



# **Necessary and Sufficient Conditions for Thermal Feasibility of Periodic Real-Time Tasks**

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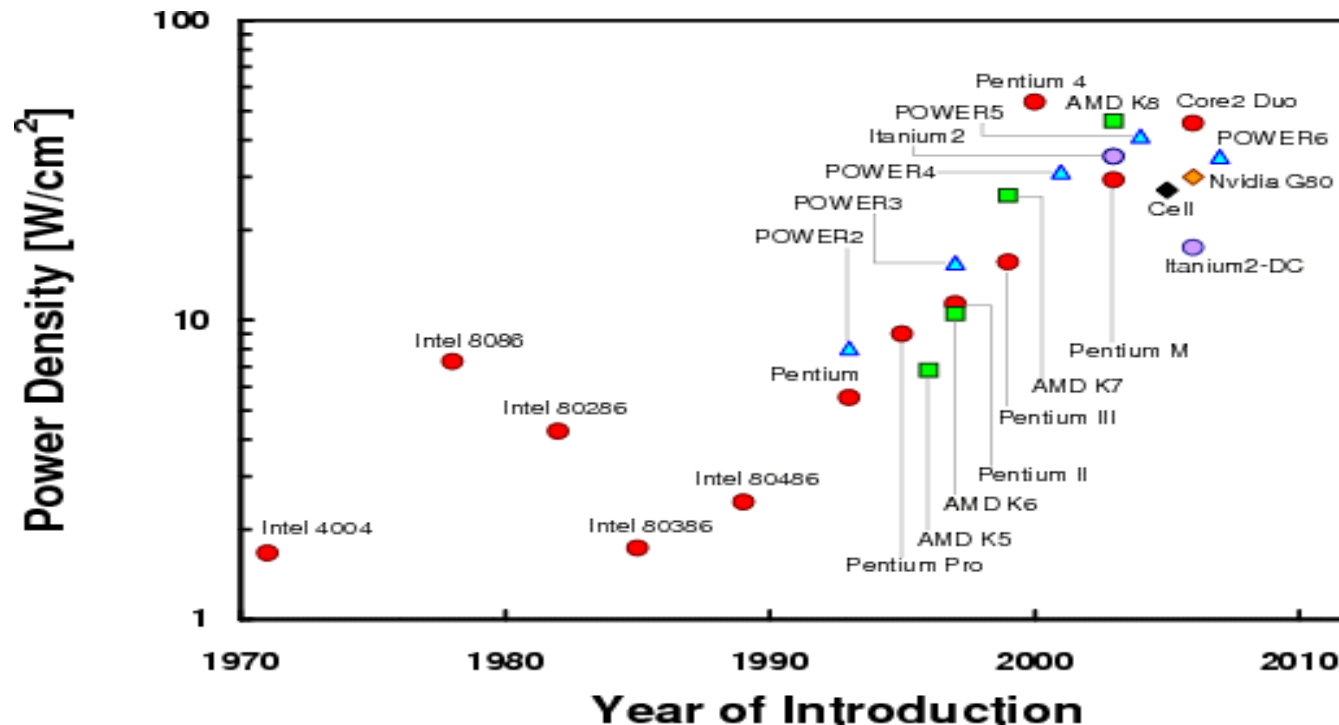


# Outline

- Introduction
  - What is a real-time system?
  - Why are thermal constraints important?
- Proposed solution
  - Thermally optimal scheduling algorithm for unicycle
  - Extensions to multi-core
  - Thermally optimal partitioned scheduling solution for multicore



# Introduction: Why Thermal Constraints are Important



- Rapid rise in Power densities of Integrated Circuits
- Localized power densities 2 orders of magnitude higher than average power densities
- High power densities cause thermal hotspots decreasing reliability/performance



# Our Work

- This work considers the scheduling of periodic tasks with thermal and timing constraints
  - All periodic task deadlines have to be met
  - System temperature has to be less than  $\Delta$
- Propose a thermally optimal scheduling strategy for uni-core
- Propose a thermally optimal partitioned scheduling algorithm for execution on multi-core



# Challenges

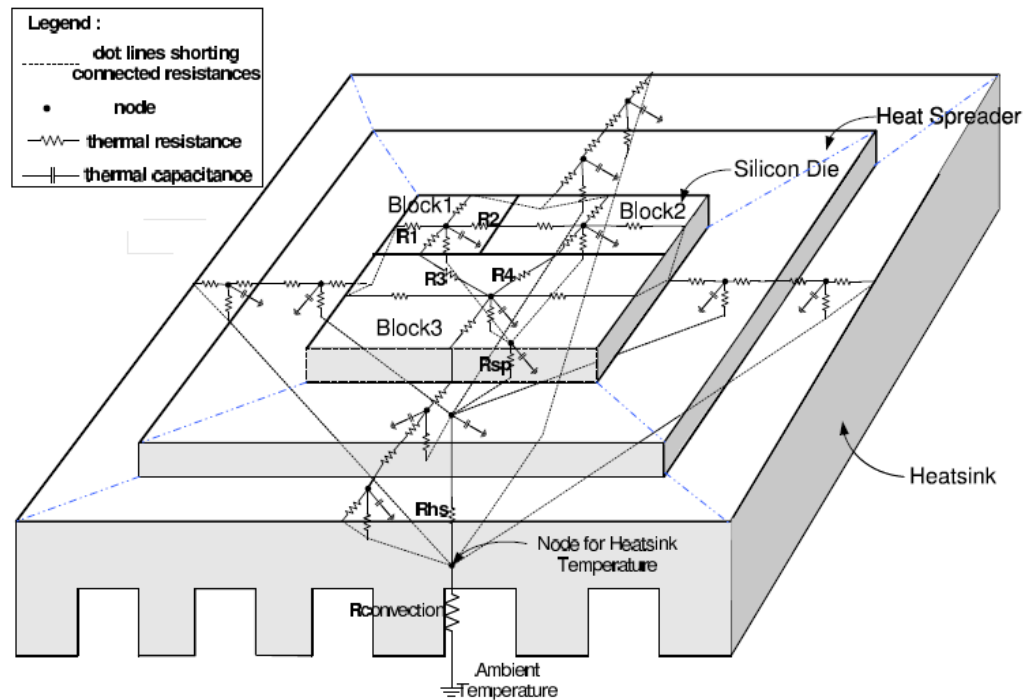
- Processor temperature typically reduced by employing DVFS
- DVFS causes reduction in processor performance
  - Lead to deadline miss in real-time systems
- Additional challenges exist for multi-core systems



