Resource Sharing in Hierarchical Fixed-Priority Pre-emptive Systems

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Roadmap

- Motivation
- Hierarchical Scheduling Problem
  - System model
  - Schedulability analysis for independent applications
- Resource Access Policies
  - SRP and HSRP
  - Schedulability analysis with shared resources
  - Example
- Conclusions

Motivation

- Automotive and Avionics applications
  - Emerging trend: multiple applications on a single processor
    - Made possible by the advent of advanced high performance microprocessors
    - Driven by the desire for cost reductions and functionality enhancement
  - Requirements:
    - Temporal isolation: applications must behave as if they were running on individual microprocessors
    - Access to shared resources under mutual exclusion Examples: memory mapped peripherals, FLASH memory, data structures etc.

System Model

- Multiple applications on a single processor
  - Each application comprises multiple tasks
    - Task parameters: Priority, period (T_i), deadline (D_i), execution time (C_i) , Release jitter (J_i)
    - Worst-Case Response Time (R_i)
    - Assume $D_i \leq T_i$
  - A Periodic Server is used to schedule each application
    - Server parameters: Priority, period (T_S), capacity (C_S)
    - Tasks executed until the server's capacity is exhausted, then suspended until capacity replenished at next period
    - If no tasks ready then capacity assumed to be idled away (e.g. by an idle task carrying out BIT, memory checks etc.)

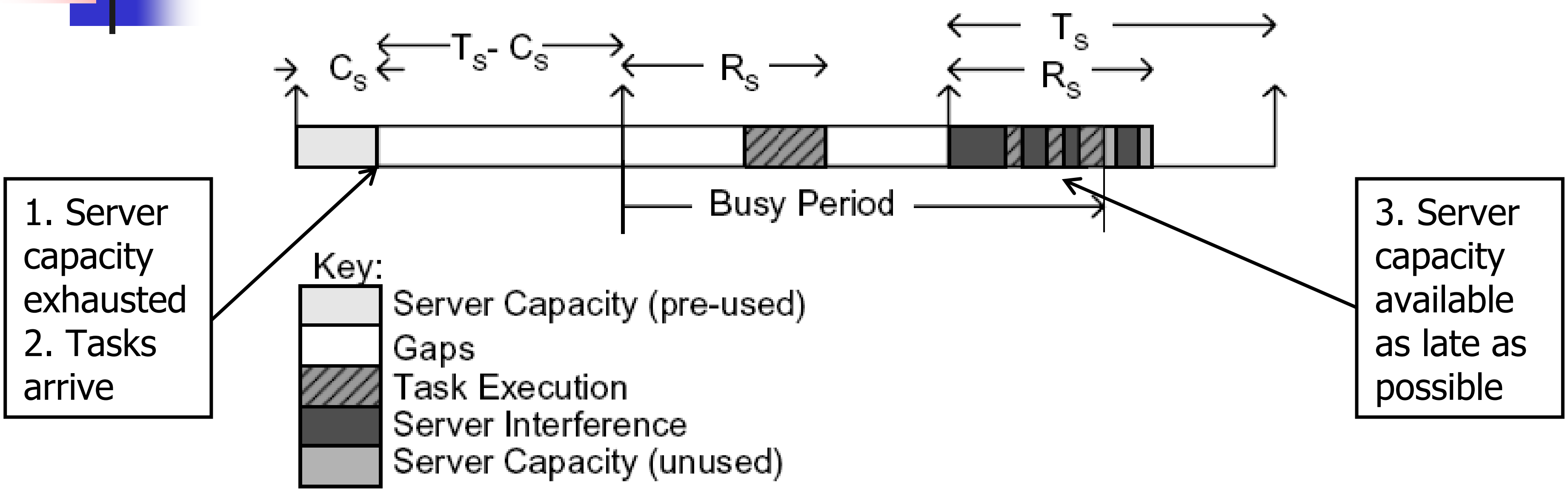
System Model

- Fixed Priority Pre-emptive Scheduling
  - Global scheduling of servers
  - Local scheduling of tasks within a server

Schedulability Analysis

- Using Response Time Analysis:
  - Determine worst-case scenario (critical instant) leading to worst-case response time for a task
  - Calculate busy period and hence worst-case response time given critical instant arrival pattern
  - Compare worst-case response time with task deadline

Critical Instant



1. Server capacity exhausted as early as possible then…
2. Task of interest and all higher priority tasks arrive just after server capacity exhausted
3. Server capacity available as late as possible due to interference from higher priority servers

Busy period (w_i)

- Three components:
  1. Task load released during the busy period

$$L_i(w_i) = C_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{w_i + J_j}{T_j} \right\rceil C_j$$

