A Stochastic Local Hot Spot Alerting Technique

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Overview

- Motivation and Background
- Uncertainty-Aware Estimation Frameworks
- The Proposed Hot Spot Alerting Algorithm
- Experimental Results
- Conclusion

Introduction

- As IC process geometries shrink below 65nm
  - Higher power density
  - Higher operating temperature
  - Lower circuit reliability
- Thermal control becomes a first-order concern
  - Gate oxide lifetime is highly dependent on the T_J of IC
  - Elevated temperature is a major contributor to lower IC reliability
- Local hot spots becomes more prevalent in VLSI
  - Non-uniform power density
  - Degraded supply voltage levels

➡ *Identifying and removing local hot spots is a major task*

Prior Works

- K. Skadron, et al. (ISCA 2003)
  - Architectural-level thermal model, *HotSpot*
- W. Huang, et al. (DAC 2004)
  - Compact thermal model for temp-aware design
- D. Brook, et al. (HPCA 2001)
  - Thermal control mechanism, *Wattch*
- J. Srinvasan, et al. (ICS 2003)
  - Predictive dynamic thermal management
- R. Mukherjee, et al. (DAC 2006)
  - Thermal sensor allocation and placement

Problem Statements

- Much past work has examined techniques for:
  - Thermal modeling
  - Thermal management
- Thermal modeling, based on equivalent circuit models
  - Cannot consider real structures that have complex shapes and boundary conditions
- Thermal management, depends on thermal sensors
  - Can hardly observe peak power dissipation and resulting peak temp. (due to non-uniform power density)

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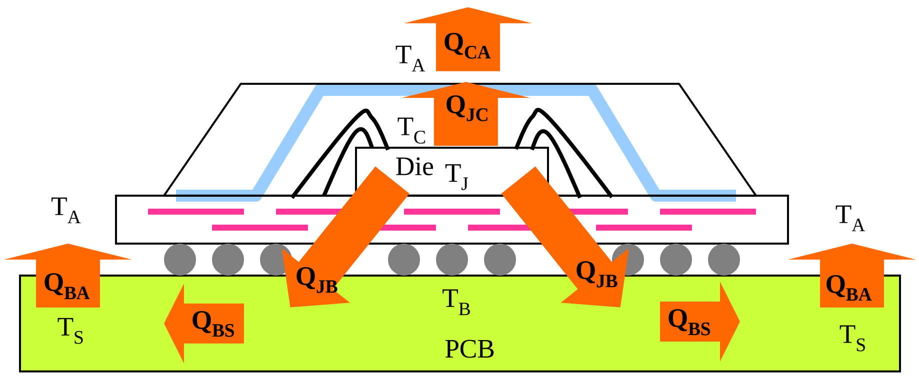
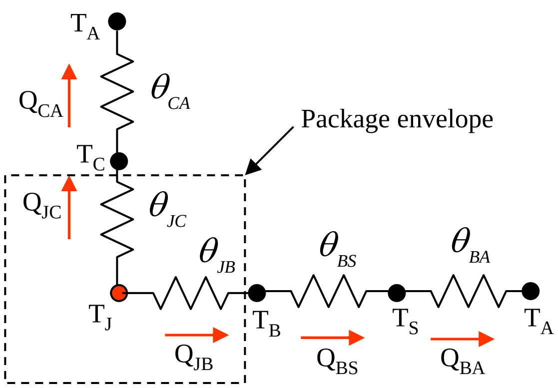
- Gives rise to uncertainty in profiling local hot spots
  - Renders the problem of identifying hot spots a stochastic one

Background (1/3)

- IC package can be characterized by thermal resistance
  - Heat is dissipated from the die into the ambient air
  - Value of the thermal resistance determines the temperature rise of the junction above a reference point



Heat flow in the PBGA + HS package



One of the IC package heat transfer paths and the corresponding thermal resistive model

Background (2/3)

