Phone-nomenon: A System-Level Thermal Simulator for Handheld Devices

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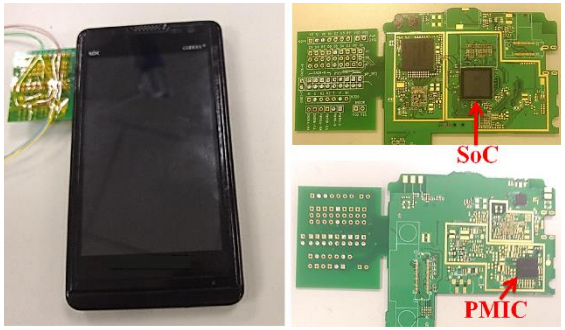
Outline

- Motivation
- Thermal model for handheld devices
  - Modeling for internal heat transfer effects
  - Modeling for boundary conditions
- Overall thermal simulation flow
- Experimental results
- Conclusions

Motivation (1/3)

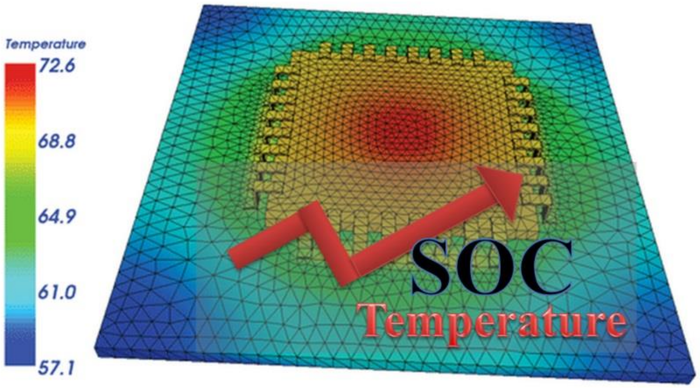


- The sales of handheld devices have surpassed that of PCs in 2011
- Relative high power consumption on small-form factor

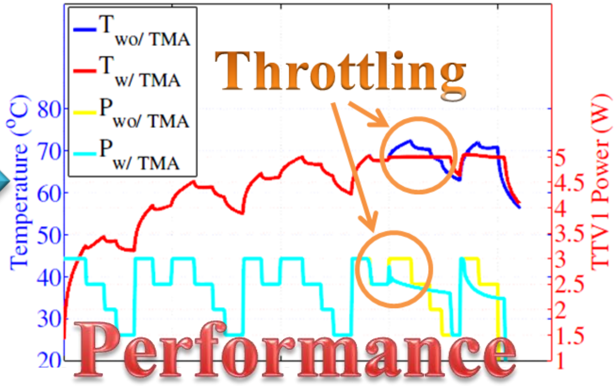
- Why consider thermal issues on smartphones
  - **Higher performance on application processors (AP)** (A4~A12, Exynos 4~9 Series, Snapdragon 200~850 Series, Helio P10~90)
  - **Cooling techniques**
    - PC: active cooling (fans, forced convection)
    - Smartphone: passive cooling (free air, free/nature convection)

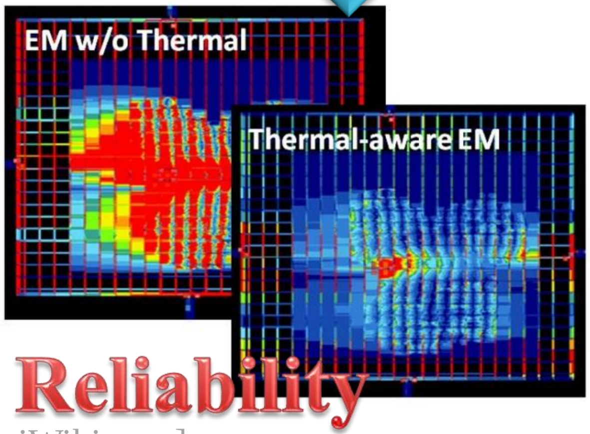
Motivation (2/3)

- When device executes heavy operations

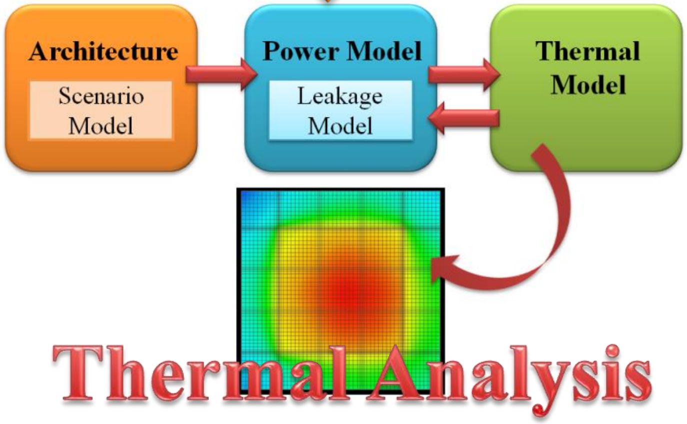


[Electronics cooling]

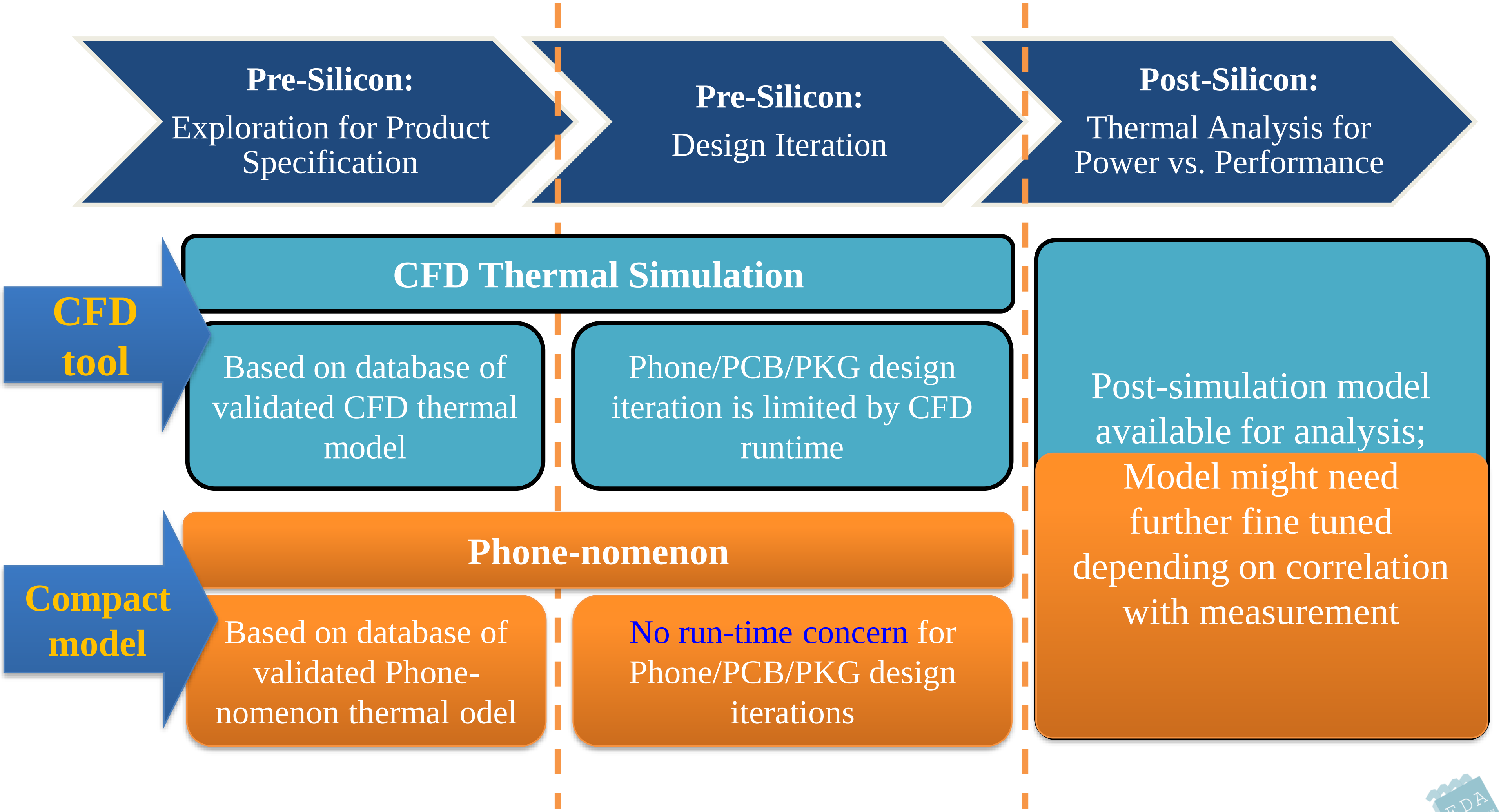




[SemiWiki.com]



