Efficient Power Management Schemes for Dual-Processor Fault-Tolerant Systems

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Outline

- Background and Motivation
- System Models
- POED Algorithm
- Application to Energy Efficient Fault-Tolerant Real-Time Systems
- Simulation Results and Discussions
- Conclusions

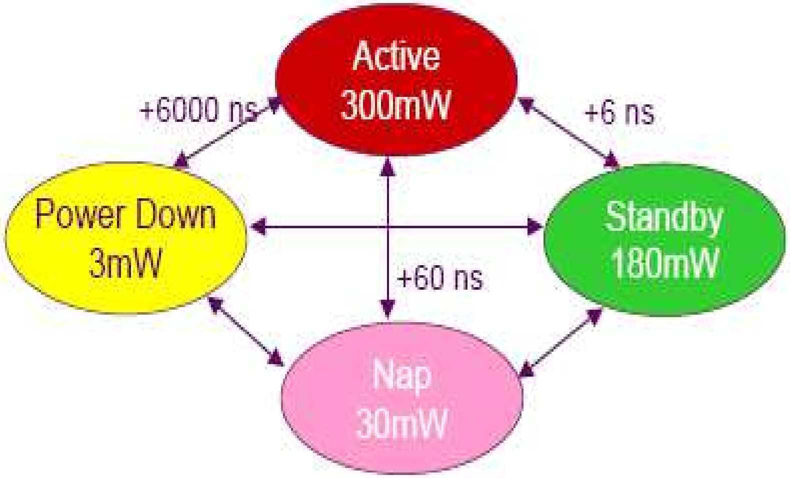
Energy is Precious: Everywhere!

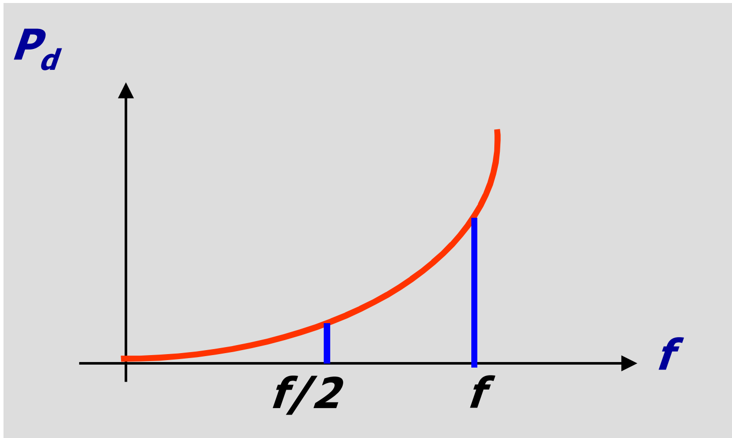
- **Popularity mobile devices**
  - **Smart phones: 492 million in 2011**
  - ***Battery* operated: limited capacity;**
    Smart phones: a few days
    Laptop: 3 – 10 hours

- **Data centers and servers**
  - **Excessive heat → cooling**
  - **Operation cost:**
    1.5% electricity in US (2007)
    → billion $

Power Reduction Techniques

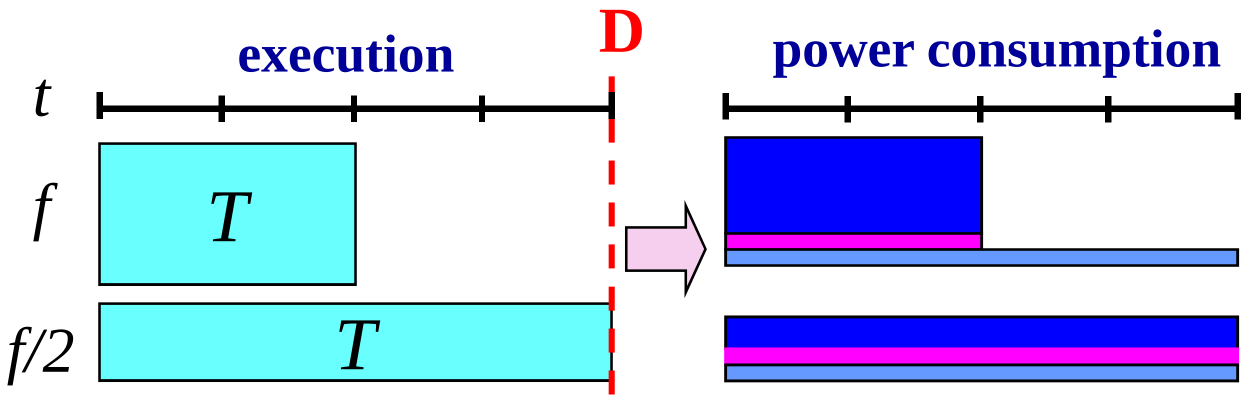
- LCD
  - Brightness; on/off
- Memory
  - Different power states
- Disks → SSD
  - Spin down
- CPU
  - *Voltage/frequency scaling*
  - Low power states: 1-5% of the peak power





A Simple System-Level Power Model

Example: **A real time task *T* needs 2 units with processing speed *f***



E = P * t;

Energy from:

P_s: the same;

P_{ind}: increases;

P_d: decreases

- **A simple system power model**

  $$P(f) = P_s + (P_{ind} + P_d) = P_s + P_{ind} + C_{ef} f^m$$

Minimum energy efficient frequency

$$f_{ee} = \left(\frac{P_{ind}}{c_{ef} \cdot (m-1)} \right)^{\frac{1}{m}}$$

[Zhu '06]

