Online Scheduling Switch for Maintaining Data Freshness in Flexible Real-Time Systems

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Motivation

Maintaining data quality in real-time systems is important.

- Real-time data are used to capture current status of entities in the system.
- Real-time data have time semantics and their quality degrade with time.
- Many scheduling policies are available.
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Many real-time systems exhibit multi-modal behavior.

- Each mode is characterized by a different task set.
- Different modes have varying system workloads.
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Example: Aircraft Control Systems

- Real-time data: aircraft position, speed, direction, altitude, etc.
- Different modes: landing, takeoff, normal cruise, etc.
Motivation

Goals:

▶ Maintaining data freshness in flexible real-time systems.
▶ Achieving the tradeoff between higher data quality and better schedulability.
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Problems:

▶ Which scheduling policy should be applied to a mode?
▶ When to do the switch to maintain data freshness during the transition?
Temporal Validity and Data Staleness

- A validity interval is associated with a data value.
- A data value is fresh within the validity interval.
- Staleness is used to measure the degradation in data freshness.
- Increases linearly within the validity interval until the data is refreshed.

$V_1$: validity length of $X_1$  
$V_2$: validity length of $X_2$
Algorithms for Maintaining Data Freshness

Half-Half \[\textit{[Ramamritham 93]}\]

- Period \((P_i)\) and relative deadline \((D_i)\) of an update transaction \(\tau_i\) are each set to be one-half of the data validity length \((V_i)\).

More-Less \[\textit{[Xiong & Ramamritham 99]}\]

- Validity Constraint (to ensure data validity):
  - Period + Relative Deadline \(\leq\) Validity Length

- Deadline Constraint (to reduce workload):
  - Computation Time \(\leq\) Relative Deadline \(\leq\) Period

- Schedulability Constraint (by deadline monotonic):
  - Response time of the 1st instance \(\leq\) Relative Deadline
  - 1st instance response time is the longest response time of all instances of a transaction if all periodic transactions start synchronously
Algorithms for Maintaining Data Freshness

Remark

- More-Less is pessimistic because the relative deadline is fixed and equal to the worst case response time of the transaction.
Algorithms for Maintaining Data Freshness

Deferrable Scheduling with Fixed Priority (DS-FP) [Xiong, Han & Lam 05]

- Adopts the sporadic task model.
- Defers the sampling time, $r_{i,j+1}$, of $J_{i,j}$'s next job as late as possible.
- Increases the distance of two consecutive jobs as much as possible.

![Diagram showing scheduling algorithm]
Utilization-based Scheduling Selection

- Try \textit{HH}. Use Liu & Layland’s schedulability test condition.

\begin{itemize}
  \item Calculate Period and Deadline under HH
  \item Schedulable? \quad Apply HH
  \item Calculate Period and Deadline under ML
  \item Schedulable? \quad Apply ML
  \item Apply DSFP in the new mode
  \item Schedulable? \quad Success
  \item Error
\end{itemize}
Utilization-based Scheduling Selection

▶ Try ML. Need to satisfy the three constraints in ML.
Utilization-based Scheduling Selection

- Try DS-FP. Use the schedulability test condition invented in [Han, Chen, Xiong & Mok 08]
An Example: Mode 1 is schedulable under $HH$

Mode 1: $T_2: \{C_2=3, V_2=15\}$  $T_3: \{C_3=3, V_3=47\}$

$U_{HH} = \frac{2 \times C_1}{V_1} + \frac{2 \times C_2}{V_2} = 0.525 < 0.828$
Switch to **DS-FP** in mode 2 to increase schedulability

**Mode 2:**

- $T_1$: $\{C_1=2, V_1=6\}$
- $T_2$: $\{C_2=3, V_2=15\}$
- $T_3$: $\{C_3=3, V_3=47\}$

**Repeating pattern**

- Mode 2 is not schedulable under **ML** but has a repeating pattern under **DS-FP**
Switch to $ML$ in mode 3 to improve data quality

Mode 3:  

- $T_1$: $\{C_1=2, V_1=6\}$
- $T_2$: $\{C_2=3, V_2=15\}$
- $T_3$: $\{C_3=3, V_3=49\}$

$J_3, 0$ completes before $V_3/2$

- Mode 3 is schedulable under $ML$ but not $HH$
Scheduling Switch with Validity Constraint

▶ Major Challenges
  ▶ The temporal validity of the tasks persistent through the switch could be violated during the scheduling switch.
  ▶ How to choose the switch point to avoid these violations?
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▶ Clean Switch
  ▶ There is no outstanding execution from the old task set at the switch point.
  ▶ The new policy can schedule the new task set independently.
Scheduling Switch with Validity Constraint

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  ▶ The temporal validity of the tasks persistent through the switch could be violated during the scheduling switch.
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▶ Clean Switch
  ▶ There is no outstanding execution from the old task set at the switch point.
  ▶ The new policy can schedule the new task set independently.

▶ Non-clean Switch
  ▶ How to schedule the outstanding executions from the old task set?
Search-based Switch

Basic Idea:

- Strictly follows the clean switch requirements.
- We only need to check the temporal validity at the begin of each idle period.

