Early Experiences with Node-Level Power Capping on the Cray XC40 Platform

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Outline

- Background and Motivation
- Cray XC40 Power Management
- Experimental Approach
- Results
  - Don’t hit the power cap
  - Power usage can exceed the cap
- Next Steps and Conclusion

Large-Scale HPC is Power Intensive

- Trinity 2016 ATS-1 platform: 42 PF @ < 10 MW
  - Procurement contract: $174M
  - Five year energy bill: ~$50M
- APEX 2020 system targets:
  - Wall plate power < 20 MW
  - Peak power < 18 MW (max achievable in practice)
  - Nominal power < 15 MW (for APEX workloads)
- Multi-megawatt transient swings a possible issue
- Current practice mostly ignores power management
  - Run system at max performance (max power) settings all the time
  - No real incentive to actively manage power, other than for research
- Expect future large-scale systems to be power constrained

APEX
Alliance for Application Performance at Extreme Scale
LANL, LBL, SNL

Power budget is a critical resource
Need to direct it to where it has most benefit

Many Power Management Techniques

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- P-states, C-states, T-states, turbo boost, slack time throttling, power caps, concurrency throttling, GPU/CPU power shifting, hardware overprovisioning, mem throttling, net throttling, …

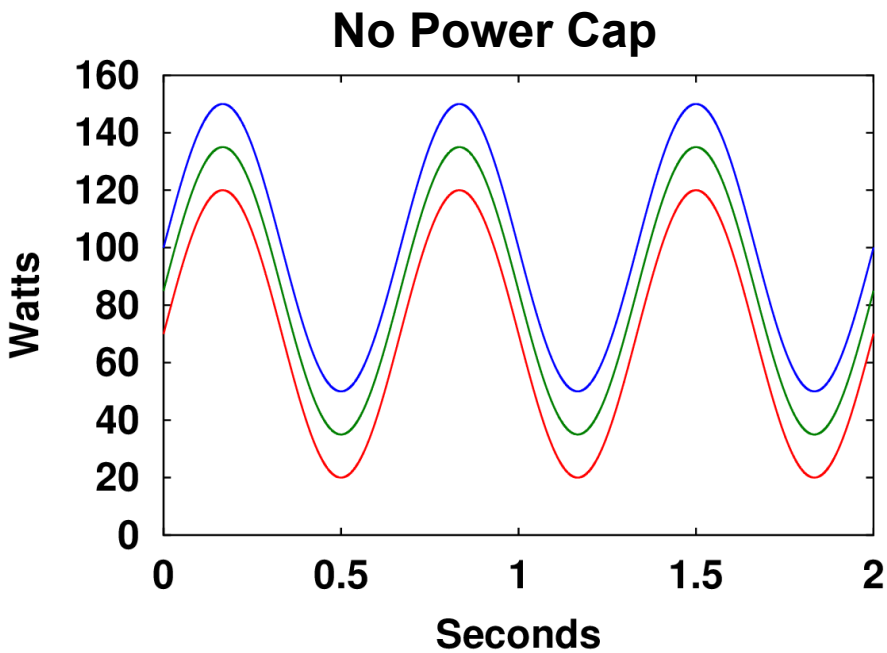
- Key questions:
  - Which techniques are effective for large-scale HPC systems?
  - Can we actually deploy these on large-scale systems + show benefit?
  - How do we get vendors, system operators, and users on board?

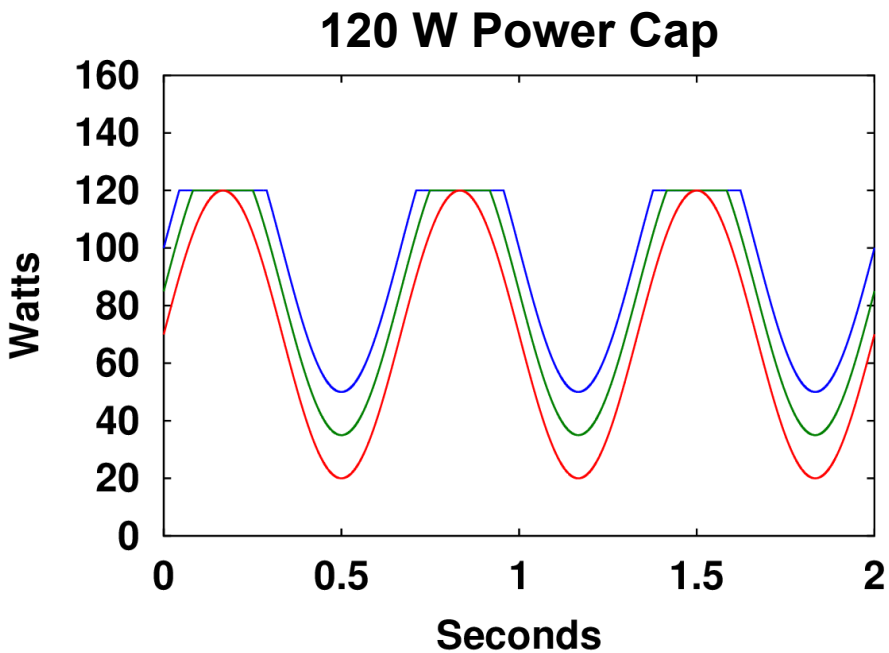
- Vendors starting to provide system-level power measurement and control capabilities; how well do they work? ☺

We evaluate Cray's power capping infrastructure, intended for use by workload managers and admins

Power Capping

- Software specifies desired power limit, hardware enforces
- Hardware continuously monitors power draw, takes action if power usage over limit (e.g., lower CPU freq, clock gating)
- Usually implemented as avg. power over sliding time window
- Initial work in HPC context by Rountree'12 et al. using RAPL



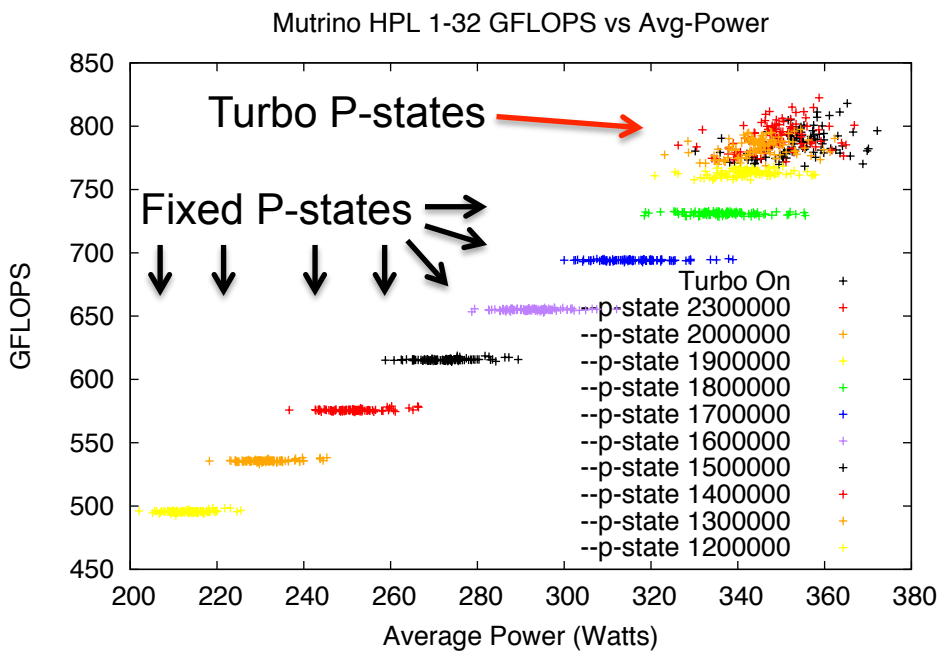


Power Caps Provide Predictable Power

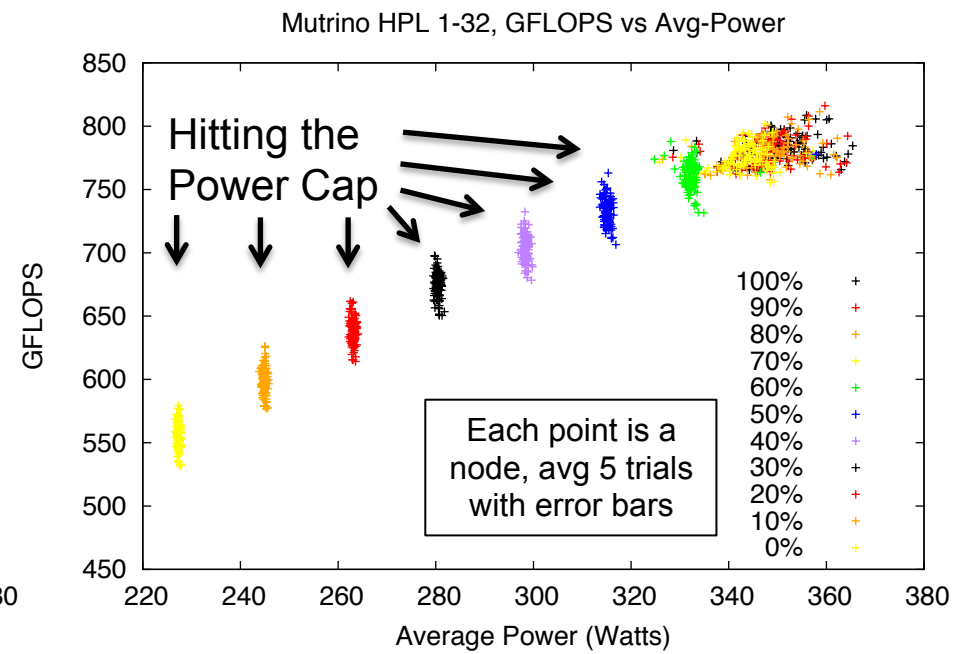
- Power capping appealing due to max power draw "guarantee"
  - Recapture (*WallPlate – Pcap*) headroom and reallocate elsewhere
  - Potentially useful for doing power aware scheduling
- P-state control appealing due to predictable performance, power unknown

Single-node HPL Variability Across 100 Nodes

P-State Sweep (Fixed Performance, Variable Power)



Power Cap Sweep (Fixed Power, Variable Performance)



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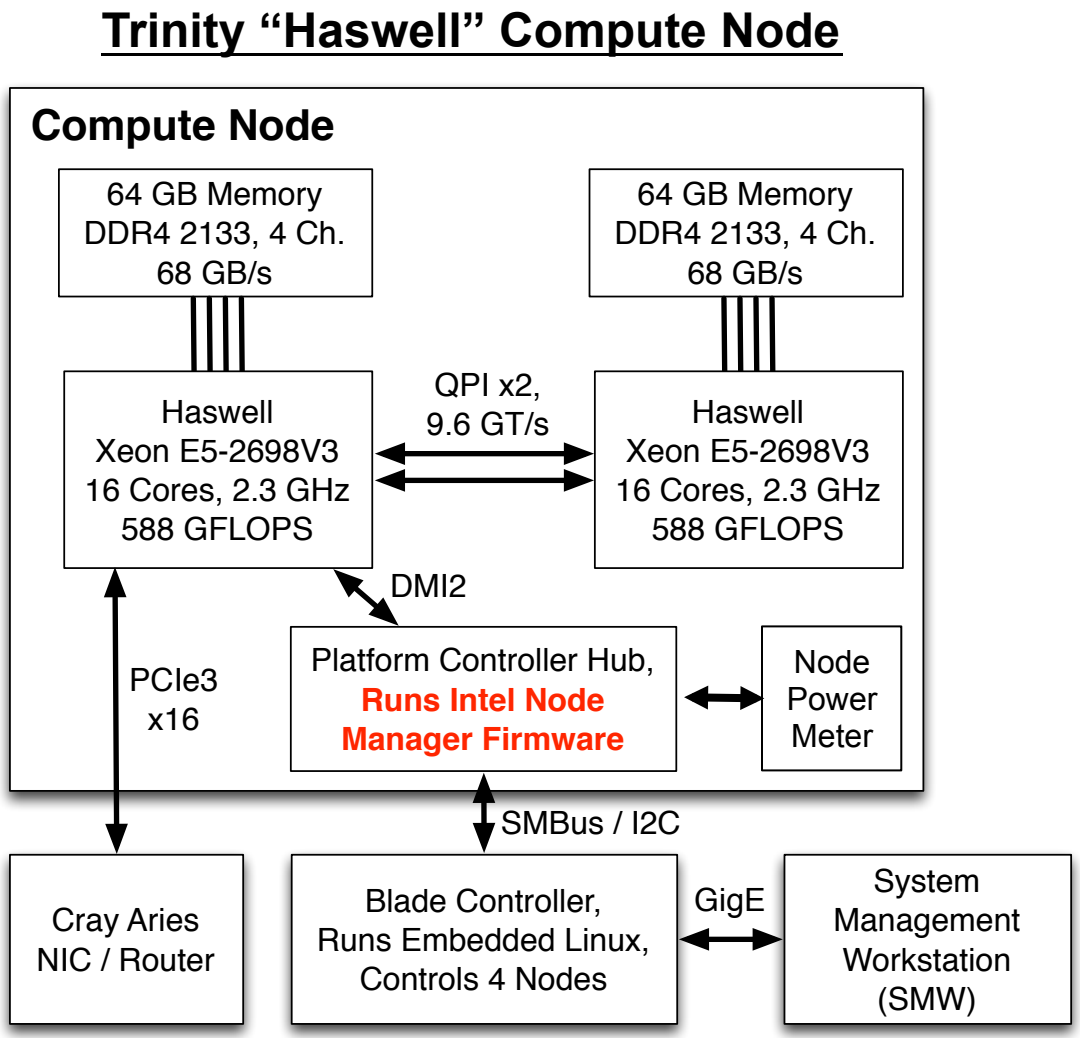
Node-Level Power Capping