- Thermal resistance is defined as

$$\theta_{JX} = (T_J - T_X) / P$$

  - θ_{JX} is the thermal resistance from device junction to specific point
  - T_J is the device junction temperature
  - T_X is the reference temperature for specific point
  - P is the device power dissipation

- When reference temperatures are specified for T_A, T_B, or T_C

$$\theta_{JA} = \frac{(T_J - T_A)}{P} \qquad \theta_{JB} = \frac{(T_J - T_B)}{P} \qquad \theta_{JC} = \frac{(T_J - T_C)}{P}$$

Junction-to-air — Junction-to-board — Junction-to-case

  - T_A, T_B and T_C are temperatures of ambient air, PCB board, and the case top

Background (3/3)

- Junction-to-air thermal resistance can be calculated as

$$\theta_{JA} = \left(\frac{1}{\theta_{JB} + \theta_{BS} + \theta_{BA}} + \frac{1}{\theta_{JC} + \theta_{CA}} \right)^{-1}$$

  - The junction temperature can be estimated with: $T_J = T_A + P \cdot \theta_{JA}$
  - The goal of thermal design is to maintain the θ_{JA} value small so that the junction temperature T_J does not exceed some specified maximum value

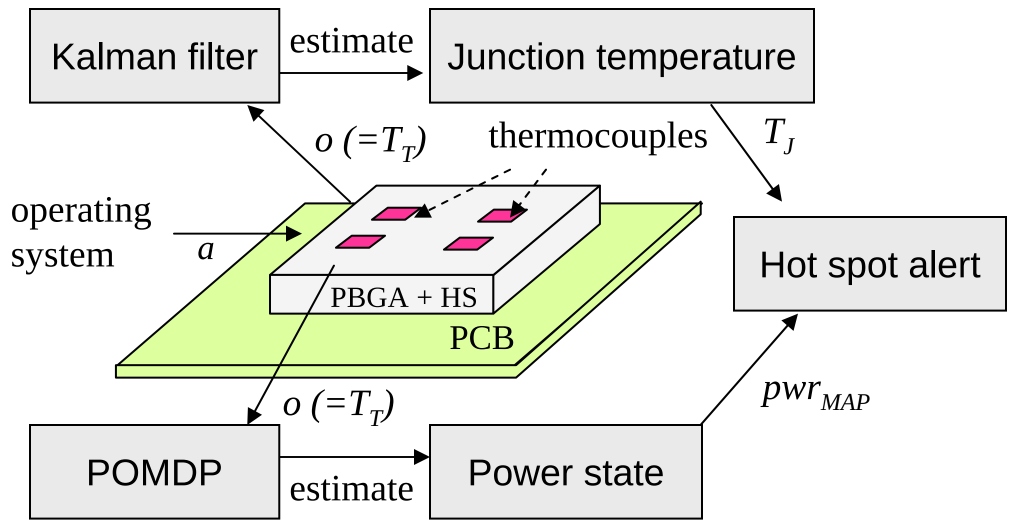
- θ_{JA} cannot be modeled directly due to the complexity of thermal models for package, cooling system, and board stack
  - θ_{JA} is assumed to be a single parameter under the assumption that P is distributed uniformly across the die: *not realistic*

Motivation

- Develop a hot spot alerting technique by estimating the *junction temperature* and the *system power state*
  - The thermal time constant of the die is larger than the circuit clock speed
  - Recognizing a temperature rise by relying on thermal sensors and subsequently employing thermal control mechanisms can result in too late a response
- Our proposed hot spot alerting technique combines:
  - State estimation for the junction temperature using Kalman Filter (KF)
  - State estimation for the system power dissipation using Partially Observable Markov Decision Process (POMDP)

Overview of Estimation Framework

- Use (external temperature) observations to estimate the *Junction Temperature* (T_J) and *the Power state* (pwr_{MAP})