Motivation (3/3)



Pre-Silicon:
Exploration for Product Specification

Pre-Silicon:
Design Iteration

Post-Silicon:
Thermal Analysis for Power vs. Performance

CFD tool

CFD Thermal Simulation

Based on database of validated CFD thermal model

Phone/PCB/PKG design iteration is limited by CFD runtime

Compact model

Phone-nomenon

Based on database of validated Phone-nomenon thermal odel

No run-time concern for Phone/PCB/PKG design iterations

Post-simulation model available for analysis;

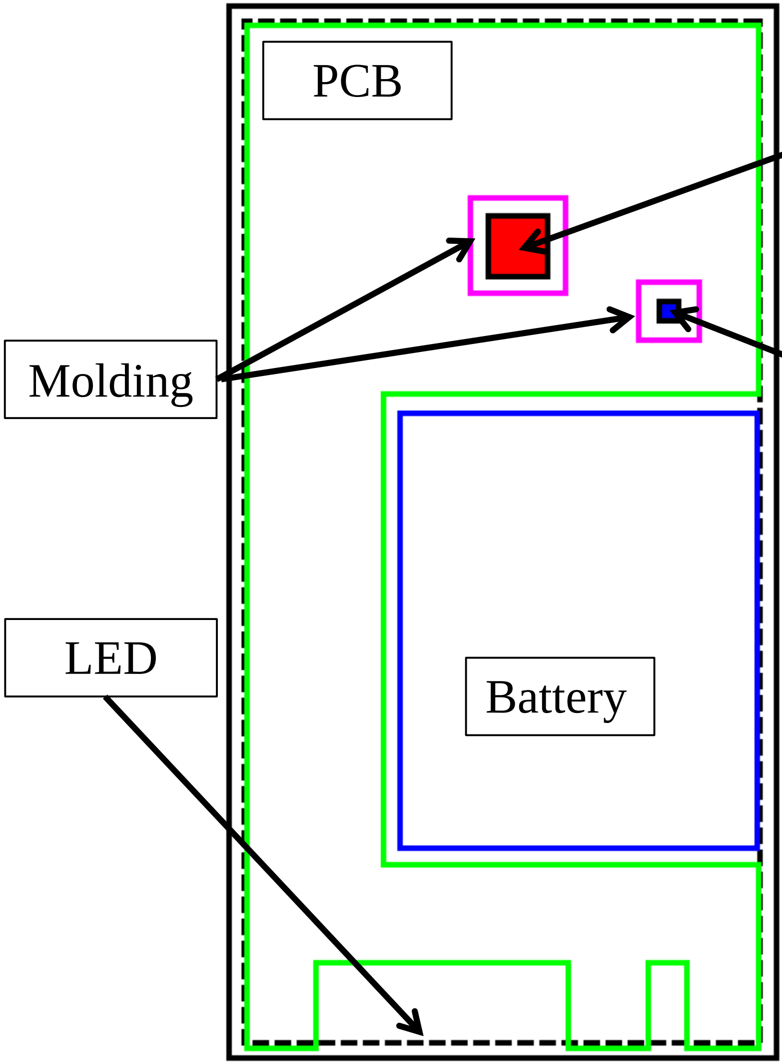
Model might need further fine tuned depending on correlation with measurement

Contributions

- Phone-nomenon considers the heat transfer mechanism around handheld devices
  - Internal heat transfer
  - External heat transfer
- Phone-nomenon builds an iterative framework thermal simulation flow
- Phone-nomenon can achieve two and three orders of magnitude speedup with 3.58% maximum error and 1.72°C difference for steady-state and transient simulations

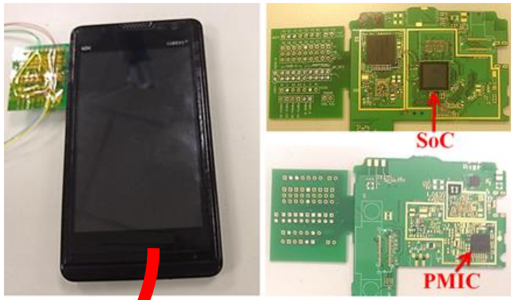
Handheld Device Architecture

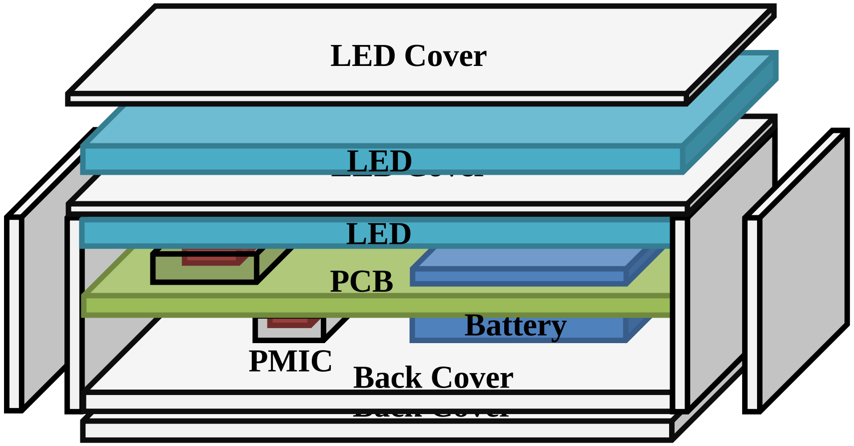
Thermal Test Vehicle



SoC (FCCSP) Die
Geometry:
7.62*7.62*0.075(mm^3)

