Scheduling and Voltage Scaling for Energy/Reliability Trade-offs in Fault-Tolerant Time-Triggered Embedded Systems

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Paul Pop, Viacheslav Izosimov
August 23, 2007
Embedded Systems
Design of Embedded Systems

- Application model
- System platform model
- System-level design tasks
- Model of system implementation
- Software Hardware synthesis synthesis
- Analysis
Permanent faults are decreasing
Transient faults are increasing

From: Cristian Continescu, Trends and challenges in VLSI circuit reliability, 2003
- Tolerate faults gracefully
- Expressions for reliability for fault-tolerance

**Replication**

- PE₂
- PE₁
- P₁

**Re-execution**

- PE₂
- PE₁
- P₁
- P₁

**Passive Replication**

- PE₂
- PE₁
- P₁
Embedded Systems Model

- **Input**
  - Application
  - Architecture
  - Reliability goal: 0.999 999 999

\[ R_0 = 0.999 \, 981 \]

PE_1 PE_2
P_1 4 4
P_2 4 4
P_3 3 3
P_4 4 4
P_5 4 4

PE_1 PE_2

Deadline

Bus

1  2

k=1
Fault-Tolerant Scheduling

- Input
  - Application
  - Architecture
  - Reliability goal: 0.999 999 999
- Fault-tolerance for \( k=1 \) faults

\[
R_0 = 0.999 999 999 927
\]

Deadline

<table>
<thead>
<tr>
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<th>P_5</th>
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Bus

1 2

k=1
Fault-Tolerant Scheduling

- Fault tolerant scheduler
  - Full transparency
    - Good debugability
    - Little memory

Fully Transparent Scheduling

Only 1 fault
Fault-Tolerant Scheduling

- Can be done faster
  - Sacrifice local transparency

Fully Transparent Scheduling

Only 1 fault

Deadline

$P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5$
Fault-Tolerant Scheduling

- Can be done faster
  - Sacrifice local transparency
  - More complex online scheduler

Slack Sharing Scheduling

Only 1 fault

Deadline

PE1

PE2

Bus

m1

m2

PE1 PE2

P1 4 4
P2 4 4
P3 3 3
P4 4 4
P5 4 4

k=1
Fault-Tolerant Scheduling

- Even faster
  - Sacrifice all transparency
  - Schedule for each fault scenario

**Slack Sharing Scheduling**

<table>
<thead>
<tr>
<th>PE₁</th>
<th>P₁</th>
<th>P₂</th>
<th>P₁/2</th>
<th>P₄</th>
<th>P₅</th>
<th>P₄/5</th>
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<tr>
<td>PE₂</td>
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<tr>
<td>Bus</td>
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Deadline

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<tr>
<td>P₁</td>
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<tr>
<td>P₂</td>
<td>4</td>
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<td>P₃</td>
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<td>P₄</td>
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<td>P₅</td>
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</table>

PE₁ PE₂

k=1
Fault-Tolerant Scheduling

- Even faster
  - Sacrifice all transparency
  - Schedule for each fault scenario
  - At most $k$ re-executions

![Diagram showing PE1, PE2, P1, P2, P3, P4, P5 with a bus and deadline line. PE1 has P1, P1, P2, P4, P5 and PE2 has P3. Connections between P1 to P2 and P2 to P3 are shown with m1 and m2. The bus has a 1 and 2.]
Fault-Tolerant Scheduling

- Even faster
  - Sacrifice all transparency
  - Schedule for each fault scenario
  - At most $k$ re-executions

- \( k = 1 \)
Fault-Tolerant Scheduling

- Even faster
  - Sacrifice all transparency
  - Schedule for each fault scenario
  - At most $k$ re-executions
  - All faults information is shared

**Conditional Scheduling**

<table>
<thead>
<tr>
<th>PE₁</th>
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<th>P₂</th>
<th>P₄</th>
<th>P₅</th>
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</thead>
<tbody>
<tr>
<td>PE₂</td>
<td>P₃</td>
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<tr>
<td>Bus</td>
<td>1</td>
<td>2</td>
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</tbody>
</table>

Deadline

$P_1$ 4 4
$P_2$ 4 4
$P_3$ 3 3
$P_4$ 4 4
$P_5$ 4 4

$k=1$
Fault-Tolerant Schedulings

**Fully Transparent Scheduling**

<table>
<thead>
<tr>
<th>PE₁</th>
<th>P₁</th>
<th>P₁</th>
<th>P₂</th>
<th>P₂</th>
<th>P₄</th>
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<table>
<thead>
<tr>
<th>PE₂</th>
<th>P₃</th>
<th>P₃</th>
</tr>
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</table>

| Bus | 1   | 2   |

**Slack Sharing Scheduling**

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<tr>
<th>PE₁</th>
<th>P₁</th>
<th>P₂</th>
<th>P₃/4</th>
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<th>P₄/5</th>
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<table>
<thead>
<tr>
<th>PE₂</th>
<th>P₃</th>
<th>P₃</th>
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</table>