Uncertainty-aware estimation framework

Temperature Estimation Framework

- Kalman Filter
  - Estimate the state of a system based on the previous state, previous action, and the current observation
- Kalman Filter-based Temperature Estimation (KFTE) Framework
  - *s* is a state representing the junction temperature T_J
  - *a* is a voltage-frequency assignment action given by an operating system
  - *o* is a temperature observation T_T
  - **X** denotes a state transition matrix
  - **Y** denotes an action-input matrix
  - **Z** denotes an observation matrix

$$s^{t+1} = \mathbf{X}s^t + \mathbf{Y}a^t + u^t, \quad u^t \sim N(0, Q^t)$$

u: temperature variation

$$o^{t+1} = \mathbf{Z}s^{t+1} + v^{t+1}, \quad v^{t+1} \sim N(0, R^t)$$

v: observation noise

Power Profile Estimation Framework (1/2)

- PODMP (Partially Observable Markov Decision Process)
  - To model the uncertainty in parameter observations

- POMDP is a tuple <*S, A, O, T, Z*> such that
  - *S* is a finite set of states
  - *A* is a finite set of actions
  - *O* is a finite set of observations
  - *T* is a state transition probability function
  - *Z* is an observation function

- POMDP maintains a *belief state,* $b^t(s)$
  - A probability distribution over the possible states of the system
  - $\sum_{s \in S} b^t(s) = 1$

Power Profile Estimation Framework (2/2)

- POMDP-based Power Profile Estimation (P3E) Framework
  - *b* is a belief state about power state of the system
  - *a* is an action input
  - *o* is an temperature observation
  - *T* is a state transition function
  - *Z* is an observation function

- Estimation of power state is performed by obtaining the maximum a posterior (MAP) value
  - Based on the Bayesian approach

Hot Spot Alerting Algorithm (1/4)

- Estimation of junction temperature of the chip
  - Assume that a thermal sensor receives streams of sensor data

Initialize

- Initialize noise & error variation: $Q^t = Q^0 \quad R^t = R^0 \quad E^t = R^0$
- Initialize the first state: $s^t = s^0$

Predict ($t \leftarrow t+1$)

- Predict the next state: $s_-^{t+1} = \mathbf{X} s^t + \mathbf{Y} a^t$
- Predict the error variance: $E_-^{t+1} = \mathbf{X} E^t \mathbf{X}^{\mathrm{T}} + Q^{t+1}$

Update

- Kalman gain: $\mathbf{K}^{t+1} = E_-^{t+1} \mathbf{Z}^{\mathrm{T}} (\mathbf{Z} E_-^{t+1} \mathbf{Z}^{\mathrm{T}} + R^{t+1})^{-1}$
- Update the state prediction with observation:

$$s^{t+1} = s_-^{t+1} + \mathbf{K}^{t+1} (o^{t+1} - \mathbf{Z} s_-^{t+1})$$

- Update the error variance: $E^{t+1} = (\mathbf{I} - \mathbf{K}^{t+1} \mathbf{Z}) E_-^{t+1}$

Junction temperature estimation

Hot Spot Alerting Algorithm (2/4)

- Estimation of power state of the system
  - Based on the Bayesian approach

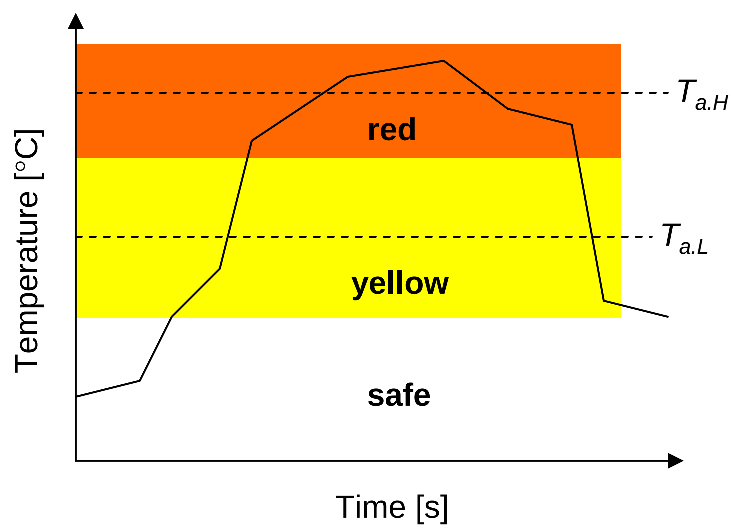
$$Prob(b^t \mid h^t) = \frac{Prob(h^t \mid b^t) \cdot Prob(b^t)}{Prob(h^t)}$$