- Blade controller receives power cap command from management network
- Blade controller relays command to Intel PCH
- PCH runs Intel's Node Manager firmware, which enforces the power cap
- Cray node-level power meter provides feedback to Node Manager
- Node manager makes use of each socket's RAPL
- Power capping algorithm not disclosed by Intel

Specification: Intel Intelligent Power Node Manager 3.0, March 2015, Doc# 32200-001US

Job/System-Level Power Capping

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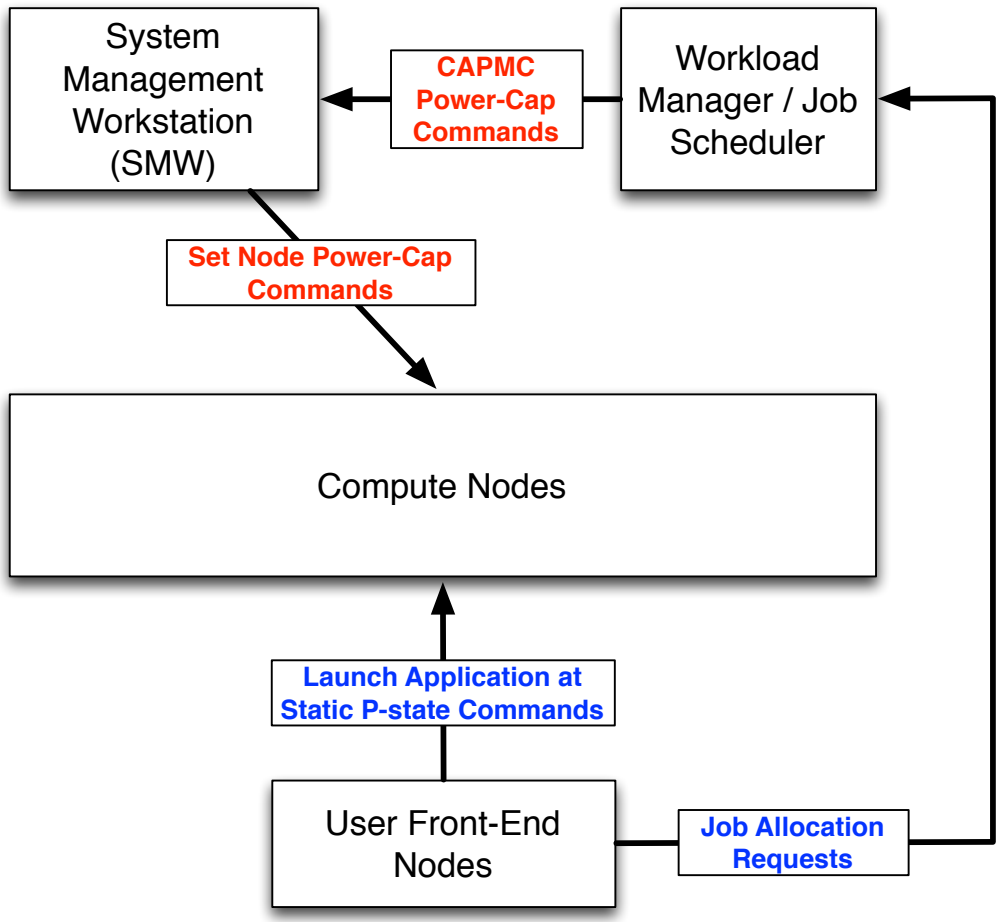
Cray XC40 Power Management Architecture



- A single management workstation controls system, the SMW
- Node-level power caps set from SMW, distributed to compute nodes via out-of-band management network
- Admins use `xtpmaction` command to set power caps manually
- Workload managers use Cray's CAPMC web API to set power caps
- Users may launch their job at a fixed p-state, default is P0 (turbo on)

See: Monitoring and Managing Power Consumption on the Cray XC System, April 2015, S-0043-7203

Power Management Limitations

- Setting power cap requires administrative privilege
- Users cannot dynamically change P-states
- Users cannot dynamically change Power Caps
- Users cannot access RAPL, other than via read-only PAPI
- Users cannot access Cray Power Management Database
- 1 Hz power samples for each node collected by default, configurable up to 5 Hz for small sets of nodes

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Testing Procedure

- Test system was "Mutrino" Cray XC40 @ Sandia, Mini Trinity
  - 100 Haswell compute nodes, identical to Trinity Haswell nodes
  - Testing performed in dedicated mode with no other users
  - Always used 32 MPI processes per node, 1-1 pinned to physical CPUs
- Test configurations cross-product of:
  - 4 workloads (HPL, HPCG, S3D, CTH)
  - 5 scales (1, 8, 32, 64, 96 nodes)
  - 8 p-states (1.2, 1.4, 1.6, 1.8, 1.9 2.0, 2.3, 2.301 GHz)
  - 5 power caps (230, 276, 322, 369, 415 watts)
  - 3 trials each configuration

> 2400 Runs

- For each trial, collected
  - Energy consumed and total runtime from Cray RUR
    (energy consumed includes CPUs, memory, PCH; excludes Aries NIC)
  - 10 Hz power samples and CPU 0 freq samples using Power API

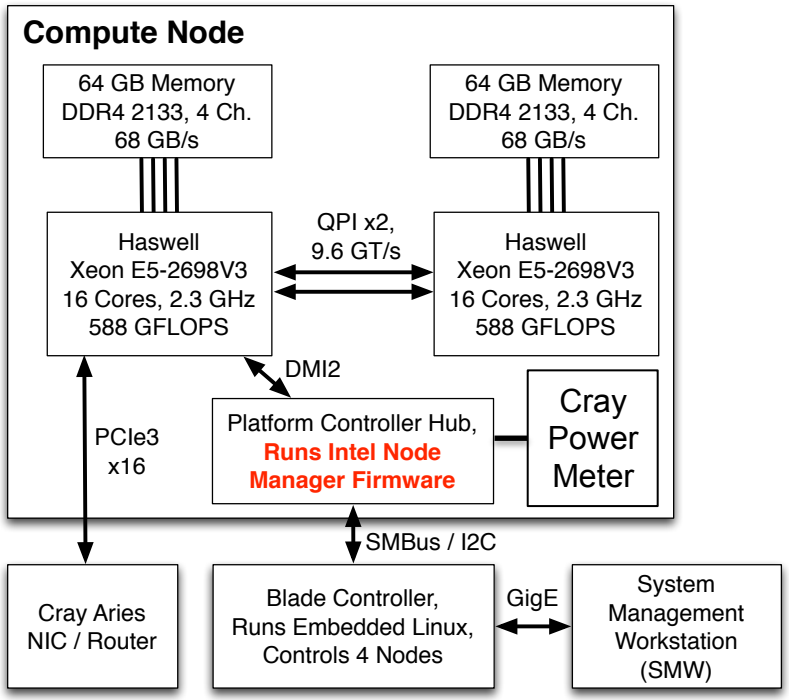
powerapi.sandia.gov

Workloads

- Weak scaling (scaled problem size with node count)
- Top 500 Benchmarks
  - HPL – High Performance Linpack
    - Compute intensive
    - 24 GB per node (N = 549K for 96 nodes)
  - HPCG – High Performance Conjugate Gradient
    - Memory intensive
    - 30 GB per node (104x104x104)
- Application Benchmarks
  - S3D – Combustion Simulation
    - Network intensive, 3-D nearest neighbor exchanges
    - 48^3 gridpoints per node
  - CTH – Shock Physics Hydro Code
    - Memory and network bandwidth intensive
    - Shaped charge input deck, ~ 50 GB per node

“Mutrino” Test System

- Cray XC40 with 100 compute notes
- Trinity lookalike system, but smaller
- Power cap range 230 to 415 W
- P-state range 1.2 to 2.3 GHz
- Max turbo 3.6 GHz, AVX freq 1.9 GHz



Power Cap Settings Tested (5)

Cray Power Cap Setting	Power Cap Per-Node (Watts)	Savings Potential (Watts)	Savings Potential (Percentage)
No Cap	~ 415 W	N/A	N/A
75%	369 W	46 W	11%
50%	322 W	93 W	22%
25%	276 W	139 W	33%
0%	230 W	185 W	45%

P-State Settings Tested (8)

Cray P-state Name	Clock Frequency (GHz)	Percent of Peak
2301000	2.3–3.6 (Turbo On)	> 100%
2300000	2.3	100%
2000000	2.0	87%
1900000	1.9	83%
1800000	1.8	78%
1600000	1.6	70%
1400000	1.4	61%
1200000	1.2	52%

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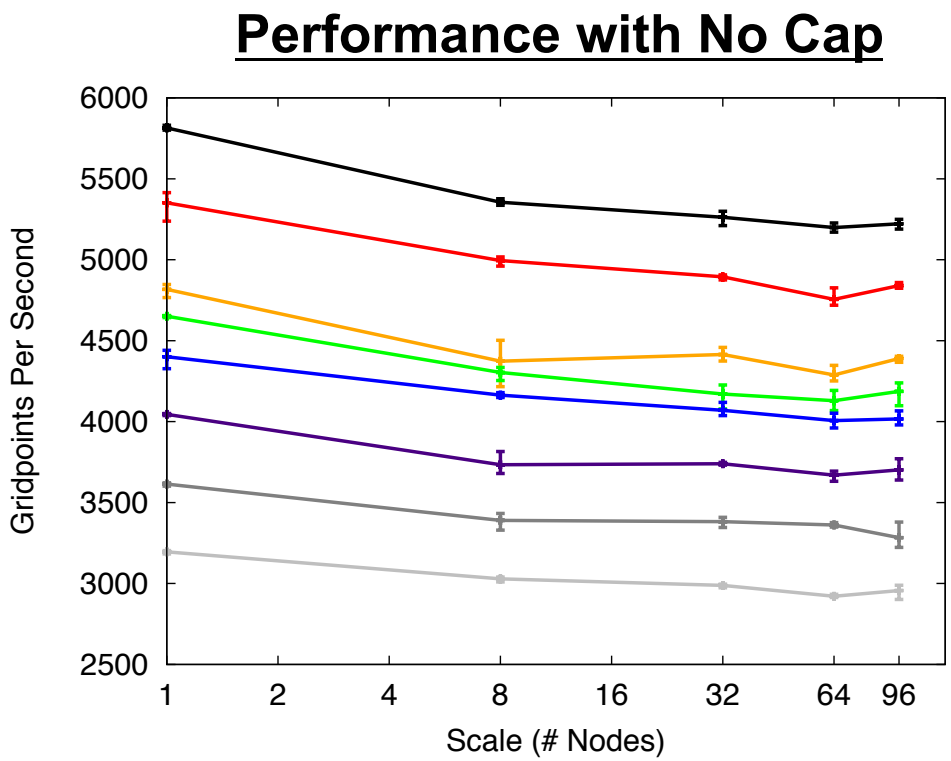
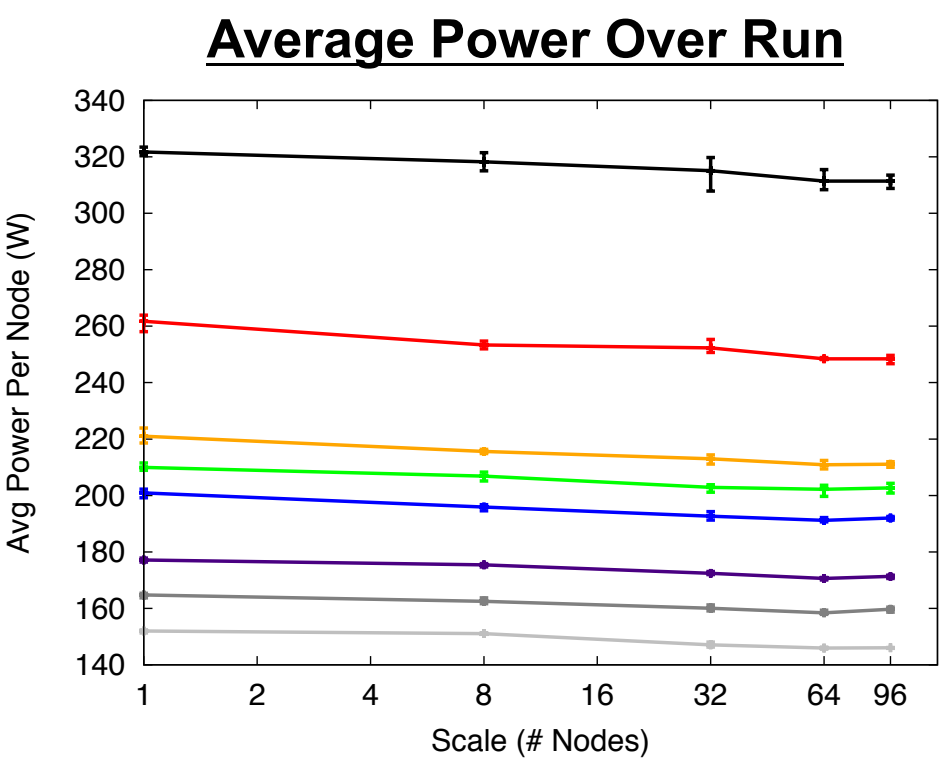
S3D No Cap: "Things Look Good"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