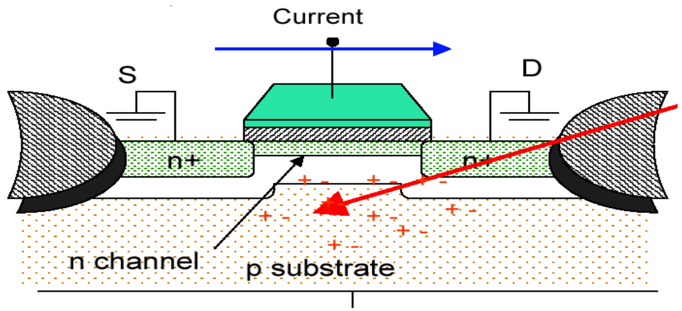
Fault-Tolerant System Design

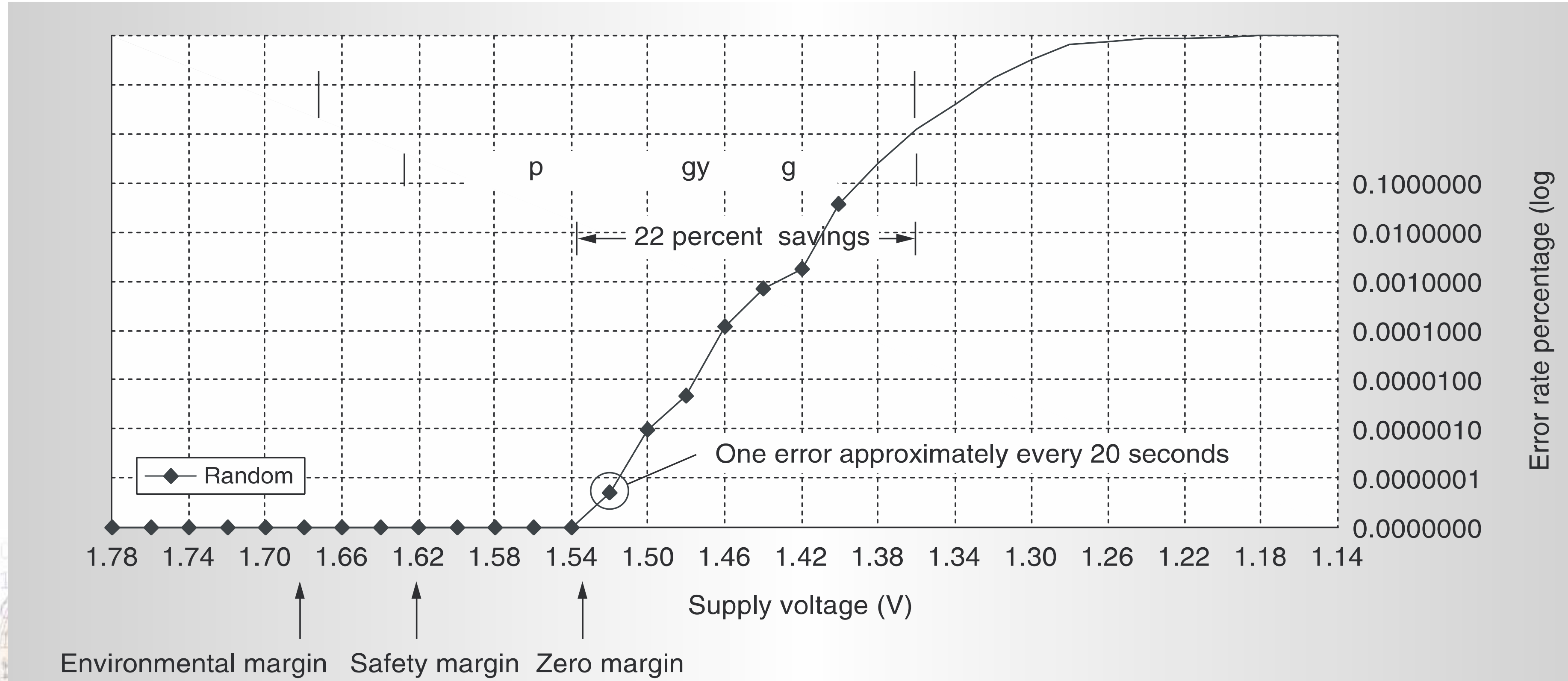
- **Faults**
  - **Transient fault**
    - ✓ **Temporary, will disappear**
  - **Permanent fault**
    - ✓ **System component → replacement/redundancy**

- **Techniques**
  - **Time redundancy**
    - ✓ **available system slack for recovery execution**
    - ✓ **only tolerate transient fault w/o permanent fault**
    - ✓ **task with utilization > 50% can not be managed**
  - **Hardware redundancy**
    - ✓ **Both transient & permanent fault (e.g., duplex, TMR system)**
    - ✓ **Tremendous energy consumption**

Transient Faults/Reliability *vs.* DVFS

- **Transient faults *vs. Critical charge* Q_{crit}**
  - **smallest charge needed to flip circuit states**





[Ernst-Micro-2004]

Figure 3. Measured error rates for an 18×18-bit field-programmable gate array multiplier block at 90 MHz and 27° C.