$t_1$: $C_1=4$ $V_1=16$

$t_2$: $C_2=5$ $V_2=26$

MCR = 33

Switch Latency $T = 17$

$t_1 = 33$  $t_2 = 45$
Search-based Switch

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![Diagram showing the operation of the Search-based Switch with a timeline and data points.](image)
Search-based Switch

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Adjustment-based Switch

Basic Ideas:

- Takes every time point in \([t_{MCR}, t_{MCR} + t_L]\) as the candidate for scheduling switch.
- Converts the non-clean switch to clean switch scenario through schedule adjustment.
- Pushes all outstanding executions back to the switch point \(t_w\). Adjust the schedule in \([t_{MCR}, t_w]\) backwards from time \(t_w\) to guarantee the validity constraints.

![Diagram showing time points and schedule adjustments]

MCR = 33
Switch Latency \(T = 17\)
Each time is a candidate for scheduling switch

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Performance Evaluation

Simulation Model and Parameters

- Single CPU, main memory based RTDBS and up to 10 modes in the system.
- The number of real-time data objects in the system varies from 1 to 20.
- The validity length is uniformly distributed from 50 to 150 time units.
- the computational time is uniformly distributed from 1 to 5 time units.

Experiment Design

- Single scheduling policy vs. Online utilization-based scheduling switch (UBSS).
- Search-based Switch (SBS) vs. Adjustment-based Switch (ABS).

Performance Metrics

- CPU Utilization, Scheduling Success Ratio, Data Staleness, Scheduling Overhead and Switch Latency.
Success Ratio vs. CPU Utilization

- The success ratio drops along with the increase of the density factor.
- DS-FP performs the best.
- The CPU utilization of UBSS is between the ML and DS-FP.
- DS-FP and UBSS outperform ML.
Data Staleness Improvement with UBSS

Heavy System Workload vs. Light System Workload

![Graphs comparing heavy and light system workloads](image-url)
DS-FP and UBSS have the same scheduling success ratio.

UBSS greatly reduces the online scheduling overhead especially when the density factor is low.
Search-based vs. Adjustment-based Switch

- Switch scenario: DS-FP to ML
- $\mathcal{T}_{k+1} \subseteq \mathcal{T}_k$ and is specified by a given percentage $p$.
- ABS always outperforms SBS in terms of the switch success ratio
- ABS always has lower switch latency.
Conclusion

▶ We studied the problem how to maintain the temporal validity of real-time data in the presence of mode changes in flexible real-time systems.

▶ We proposed the online utilization-based scheduling switch (UBSS) to get the tradeoff between higher data quality and better schedulability.

▶ Two algorithms are proposed to search for the proper switch point online to maintain the data temporal validity during the transition.
Appendix: Search-based Switch Algorithm

Alg 1 Search-based Switch Algorithm

Input: $T_k, T_{k+1}, \Psi_k, \Psi_{k+1}$, the search start time $t_0$ and $t_L$.
Output: $t_w$.

1: for $t = t_0$ to $t_0 + t_L$ do
2: if $t = t_1$ then
3: // $t_1$ is the begin point of an idle period
4: $f = true$;
5: // Whether $t$ is a possible candidate for $t_w$
6: for each $\tau_i \in T_k \cap T_{k+1}$ do
7: $t_s =$ release time of $\tau_i$’s last job in $\Psi_k$;
8: $l =$ time to finish $\tau_i$’s first job in $\Psi_{k+1}$;
9: if $t - t_s + l > V_i$ then
10: $f = false$;
11: if $f = true$ then
12: return $t$;
13: return no $t_w$ exists;
Appendix: Adjust-based Switch Algorithm

Alg 1 Adjustment-based Switch Algorithm

Input: $T_k, T_{k+1}, \Psi_k, \Psi_{k+1}, t_0$ and $t_L$.

Output: $t_w$.

1: for $t = t_0$ to $t_0 + t_L$ do
2:   // $\sum_i \Gamma_i(t)$ is accumulated outstanding execution at $t$
3:   if $I(t_0, t) < \sum_i \Gamma_i(t)$ then
4:     continue;
5:   else
6:     // Adjust the schedule of $T_k$ in $[t_0, t]$
7:     $f =$ ScheduleAdjustment $(T_k, t_0, t)$;
8:     if $f =$ fail then
9:        continue;
10:    else
11:      for each $\tau_i \in T_k \cap T_{k+1}$ do
12:         $t_s =$ adjusted request time of $\tau_i$'s last job in
13:         $l =$ time to finish $\tau_i$'s first job in $\Psi_{k+1}$;
14:         if $t - t_s + l > V_i$ then
15:            // The temporal validity is violated.
16:            $f =$ fail;
17:         if $f =$ success then
18:            return $t$;
19:      return no $t_w$ exists;
Future Works

▶ Suppose the MCR latency requirement is infinite, if the old and new task sets are schedulable under the old and new scheduling policies respectively, does there exist a proper switch point using SBS or ABS?

▶ How to handle the situation when the proper switch point cannot be found?

▶ SBS and ABS are both synchronous algorithms. Can we design asynchronous algorithms? If so, how should scheduling switch be conducted?