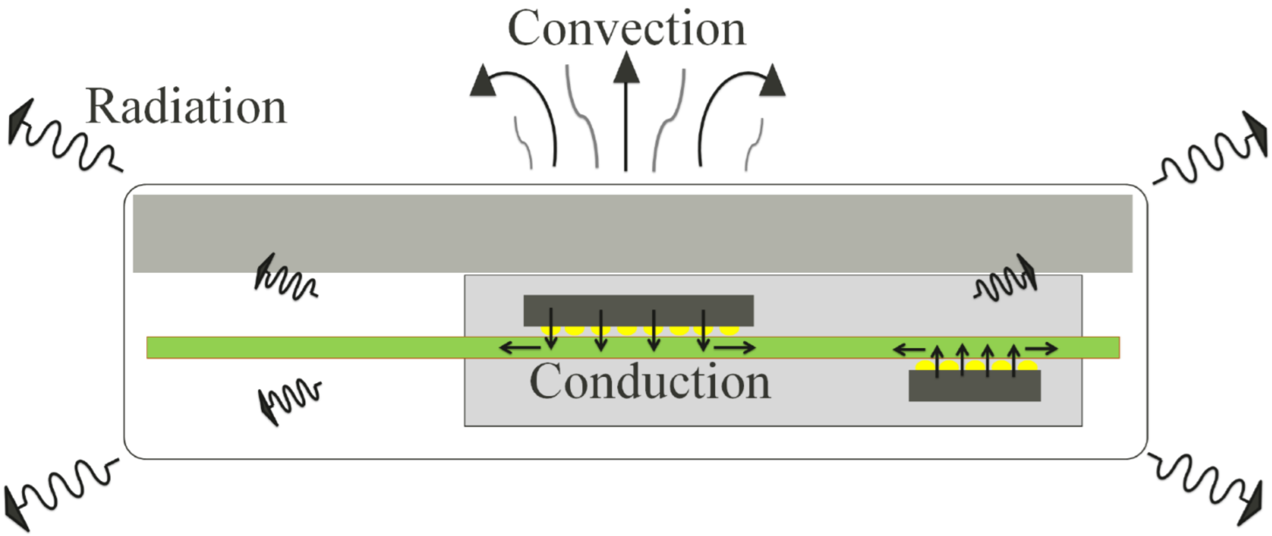
PMIC (TFBGA) Die
Geometry:
2.54*2.54*0.3 (mm^3)





Heat Transfer Mechanisms for Handheld Devices

- Internal heat transfer
  - Conduction, ~~convection~~, radiation
- External heat transfer
  - Convection, radiation

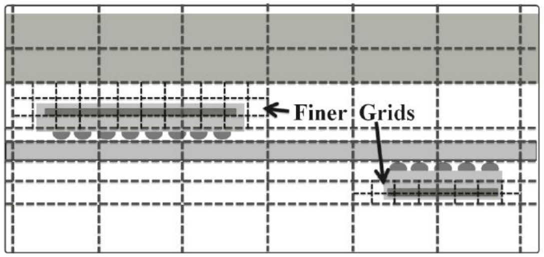


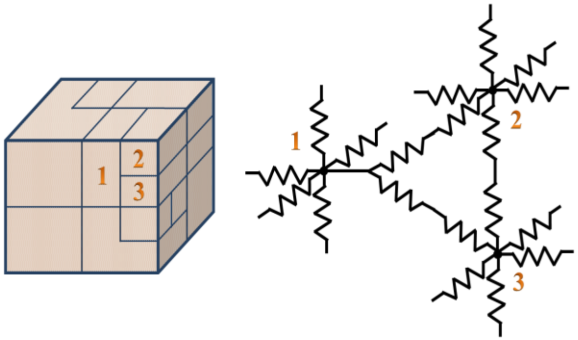
Internal Heat Transfer

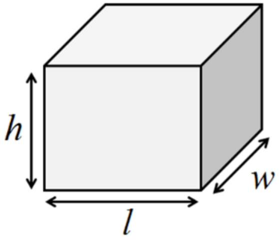
Conduction for Solid Structure

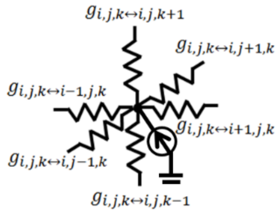
Circuit simulation **Thermal simulation**

Voltage (*V*) ←→ Temperature (*T*)
Current (*I*) ←→ Power (*P*)





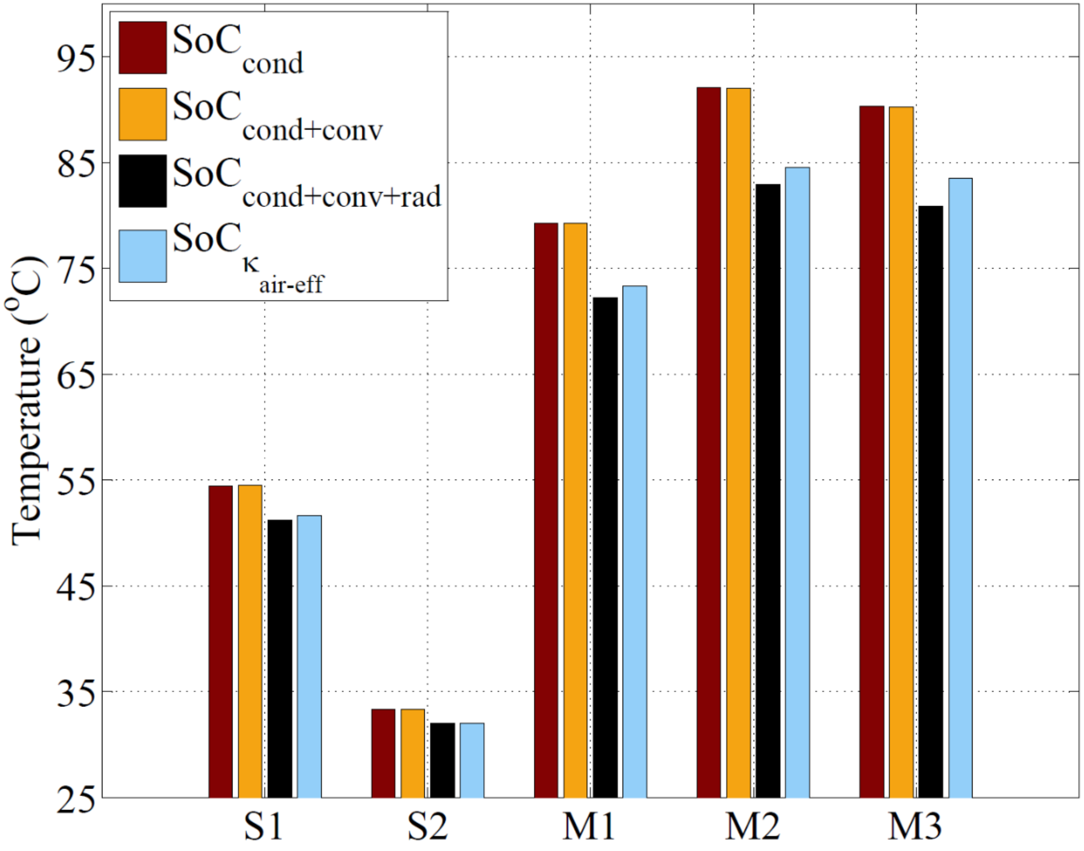


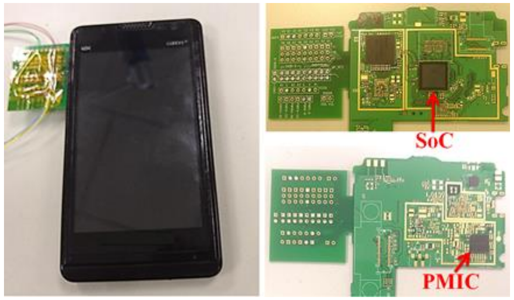


- **By using finite difference method, the heat transfer governing equation for conduction → $C\frac{dT}{dt} + GT = P$ in matrix form (C: heat capacitance, G: thermal conductance)**
- **By LU factorization and backward Euler on the time differential part, the temperature T can be solved**

Internal Heat Transfer

Why Considering Conduction and Radiation for Air





Case	Power (W) (SoC)	Power (W) (PMIC)
S1	1	0
S2	0	0.5
M1	1.5	0.7
M2	1.8	1
M3	2	0.5

The thermal effect of internal air in the smartphone. All results are obtained by Icepak

Internal Heat Transfer

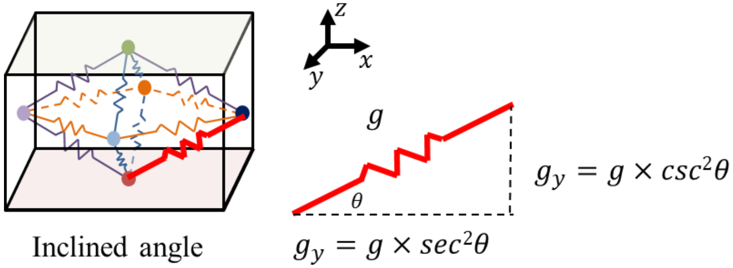
Conduction and Nature Convection for Air