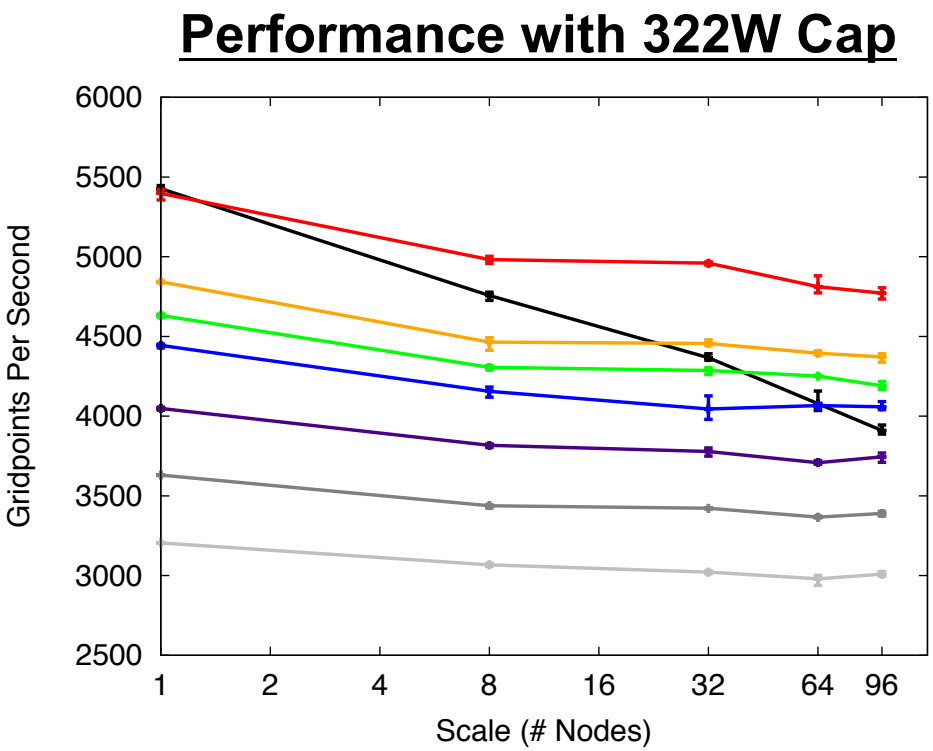


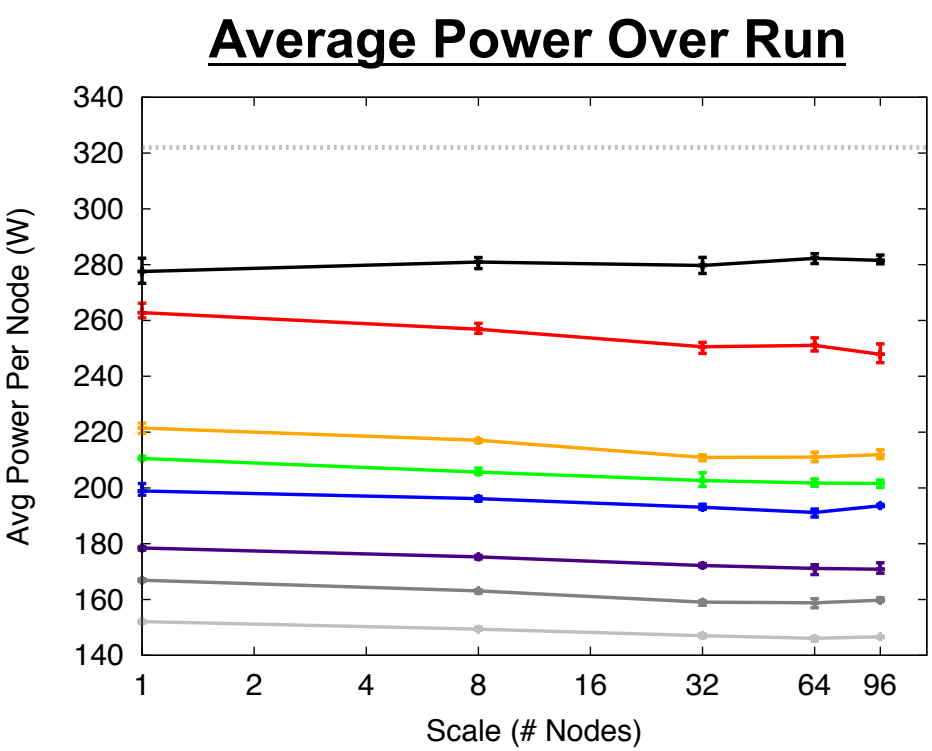


S3D 322W Cap (50%): "Turbo Hits the Cap"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

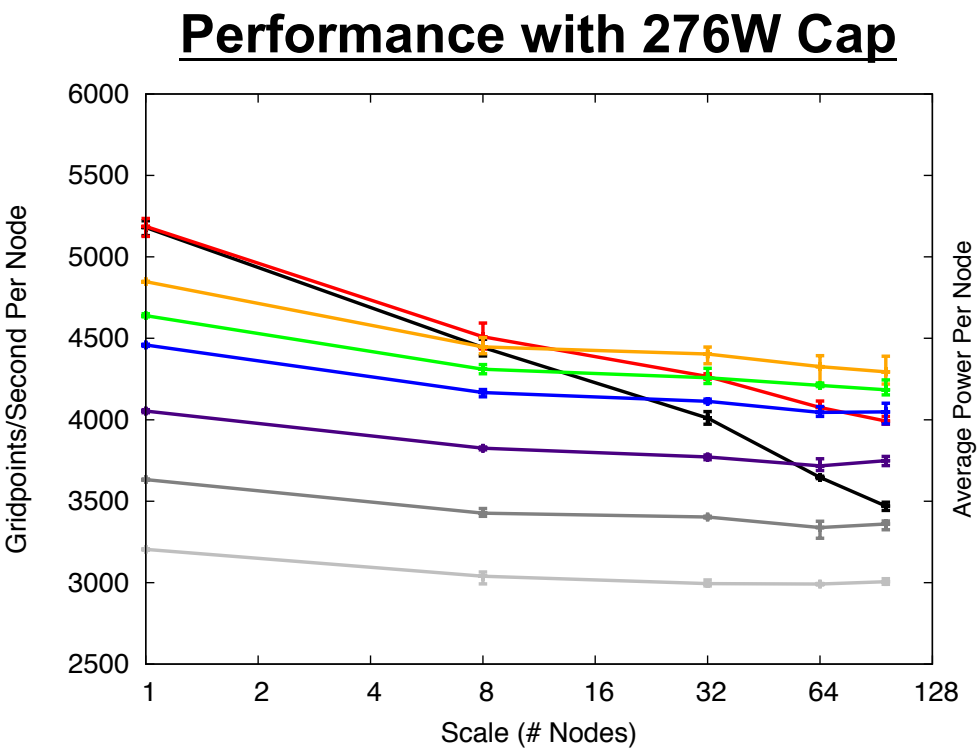


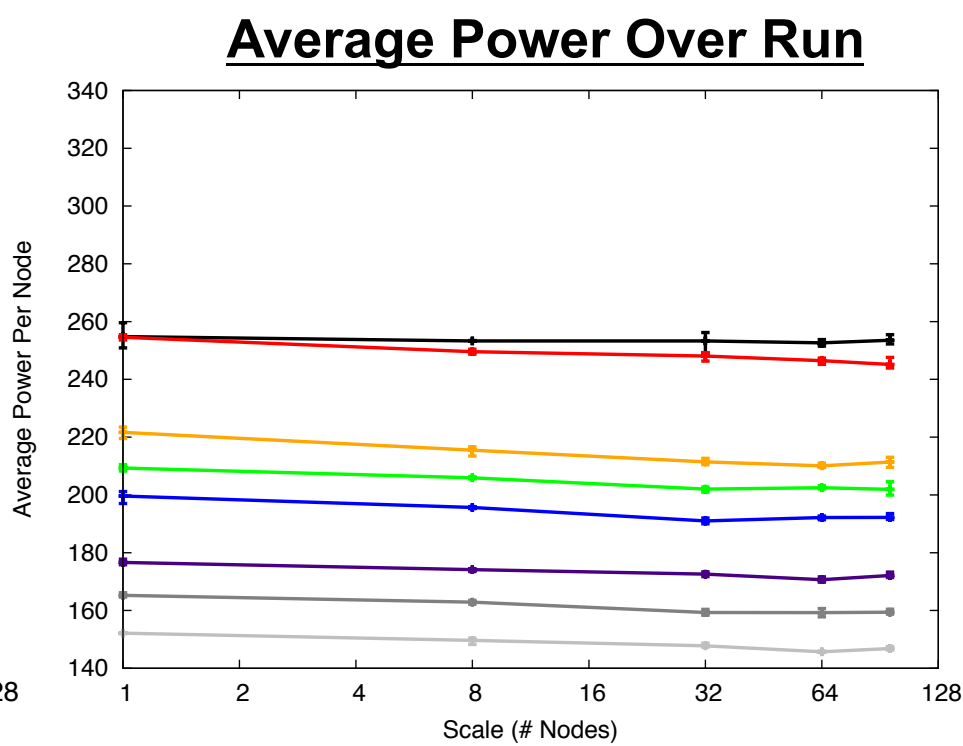


S3D 276W Cap (25%): "2.3 GHz Hits the Cap"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

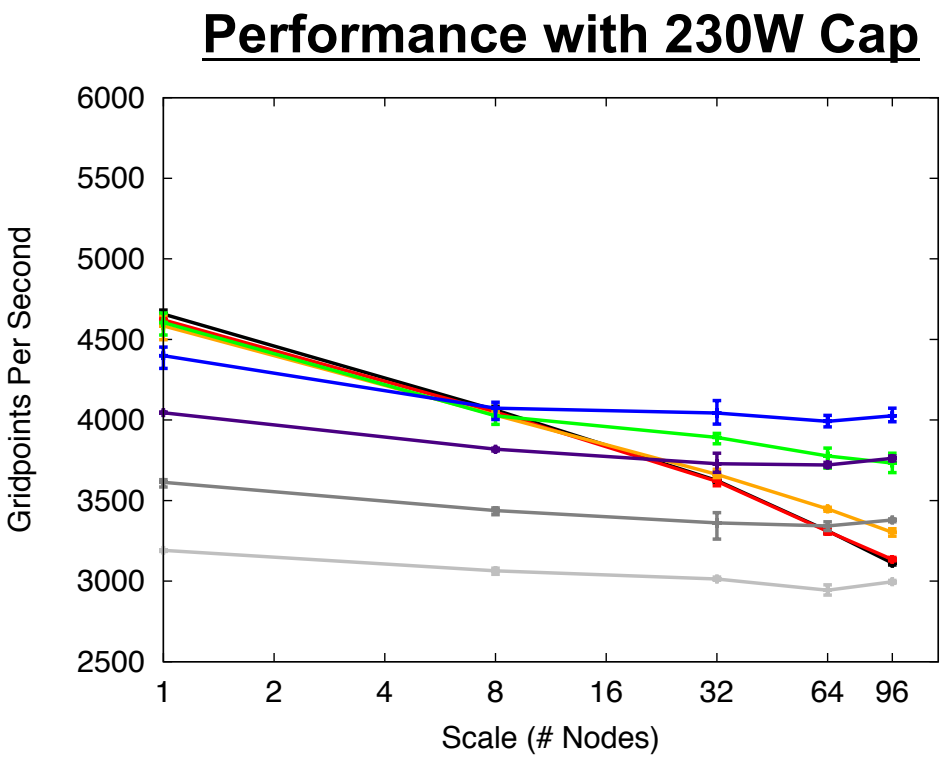


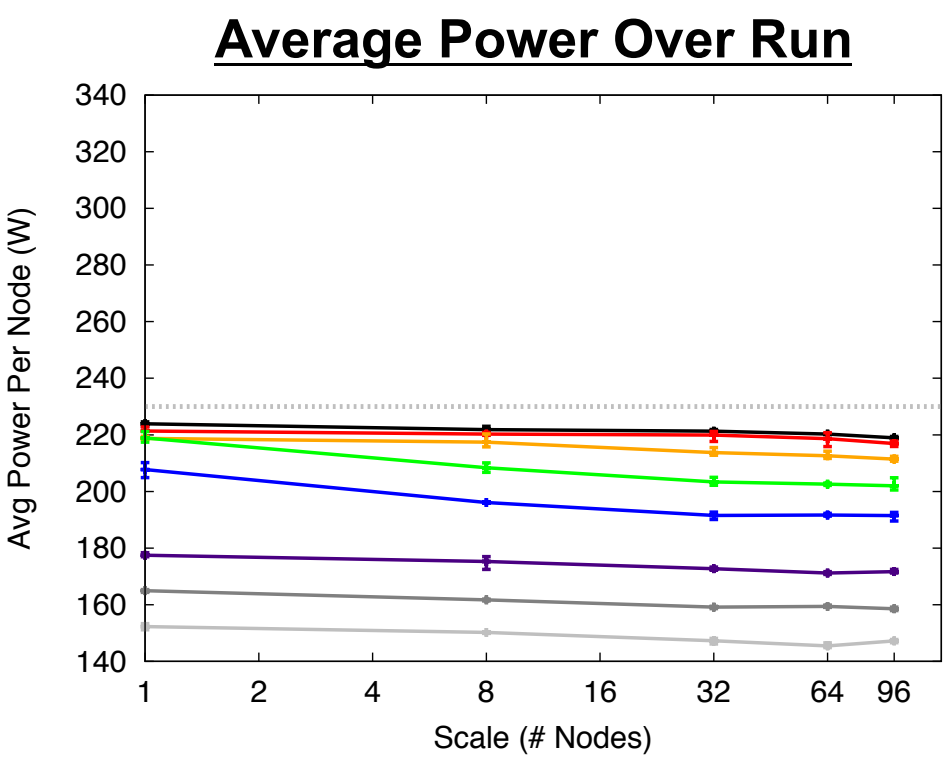


S3D 230W Cap (0%): "> 1.9 GHz Hits the Cap"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz





Hitting cap leads to increasing performance degradation with scale

S3D Summary

- As power cap increases, the highest N p-states experience performance degradation with scale
- This seems to make sense:
  When you hit the cap, thus triggering power throttling, bad things start to happen
- What about the other apps?