Co-Management of Energy and Reliability

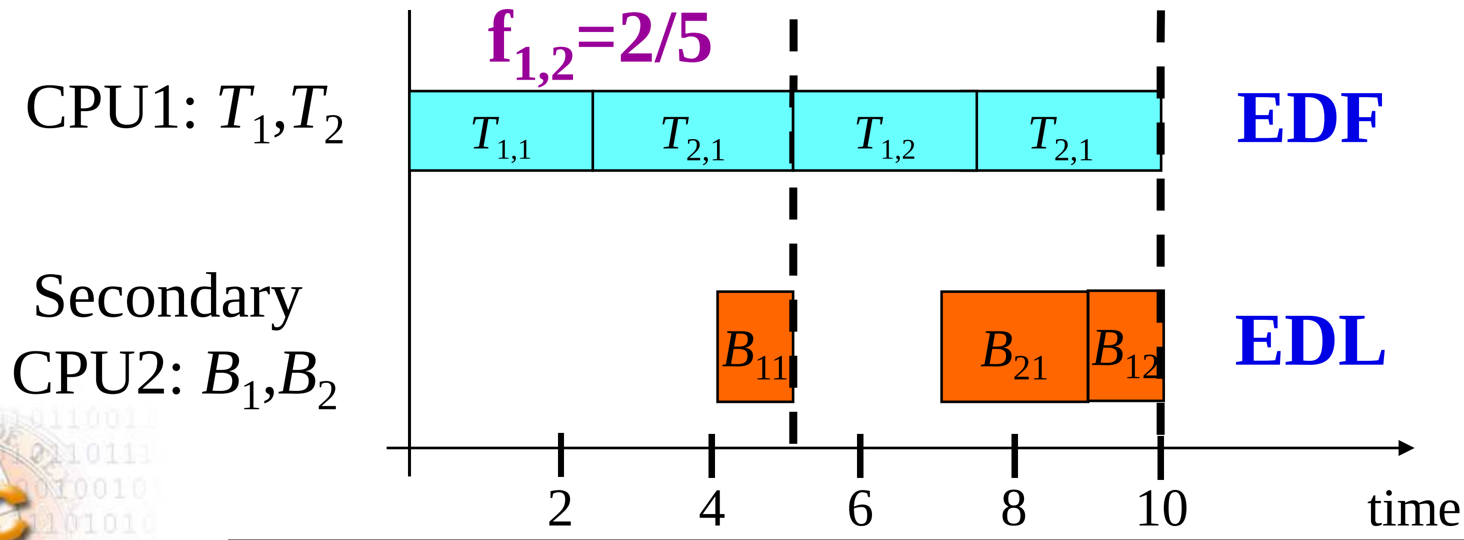
- **Reliability-Aware Power Management** [Zhu ’06, Qi ’11]
  - **low supply voltage (DVFS) → more transient fault**
  - **time redundancy**
- **Standby-Sparing** [Ejlali ’09] **and** [Haque ’11]
  - **dual-processor systems, aperiodic/periodic tasks**
  - **primary processor: primary tasks, DVFS**
  - **spare processor: backup tasks, DPM, deallocation**
  - **minimize the overlap between primary and backup**
  - **tolerate transient fault and one permanent fault**
- **Secondary Execution Time Shifting (SETS)** [Unsal ’09]
  - **periodic tasks**
  - **a mixed manner (P/B tasks)**
  - **static scheme to reduce overlap between primary and backup**

Application Model

- n periodic real-time tasks $\Psi = \{T_1, \ldots, T_n\}$;
- T_i: (c_i, p_i)
  - c_i : worst case execution time (WCET) at $f_{\max}$ ($f_{max} = 1$);
  - p_i: period;
  - WCET = c_i/f_i in a lower frequency;
  - $u_i = c_i/p_i$
  - $U = \sum u_i,\ i = 1, \ldots n$
- B_i: backup for T_i
  - same parameters (c_i & p_i)
  - no DVFS（transient fault）
  - different CPUs for T_i and B_i (permanent fault)

Problem to Solve

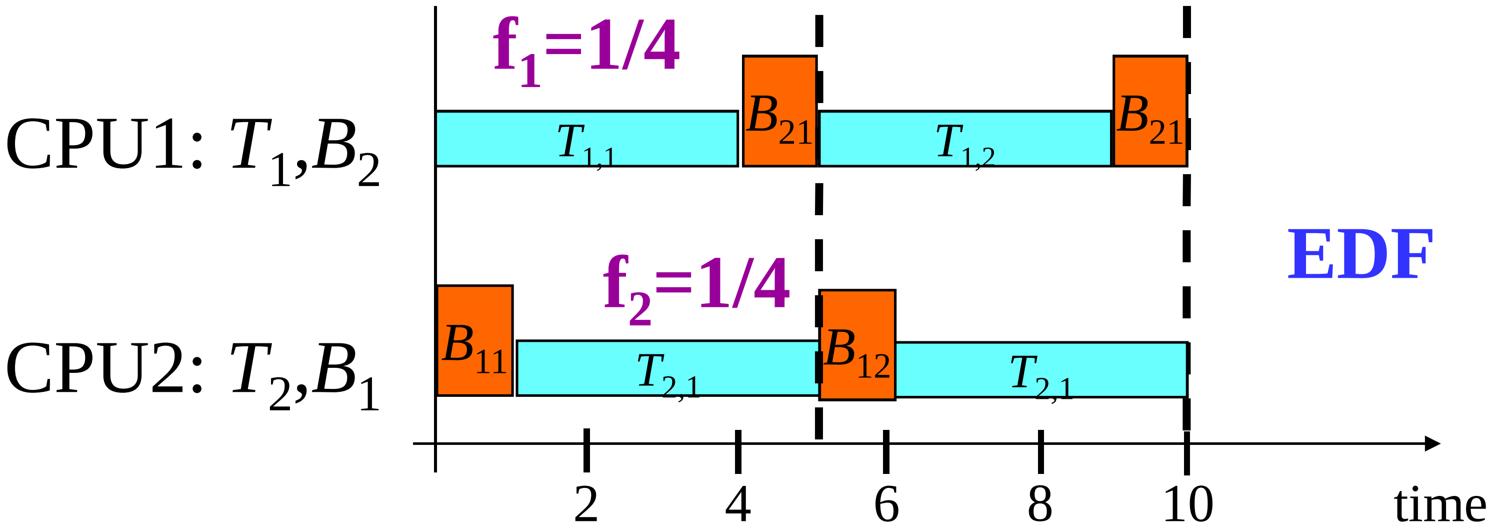
- **Hardware redundancy: Dual-CPU systems**
  - **Tolerate *a single permanent* fault**
  - **Tolerate transient faults**
- **Each task: *primary* & *backup* copies**
  - **Primary & backup need on *different* CPUs**
- **Standby-Sparing in Dual-CPU** [Haque '11]
  - **Example: $T_1(1, 5)$ and $T_2(2, 10)$**