- Conduction for air
  - The thermal conductivity of an air block is temperature dependent [1]
    - $\kappa_{air-cond} = -4.66 \cdot 10^{-3} + 1.68 \cdot 10^{-3} T_{air,K} - 3.73 \cdot 10^{-7} T_{air,K}^{2} + 6.94 \cdot 10^{-10} T_{air,K}^{3} - 6.13 \cdot 10^{-13} T_{air,K}^{4} + 1.97 \cdot 10^{-16} T_{air,K}^{5}$, where $T_{air,K} = T_{air} + 273.15$ is the air temperature in Kelvin.
    - Since $\kappa_{air-cond}$ for 80^{o}C is 14% more than 25^{o}C, we apply above equation into our model
- Nature convection for air
  - Rayleigh number (Ra) which is described as nature convection
  - Ra is much less than 1708 in most smartphones and scenarios, therefore no need to consider this effect

Internal Heat Transfer

Thermal Radiation for Air

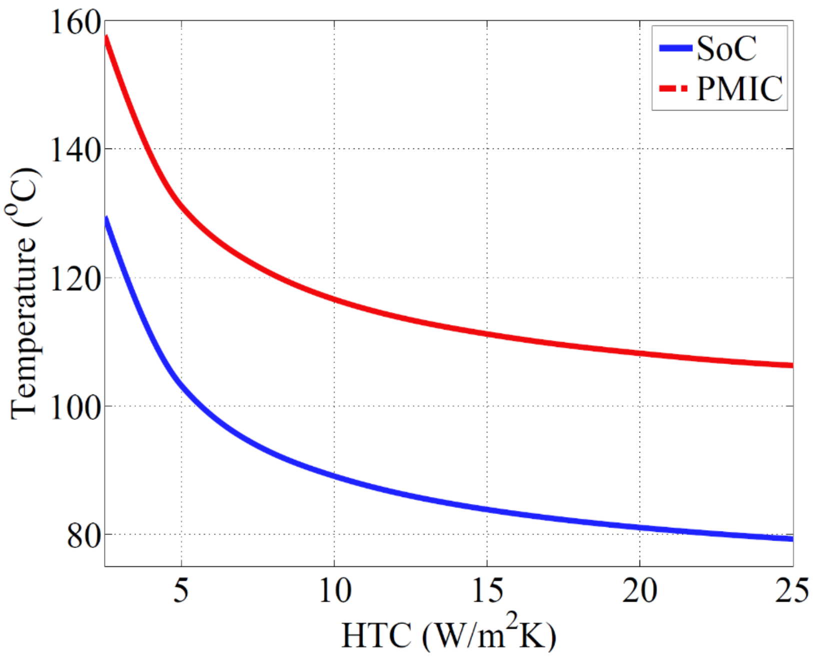
- We develop a thermal resistive network to consider the thermal radiation
- Heat flux between plates
  - $q_{ij} = \sigma F_{ij} A_i \left| {T_i}^4 - {T_j}^4 \right|$



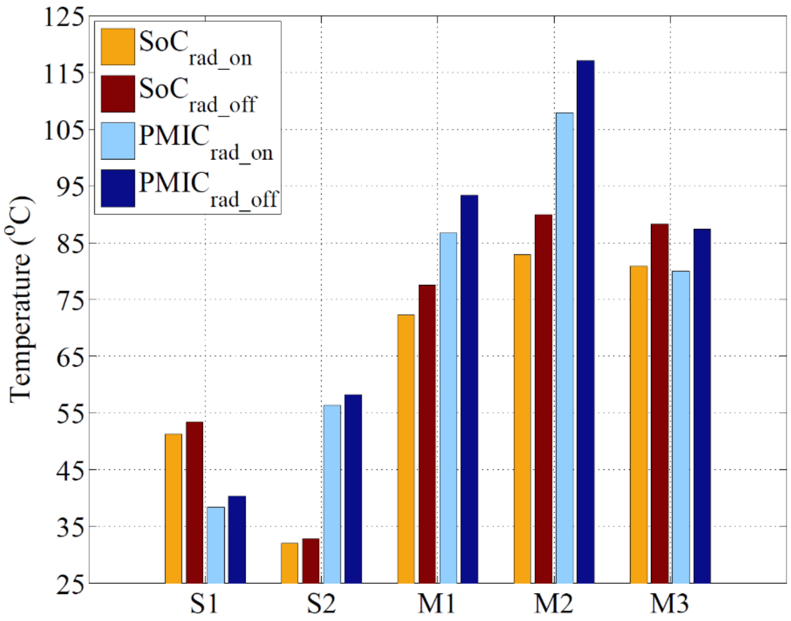
- Thermal equilibrium equation
  - $q_{ij} = g_{ij} \left| T_{i,K} - T_{j,K} \right|$ (i.e. $q = g\Delta T$)
- Air effective thermal conductivity (ETC) for radiation
  - $g_{ij} = \frac{F_{ij} A_i \sigma \left({T_i}^4 - {T_j}^4 \right)}{\left(T_i - T_j \right)}$
- By combination of series and parallel circuits
  - $\kappa_{air-rad}$

External Heat Transfer (B.C.)

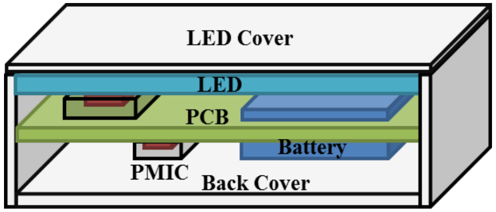
Why Considering Conduction and Radiation for Air



Chip temperature versus effective HTCs. The power values of SoC and PMIC are 1.8W and 1.0W, respectively.



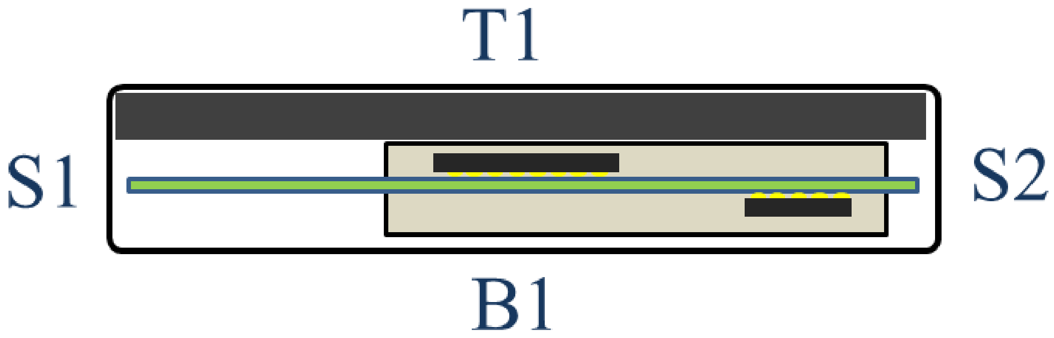
The influence of external thermal radiation effect for five test cases.



External Heat Transfer (B.C.)

Nature Convection [2]

- Effective HTCs (convection) between covers and air
- For four vertical sides (S1~S4): $Nu = 0.68 + \frac{0.67Ra^{1/4}}{\left(1+(0.492/Pr)^{9/16}\right)^{4/9}}$
- For top side (T1): $Nu = 0.54Ra^{1/4}$
- For bottom side (B1): $Nu = 0.27Ra^{1/4}$
- Effective HTCs: $h_{b,conv} = \frac{k_{air}}{L} Nu$



External Heat Transfer (B.C.)