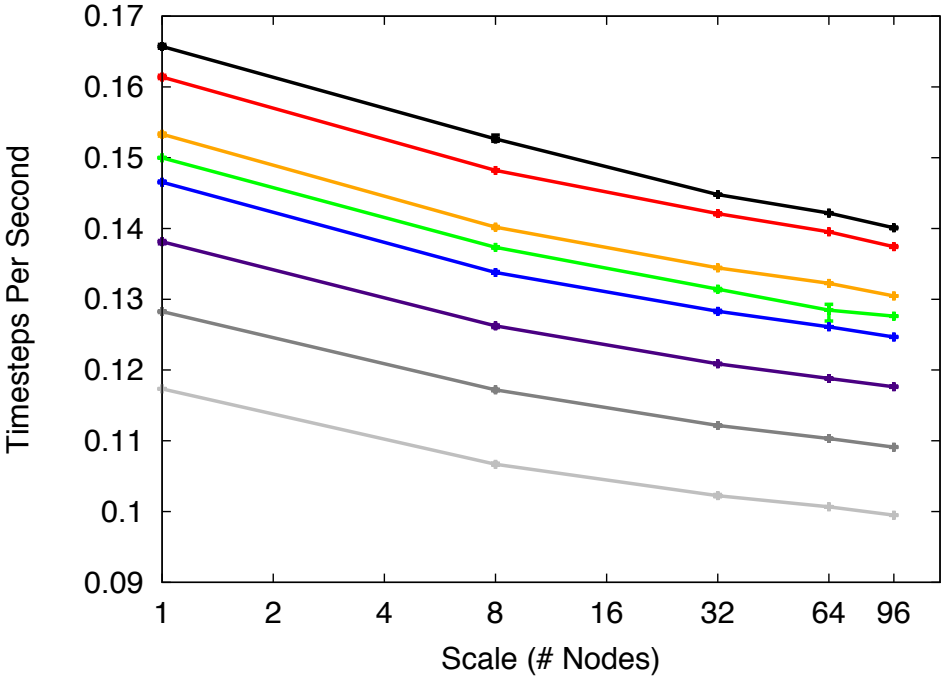
CTH

CTH No Cap: "Things Look Good"

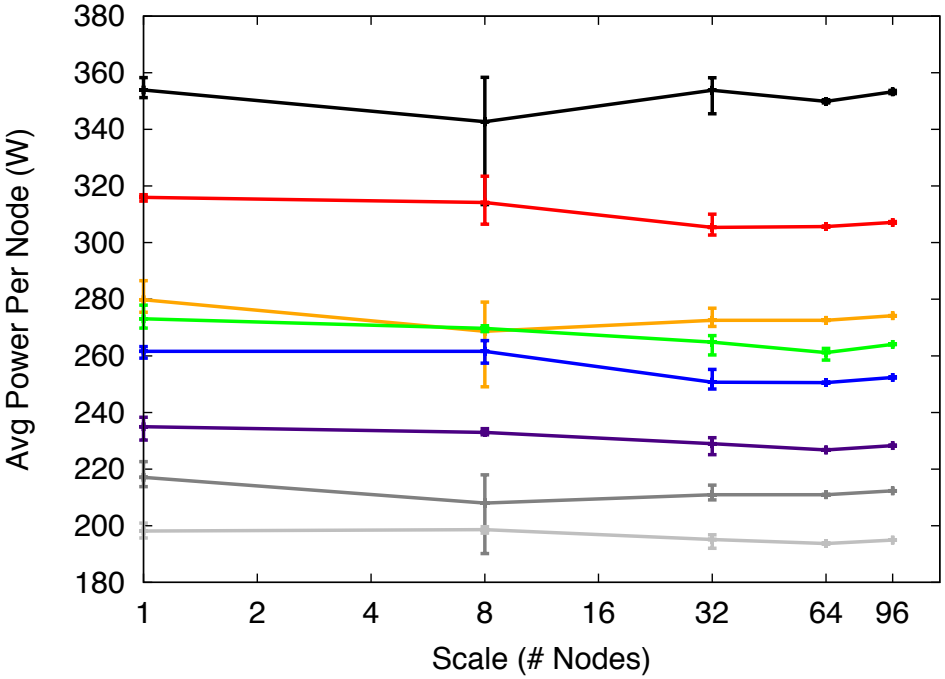
P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with No Cap



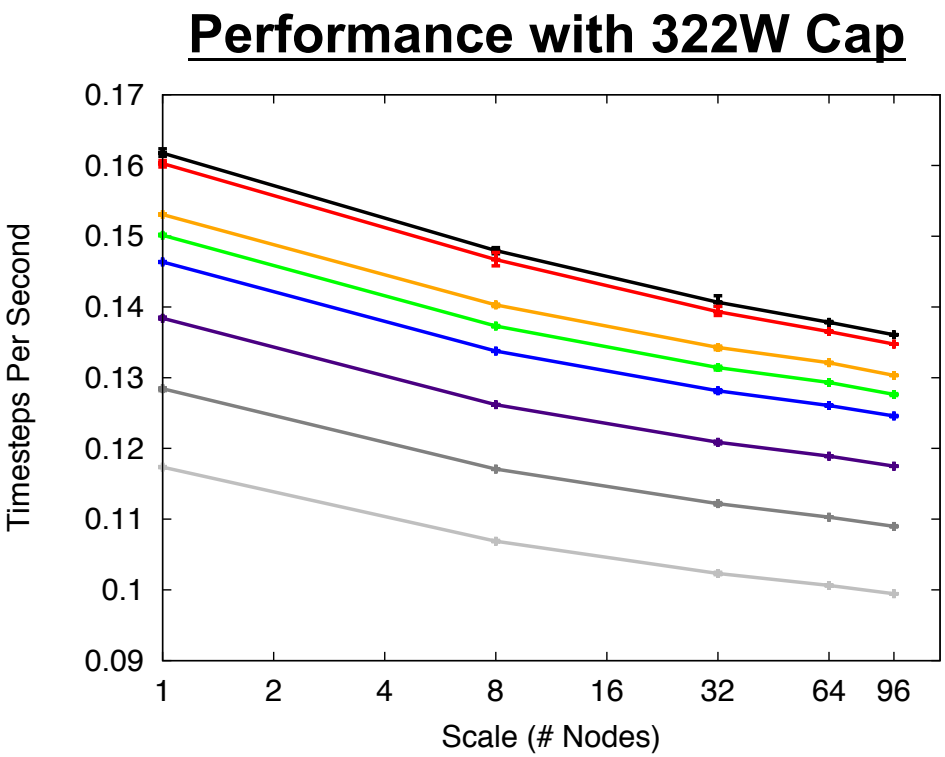
Average Power Over Run

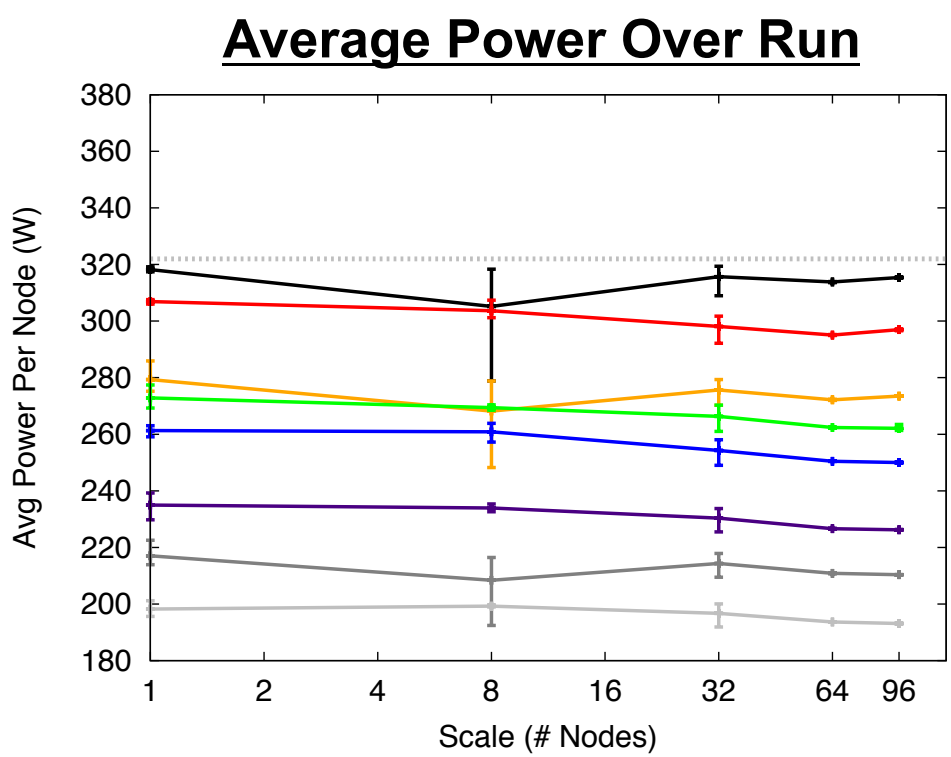


CTH 322W Cap (50%): "Turbo & 2.3 GHz Hit Cap"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

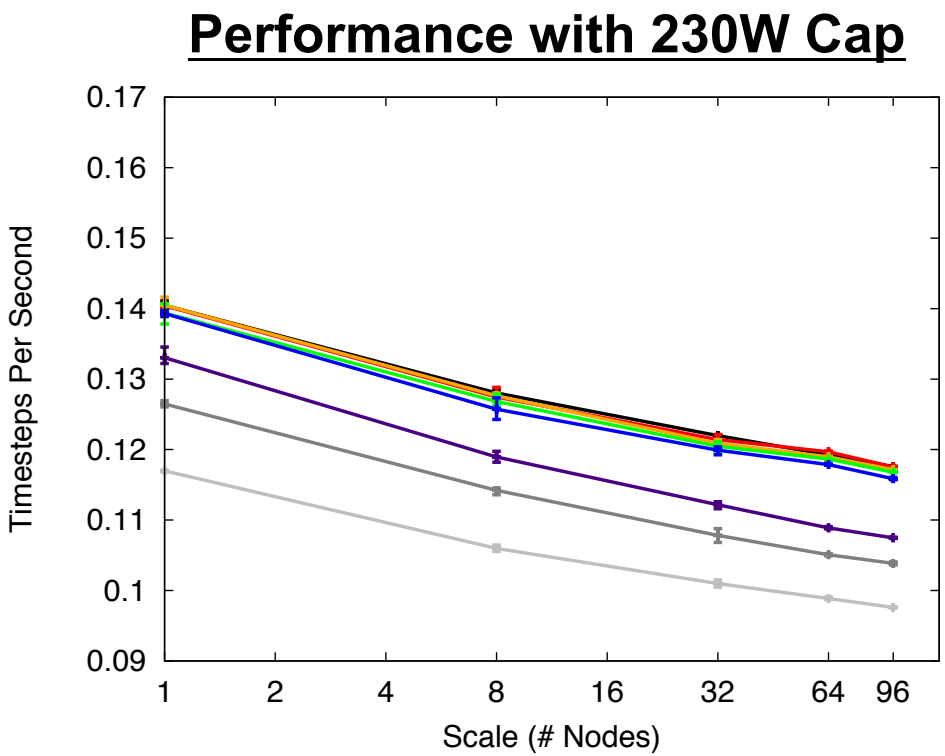


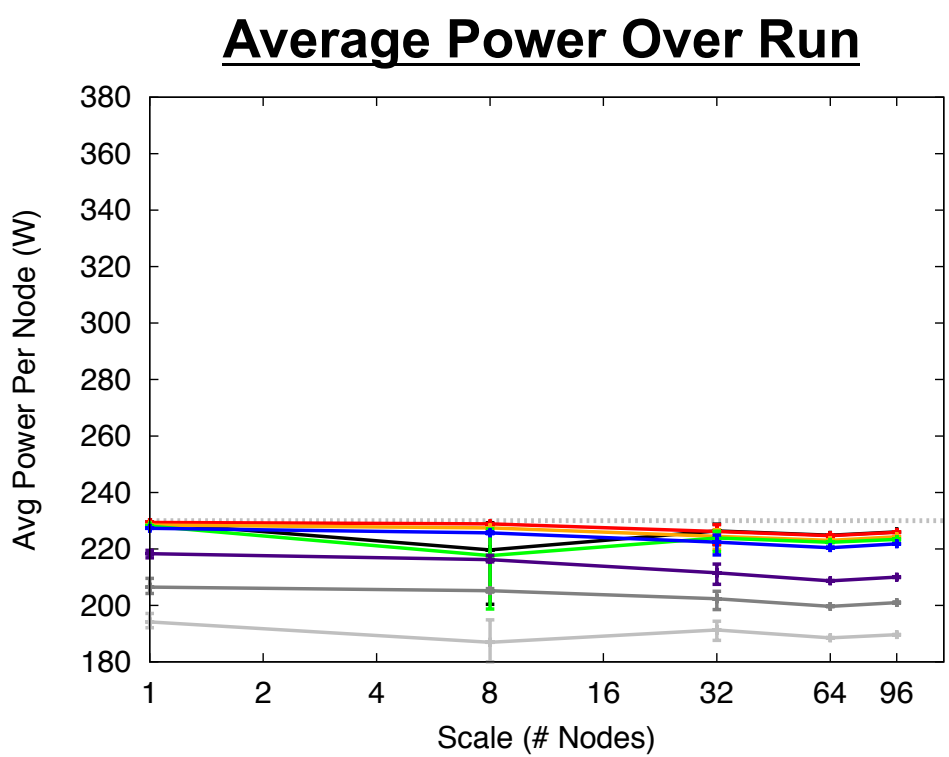


CTH 230W Cap (0%): "> 1.6 GHz Hit Cap"