  - *h* is a stream of action-observation pairs
  - *Prob*(b^t | *h*) is the posterior probability density function
  - *Prob*(h^t | b^t) is the likelihood function
  - *Prob*(h^t) is the prior distribution
  - *Prob*(b^t) is the probability of belief state
- The most probable power state can be computed as MAP

$$b_{MAP} = \arg\max_{b \in B} Prob(b^t \mid h^t) = \arg\max_{b \in B} Prob(h^t \mid b^t) \cdot Prob(b^t)$$
$$= \arg\max_{b \in B} Prob(a^{t-1}, o^t \mid b^t) \cdot Prob(b^t)$$

Hot Spot Alerting Algorithm (3/4)

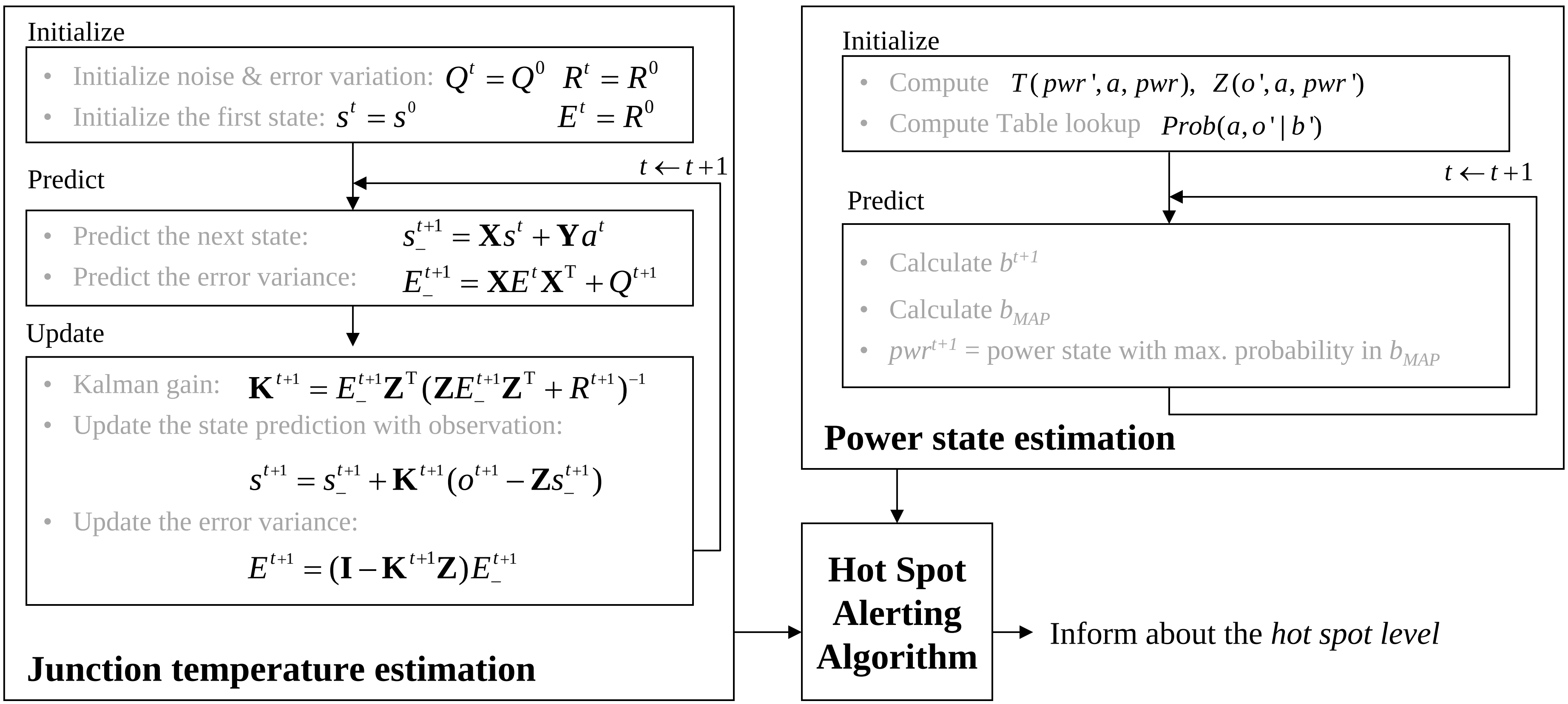
- The proposed hot spot alerting algorithm
  - Define *red* and *yellow* hot spot levels in terms of degree of thermal threat
  - $T_{a.H}$ and $T_{a.L}$ are pre-defined temperature thresholds ($T_{a.L} < T_{a.H}$)
  - P_a is a power dissipation threshold
  - $G_{j.a}$ is a temp. gradient threshold