# Thermal Models

Duality between heat transfer and electrical phenomenon:

- Heat transfer modeled as current passing through resistance
- Delay in heat increase modeled as a thermal capacitance
- RC pair for each architectural Unit

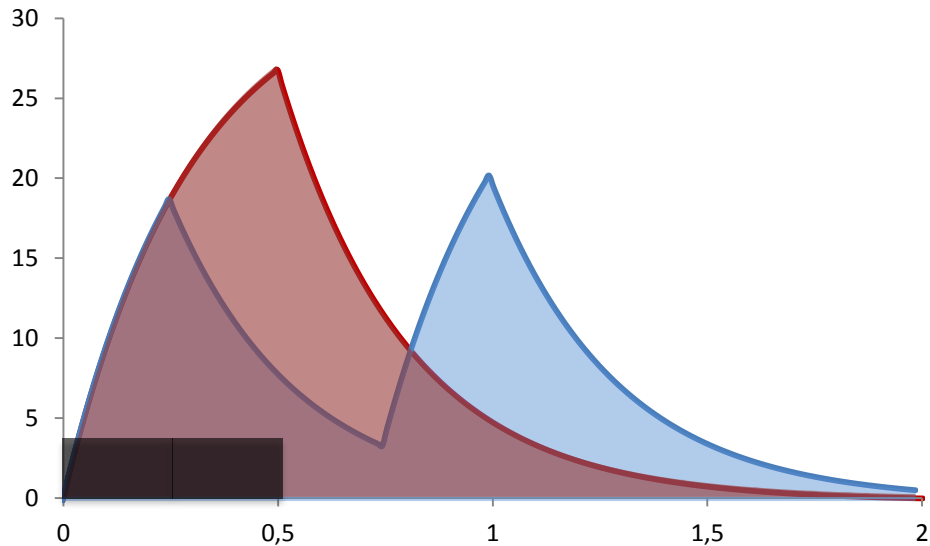




# Total Thermal Impact

- Example

- Task  $\tau$  with computation time of  $C_\tau = 0.5 \text{ sec}$
- Power consumption of  $\tau$  is constant =  $P_\tau$

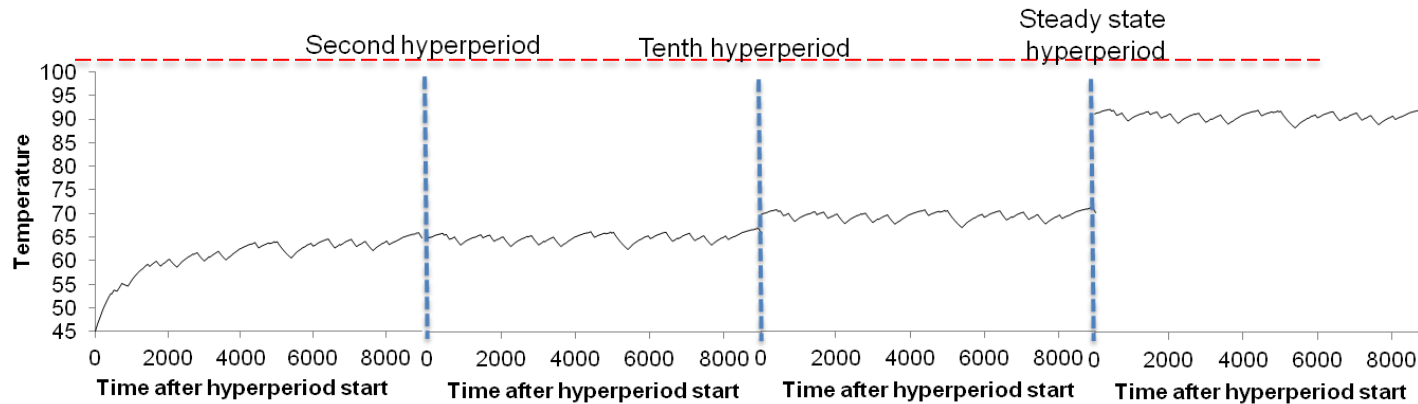


- TTI of  $\tau$  is the area under its thermal profile (Red region)
- TTI is only dependant on the energy consumption of  $\tau$