Thermal Radiation

- Energy released by the oscillations of electrons in matter (electromagnetic wave emits)
- Subsequent transport does not require any presence of any matter
- Effective HTCs (radiation) between covers and air
- For each side (S1~S4, T1 and B1) Effective HTCs $h_{b,rad} = \alpha e\left(T_{b,K} + T_{\infty,K}\right)\left({T_{b,K}}^{2} + {T_{\infty,K}}^{2}\right)$ [2]

α is Stefan Boltzmann constant : $5.673 * 10^{-8} W m^{-2} K^{-4}$
e is emissivity : 0.72~0.9

Internal/External Heat Transfer

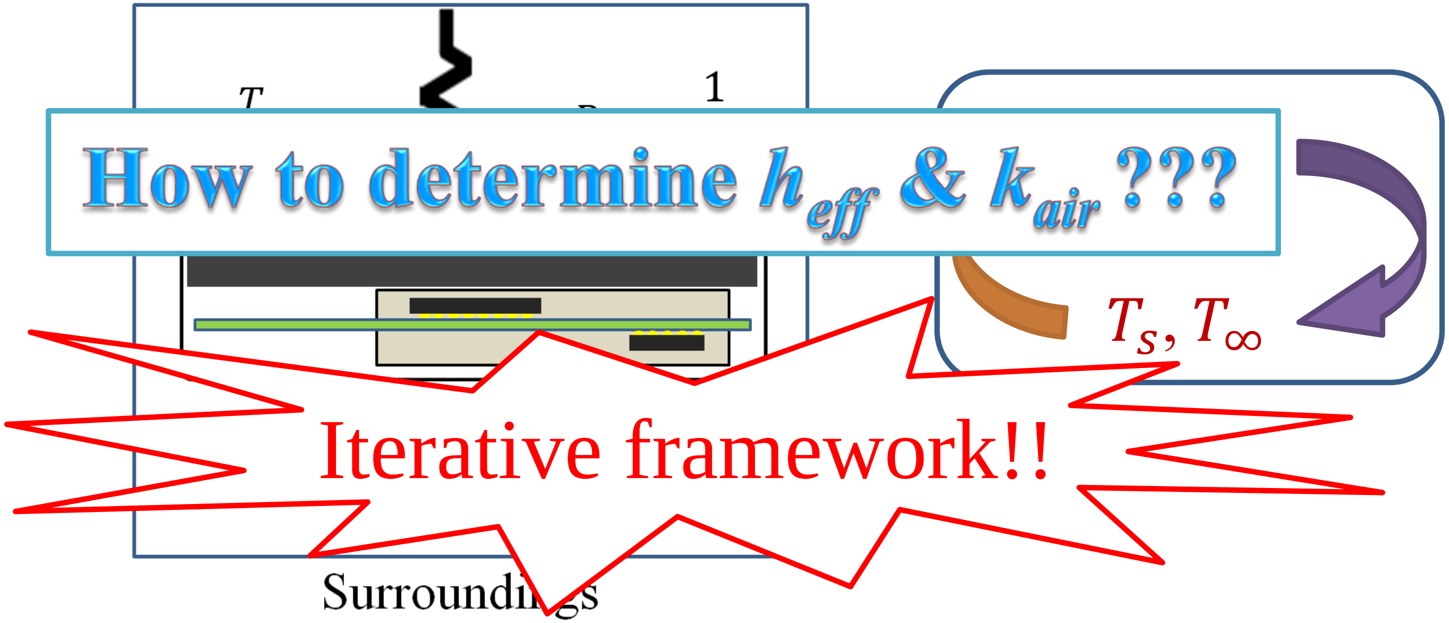
Summary

- Combine convection and radiation for inside air block

$$\text{ETCs: } k_{air}(T_{b,K}) = \kappa_{air-cond} + \kappa_{air-rad}$$

- Combine convection and radiation on the boundaries

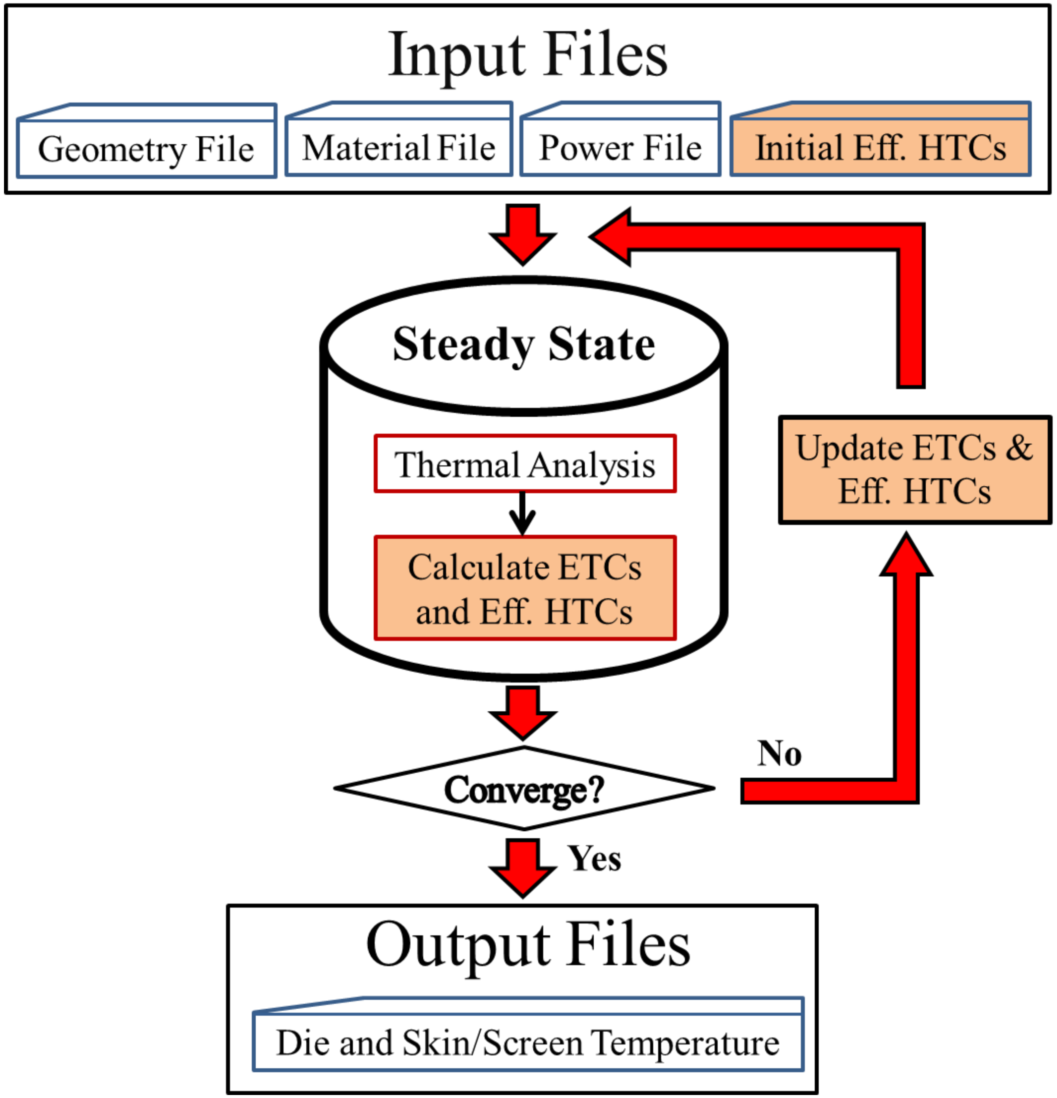
$$\text{Effective HTCs: } h_b(T_{b,K}) = h_{b,conv} + h_{b,rad}$$



How to determine h_{eff} & k_{air} ???

Iterative framework!!