P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz





Unlike S3D, CTH does not experience performance degradation with scale when it hits the cap

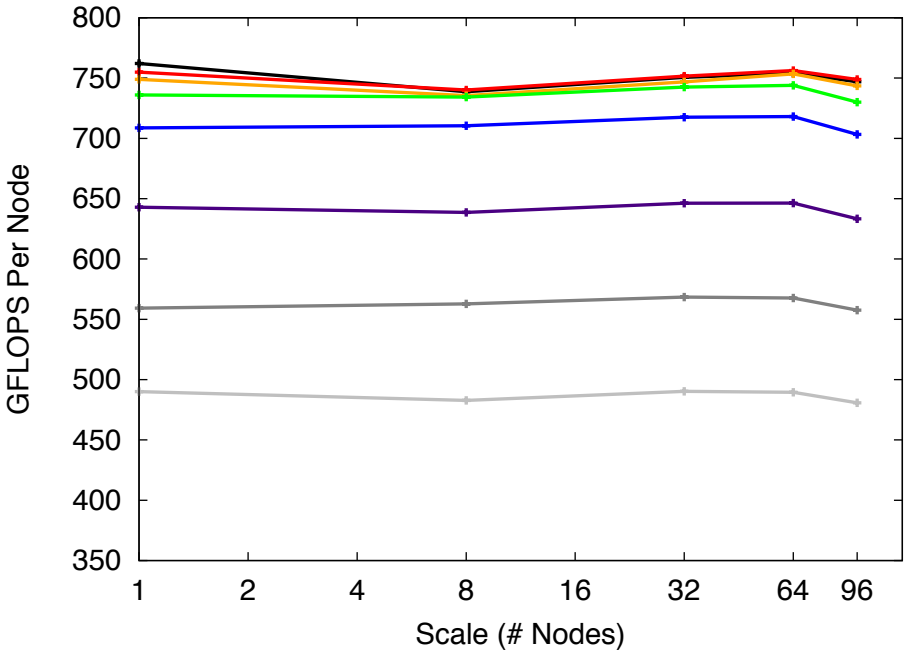
HPL

HPL No Cap: "Things Look Good"

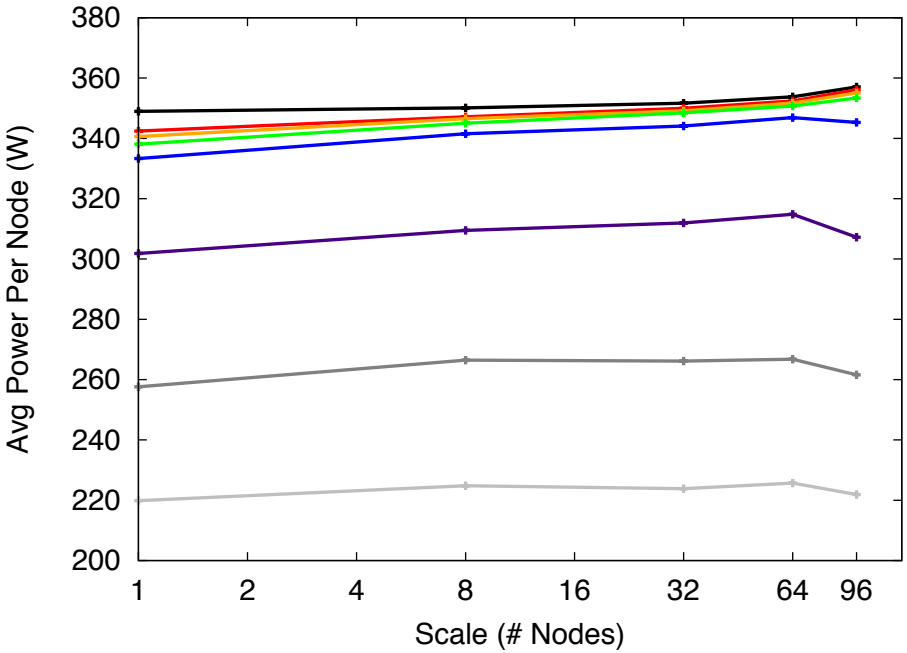
P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with No Cap



Average Power Over Run



HPL 322W Cap (50%): "> 1.6 GHz Hit Cap"

P-states:

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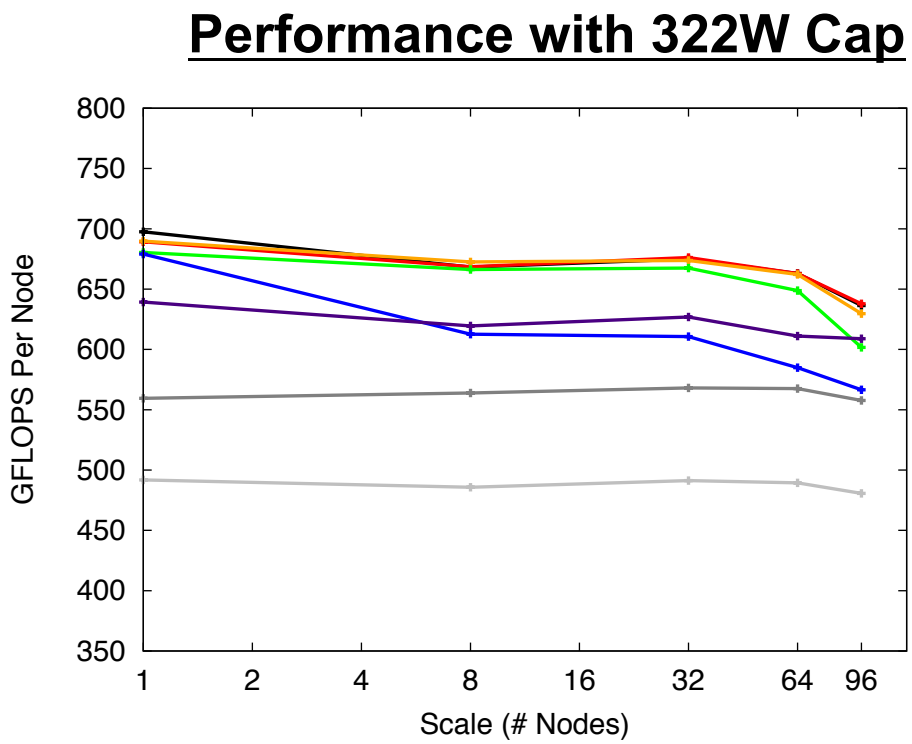
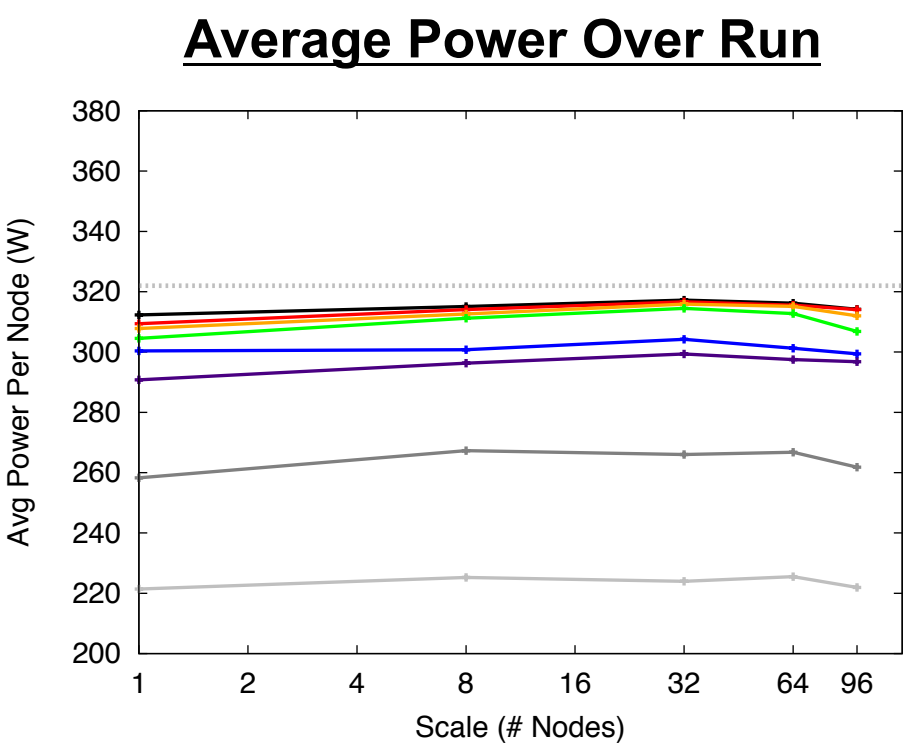
- 1.2 GHz



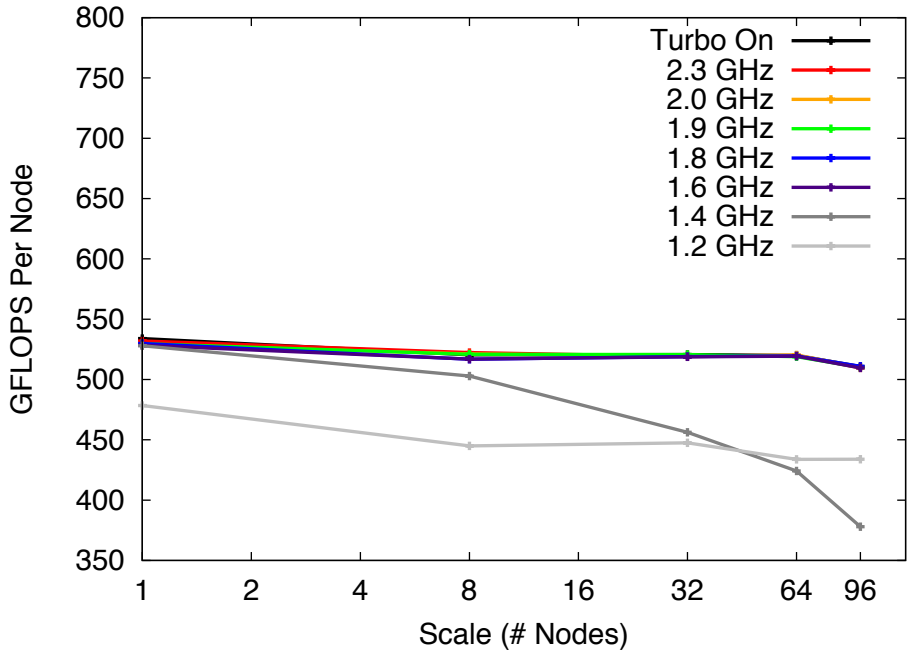


HPL 230W Cap (0%): "All P-states Hit Cap"

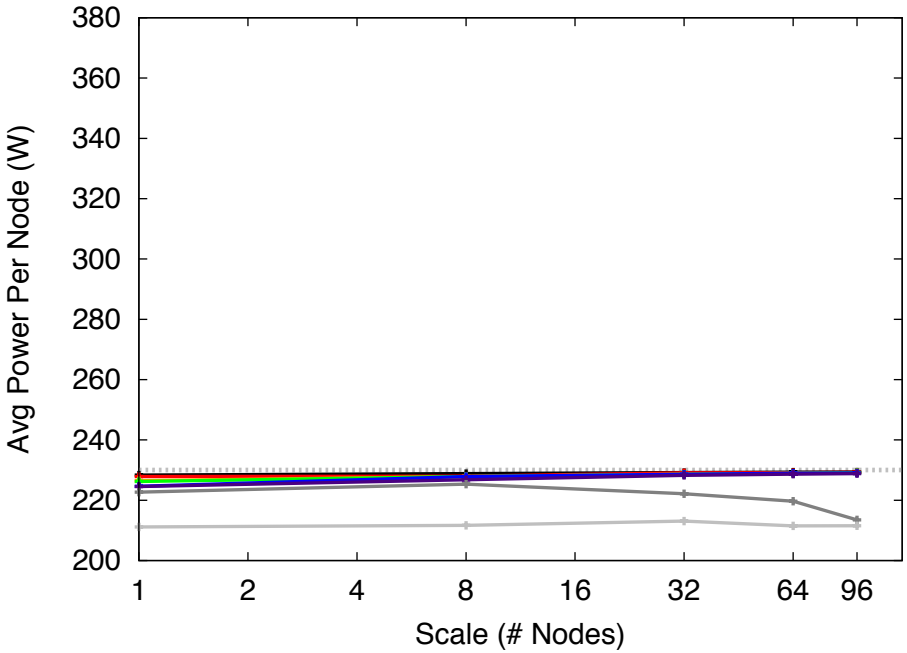
P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with 230W Cap