# Thermal Steady State

- Temperature at the start of successive hyperperiods increases monotonically



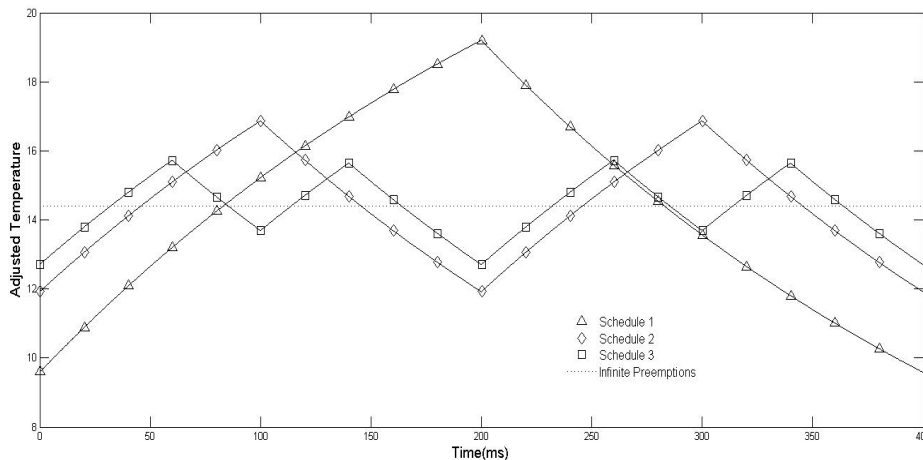
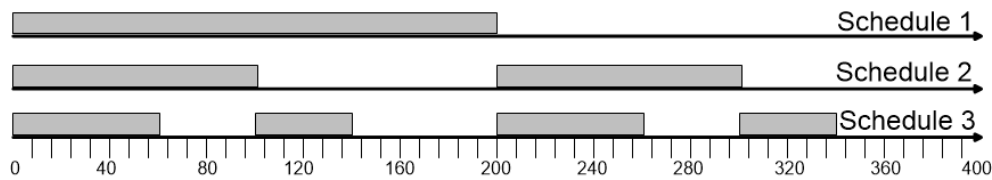
- Thermal Steady State
  - Temperature at the start and end of hyperperiod are equal





# Theoretical Results

- Integral of processor temperature at thermal steady state is independent of the schedule. (RTCSA 2013)
  - Integral is equal to the TTI of all periodic task instances within the hyperperiod
  - Integral is only a function of the periodic taskset.





# Thermal Utilization: Single Core

- Thermal Utilization of a taskset defined as

$$\frac{LB(\theta_{\max})}{\Delta}$$

- where  $LB(\theta_{\max})$  is a lower bound on maximum temperature over all possible scheduling policies
- Hence, tasksets with thermal utilization  $>1$  are not thermally feasible



# Scheduling Strategy (GPS)

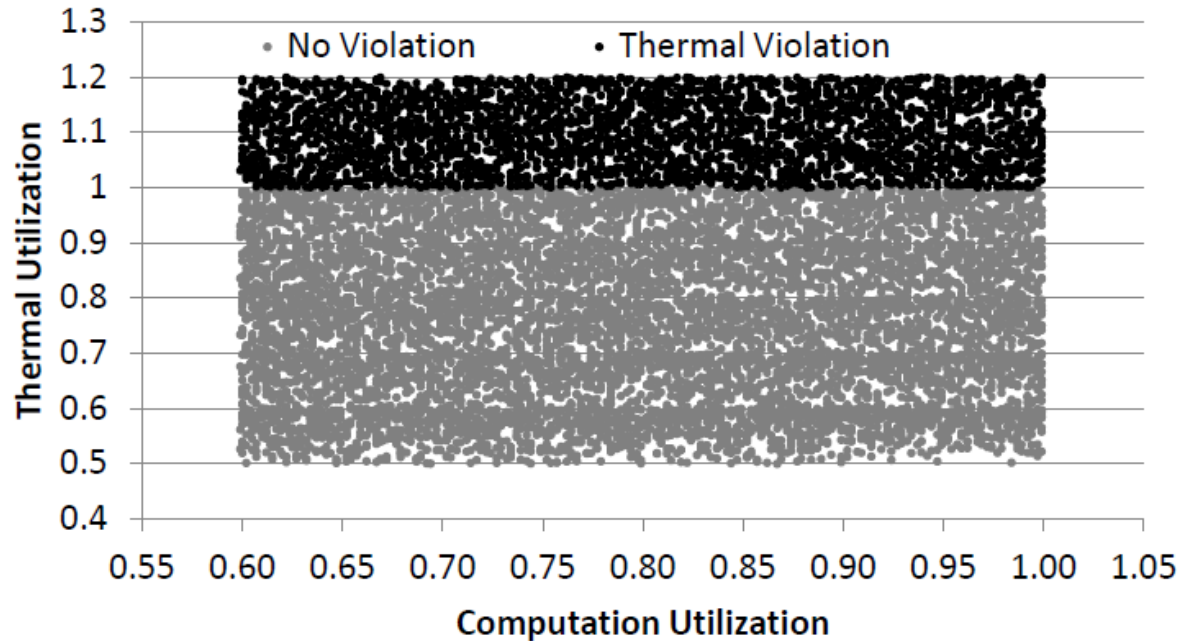
- Each periodic task is executed at a constant rate equal to

$$\frac{C_{\tau}}{T_{\tau}}$$

- Distributes power uniformly across the hyperperiod
- Optimal in the sense that if GPS cannot meet thermal and deadline constraints of a taskset, then no other scheduling policy can meet the same constraints
- On uniprocessors, GPS guarantees thermal feasibility if thermal utilization  $\leq 1$ 
  - Ideal policy which cannot be implemented in practice
  - Can be approximated well by Worst-case Fair Weighted Fair Queueing (WF2Q+)