Steady-State Thermal Simulation Flow



Input Files

Geometry File

Material File

Power File

Initial Eff. HTCs

Steady State

Thermal Analysis

Calculate ETCs and Eff. HTCs

Converge?

No

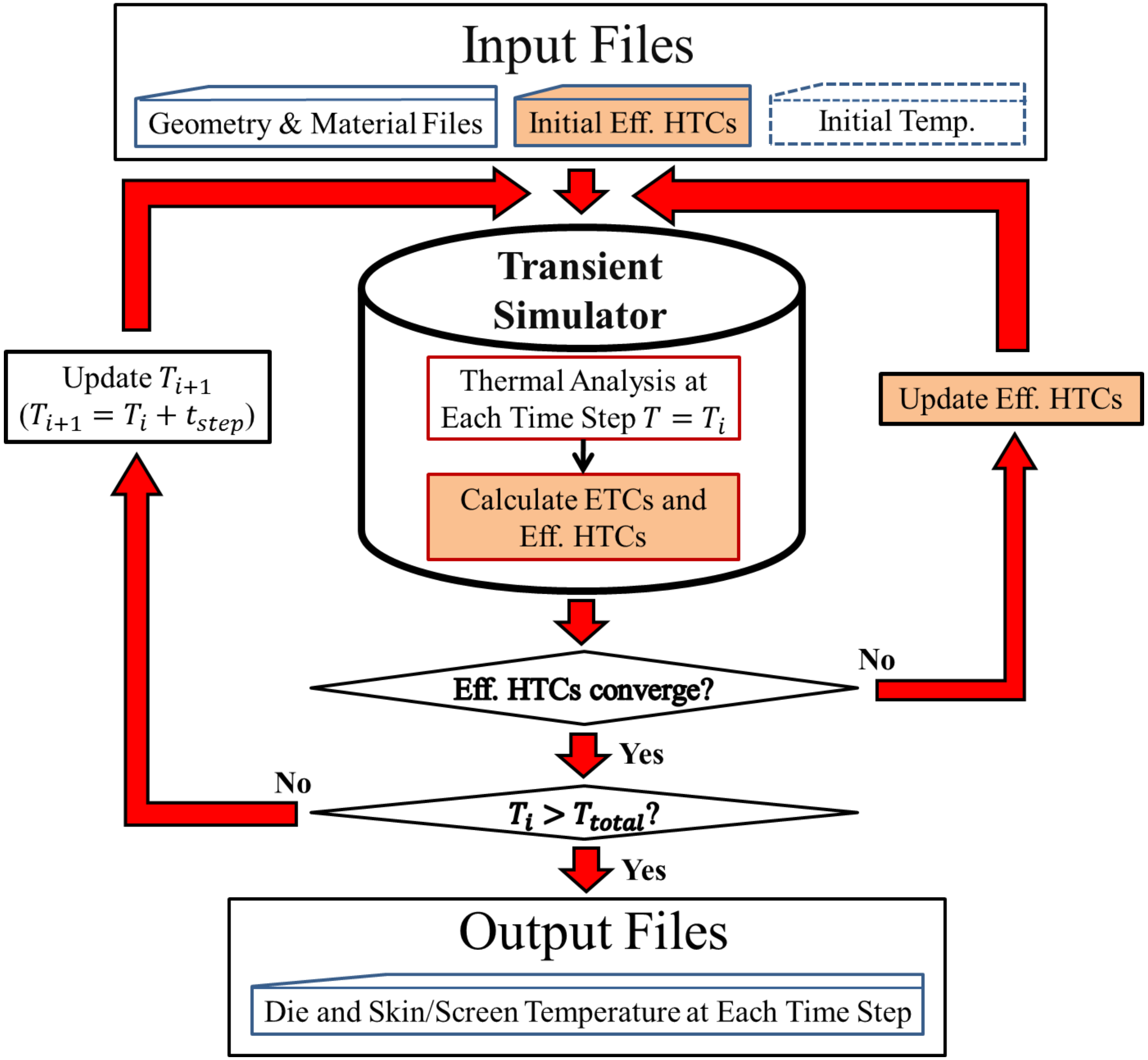
Update ETCs & Eff. HTCs

Yes

Output Files

Die and Skin/Screen Temperature

Transient Thermal Simulation Flow



Input Files

Geometry & Material Files

Initial Eff. HTCs

Initial Temp.

Transient Simulator

Thermal Analysis at Each Time Step $T = T_i$

Calculate ETCs and Eff. HTCs

Update T_{i+1} $(T_{i+1} = T_i + t_{step})$

Update Eff. HTCs

Eff. HTCs converge?

No

Yes

$T_i > T_{total}$?

No

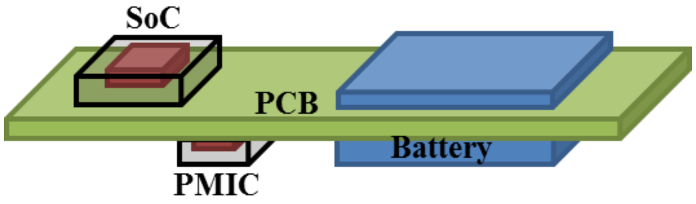
Yes

Output Files

Die and Skin/Screen Temperature at Each Time Step

Test Cases for Steady-State Simulations

	Case	Power (W) (SoC)	Power (W) (PMIC)
Single heat source	S1	1	0
	S2	0	0.5
Multiple heat source	M1	1.5	0.7
	M2	1.8	1
	M3	2	0.5



Steady-State Results (1/2)

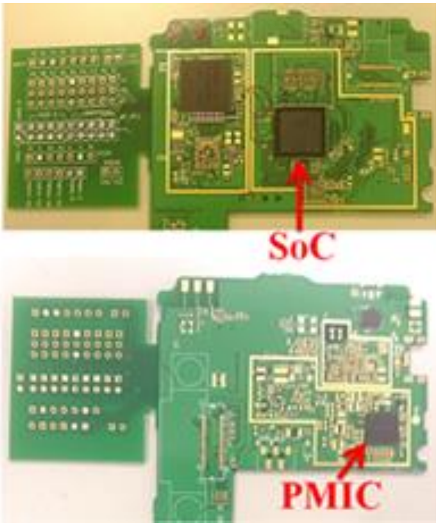
Case	Measurement		Icepak		Phone-nomenon					
	Temperature (°C)		Temperature (°C)		Temperature (°C)		◊Error (%)			
							Measurement		Icepak	
	SoC	PMIC	SoC	PMIC	SoC	PMIC	SoC	PMIC	SoC	PMIC
S1	50.2	NA	51.25	38.38	51.34	38.19	4.52	NA	1.04	3.58
S2	NA	55.0	32.01	56.31	31.91	57.18	NA	7.27	2.02	2.33
M1	69.2	81.1	72.22	86.72	72.26	87.63	6.92	11.64	1.18	0.46
M2	80.3	104.3	82.90	107.89	83.61	108.94	4.18	5.85	1.76	0.31
M3	78.6	75.6	80.86	79.98	81.94	80.78	6.23	10.24	1.49	0.75