Average Power Over Run



1.4 GHz only experiences performance degradation with scale, performance drops below 1.2 GHz floor!

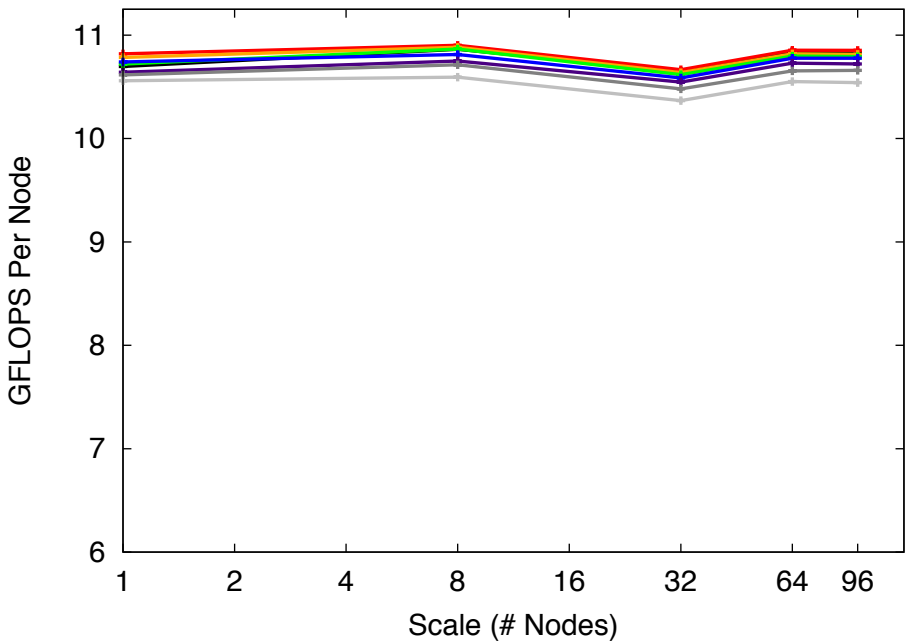
HPCG

HPCG No Cap: "Things Look Good"

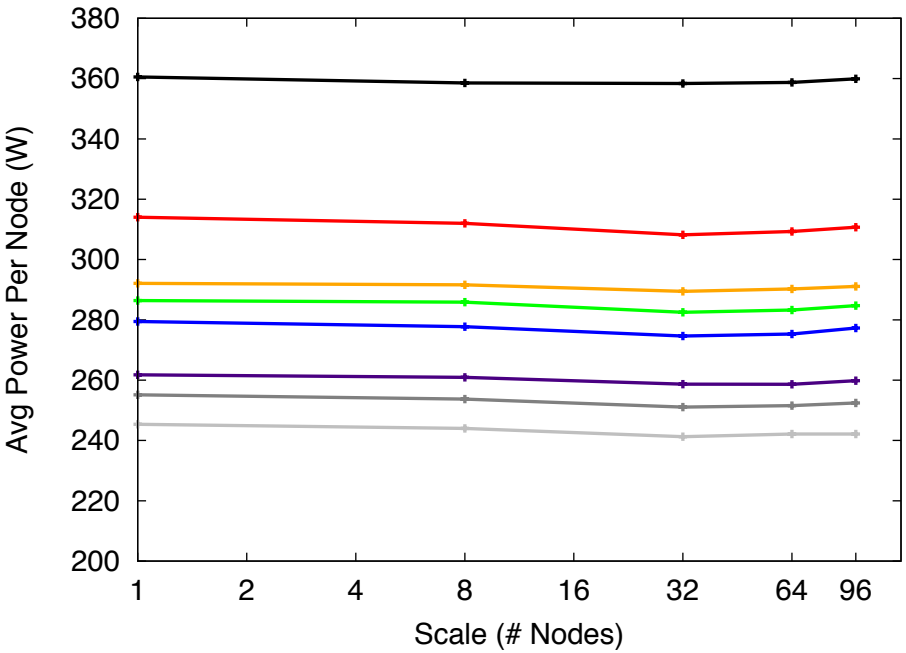
P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with No Cap



Average Power Over Run



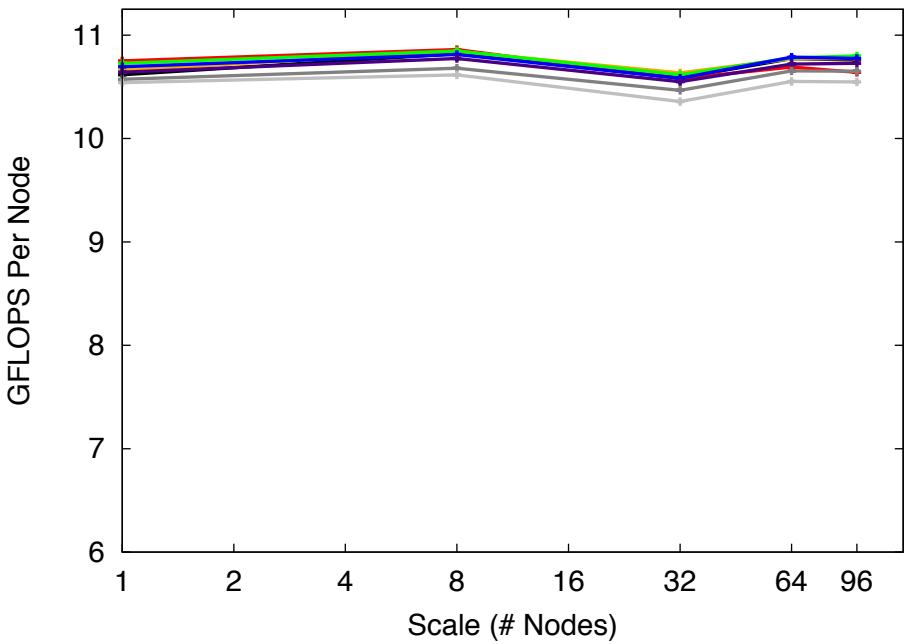
HPCG not affected much by p-state selection;
1.2 GHz: 3% reduced performance, 33% reduced power

HPCG 322W Cap (50%): "Turbo Hits Cap"

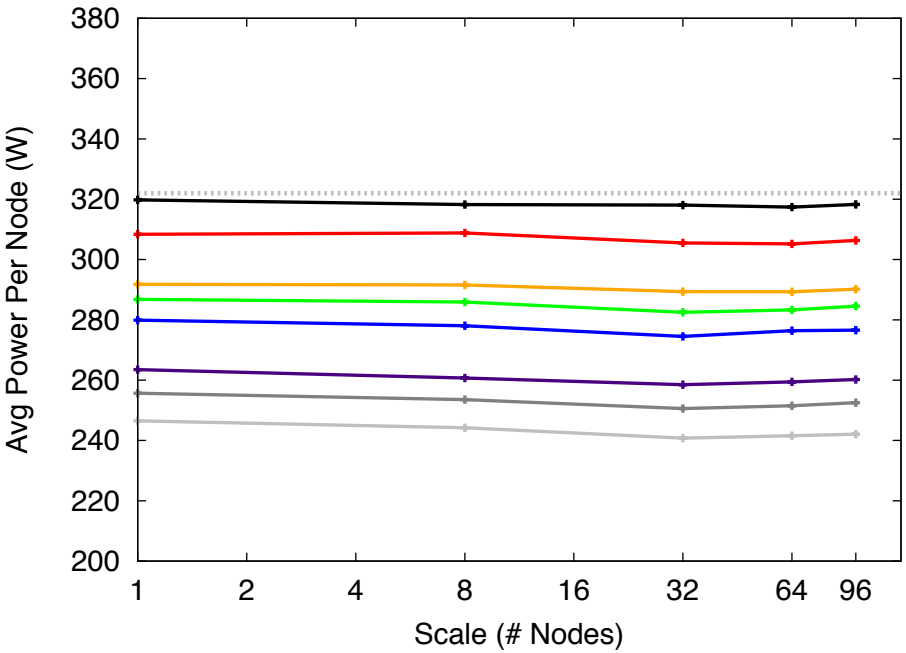
P-states:

- Turbo-On
- 2.3 GHz
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with 322W Cap



Average Power Over Run



HPCG 230W Cap (0%): "All P-states Hit Cap"

P-states:

- Turbo-On
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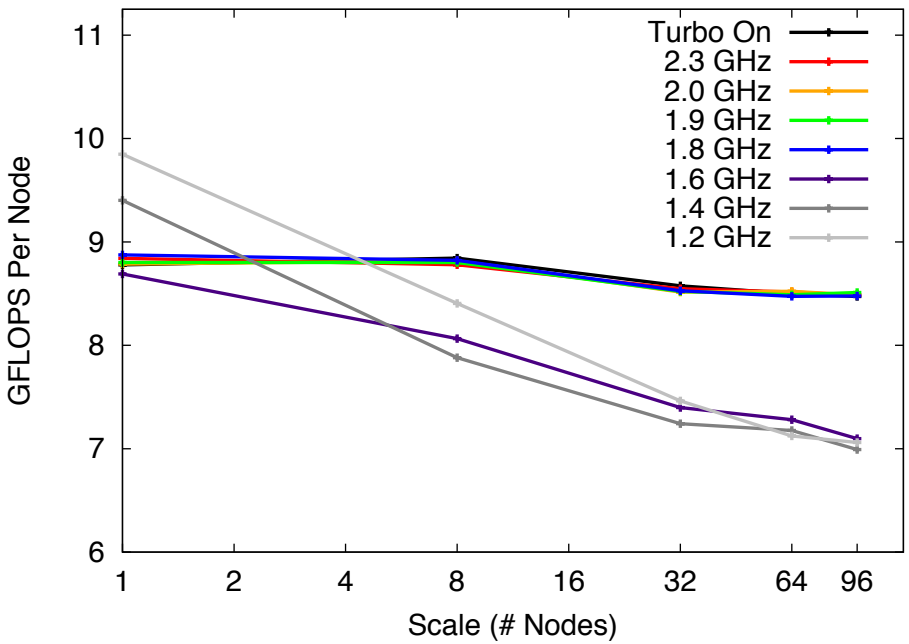
- 2.0 GHz
- 1.9 GHz
- 1.8 GHz
- 1.6 GHz
- 1.4 GHz
- 1.2 GHz

Performance with 230W Cap



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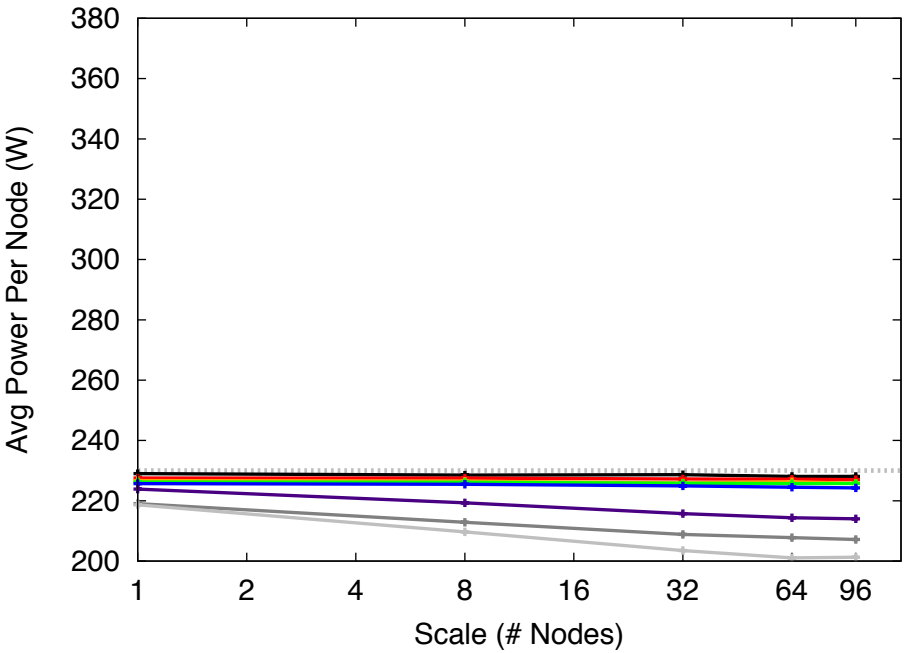


What?
Lowest P-states degrade with scale, not highest!