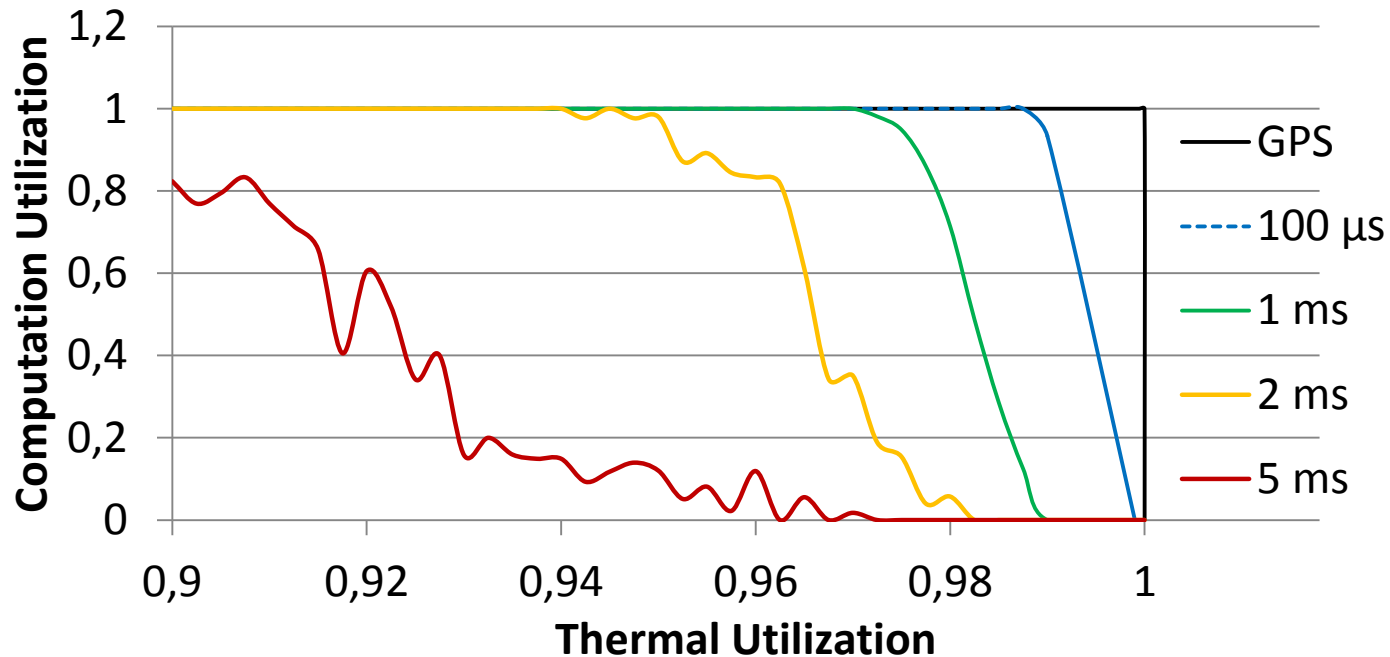
# GPS: Unicore Results



- Empirically validates that thermal utilization less than or equal to 1 is necessary and sufficient for thermal feasibility



# Additional Unicore Results



WF2Q+ successfully schedules more tasksets when minimum preemption duration decreases

WF2Q+ performs very well for reasonable minimum preemption duration



# Multicore Extension

- Unit Thermal Impact  $\zeta$  is a square matrix with dimensions equal to number of core
  - $\zeta_{i,j}$  is the TTI of Core  $i$  when core  $j$  consumes unit power.
- Consider partitioned scheduling of periodic tasks on multicore
  - If each task  $\tau$  is assigned to core  $j$ :

$$\int_0^L \Theta(t) dt = L \cdot \sum_{\tau \in \Gamma} \frac{P_\tau C_\tau}{T_\tau} \zeta e_j$$

- Thermal utilization of core  $i$  is defined as:

$$\frac{1}{L\Delta} \cdot \int_0^L \Theta(t)_i dt$$

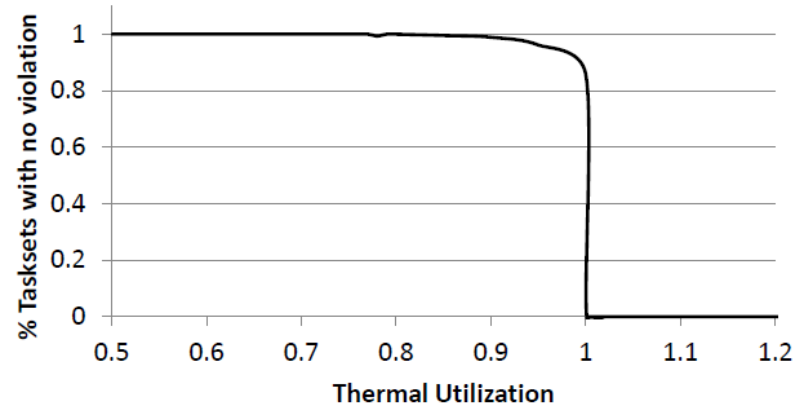
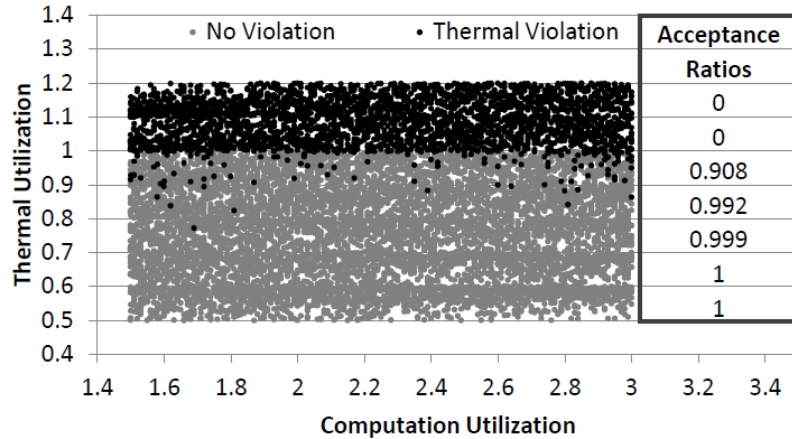