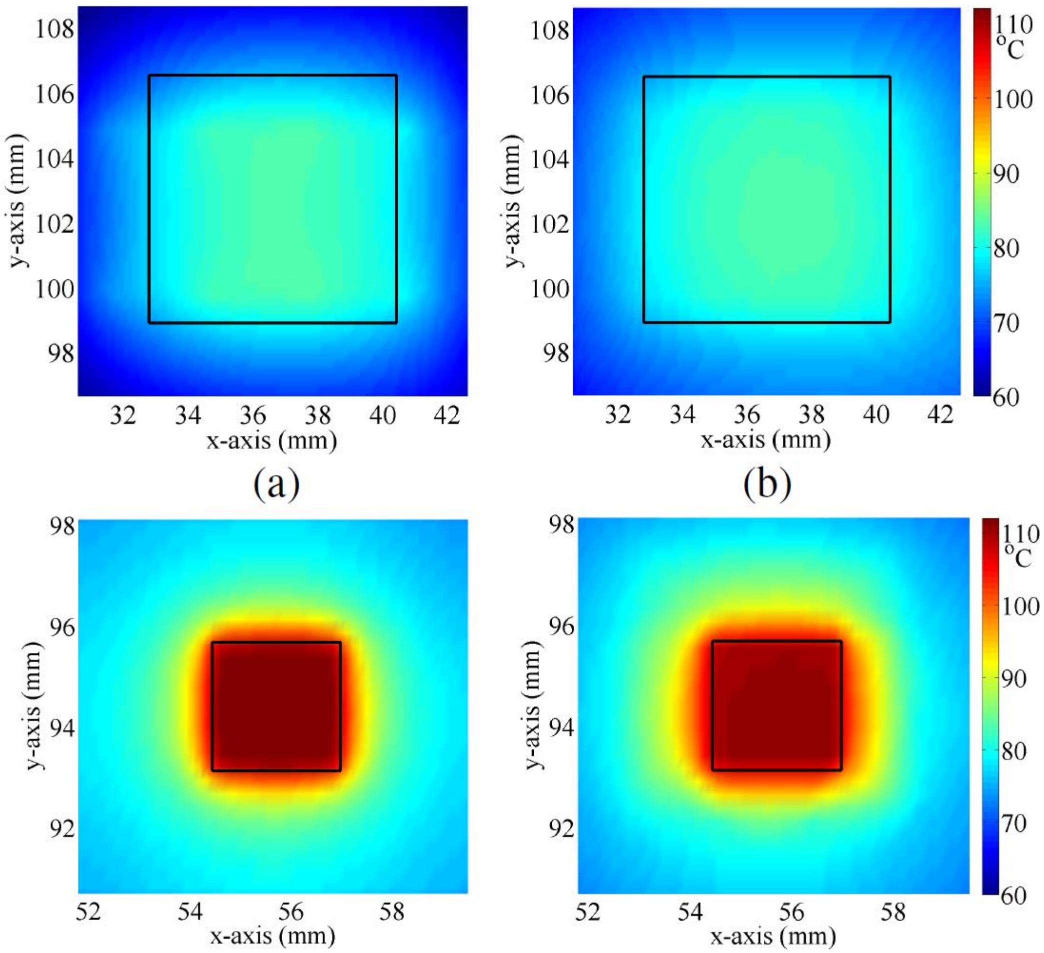
◊ Error at the middle point of die

Error < 11.64%

Error < 3.58%

Steady-State Results (2/2)





(a) (b)

SoC

(c) (d)

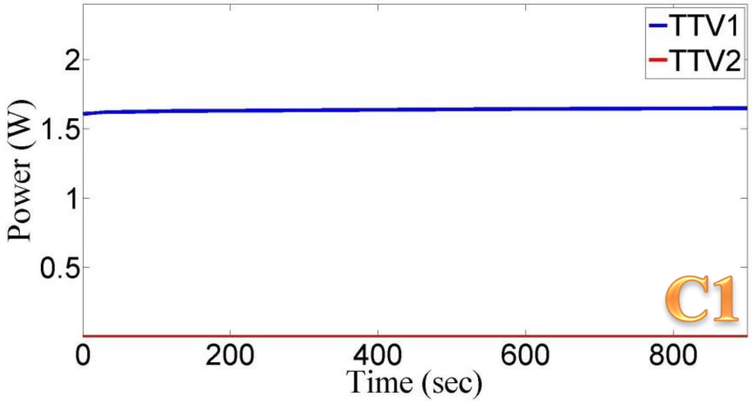
PMIC

Icepak **Phone-nomenon**

Test Cases for Transient Simulations

Constant (total time): 900sec (on)

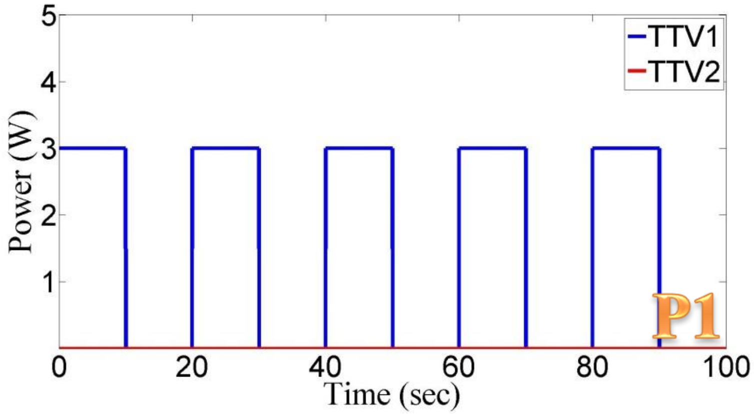
Constant workload	**SoC Power (W)**	**PMIC Power (W)**
C1	1.590~1.640	0.000
C2	0.000	1.025



Periodic-1 (total time): [10sec (on) +10sec (off)]*5

Periodic-2 (total time): [8.4sec (on) +8.4sec (off)]*5

Periodic workload	**SoC Power (W)**	**PMIC Power (W)**
P1	3.000	0.000
P2	0.000	1.160



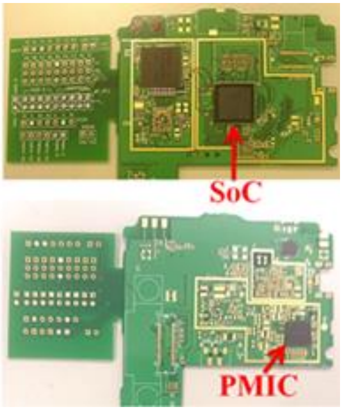
Transient Results (1/2)