do forever
predict the junction temperature, T_j^{t+1}
predict the power state of the processor, pwr^{t+1}
if $T_j^{t+1} \geq T_{a.H}$
alert *red* hot spot
else if $T_{a.L} \leq T_j^{t+1} < T_{a.H}$
if $pwr^{t+1} \geq P_a$
alert *red* hot spot
else
alert *yellow* hot spot
else
if $\partial T_j / \partial t \geq G_{j,a}$
alert *yellow* hot spot
return hot spot level

Hot Spot Alerting Algorithm (4/4)

- The flow of the proposed estimation technique



Experimental Setup

- The technique is applied to a 32bit RISC processor
- Set the parameter values for estimation framework

	power [W] state			observation [°C] state		
	pow_1	pow_2	pow_3	o_1	o_2	o_3
range	[0.6 1.4]	(1.4 2.2]	(2.2 3.0]	[86 93]	(93 100]	(100 107]

- PBGA package thermal performance data (T_A=70°C)

Air velocity		T_{J_max}[°C]	T_{T_max}[°C]	ψ_{JT} [°C/W]	θ_{JA} [°C/W]
m/s	ft/min				
0.51	100	107.9	106.7	0.51	16.12
1.02	200	105.3	104.1	0.53	15.62
2.03	300	102.7	101.2	0.65	14.21

[ψ_{JT} : Junction-to-top of package thermal characterization parameter]

Experimental Results (1/3)

