Paper 5: Energy-Efficient Work-Stealing Language Runtimes

Review

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Outline

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- Dynamic Voltage and Frequency Scaling (DVFS) – a framework to change the frequency and/or operating voltage of a processor(s) based on system requirements.

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- Uses CPUFreq, a linux kernel framework, that decides on whether to increase/decrease frequency of a processor(s).

Background
DVFS

- Dynamic Voltage and Frequency Scaling (DVFS) – a framework to change the frequency and/or operating voltage of a processor(s) based on system requirements.
- Uses CPUFreq, a linux kernel framework, that decides on whether to increase/decrease frequency of a processor(s).
- Consists of two elements:
    - Governor : Directs the driver to change frequency when required.
    - Driver : Performs actions based on governor's decision.

Outline

Background

Work-Stealing

- Work-Stealing
  - Work-First Principle
  - Deque Management
  - Work-Stealing Scheduler
- Covered in course lectures.

Outline

Problem Statement

Objective

Improve energy efficiency of work stealing runtime with minimal performance loss

Outline

Related Work

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- Optimization of work-stealing runtimes
  - *A-Steal*: An adaptive scheduler to take parallelism feedback into account.
  - *SLAW*: Adds adaptive scheduling policies based on locality information.
  - *AdaptiveTC*: Improves system performance through adaptive thread management.
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- Energy efficiency of multi-threaded programs
  - Various DVFS-based solutions have been proposed earlier.
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- Other approaches include thread migration, hardware/software approximation, or a combination of all of them.

Outline

Contributions

- HERMES – The first framework addressing energy efficiency in work-stealing systems.

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- Programs are *tempo-enabled* : Different threads may execute at different speeds(*tempo*). Two novel, complementary tempo control strategies:
  - workpath-sensitive
  - workload-sensitive

Contributions

- HERMES – The first framework addressing energy efficiency in work-stealing systems.
- Programs are *tempo-enabled* : Different threads may execute at different speeds(*tempo*). Two novel, complementary tempo control strategies:
  - workpath-sensitive
  - workload-sensitive
- A prototyped implementation demonstrating an average of 11-12% energy savings with 3-4% performance loss over work-stealing benchmarks.

Outline

Motivation

- In the multi-core era, work stealing received considerable interest in language runtime design.

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- In the multi-core era, work stealing received considerable interest in language runtime design.
- There is an active interest in research improving its performance-critical properties, such as adaptiveness, scalability, and fairness.
- In comparison, energy efficiency in work-stealing systems has received little attention, which is particularly unfortunate.

Outline

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- Determines thread tempo based on control flow, with threads tackling *immediate work* executing at a faster tempo.

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- Victim worker takes precedence over the thief worker in a thief-victim relationship.

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- Victim worker takes precedence over the thief worker in a thief-victim relationship.
- Two important design ideas:
  - Thief Procrastination
  - Immediacy Relay

Insights

Workpath-Sensitive Tempo Control

Thief Procrastination

At the beginning of the thief-victim relationship, the tempo of the thief worker should be set to be slower than the victim worker.

Immediacy Relay

If the thief-victim relationship terminates because the victim runs out of work, the tempo of all the thiefs should be raised. This happens in a recursive fashion.

Outline

- Selects the appropriate thread tempo based on the size of work-stealing deques.

Insights

Workload-Sensitive Tempo Control

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- Threads with longer deques run at faster tempo.
- Threshold calculation:

$$thld_i = \left(\frac{2 \times L}{K + 1}\right) \times i$$

  - $L =$ average deque size
  - $K =$ number of thresholds
  - $i \in [1, K]$

Outline

Insights
Unified Algorithm

- In workpath-alone executions, a non-immediate worker may have many deque items to work on.

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- Increased workpath length means increased execution time, which potentially leads to additional energy consumption.

Insights
Unified Algorithm

- In workpath-alone executions, a non-immediate worker may have many deque items to work on.
- Similarly, in workload-alone executions, an immediate worker with fewer deque items is set to a lower tempo.
- Increased workpath length means increased execution time, which potentially leads to additional energy consumption.
- In both cases, a second opinion from the other strategy can lead to better decisions.

Outline

Outline

Implementation

Order of Immediacy

- Key data-structure for workpath sensitivity.
- Double linked list across workers connected by `next` and `prev` pointers.
- When a victim terminates, immediacy relay happens through this linked list.