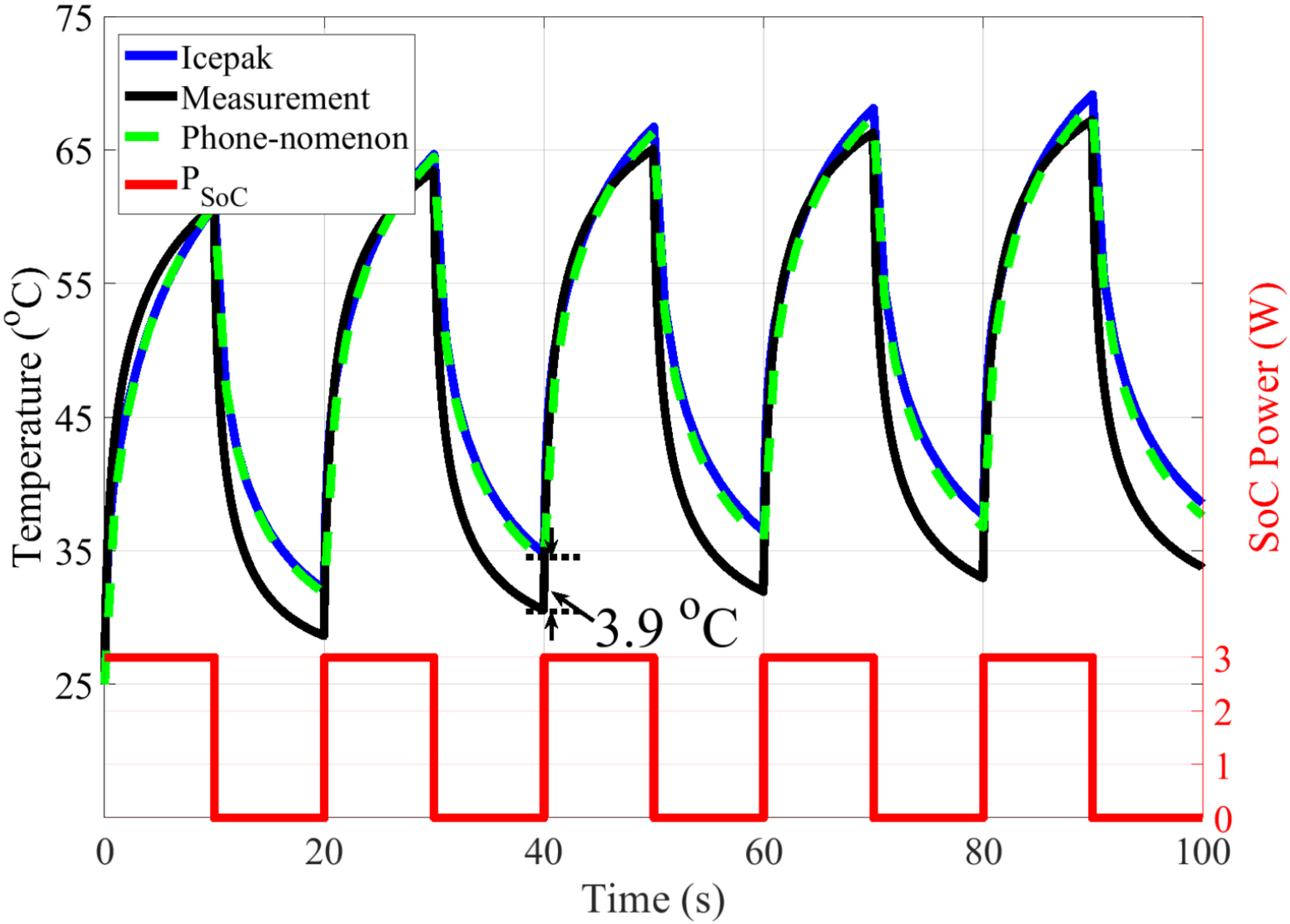
Case	Icepak	Phone-nomenon			
	Runtime (sec)	Max. error vs. Measurement (^{o}C)	Max. error vs. Icepak (^{o}C)	Runtime (sec)	Speedup (×)
C1	41524	1.10	1.65	32.17	1290.89
C2	40918	0.92	3.50	29.72	1376.97
P1	34967	1.44	3.90	8.72	4011.36
P2	37578	1.72	3.65	6.50	5779.45

Time step in TNS:
C1/C2: 1 sec
P1: 1 sec
P2: 0.7 sec

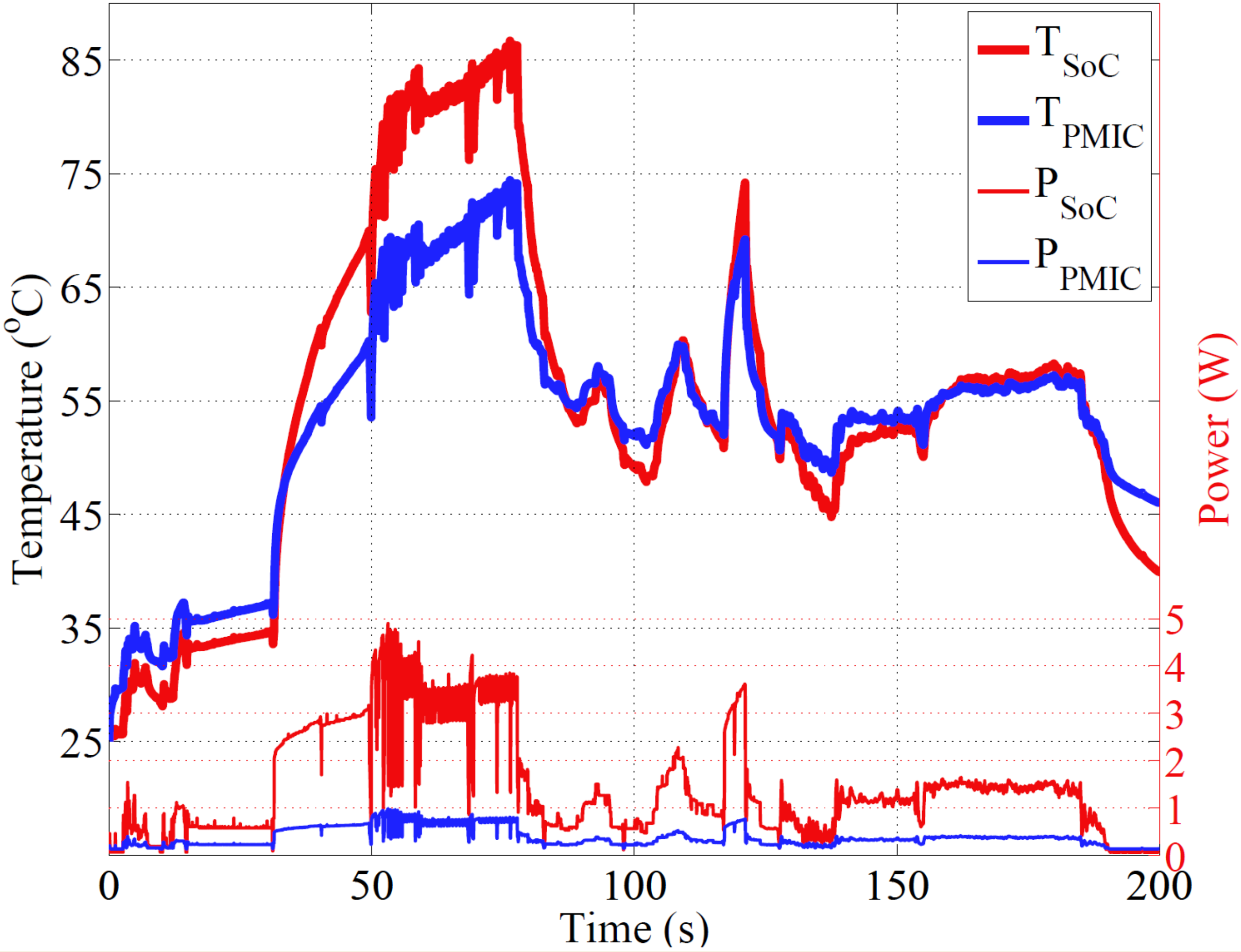
Speedup > 1290.89 times
Maximum error vs. Icepak < 1.72°C
Maximum error vs. Measurement < 3.90°C

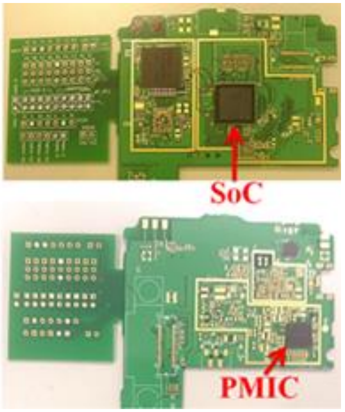
Transient Results (2/2)





Transient Results of Phone-nomenon for A Real Case





Conclusion

- This work develops Phone-nomenon, an iterative framework consider heat transfer mechanisms
- The experimental results have verified that Phone-nomenon can accurately (**less than 3.58%** vs. Icepak) and efficiently (**1000×**) estimate the temperatures of smartphones.
- This work also builds thermal test vehicle and measures the temperatures for validation. And Phone-nomenon can accurately (**less than 3.90 °C** vs. measurement) estimate those of smartphones.

Thank you for listening
Q & A

Reference

[1] D. L. Carroll, H. Y. Lo, and L. I. Stiel. Thermal conductivity of gaseous air at moderate and high pressures. Journal of Chemical and Engineering Data 13.1, pages 53–57, 1968.

[2] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine. Principles of heat and mass transfer, seventh edition. John Wiley & Sons, 2013.