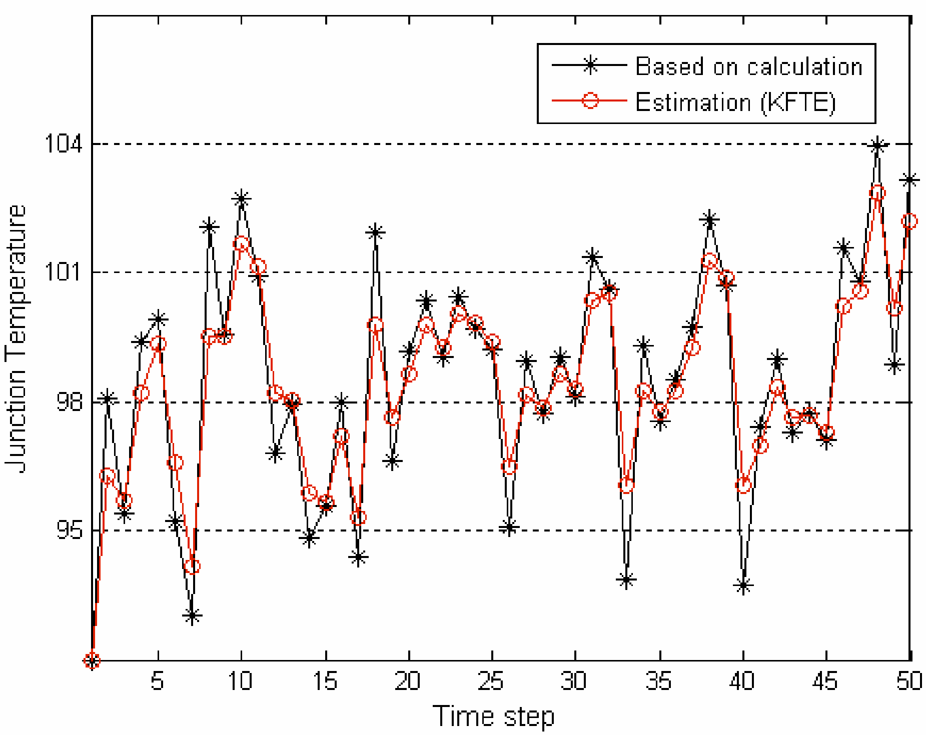
- Arbitrarily choose a sequence of 50 application programs
  - E.g., gap_1 - $gzip_2$ - gap_3 -gcc_4 -…- gap_{50}.

- Trace of estimation for the junction temperature
  - Calculation:

    We estimate T_T *by*

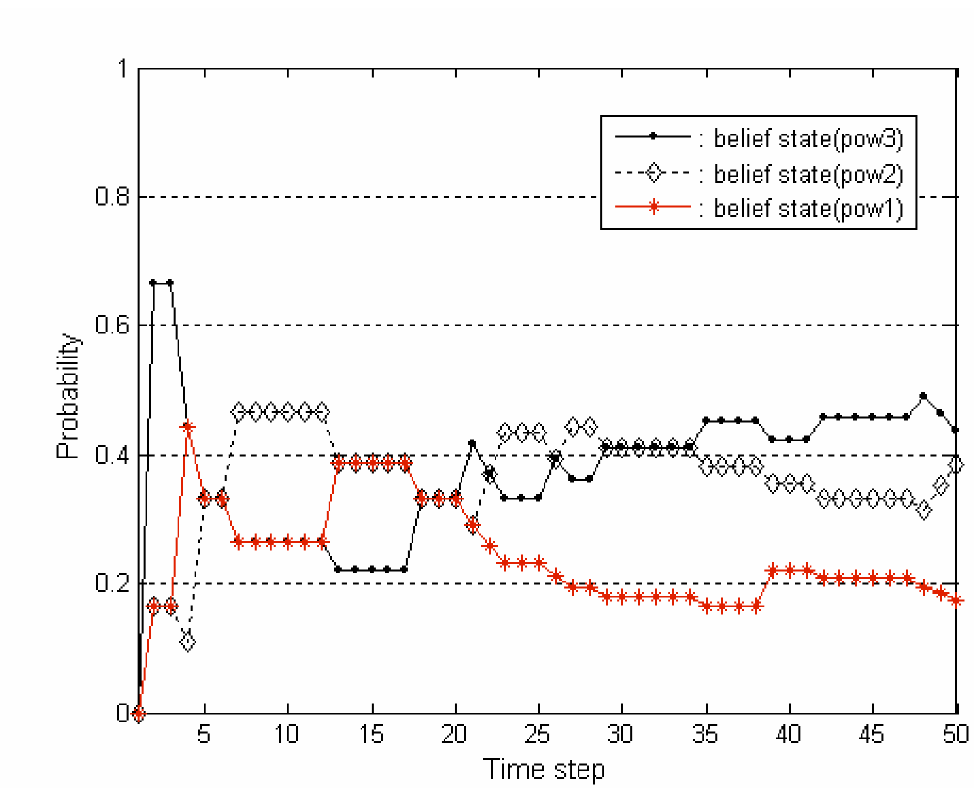
    $T_T = T_A + P \cdot (\theta_{JA} - \psi_{JT})$, where