Implementation
Order of Immediacy

structure WORKER
  DQ // deque (array)
  H // head index
  T // tail index
end structure

structure WORKER
  DQ // deque (array)
  H // head index
  T // tail index
  next // next immediate work
  prev // prev immediate work
  thld // size thresholds (array)
  S // size threshold index
end structure

Outline

- Achieved through DVFS as modern CPUs support a limited and discrete set of frequencies.

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- Let $\{f_1, f_2, ..., f_n\}$ be set of frequencies supported by the CPU core, where $f_i > f_{i+1}$ for any $i \in [1, n-1]$

```
procedure DOWN(w, v)
    f ← frequency of core hosting v
    if f == f_i and i < N then
        ...// scale core hosting w to f_{i+1}
    end if
end procedure
```

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```

- $N <= n$. This is called N-frequency tempo control.

Outline

Implementation

Worker-Core Mapping

- Relationship between workers (threads) and hosting CPU cores should be known.

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- Two scheduling strategies are used.
  - Static : each worker is pre-assigned to CPU core.
  - Dynamic : each worker thread may migrate from one core to another during program execution.

- Relationship between workers (threads) and hosting CPU cores should be known.
- Two scheduling strategies are used.
  - Static : each worker is pre-assigned to CPU core.
  - Dynamic : each worker thread may migrate from one core to another during program execution.
- Only requirement of dynamic scheduling is that the worker **must** stay on its host core.

Outline

- HERMES does not adjust CPU frequencies when a worker becomes idle (when pop and steal both fail).

Implementation

Tempo Setting of Idle Workers/Core

- `HERMES` does not adjust CPU frequencies when a worker becomes idle (when pop and steal both fail).
- `YIELD`: The core is reallocated to another worker.

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- `YIELD`: The core is reallocated to another worker.
- `YIELD` happens very rarely in practice.

Algorithm 2.1 Worker

```
w : WORKER
procedure SCHEDULE(w)
  loop
    t ← POP(w)
    if t==null then
      v = SELECT()
      t ← STEAL(v)
      if t==null then
        YIELD(w)
      else
        WORK(w, t)
      end if
    else
      WORK(w, t)
    end if
  end loop
end procedure
```

Algorithm 3.1 Worker

```
w : WORKER
procedure SCHEDULE(w)
  loop
    t ← POP(w)
    if t==null then
      w0 = w.next
      for w0 != null do
        UP(w0)
        w0 ← w0.next
      end for
      w.prev.next ← w.next
      w.next.prev ← w.prev
      w.next ← null
      w.prev ← null
      v = SELECT()
      t ← STEAL(v)
      if t==null then
        YIELD(w)
      else
        DOWN(w, v)
        if v.next != null then
          w.next ← v.next
          v.prev ← w.prev
        end if
        v.next ← w
        w.prev ← v
        WORK(w, t)
      end if
    else
      WORK(w, t)
    end if
  end loop
end procedure
```

Implementation

API

Algorithm 2.3 Pop

```
w : WORKER
procedure POP(w)
  w.T– –
  if w.H > w.T then
    w.T++
    LOCK(w)
    w.T– –
    if w.H > w.T then
      w.T++
      UNLOCK(w)
      return null
    end if
  end if
  UNLOCK(w)
  return w.DQ[w.T]
end procedure
```

Algorithm 3.4 Pop

```
w : WORKER
procedure POP(w)
  w.T– –
  if w.H > w.T then
    w.T++
    LOCK(w)
    w.T– –
    if w.H > w.T then
      w.T++
      UNLOCK(w)
      return null
    end if
  end if
  UNLOCK(w)
  if w.T - w.H < w.thld[w.S] then
    if w.S > 0 then
      if w.prev ! = null then
        w.S– –
        DOWN(w)
      end if
    end if
  end if
  return w.DQ[w.T]
end procedure
```

Implementation

API

Algorithm 2.4 Steal

```
v : WORKER // victim
procedure STEAL(v)
    LOCK(v)
    v.H++
    if v.H > v.T then
        v.H– –
        UNLOCK(v)
        return null
    end if
    UNLOCK(v)
    return v.DQ[v.H]
end procedure
```

Algorithm 3.5 Steal

```
v : WORKER // victim
procedure STEAL(v)
    LOCK(v)
    v.H++
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        return null
    end if
    UNLOCK(v)
    if v.T - v.H < v.thld[v.S] then
        if v.S > 0 then
            if v.prev ! = null then
                v.S ––
                DOWN(v)
            end if
        end if
    end if
    return v.DQ[v.H]
end procedure
```