Summary

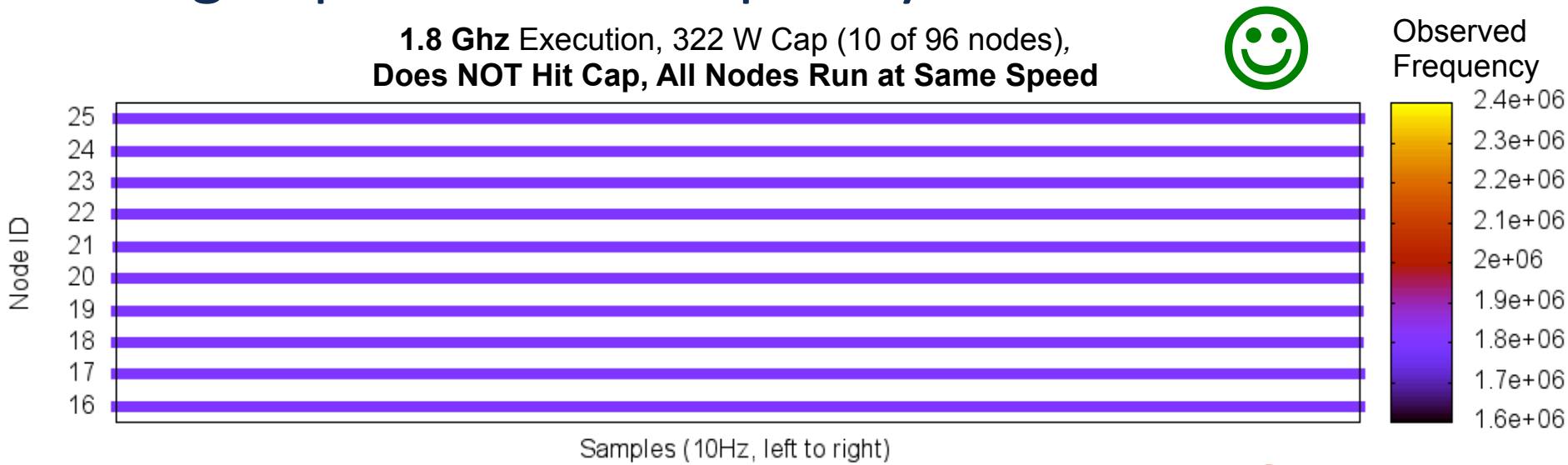
- S3D makes sense, highest p-states degrade with scale
- CTH looks good, even when hitting cap
- HPL sees degradation with scale, not highest p-states
- HPCG performance degrades with scale for lowest p-states

- Don't know exact reason, still investigating
- Believe to be due to OS-noise like affects, throttling mechanism introducing performance variability across nodes
  - Don't know why performance would drop below 1.2 GHz floor
  - Don't know why not always highest p-states. Maybe some sort of resonance between the application and the power capping policy

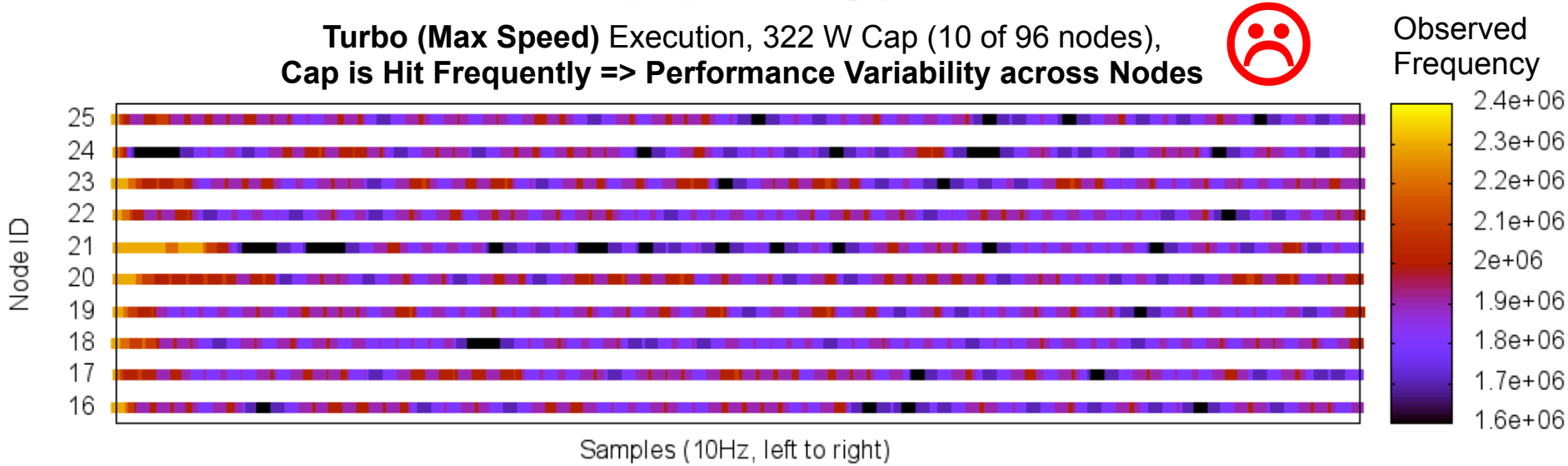
Don't Hit the Cap

S3D CPU 0 Frequency Over Time for 10 Nodes Hitting Cap Leads to Frequency Oscillation

1.8 Ghz Execution, 322 W Cap (10 of 96 nodes),
Does NOT Hit Cap, All Nodes Run at Same Speed



Turbo (Max Speed) Execution, 322 W Cap (10 of 96 nodes),
Cap is Hit Frequently => Performance Variability across Nodes



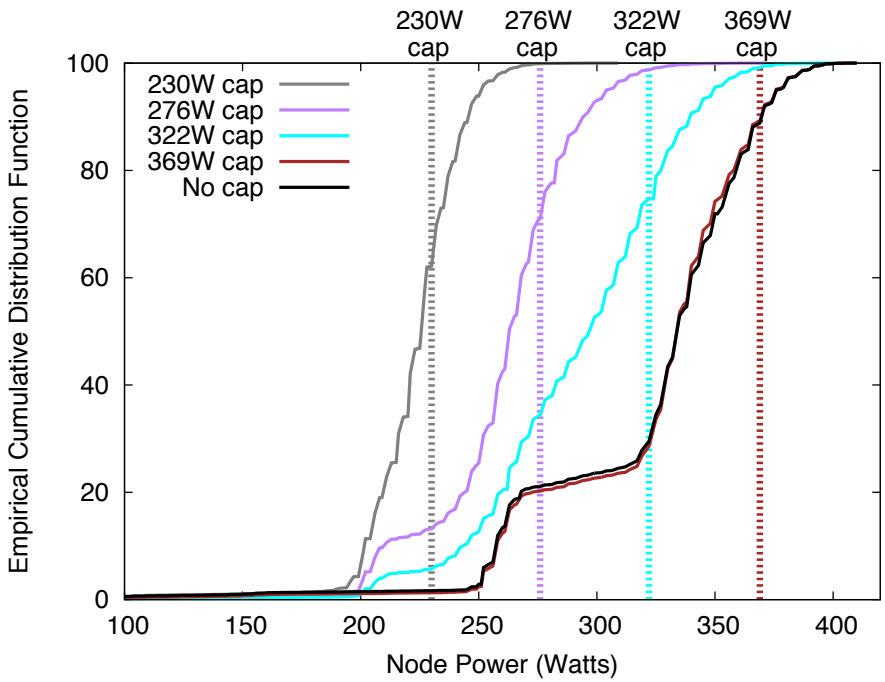
Outline

- Background and Motivation
- Cray XC40 Power Management
- Experimental Approach
- Results
  - Don't hit the power cap
  - Power usage can exceed the cap
- Next Steps and Conclusion

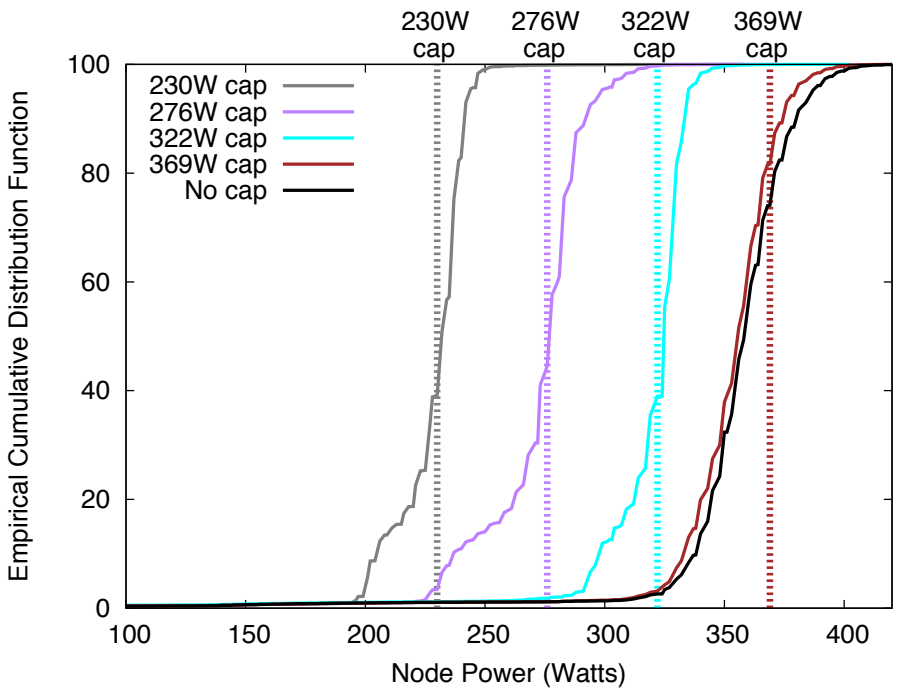
Power Usage Can Exceed the Cap

CDFs of 10 Hz node-level power samples taken over entire run,
Power API tool used to collect samples in-band

S3D



CTH



> 50% of samples can exceed cap.
What happens if all nodes exceed cap at same time?

Outline

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Conclusion

- Next steps
  - Further analysis, what exactly is causing poor scalability?
  - Investigate mitigation techniques
  - Dig deeper into what Node Manager is doing and relation to RAPL
  - Test at large-scale on Trinity
- Takeaways, advice to users and system operators
  - Don't hit the node-level cap if possible. Use other power management techniques (e.g., runtime system concurrency throttling) to avoid triggering the capping mechanism's performance throttling.
  - Power usage can exceed the cap for short durations
  - App performance under p-state control better behaved than under power capping. HPCG behaves more similarly to S3D and CTH apps than HPL. (See P-state vs. P-cap comparison in paper)

Acknowledgements

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- Steve Martin
- David Rush
- Courtenay Vaughan

PowerAPI BOF
Wed @ 5:30p / Room 13a

Thank You

Power Monitoring and Accounting

- Power Management Database (PMDB) runs on SMW
- Blade controllers collect power info, funnel to PMDB
  - Maintain energy counter for each node, based on 10 Hz power samples
  - 1 Hz point-in-time power samples for each node stored in PMDB
- Users have in-band access to Cray node-level power and energy counters: **/sys/cray/pm_counters/energy**
- Cray Resource Utilization Reporting (RUR) gathers energy used for each job run. Report written to user's ~/rur.out file:

```
uid: 20983, apid: 175244, jobid: 349.mutrino-moab,
cmdname: ./bin/mpicth_244, plugin: energy
{"nodes_throttled": 2, "nodes_with_changed_power_cap": 0,
"max_power_cap_count": 0, "energy_used": 25015991,
"max_power_cap": 0, "nodes_accel_power_capped": 0,
"min_power_cap": 0, "min_power_cap_count": 0,
"nodes_power_capped": 0, "nodes": 96}
```

Power Caps – Performance Impact

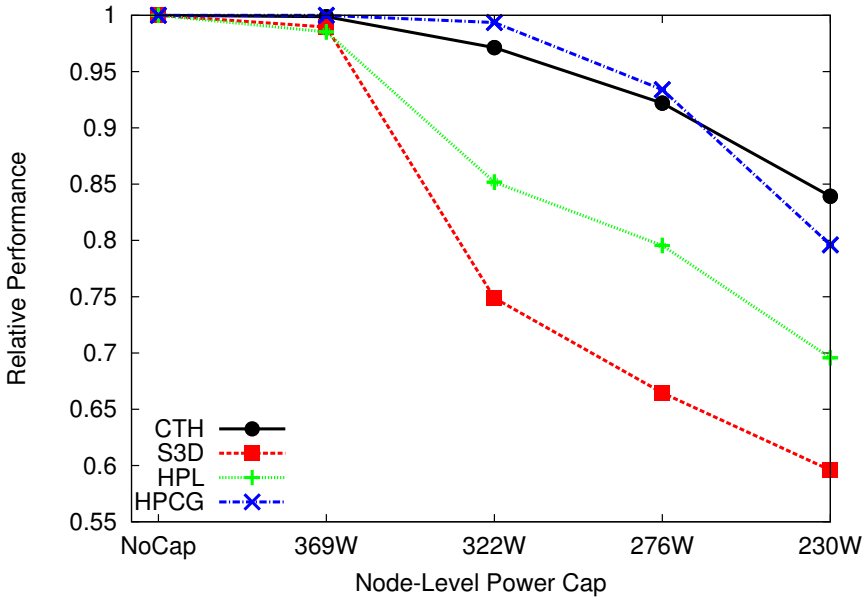
- As power budget is decreased, application power hits the cap
  - System slows down the processor to stay under the cap
  - Performance degrades