# Thermal Utilization Minimization using Partitioned Scheduling (TRuMPS)

- Partitioned scheduling
  - All instances of a periodic task execute on the same core
- TRuMPS
  - Formulate task assignment to core as a Mixed Integer Program (MIP) with an objective of minimizing the maximum thermal utilization across all cores
  - Use GPS/WF2Q+ to execute task instances on each core



# TRuMPS: Multicore Results

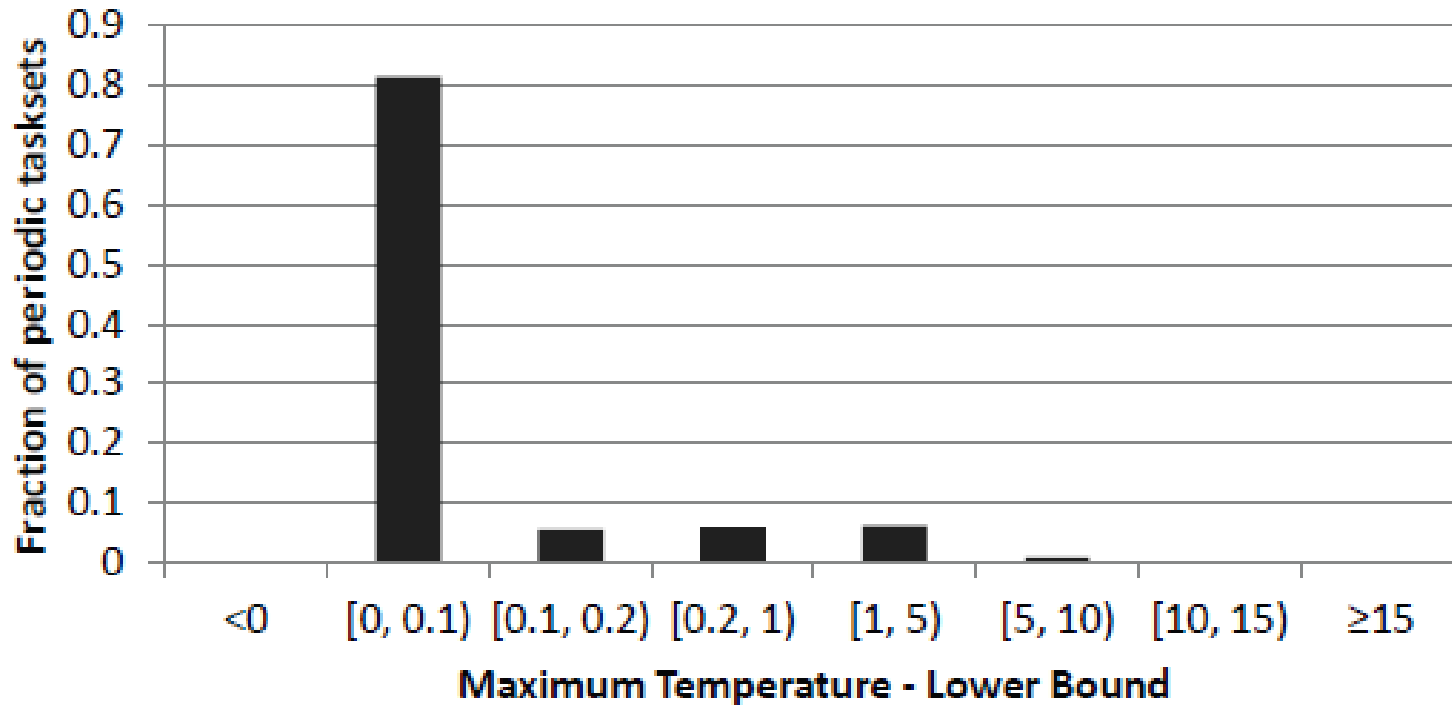


- No taskset with thermal utilization  $>1$  is schedulable
- Some tasksets with thermal utilization less than or equal to 1 are not schedulable, possibly due to partitioned scheduling





