Thermal-Aware Energy Minimization for Real-Time Scheduling on Multi-core Systems

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1. INTRODUCTION

With exponentially increased transistor density on multi-core platforms, the power explosion and consequently soaring chip temperature have become critical challenges for system designers. Moreover, the increasing chip temperature results in higher leakage power, hence further aggravates the increment of the overall power consumption [1]. Thus, the dramatically growing power/energy consumption and chip temperature severely affect the cost, reliability and performance of the systems [4].

In this paper, we study the problem on how to minimize the overall energy consumption for a real-time schedule on multi-core platform with consideration of the interdependence between leakage and temperature. We first develop an analytical solution for energy calculation on multi-core systems, which has no computation of integration on power. Then, based on our energy calculation method, we propose an energy minimization algorithm to schedule real-time tasks on multi-core systems. Validation of our proposed scheme through experiments is a part of our future work.

The system models used in this work are briefly introduced below. We consider a multi-core platform consisting of m identical cores. Each core has n different *running modes*, each of which is characterized by a pair of supply voltage and working frequency. Let $\mathbf{S}$ represent a speed schedule, which indicates how to vary the frequency and voltage on each core at different time instants. We call an interval $[t_{q-1}, t_q]$ as a *state interval* if each core runs only at one running mode within that interval. Let s denote the total number of state intervals in $\mathbf{S}$, and let κ_q denote the running modes of all cores within the q^{th} state interval. The system power consumption at time t, denoted by $\mathbf{P}(t)$, can be formulated as [2]

$$\mathbf{P}(t) = \mathbf{\Psi} + \mathbf{\Phi} \cdot \mathbf{T}(t) \quad (1)$$

where $\mathbf{T}(t)$ represents the system temperature vector at time t, and $\mathbf{\Psi}$ and $\mathbf{\Phi}$ are constant matrices depending on the system running mode. Then the system thermal model can be formulated as [3, 5]

$$\mathbf{C}\frac{d\mathbf{T}(t)}{dt} + \mathbf{G}\big(\mathbf{T}(t) - T_{amb}\big) = \mathbf{\Psi} \quad (2)$$

where $\mathbf{C}$ is the system capacitance matrix, $\mathbf{G}$ is a comprehensive matrix with consideration of leakage power and system conductances, and T_{amb} is the ambient temperature. For a state interval $[t_{q-1}, t_q]$, once $\mathbf{T}(t_{q-1})$ is determined, based on equation (2), $\mathbf{T}(t_{q-1})$ can be solved by

$$\mathbf{T}(t_q) = e^{\mathbf{A}_{\kappa_q}\Delta t_q}\big(\mathbf{T}(t_{q-1}) - T_{amb}\big) + \mathbf{A}_{\kappa_q}^{-1}(e^{\mathbf{A}_{\kappa_q}\Delta t_q} - \mathbf{I})\mathbf{B}_{\kappa_q} + T_{amb} \quad (3)$$

where $\mathbf{A}_{\kappa_q} = -\mathbf{C}^{-1}\mathbf{G}_{\kappa_q}$, $\mathbf{B}_{\kappa_q} = \mathbf{C}^{-1}\mathbf{\Psi}_{\kappa_q}$, and $\Delta t_q = t_q - t_{q-1}$. Note that, bold text and normal text are respectively used for a vector/matrix and a value. Thus, given a schedule $\mathbf{S}$ and its initial temperature $\mathbf{T}(0)$, we can sequentially calculate the temperature at the end of each state interval.

2. OUR PROPOSED WORK

THEOREM 1. *Given a state interval $[t_{q-1}, t_q]$, let $\boldsymbol{T}(t_{q-1})$ and $\boldsymbol{T}(t_q)$ represent the temperature at time t_{q-1} and t_q, respectively. Then the system energy consumption within $[t_{q-1}, t_q]$ can be formulated by*

$$\boldsymbol{E}(t_{q-1}, t_q) = \Delta t_q \boldsymbol{\Psi}_{\kappa_q} + \boldsymbol{\Phi}_{\kappa_q}\boldsymbol{G}_{\kappa_q}^{-1}\Big(\Delta t_q \boldsymbol{\Psi}_{\kappa_q} - \boldsymbol{C}\big(\boldsymbol{T}(t_q) - \boldsymbol{T}(t_{q-1})\big)\Big) \quad (4)$$

From Theorem 1, we see that once the temperature trace of a schedule is determined, its energy consumption for each state interval can be rapidly calculated. Accordingly, the total system energy consumption for a schedule $\mathbf{S}$, denoted by $E_{total}(\mathbf{S})$, can be represented as

$$E_{total}(\mathbf{S}) = \sum_{q=1}^{s}\sum_{i=1}^{m} E_i(t_{q-1}, t_q) \quad (5)$$

Given a real-time task set and a multi-core system, let $\mathcal{S}$ represent the set of feasible schedules, i.e. $\mathcal{S} = \{\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_L\}$. Then, based on the energy calculation method, our energy minimization algorithm can be briefly described as: Find a schedule $\mathbf{S}_{k^*}$, $\mathbf{S}_{k^*} \in \mathcal{S}$, such that

$$E_{total}(\mathbf{S}_{k*}) = min\{E_{total}(\mathbf{S}_k)\big|\ k = 1, 2, ..., L\} \quad (6)$$

In the future, we plan to conduct extensive experiments to evaluate the accuracy of our proposed energy formulation technique, and estimate the performance of the proposed energy minimization method.

3. REFERENCES

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