Slack time on secondary CPU is wasted!

Mixed Allocation of P/B Tasks

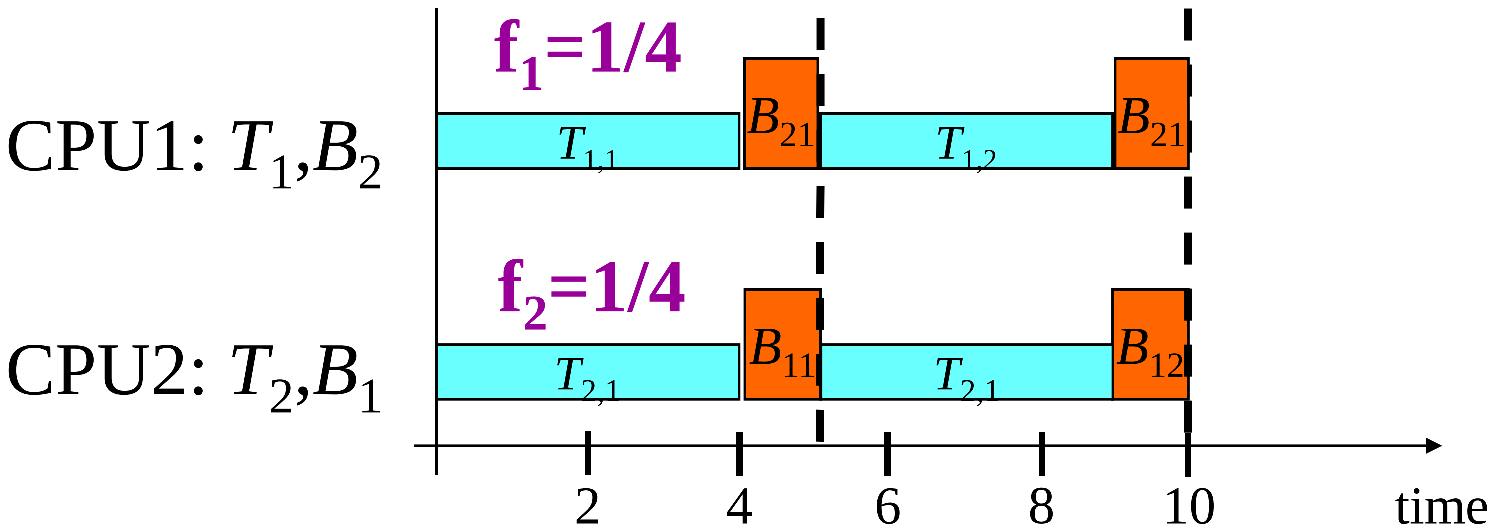
- **Each CPU gets a set of mixed P/B tasks**
  - **Scale down primary tasks**



Problem: backup tasks run concurrently with primary tasks → more energy consumption!

Differentiate Executions of P/B Tasks

- **P/B tasks: different preferences**
  - **Primary tasks: as soon as possible (*ASAP*)**
  - **Backup tasks: as late as possible (*ALAP*)**



Problem: how to efficiently schedule RT tasks with different *preferences* on each CPU?

RT Tasks with Preferences and Schedule

- **A set of *n* periodic tasks: $\Psi = \{T_1, \ldots, T_n\}$**
  - **Each task has a *preference*: *ASAP* or *ALAP***
  - **ASAP tasks (Ψ_S) & ALAP tasks (Ψ_L)**

$$\Psi = \Psi_S \cup \Psi_L$$

[Guo TR'12]

- **A feasible schedule of tasks**
  - **Schedule:** $S : t \rightarrow T_i, 0 \le t \le LCM, 1 \le i \le n$
  - **T_i is executed in time slot [t, t+1):** $S(t) = T_i$
  - **No deadline miss**

Accumulated ASAP/ALAP Executions

- **Accumulated ASAP execution *before* time t**

$$\Delta(S,t)=\sum_{z=0}^{t}\delta(S,z) \qquad 0\le t\le LCM$$

where $\delta(S,z)=1$ **if** $S(z)=T_i$ **and** $T_i\in\Psi_s$

- **Accumulated ALAP execution *after* time t**

$$\Omega(S,t)=\sum_{z=t}^{LCM-1}\omega(S,z) \qquad 0\le t\le LCM$$

where $\omega(S,z)=1$ **if** $S(z)=T_i$ **and** $T_i\in\Psi_L$

Optimal Preference-Oriented Schedules

- **An ASAP-optimal schedule:** S_{asap}^{opt}
  - **If S_{asap}^{opt} is a feasible schedule and, for any other feasible schedule S, there is:**

$$\Delta(S_{asap}^{opt}, t) \geq \Delta(S, t) \quad (0 \leq t \leq LCM)$$

- **An ALAP-optimal schedule:** S_{alap}^{opt}
  - **If S_{alap}^{opt} is a feasible schedule and, for any other feasible schedule S, there is:**