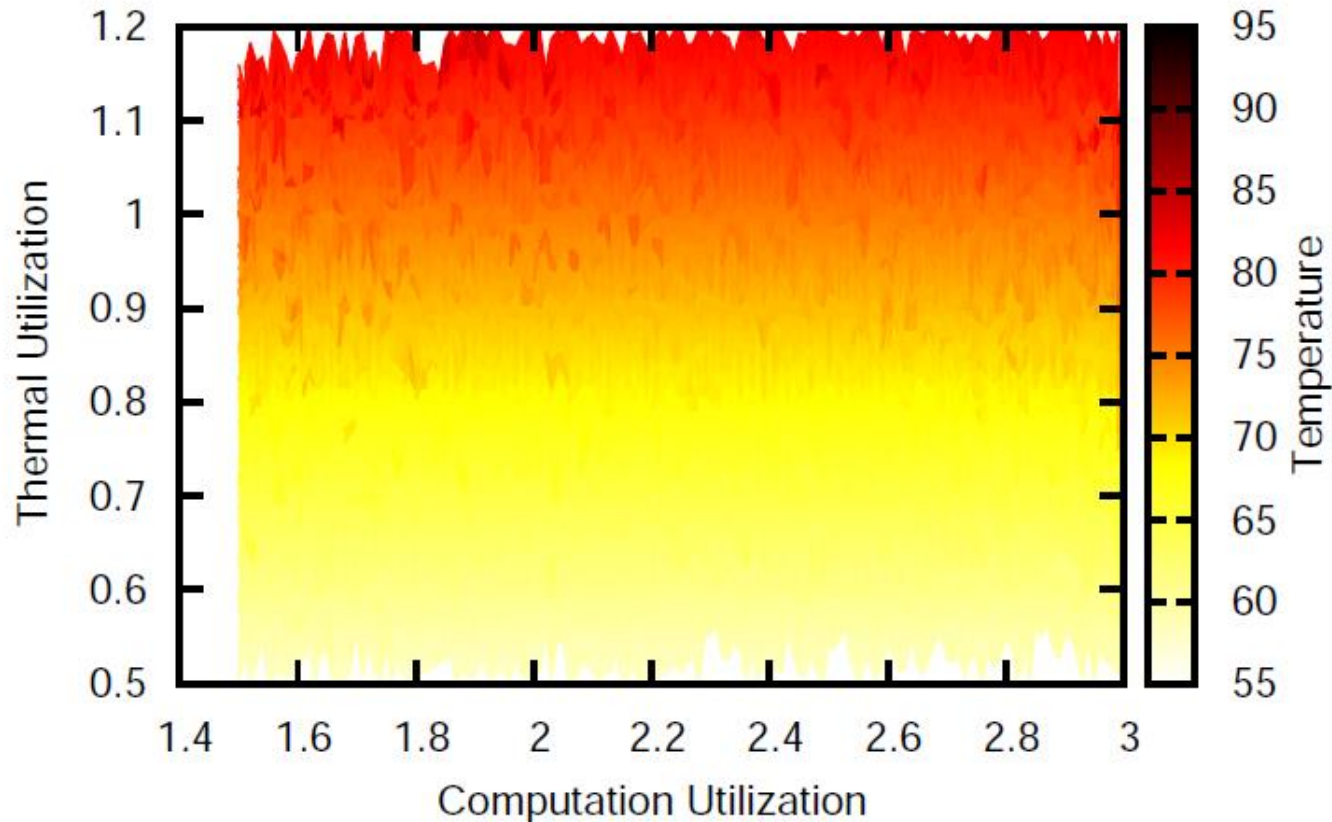
# Multicore Results Cont'd



- Approach close to the lower bound on temperature in most cases
- Some tasksets have large temperature difference due to partitioned scheduling approach



# Multicore Results Cont'd



- Maximum temperature and thermal utilization have strong correlation



# Presentation Takeaways

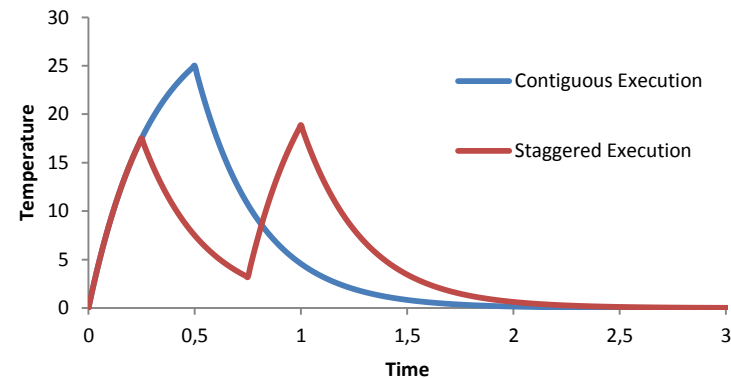
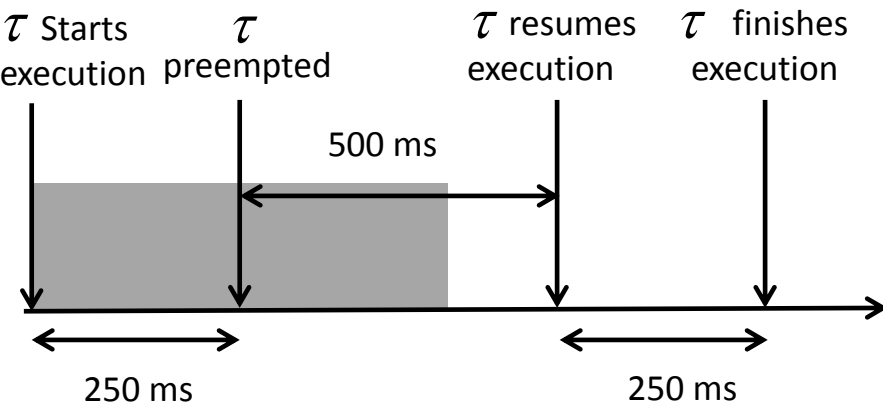
- Necessary and Sufficient Conditions for Thermal Schedulability
- GPS is a thermally optimal scheduling scheme for uncore
  - No scheduling algorithm can have lower maximum temperature
- TrUMPS performs very well for multi-core
  - Optimal partitioned scheduling scheme
  - Performance loss due to No-Migration task execution model