    $P \sim N(P_{sim}, (\Delta P)^2)$
  - Estimation: We rely on KFTE



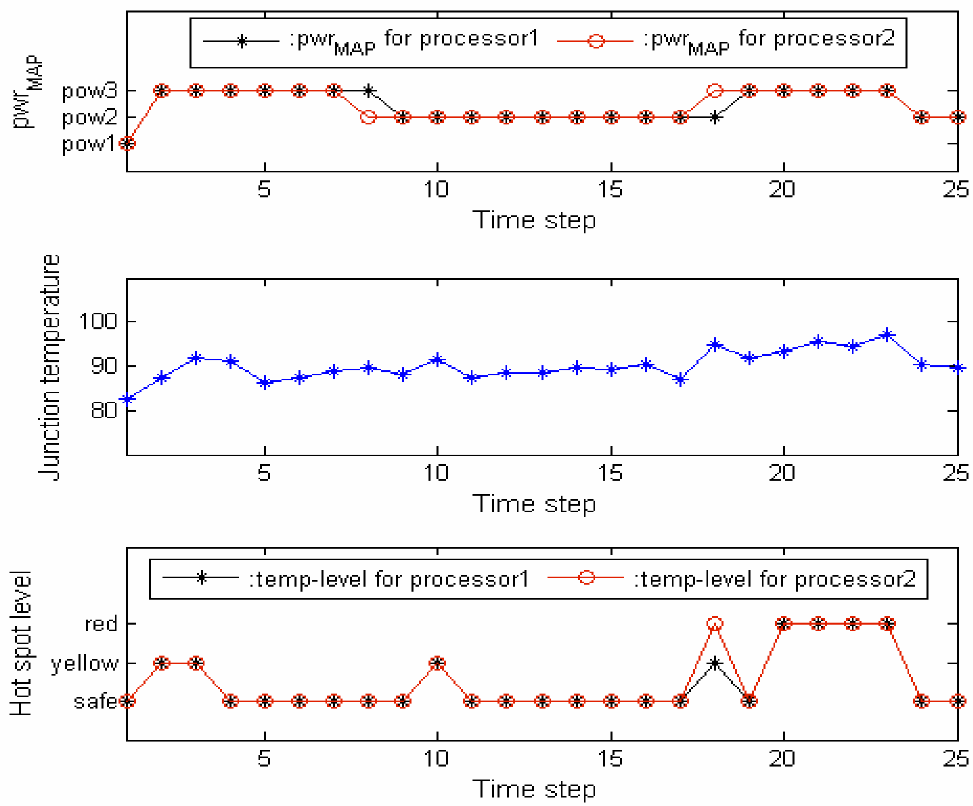
Experimental Results (2/3)

- Trace of belief state for the power state
  - e.g., belief state(pow_1): probability over power state pow_1
  - Evaluated by POMDP-based Power Profile Estimation (P3E) method



Experimental Results (3/3)

- Evaluation of the proposed hot spot alerting algorithm
  - Hot spot levels defined: *red*, *yellow*, and *safe*



Conclusion

- The stochastic hot spot alerting technique based on
  - Estimation of the junction temperature of the device
  - Estimation of the power state of the system
- The proposed uncertainty-aware estimation framework efficiently captures
  - stochastic behavior of the system
  - PVT variations in system performance parameters, and
  - inaccuracies in temperature measurements
- The ability to handle uncertainty improves the accuracy and robustness of the estimation technique
- Experimental results show that the proposed technique alerts thermal threats under large variations