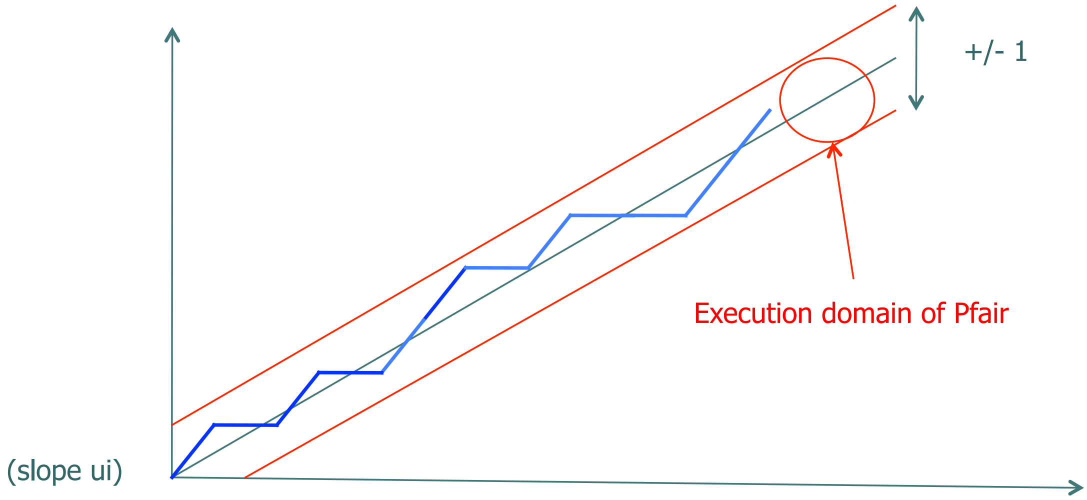
- Lag function: difference between real and fluid execution
  - Discrete time, successive time slots [t,t+1[
  - Weight of a task: $\omega_i=u_i$
- Lag

$$lag(T_i,t) = \omega_i t - \sum_{u=0}^{t-1} S(T_i,u)$$

  - First term: fluid execution
  - Second term: real execution, with $S(T_i,u)=1$ if T_i executed in slot u, else 0
- Pfair schedule: for all time t, lag in interval]-1,1[

Pfair algorithms: principle

- Example



Pfair algorithms: principle

- Property
  - If a Pfair schedule exists, deadlines are met

- Exact test of existence of a Pfair schedule

$$\sum_{i=1}^{n} u_i \leq m$$

  - Full processor utilization!

Pfair algorithms: construction of a Pfair schedule

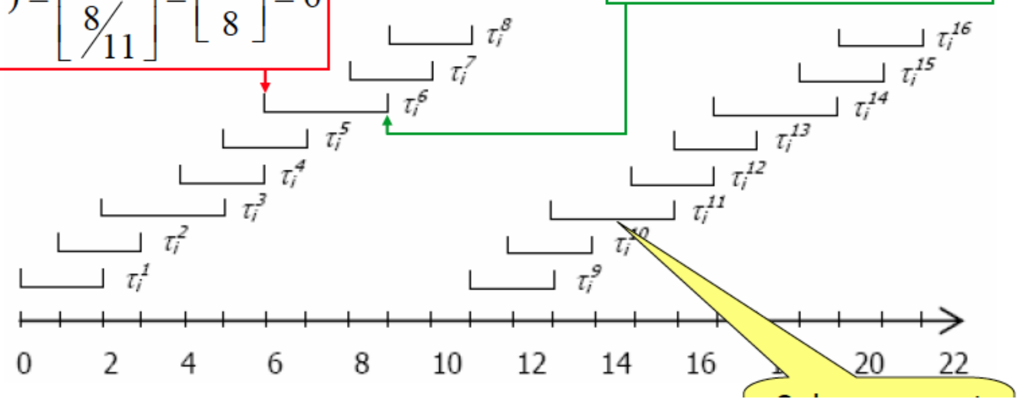
- Divide tasks in unity-length sub-tasks
  - Pfair condition: each subtask j executes in a time window between a pseudo-arrival and a pseudo-deadline
  - Pseudo-arrival: $r(T_i^j) = \left\lfloor \frac{j-1}{\omega_i} \right\rfloor$
  - Pseudo-deadline: $d(T_i^j) = \left\lceil \frac{j}{\omega_i} \right\rceil$

Pfair algorithms: construction of a Pfair schedule

- Example (to be fixed)
  - $(C_i = 8,\ T_i = 11) \rightarrow \omega_i = u_i = 8/11$

$$r(\tau_i^6) = \left\lfloor \frac{6-1}{8/11} \right\rfloor = \left\lfloor \frac{55}{8} \right\rfloor = 6$$

$$d(\tau_i^6) = \left\lceil \frac{6}{8/11} \right\rceil = \left\lceil \frac{33}{4} \right\rceil = 9$$



Pfair algorithms: scheduling algorithms

- EPDF (Earliest Pseudo-Deadline First)
  - Apply EDF to pseudo-deadlines
  - Optimal only for m=2 (2 processors)
- PF, PD, PD^2
  - EPDF with non-arbitrary tie breaking rules in case of identical pseudo-deadlines
  - All of them are optimal
  - Most efficient one: PD^2
- Ongoing works
  - Reduce numbers of context switches and migrations while maintaining optimality

Conclusion

- Multi-processor scheduling is an active research area
- Ongoing works
  - Global multi-core scheduling
  - Semi-partitioned scheduling
  - Determining upper bounds of practical factors (preemption, migration, …)
  - Implementation in real-time operating systems