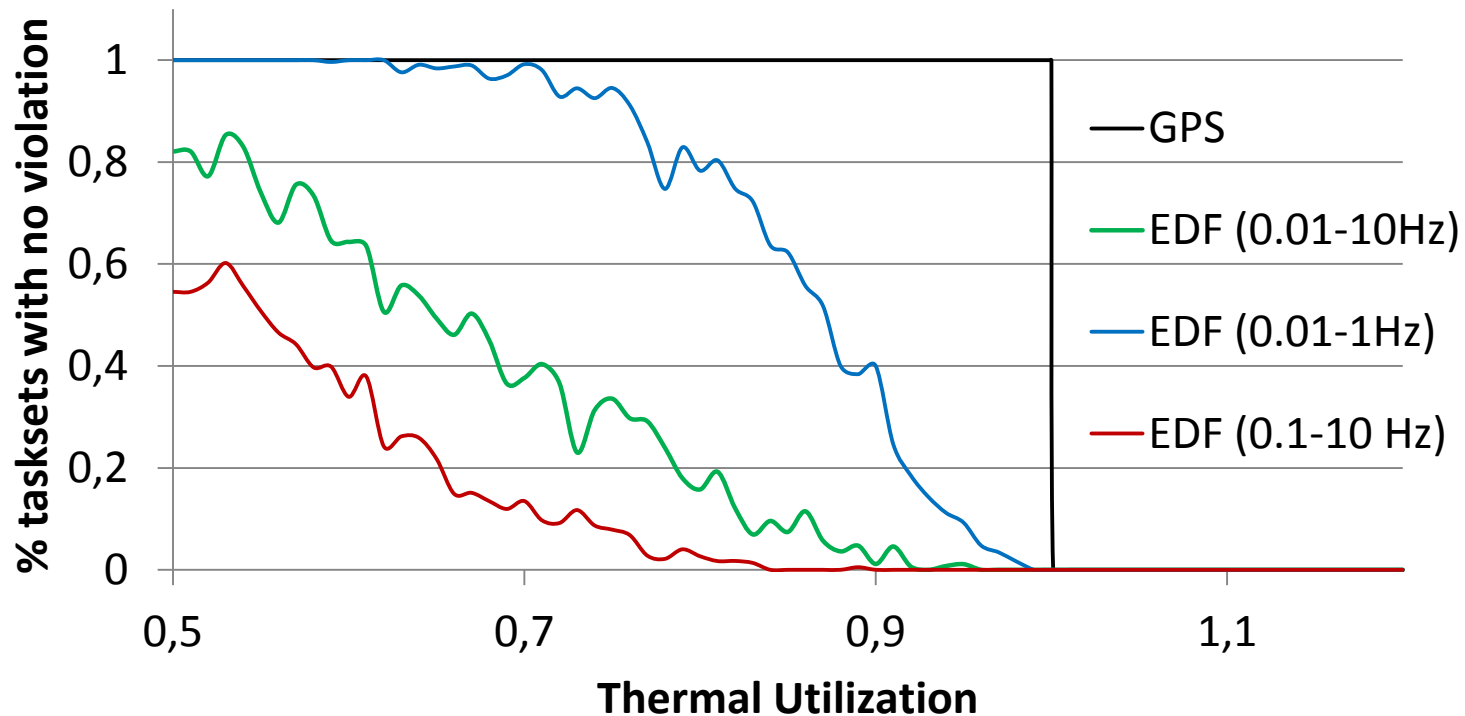




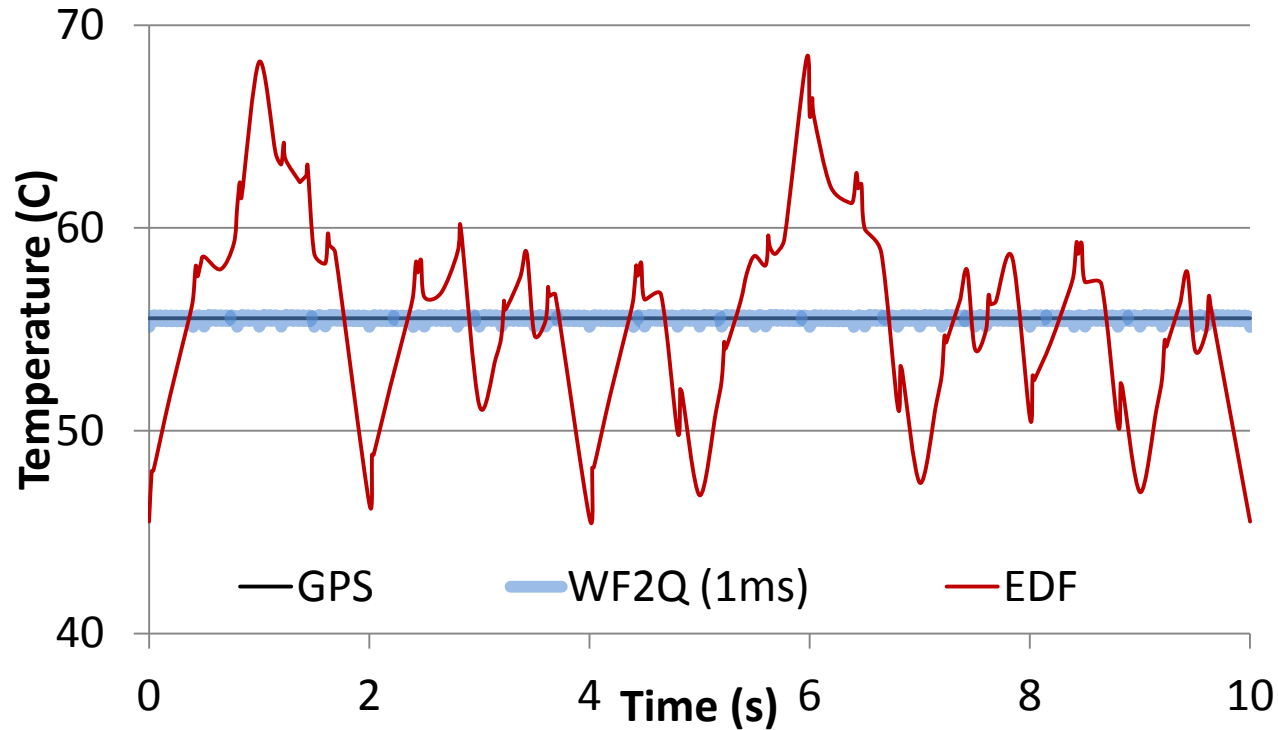
# Total Thermal Impact contd..