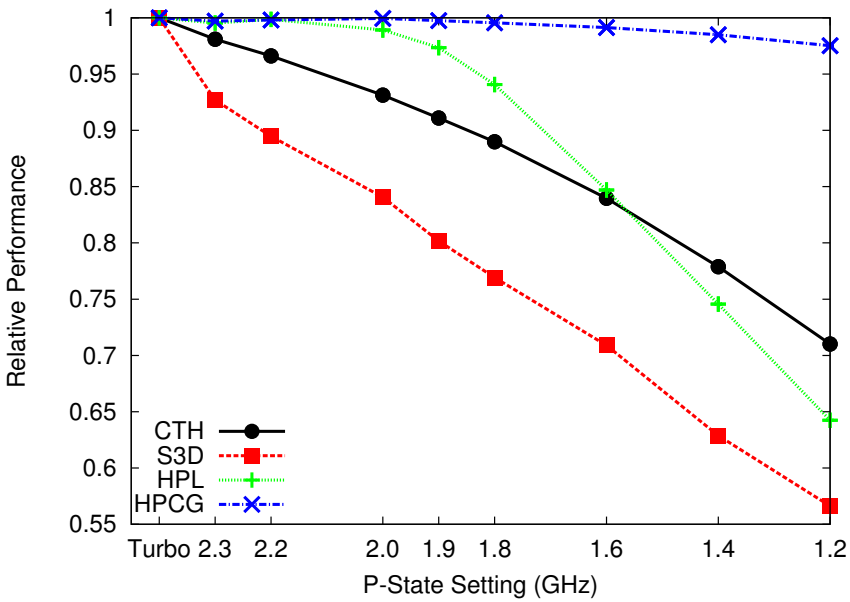
- By running at a lower frequency, avoid hitting the cap
  - With 96 nodes & 230W cap, better at 1.4 Ghz than at 2.3Ghz
  - Best is the highest frequency that stays below the cap
    - Depending on node count and power cap level
    - With 96 nodes & 230W cap, best choice is 1.8 GHz
    - With 96 nodes & 276W cap, best choice is 2.0 GHz

- Why the degradation?
  - System slows down processors by varying amounts, at different times
  - Induces load imbalance

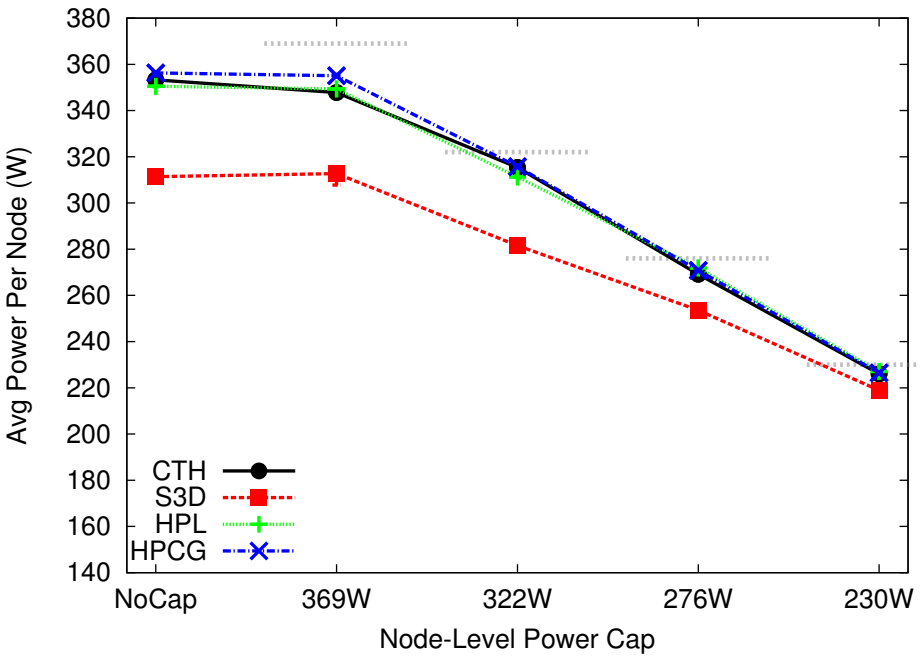
Relative Performance

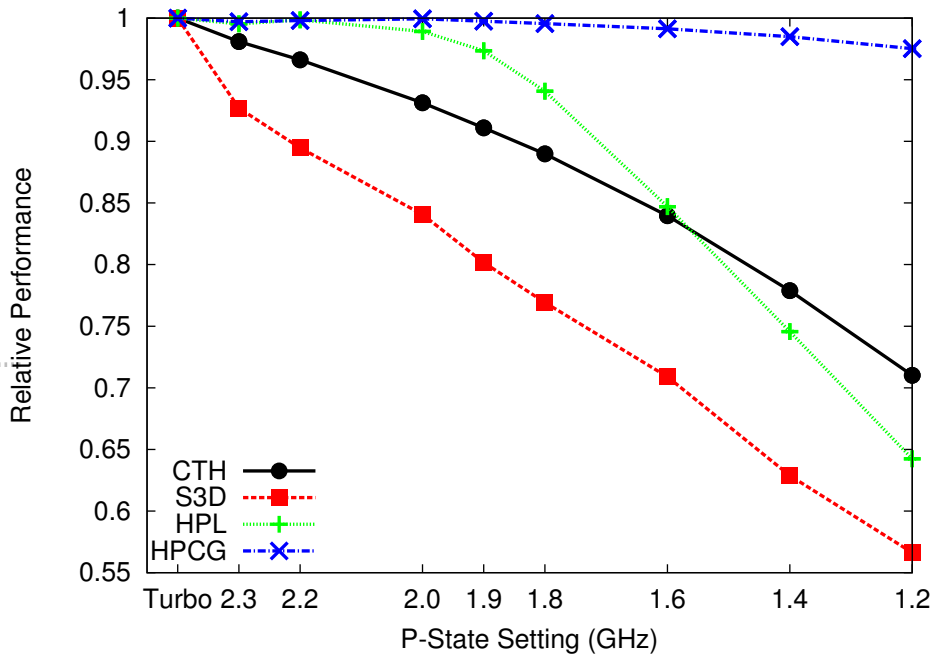
96 node runs of each app, 32 MPI processes per node
Power capping in isolation on left (Turbo on)
P-states in isolation on right (No Power Cap)



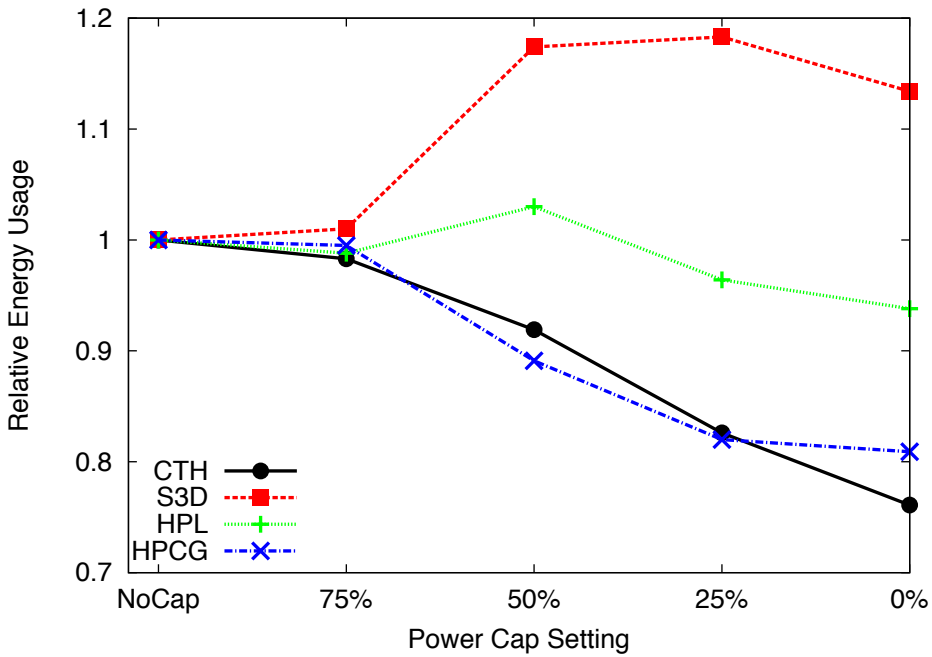


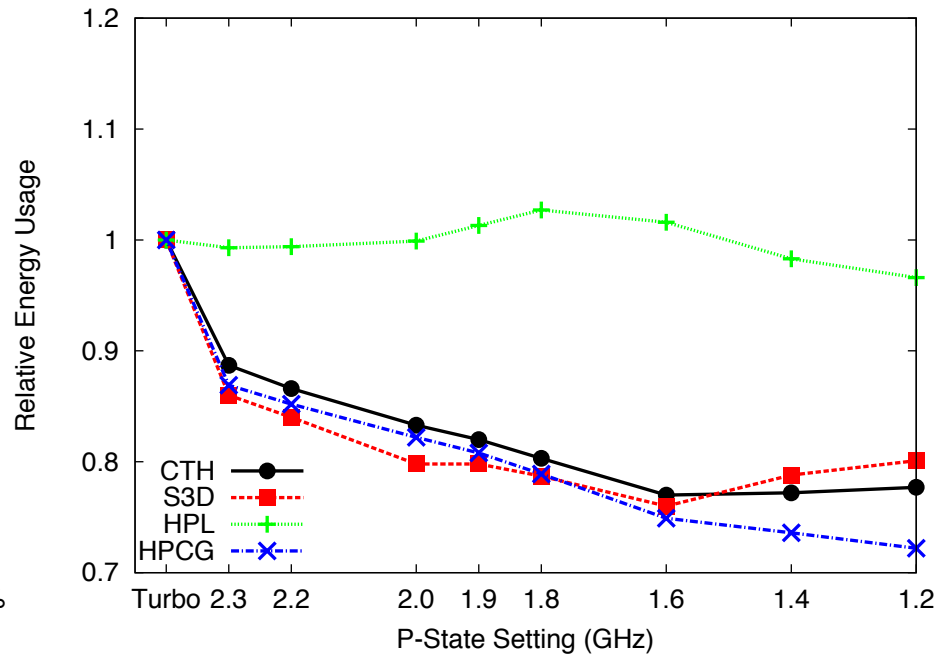
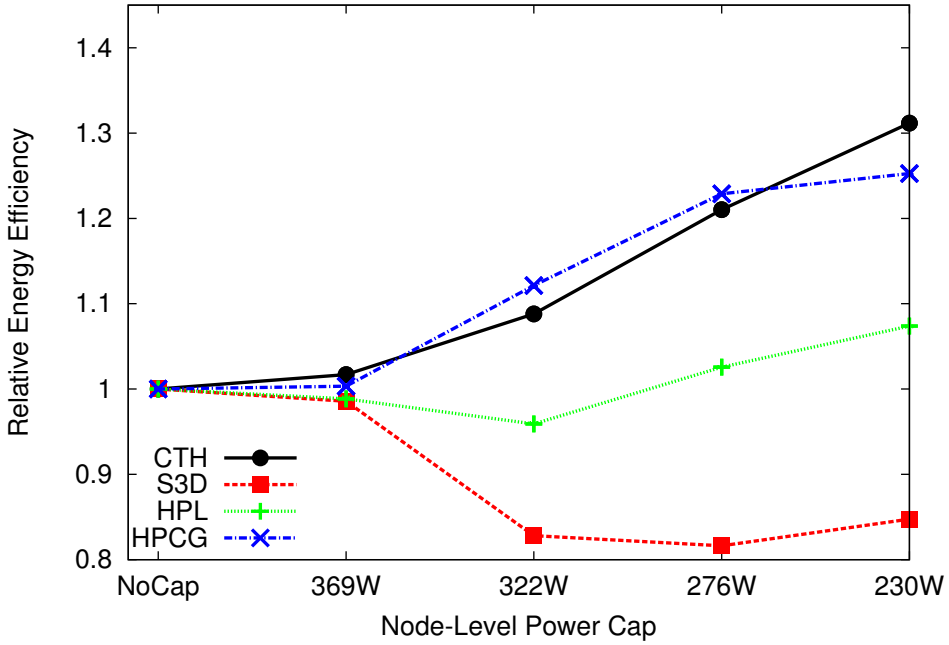
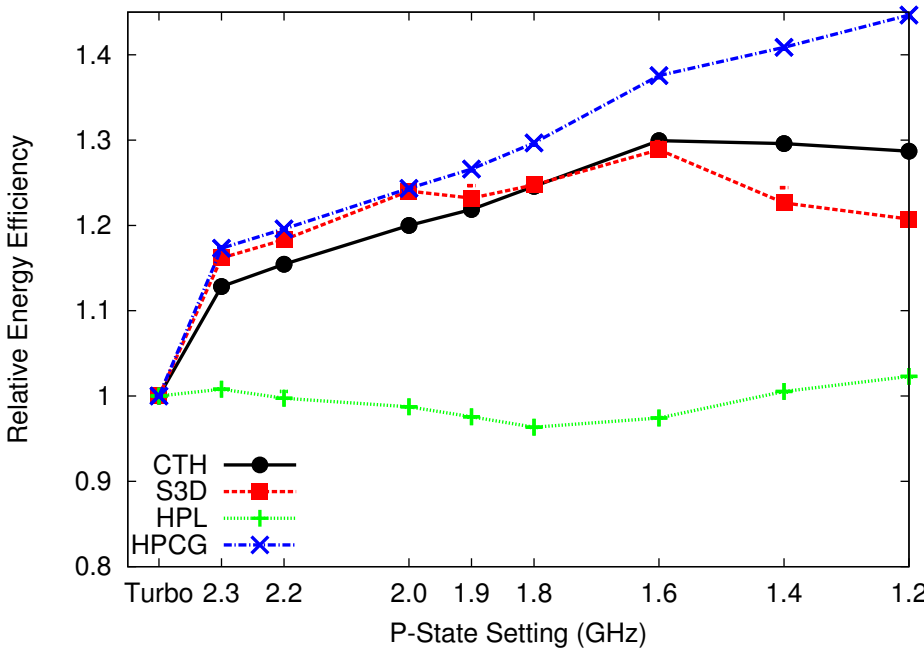
Relative Power





Relative Energy





Relative Energy Efficiency