Note, J_j is the task jitter which is increased by $(T_S - C_S)$ due to the operation of the server

  2. Gaps in complete server periods

$$\left(\left\lceil \frac{L_i(w_i)}{C_S} \right\rceil - 1 \right) (T_S - C_S)$$

Busy period (w)

3. Interference from higher priority servers in the final server period that completes task execution

$$I_S(w) = \sum_{\forall X \in hps(s)} \left\lceil \frac{w - \left(\left\lceil \frac{L_i(w)}{C_S} \right\rceil - 1 \right) T_S}{T_x} \right\rceil C_X$$

Response Time Computation

$$w^{n+1} = L(w^n) + \left(\left\lceil \frac{L(w^n)}{C_S} \right\rceil - 1 \right)(T_S - C_S) + \sum_{\forall X \in hps(s)} \left\lceil \frac{w^n - \left(\left\lceil \frac{L(w^n)}{C_S} \right\rceil - 1 \right) T_S}{T_x} \right\rceil C_X$$

- Recurrence starts with: $w_i^0 = C_i + \left(\left\lceil \frac{C_i}{C_S} \right\rceil - 1 \right)(T_S - C_S)$
- ends when $w_i^{n+1} = w_i^n$ in which case $w_i^{n+1} + J_i$ is the task's worst case response time
- alternatively, recurrence ends when $w_i^{n+1} > D_i - J_i$ in which case the task is unschedulable

Resource Access Policies

- Local Resources
  - Shared by tasks in a single application
  - Stack Resource Policy [T.P. Baker 1991]
- Global Resources
  - Shared by tasks in multiple applications
  - Hierarchical Stack Resource Policy – introduced here
    - Based on and compatible with SRP

Local resources

- Stack Resource Policy
  1. Each local resource has a local ceiling priority equal to the highest priority of any task that accesses the resource
  2. Whilst a task accesses a local resource, its priority is increased to the local ceiling priority of the resource
  3. If the server's capacity is exhausted whilst a task is accessing a local resource, then execution of the task is simply suspended until the server's capacity is replenished

Global resources

- Hierarchical Stack Resource Policy
  1. Each global resource has a global ceiling priority equal to the highest priority of any server that executes a task that accesses the resource
  2. Whilst a task accesses a global resource, the priority of its server is increased to the global ceiling priority of the resource
  3. Whilst a task accesses a global resource, the priority of the task is increased to the highest local priority within its application
  4. If the server's capacity is exhausted whilst a task is accessing a global resource, then the server continues to execute the task until the resource access is completed
  5. (Optionally) if a server overruns, then the capacity allocated at the start of its next period is reduced by the amount of the overrun

Blocking Factors

- Definitions:

B_{SO} longest time for which a task in server S can access a global resource. (Overrun time for server S)

B_S longest time for which a task in a server of lower priority than S can access a global resource with a ceiling priority equal to or higher than S. (Blocking time for server S).

B_i longest time for which a task in the same application and of lower priority than task τ_i can access either a global resource or a local resource with a ceiling priority equal to or higher than τ_i. (Blocking time for task τ_i).

Server Schedulability

- Worst-case scenario for server S
  - Blocked by a lower priority server for B_S
  - Additional interference due to overruns of higher priority servers
- With overrun & payback:

$$w_S^{n+1} = C_S + B_S + \sum_{\substack{\forall X \in hp(S) \\ servers}} B_{XO} + \sum_{\substack{\forall X \in hp(S) \\ servers}} \left\lceil \frac{w_S^n}{T_X} \right\rceil C_X$$

  - Don't need to account for overrun of S in analysis of S
  - Overrun in one period leads to reduction in capacity replenished in next period
  - Server 'execution time' in next period due to overrun + replenished capacity cannot exceed server capacity

Server Schedulability

- With overrun & no payback:
  - Must account for overrun of server S

$$w_S^{n+1} = C_S + B_{SO} + B_S + \sum_{\substack{\forall X \in hp(S) \\ servers}} \left\lceil \frac{w_S^n}{T_X} \right\rceil (C_X + B_{XO})$$

- Server schedulable if its capacity can be fully consumed within its period

Task Schedulability

- Depends on two factors
  - Worst-case load to be executed during the busy period
  - Worst-case time the server takes to execute this load