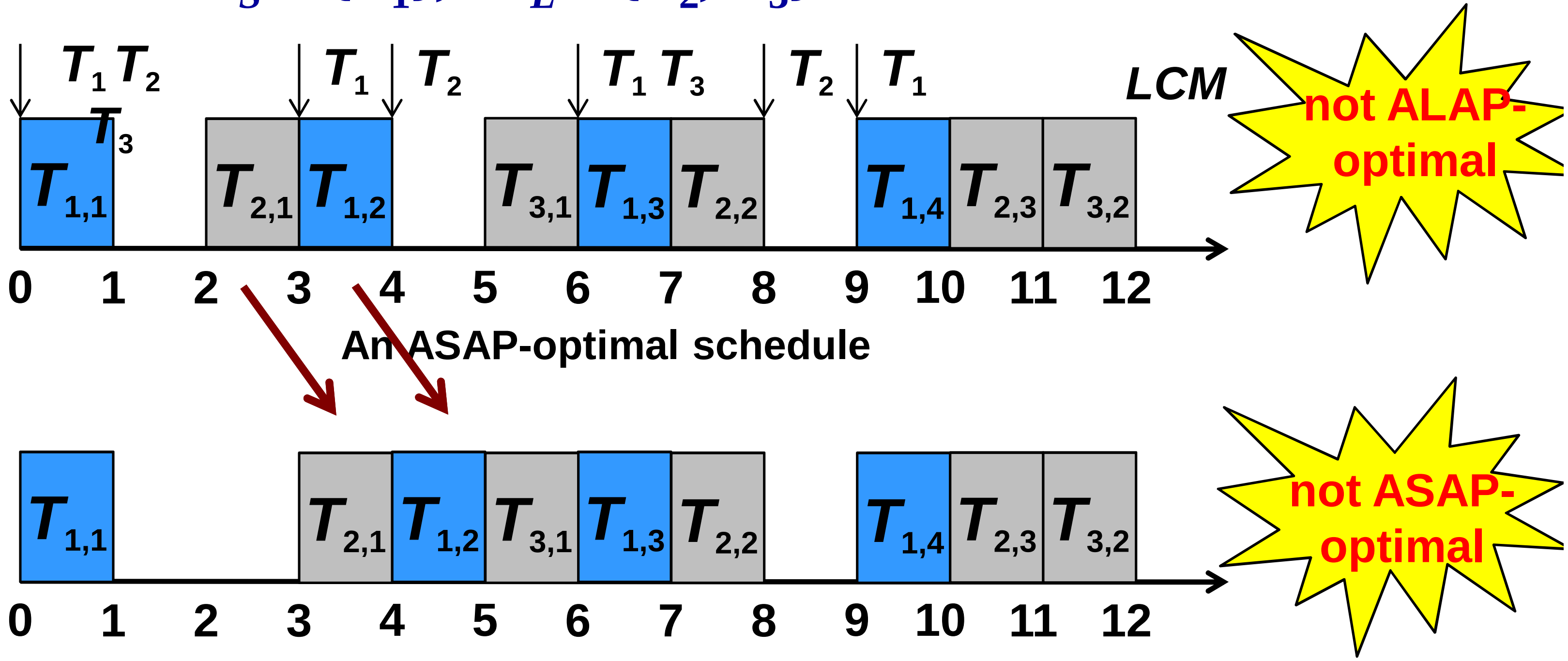
$$\Omega(S_{alap}^{opt}, t) \geq \Omega(S, t) \quad (0 \leq t \leq LCM)$$

- **An PO-optimal schedule:** S^{opt}
  - **If S^{opt} is a feasible schedule and, for any other feasible schedule S, there is:**

$$\Delta(S^{opt}, t) \geq \Delta(S, t) \text{ and } \Omega(S^{opt}, t) \geq \Omega(S, t) \quad (0 \leq t \leq LCM)$$

Optimal Schedules *vs.* System Loads

- $U < 1$: *discrepant* optimal schedules with idle time
  - Example: T_1 (1, 3), T_2 (1, 4) and T_3 (1, 6), $U = 0.75$ where $\Psi_S = \{T_1\}$, $\Psi_L = \{T_2, T_3\}$



An ALAP-optimal schedule

- $U = 1$: *harmonious* optimal schedules

Preference-Oriented Earliest Deadline Heuristic

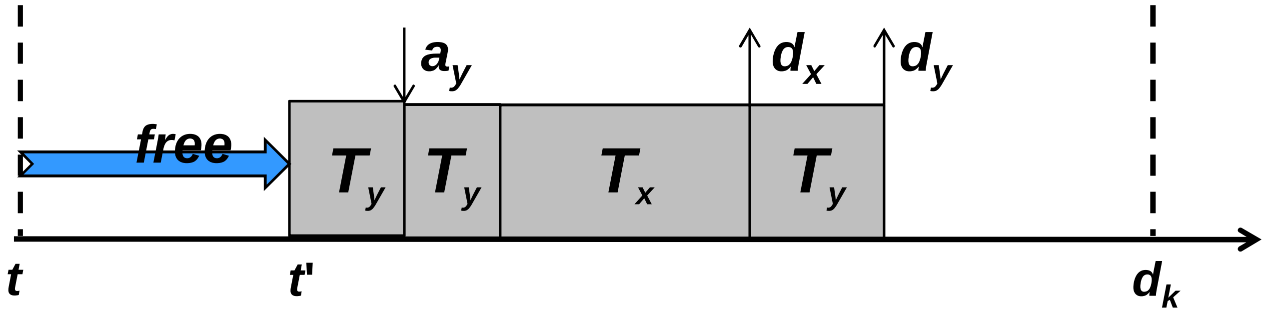
- **ASAP Scheduling Principle**
  - **At any time, if there are ready ASAP tasks, they should be executed first provided that such executions will not lead to deadline miss for ALAP tasks**
- **ALAP Scheduling Principle**
  - **If there is no ready ASAP tasks, CPU should idle provided that it will not lead to deadline miss for ALAP tasks**
- **Explicitly manage *idle time* with wrapper task** [Zhu '09]
  - **Idle time → *wrapper tasks* with deadlines**