- Unit Thermal Impact  $\zeta$  is defined as the TTI when 1W power is consumed for 1 second
- Due to linearity of RC network TTI of  $\tau$  is the  $\zeta \cdot P_\tau \cdot C_\tau$
- TTI is only dependant on energy consumption NOT how that energy is consumed.





- High Frequency periodic tasks less likely to cause thermal violations
- CRS performance does not depend on frequency of periodic tasks

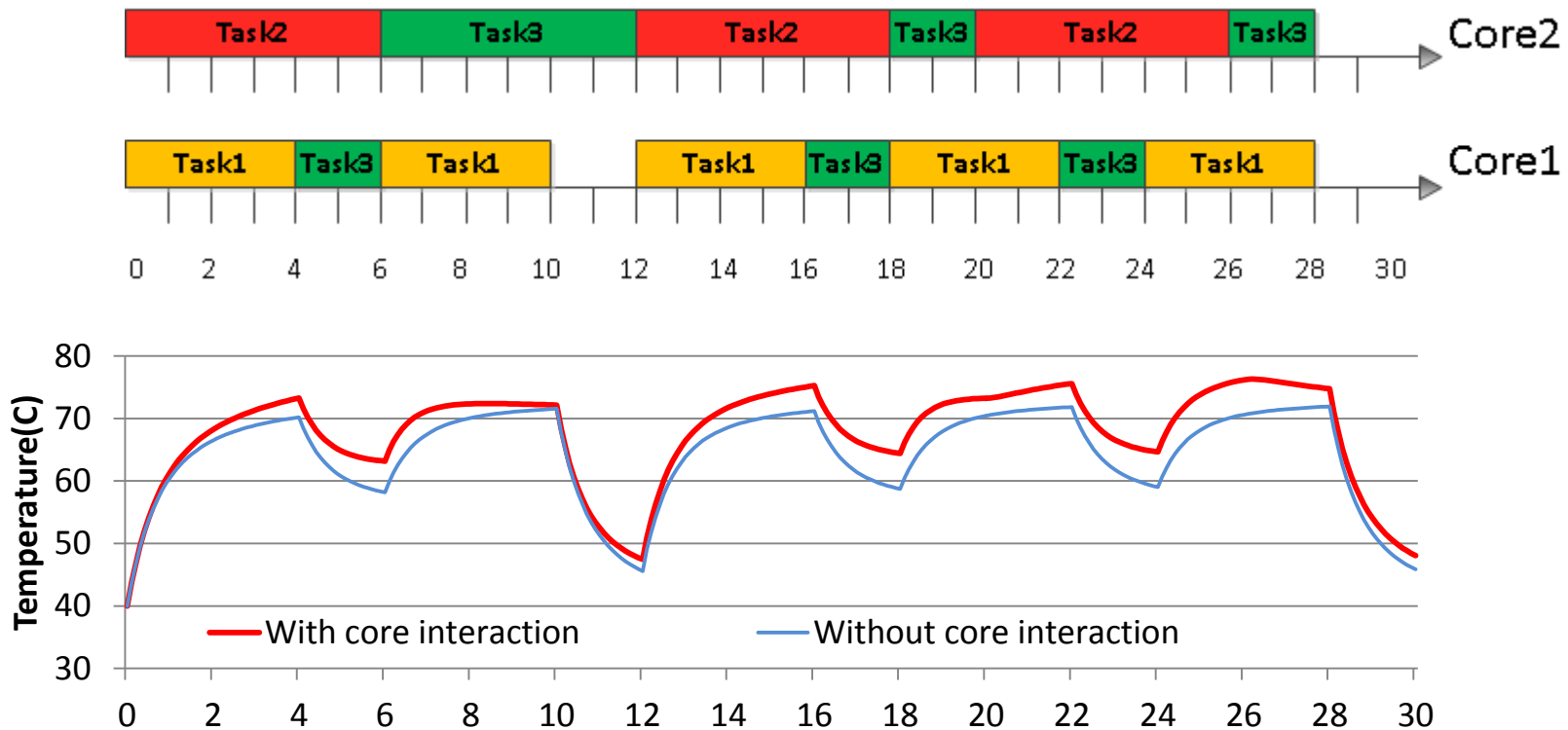


- EDF has large variations in temperature
- DCRS and CRS have similar performance



# Multicore Extension

- Challenges
  - Thermal Interaction between cores adds additionally complexity to the thermal scheduling problem.







# On going research

- Work on Global scheduling approaches on multi-core platform
  - Formulation of better scheduling schemes for multi-core
  - Schemes consider task-migration/instance migration model