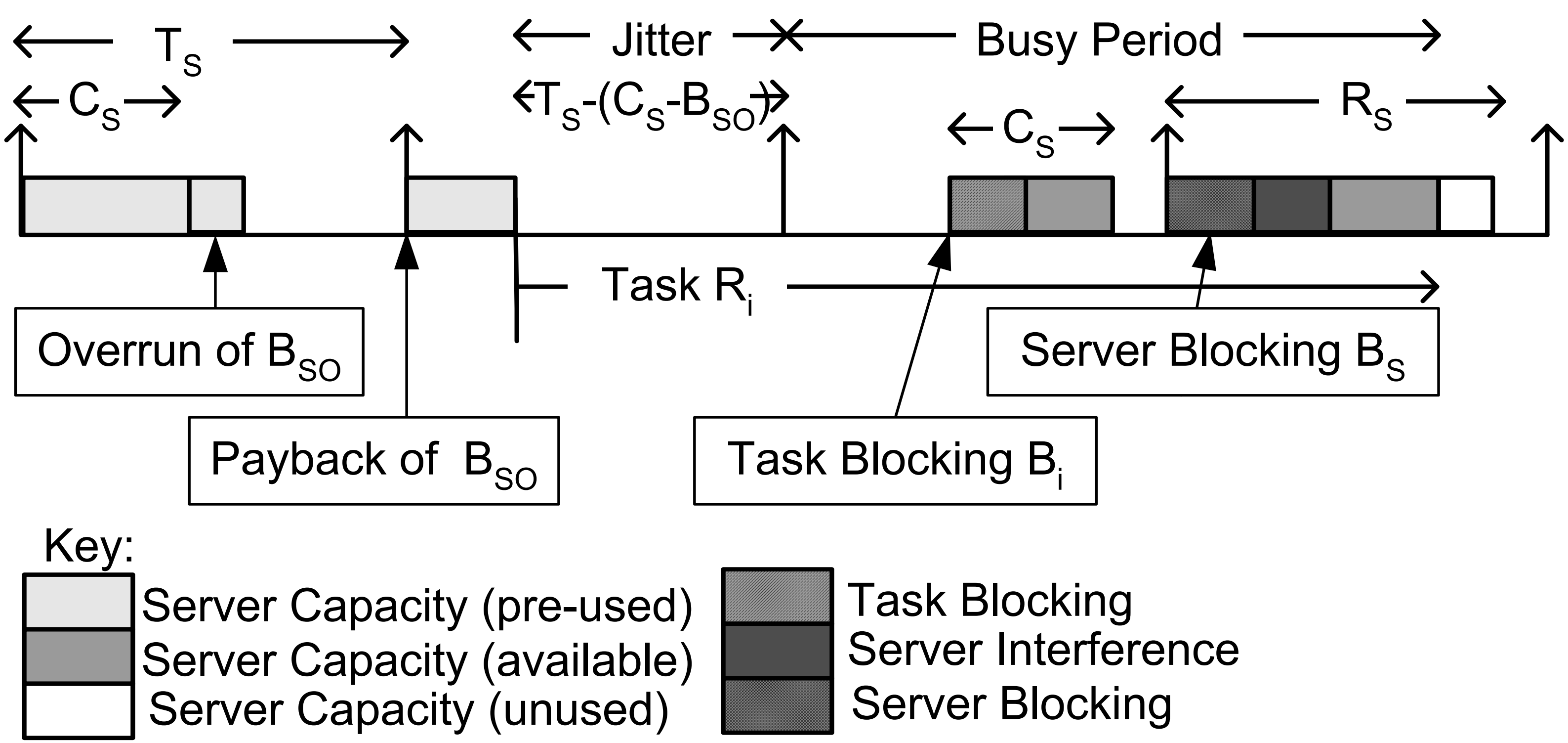
- Task Load:
  - SRP and HSRP serialise access to resources
  - Maximum blocking of task τ_i by lower priority tasks is B_i

$$L_i(w_i) = B_i + C_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{w_i + J_j}{T_j} \right\rceil C_j$$

  - Task jitter increased by:
    - $T_S - (C_S - B_{SO})$ with payback mechanism
    - $T_S - C_S$ without payback mechanism

Task Schedulability

- Worst-case scenario for server to execute task load



Task Schedulability

- Response Time Computation (overrun & payback)

$$w_i^{n+1} = L_i(w_i^n) + \left(\left\lceil \frac{L_i(w_i^n)}{C_S} \right\rceil - 1 \right)(T_S - C_S) + B_S +$$

$$\sum_{\substack{\forall X \in hp(S) \\ servers}} B_{XO} + \sum_{\substack{\forall X \in hp(S) \\ servers}} \left\lceil \frac{\max\left(0, w_i^n - \left(\left\lceil \frac{L_i(w_i^n)}{C_S} \right\rceil - 1 \right) T_S \right)}{T_X} \right\rceil C_X$$