Preference-Oriented Earliest Deadline Heuristic

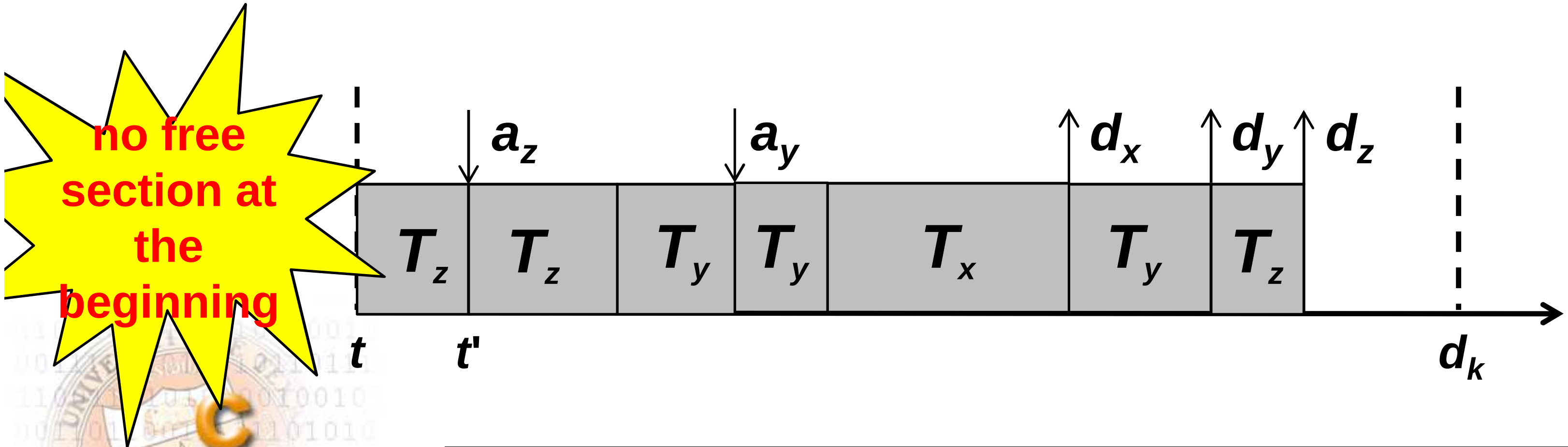
- **POED scheduling algorithm: at time *t***
  - **If T_k is a ready ASAP task with earliest deadline d_k, *check look-ahead interval* [t, d_k]**
    - ✓ **If there is free time, execute T_k (maybe wrapped execution)**
    - ✓ **Otherwise, urgent execute the earliest deadline ALAP task**
  - **If wrapper tasks T_x with deadline d_x (ASAP), *check look-ahead interval* [t, d_x]**
    - ✓ **If there is free time, execute T_x (CPU free)**
    - ✓ **Otherwise, urgent execute the earliest deadline ALAP task**
  - **No ASAP/wrapper tasks: execute ALAP tasks with EDF**