| Bus | 1   | 2   |

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<th>P₄</th>
<th>P₅</th>
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<table>
<thead>
<tr>
<th>PE₂</th>
<th>P₃</th>
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</table>

| Bus | 1   | 2   |

**Deadline**

- PE₁ PE₂
- P₁ 4 4
- P₂ 4 4
- P₃ 3 3
- P₄ 4 4
- P₅ 4 4

**k=1**
- Goal: minimise energy consumption
- Dynamic voltage scaling

<table>
<thead>
<tr>
<th>PE1</th>
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<tbody>
<tr>
<td>P1</td>
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<tr>
<td>PE2</td>
<td>PE2</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>100% $V_{ss}$</td>
<td>66% $V_{ss}$</td>
<td>33% $V_{ss}$</td>
</tr>
<tr>
<td>100% $E_0$</td>
<td>44% $E_0$</td>
<td>11% $E_0$</td>
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</table>
Energy Management

**Fully Transparent Scheduling**

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Deadline

k=1
Energy Management

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Deadline

100% E_0

\[ k=1 \]
Energy Management

**Fully Transparent Scheduling**

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Deadline

100% E₀

63% E₀
Energy Management

**Fully Transparent Scheduling**

- **PE₁**
  - P₁, P₂, P₄, P₅
- **PE₂**
  - P₃, P₃
- **Bus**
  - 1 → 2

**Deadline:** 100% $E₀$

**Slack Sharing Scheduling**

- **PE₁**
  - P₁, P₂, P₄, P₅, P₄/₅
- **PE₂**
  - P₃, P₃
- **Bus**
  - 1 → 2

**Deadline:** 63% $E₀$

**Conditional Scheduling**

- **PE₁**
  - P₁, P₂, P₄, P₅
- **PE₂**
  - P₃
- **Bus**
  - 1 → 2

**Deadline:** 38% $E₀$

$k=1$
Energy Management

**Fully Transparent Scheduling**

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Deadline:

- **Fully Transparent Scheduling**: 100% $E_0$
- **Slack Sharing Scheduling**: 63% $E_0$
- **Conditional Scheduling**: 38% $E_0$
Reliability and Energy

- Lower voltage
  - Critical energy is lowered
  - Probability of faults increases
  - Circuit operates slower
- Lower frequency
  - Longer execution time
  - Probability of faults increases
Exponential model

\[ \lambda(f) = \lambda_0 \frac{d(1-f)}{1-f_{\min}} \]
Energy Management

**Fully Transparent Scheduling**

```
PE₂  P₁ P₁ P₂ P₂ P₄ P₄ P₅ P₅
PE₁  P₃ P₃
Bus   1 2
```

**Deadline**

R=0.999 999 999 93
100% E₀

**Slack Sharing Scheduling**

```
PE₂  P₁ P₂ P₄ P₅ P₄/5
PE₁  P₃ P₃
Bus   1 2
```

R=0.999 999 999 25
63% E₀

**Conditional Scheduling**

```
PE₁  P₁ P₂ P₄ P₅
PE₂  P₃
Bus   1 2
```

R=0.999 999 958 208
38% E₀
Energy/Reliability Trade-off

- Reliability goal: 0.999 999 9

Deadline

R = 0.999 999 987
100% E₀

Voltage levels
N₁ 100% 66% 33%
N₂ 100% 66% 33%
k = 1

Product: G₁
PE₁

PE₂

Bus

1
2
- Reliability goal: 0.999 999 9
- Set reliability as hard constraint

Deadline

R = 0.999 999 878

68% $E_0$

Voltage levels

$N_1$ 100% 66% 33%
$N_2$ 100% 66% 33%

$k = 1$
- Reliability goal: 0.999 999 9
- Set reliability as hard constraint
- Trade-off 5% energy
- Meets reliability goal

Deadline

\[ R = 0.999\,999\,920 \]

73% \( E_0 \)
Problem Formulation

- **Input**
  - Application
  - Architecture
  - Reliability goal

- **Decide**
  - Fault-Tolerant Scheduling
  - Mapping
  - Fault-Tolerance Policy

- **While optimising for**
  - Energy
  - Under hard reliability goal
Problem is NP-Complete

- Normally solved using “best effort” heuristics

Use constraint logic programming

- Good performance with NP-completeness
- Optimal solutions are feasible
- Flexible model
- ECLiPSe-CLP
Comparison of Schedulers

Finishing time plot (k=1)

Finishing time plot (k=2)
Comparison of Schedulers

Energy Plot (k=1)

Energy Plot (k=2)

Reliability Plot (k=1)

Reliability Plot (k=2)
Reliability and Energy Trade-offs

Energy Plot ($k=1$)

Energy Plot ($k=2$)

Reliability Plot ($k=1$)

Reliability Plot ($k=2$)
Conclusions

- Design tool for doing
  - Fault tolerant scheduling
  - Mapping
  - Policy assignment
- Optimising for
  - Minimal energy
  - Hard constraints for timing and reliability
- Message:
  - Reliability can be met at little energy cost
Embedded Systems