Implementation

API

Algorithm 2.2 Push

```
w : WORKER
t : TASK
procedure PUSH(w,t)
    w.T++
    w.DQ[w.T] ← t
end procedure
```

Algorithm 3.3 Push

```
w : WORKER
K: number of thresholds
t: TASK
procedure PUSH(w, t)
    w.T++
    w.DQ[w.T] ← t
    if w.T - w.H > w.thld[w.S] then
        if w.S < K-1 then
            w.S++
            UP(w)
        end if
    end if
end procedure
```

Outline

1. DVFS switching cost

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2. Online profiling of workload threshold.

Implementation

Overheads

1. DVFS switching cost
2. Online profiling of workload threshold.
3. Affinity setting in dynamic scheduling.

Outline

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- K-Nearest Neighbors (`KNN`) uses pattern recognition methods to classify ojects based on closest training examples in the feature space.
- Sparse Triangle Intersection (`Ray`) calculates for each ray the first triangle it intersects given a set of triangles contained in 3D bounding box and set of rays to penetrate.
- Integer Sort (`Sort`) is a parallel implementation of Radix Sort.
- Comparison Sort (`Compare`) is similar to `Sort` but uses sample sort.
- Convex Hull (`Hull`) is a computational geometry benchmark.

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- Integer Sort (`Sort`) is a parallel implementation of Radix Sort.
- Comparison Sort (`Compare`) is similar to `Sort` but uses sample sort.
- Convex Hull (`Hull`) is a computational geometry benchmark.
- We use `KNN` and `Ray` for our experiments.

Outline

- Conducted experiments on two different systems to test effectiveness of the approach.
  - System A: 2 x 16-core AMD Opteron 6378 processors (Piledriver microarchitecture) with 64GB DDR3 1600 memory
  - System B: 8-core AMD FX-8150 processor (Bulldozer microarchitecture) with 16GB DDR3 1600 memory
- Both systems run Debian 3.2.46-1 x86-64 Linux (kernel 3.2.0-4-amd64) and support 5 different CPU frequencies.

Experimental Methodology

System Specs

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  - System A: 2 x 16-core AMD Opteron 6378 processors (Piledriver microarchitecture) with 64GB DDR3 1600 memory
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- Both systems run Debian 3.2.46-1 x86-64 Linux (kernel 3.2.0-4-amd64) and support 5 different CPU frequencies.
- Piledriver / Bulldozer were chosen as they supported *multiple clock domains*.

Outline

Experimental Methodology

Energy Consumption

- Measured through current meters over power supply lines to the CPU module.
- Data converted to NI DAQ and collected by NI LabVIEW SignalExpress with 100 samples per second.
- Supply voltage stable at 12V, so energy consumption computed as sum of current samples multiplied by 12×0.01

Outline

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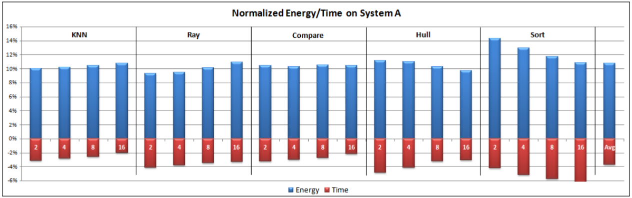
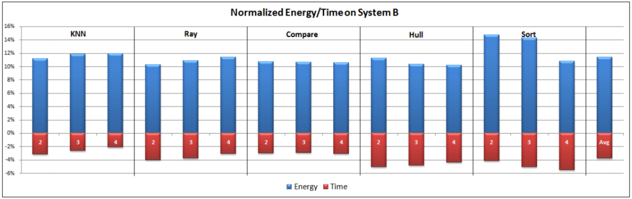
- On system A, experiments were conducted using 2, 4, 8, 16 workers.
- On system B, experiments were conducted using 2, 3, 4 workers.

- On system A, experiments were conducted using 2, 4, 8, 16 workers.
- On system B, experiments were conducted using 2, 3, 4 workers.
- In both systems, `HERMES` averages 11-12% energy savings over 3-4% performance loss.