Look-Ahead Interval

- $Q_{la} = \{T_x, T_y\}, \quad T_x, T_y \in \Psi_L$



- $Q_{la} = \{T_x, T_y, T_z\}, \; T_x, T_y \in \Psi_L, \quad T_z \in \Psi_S$

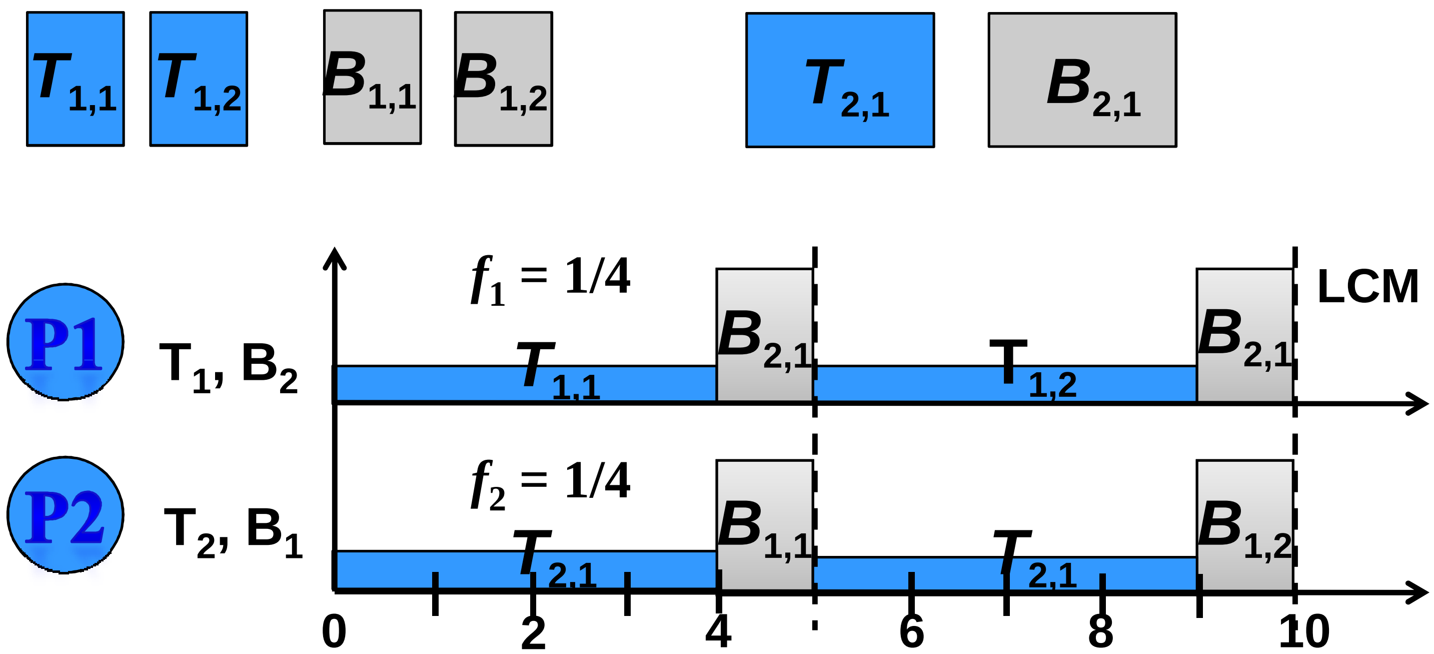


POED-Based EEFT on Duplex Systems

- **Steps:**
  - **map primary tasks to two CPUs (e.g., WFD)**
  - ***cross assign* backup tasks to CPUs**
  - **calculate scaled frequency for primary tasks on each CPU**
  - **on each CPU, execute tasks with the POED scheduler**
    - ✓ **Primary tasks have ASAP preference**
    - ✓ **Backup tasks have ALAP preference**
    - ✓ **When a task completes successfully on one CPU, notify other CPU to cancel its backup**
- **Online Extension**
  - **dynamic slack from task cancellation & AET << WCET**
  - **further slow down primary/delay backup**

An Example

- T_1 (1, 5) and T_2 (2, 10), U = 0.4



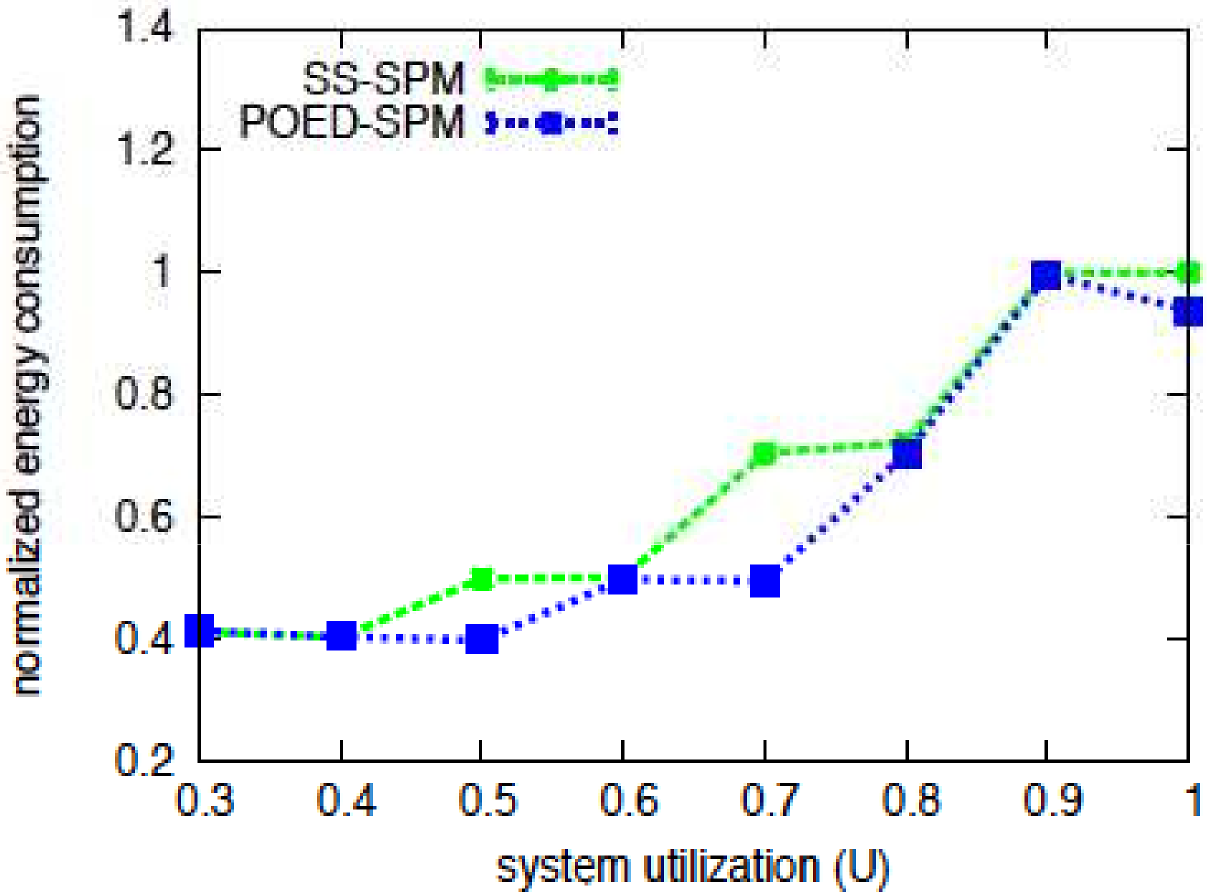
Simulation Settings

Power	P_s	0.01
	P_{ind}	0.1
	C_{ef}	1
	m	3
	frequency levels	0.4, 0.6, 0.8, 1.0
Application	Num Tasks/Task Set	10, 20, …, 100
	Utilization of Each Task	*UUniFast* scheme [Bini '04]
	Period of Each Task	$[p_{min}, p_{max}]$ uniform dist.
	p_{max}	100
	p_{min}	10
	Num Tasks Sets/Data Point	100
	U (static load)	0.3, 0.4, …, 1.0
	α_i (dynamic load)	Uniform dist. w/ average α
Processor	Num of Processors	2 (dual-processor system)