  - Re-compute task load $L_i(w)$ each iteration
  - Task jitter increased by $T_S - (C_S - B_{SO})$ due to operation of the server
  - Response time is $w_i^n + J_i$

Task Schedulability

- Response Time Computation (overrun & no payback)

$$w_i^{n+1} = L_i(w_i^n) + \left(\left\lceil \frac{L_i(w_i^n)}{C_S} \right\rceil - 1 \right)(T_S - C_S) + B_S + \sum_{\substack{\forall X \in hp(S) \\ servers}} \left\lceil \frac{\max\left(0, w_i^n - \left(\left\lceil \frac{L_i(w_i^n)}{C_S} \right\rceil - 1 \right) T_S \right)}{T_X} \right\rceil (C_X + B_{XO})$$

  - Re-compute task load $L_i(w)$ each iteration
  - Task jitter increased by $T_S - C_S$ due to operation of the server
  - Response time is $w_i^n + J_i$

Example

- Server parameters:

Server	Period	Capacity	$T - C$	U
S_A	2000	500	1500	25%
S_B	10000	2500	7500	25%
S_C	20000	5000	15000	25%

- Server response times:

Server	No Resources	HSRP No payback*	HSRP payback
S_A	500	1200	850
S_B	3500	5750	4700
S_C	10000	19550	14700

Global resource shared between all 3 applications, access time 350

*includes overrun of the server

Example (continued)

- Task parameters:

Task	T	D	C	U
τ_1	25000	25000	2300	9.6%
τ_2	50000	50000	4800	9.2%
τ_3	100000	100000	2400	2.4%

Tasks for application B

- Task response times:

Task	No Resources	HSRP No payback	HSRP payback
τ_1	10800	19000	19350
τ_2	40400	42800	42450
τ_3	89200	90750	90750

All tasks in application B access a local resource for 500 and a global resource for 350

- Payback mechanism can result in task response times being larger or smaller (Note, with payback, could make server capacity larger)

Alternative methods #1

- "Non-pre-emptive" resource access
  - Special case of Hierarchical Stack Resource Policy (HSRP)
  - Global ceiling priority of all resources set to the highest priority of *any* server
  - Can be analysed using analysis for HSRP (overrun & no payback)
  - HSRP dominates non-pre-emptive approach for both:
    - Server schedulability
    - Task schedulability
  - Non-pre-emptive approach useful if:
    - All global resource accesses are very short
    - Tasks in all applications share the same global resources

Alternative methods #2

- "Prevent and pass-on"
  - Uses ceiling priorities as per HSRP
  - When resource access required:
    - First check if sufficient server capacity remains
    - If not, then suspend server until next replenishment
    - Any capacity remaining when server suspended is available in the next server period
  - Schedulability
    - Tasks: similar to 'overrun & payback' model
    - Servers: worse than 'overrun & payback'
      - Due to need to accommodate additional preserved capacity in the server period

Alternative methods #3

- "Suspend & use next server's capacity"
  - Uses ceiling priorities as per HSRP
  - When resource locked and server capacity exhausted
    - Suspend server
    - If a task in another server needs the resource, then complete resource access using that server's capacity
  - Schedulability
    - Each pre-empting server may result in a reduction in available capacity due to the need to subsequently unlock a resource
    - Double reduction in schedulability:
      - resource unlocking for other applications
      - Extra interference due to increased capacity of higher priority servers needed for resource unlocking
  - Implementation issues
    - Next server could also run out of capacity whilst unlocking a resource on behalf of another server and so on

Recommendations

- In hierarchical fixed priority pre-emptive systems, global resources accesses have a large cumulative effect on schedulability
  - Important to make resource access times as short as possible
- Hierarchical Stack Resource Policy (HSRP)
  - An effective and analysable method of handling global resource access
- Payback mechanism?
  - Improves server schedulability which may permit larger server capacities
  - May or may not improve task response times
    - depends on system parameters
    - But larger server capacities also improve task schedulability

Contribution

- Motivation
  - Trend towards multiple applications on a single processor in both Automotive Electronics and Avionics
  - Real-world applications share resources both globally and locally: memory mapped peripherals, data buffers, shared comms devices etc.
- Contribution
  - Definition of **HSRP**, an appropriate resource locking protocol for hierarchical fixed priority pre-emptive systems based on priority ceilings and the **SRP**.
  - Schedulability analysis for HSRP.

Conclusions

- Techniques and analysis now available to design and develop hierarchical, multiple application, real-world systems using fixed priority pre-emptive scheduling

- Areas of Future Work
  - Choice of Server parameters (T and C)
  - Policies for resource access that avoid server overruns

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