Schemes for Comparisons

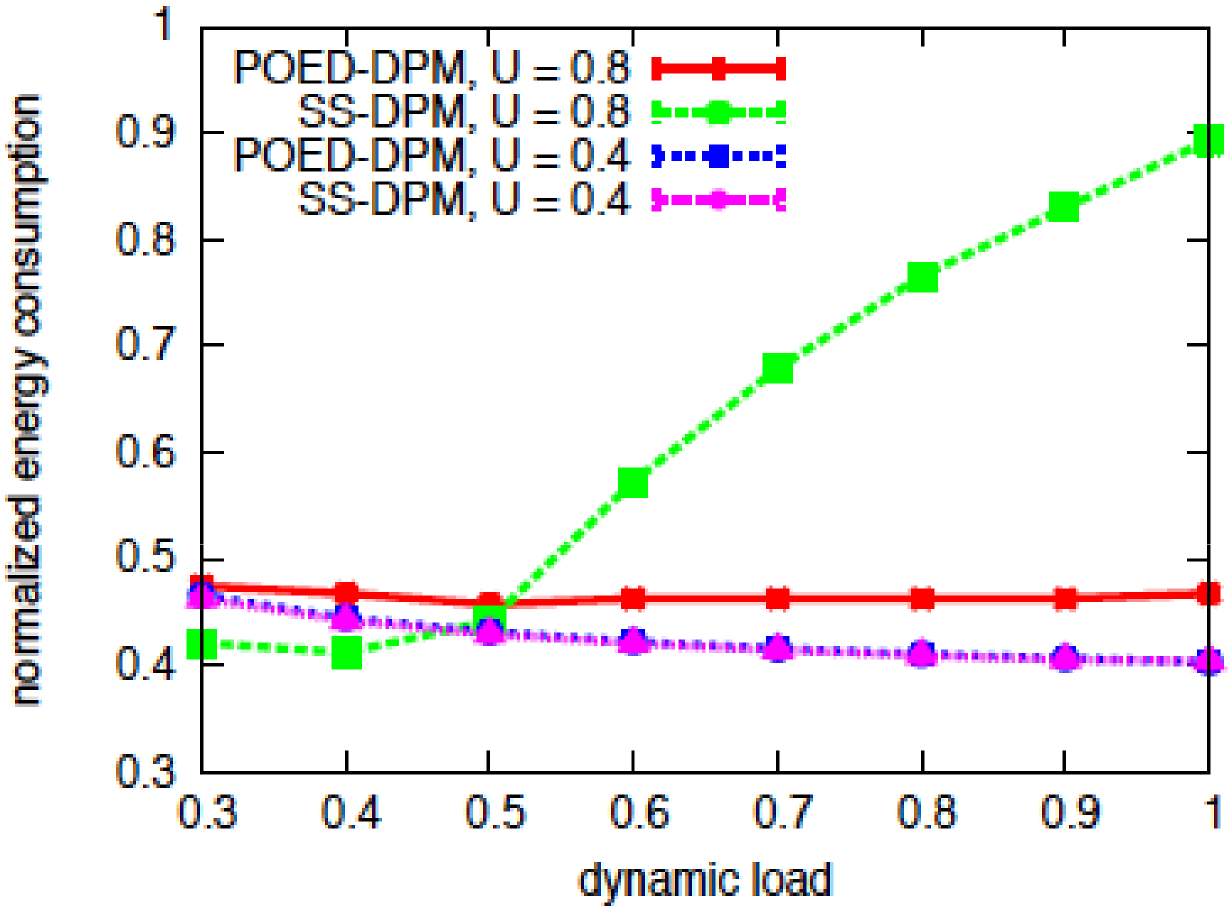
- **Baseline: *Basic-SS***
  - **Basic standby-sparing w/o scaled frequency**
- **Existing schemes for comparison**
  - ***SS-SPM***
    - ✓ **Standby-sparing w/ offline scaled frequency**
  - ***SS-DPM (ASSPT*** [Haque '11]**)**
    - ✓ **Standby-sparing w/ further scaled frequency using online slack**
- **Proposed schemes**
  - ***POED-SPM***
    - ✓ **POED w/ offline scaled frequency**
  - ***POED-DPM***
    - ✓ **POED w/ further scaled frequency using online slack**

Energy Savings: POED *vs.* Standby-Sparing



Normalized energy consumption *vs.* static load; 20 tasks per set

Energy Savings: POED vs. Standby-Sparing



Normalized energy consumption *vs.* dynamic load; 20 tasks per set

Conclusions & Future Work

- **POED-based EEFT for dual-processor systems**
- **Objective**
  - **co-management of energy with reliability**
- **Results**
  - **significant energy savings *vs.* standby-sparing**
- **Future work**
  - **Effects of additional DVFS transition**
  - **Multiprocessor system with more than two processors**

Thanks & Questions

http://www.my.cs.utsa.edu/~yguo