Results

Overall Results





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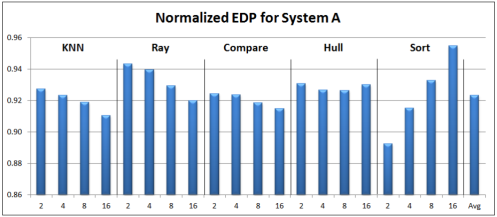
Results

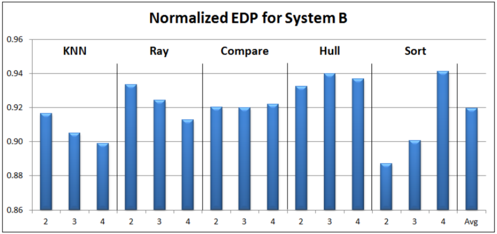
Overall Results

- Energy Delay Product(EDP): Product of energy consumption and execution time.
- EDP is often used as an indicator for demonstrating the energy/performance tradeoff.
- In both System A and System B, the average normalized EDP is about 0.92.

Results

Overall Results





Outline

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Results

Relative Effectiveness

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- Data are normalized w.r.t to the unified HERMES algorithm.

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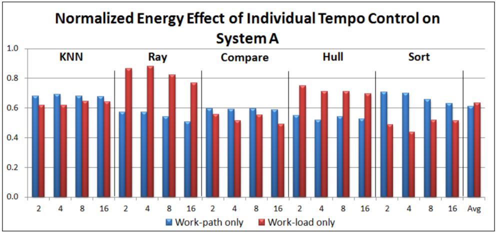
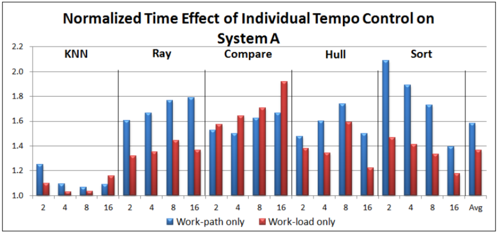
- Data are normalized w.r.t to the unified `HERMES` algorithm.
- The following set of figures show the complementary nature of the two strategies.

Results

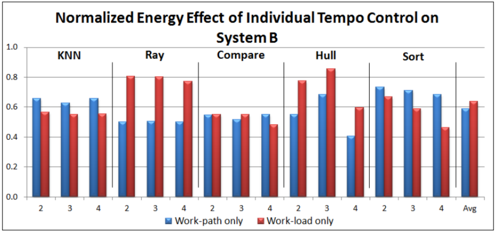
Relative Effectiveness

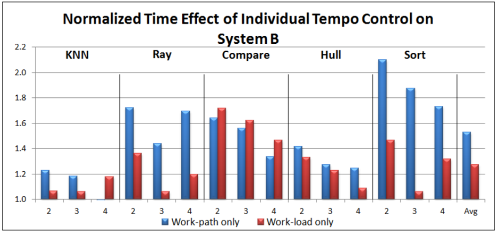




Results

Relative Effectiveness





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- We experimentally evaluate the effects of different frequency mapping strategies.

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- We only consider 2-frequency tempo control.
  - Fastest tempo is mapped to the first frequency.
  - All other tempos are mapped to the second frequency.

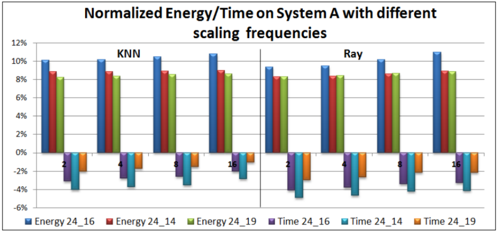
Results

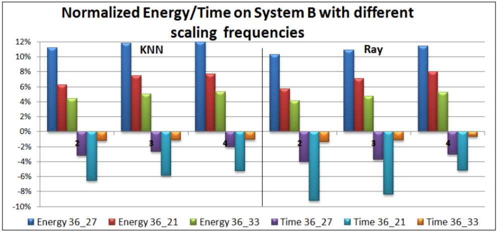
Effect of Frequency Selection

- We experimentally evaluate the effects of different frequency mapping strategies.
- We only consider 2-frequency tempo control.
  - Fastest tempo is mapped to the first frequency.
  - All other tempos are mapped to the second frequency.
- We fix the frequency for the fast tempo 2.4Ghz for System A and 3.6GHz for System B.
  - Experiment with different settings for the slow tempo.

Results

Effect of Frequency Selection





- Two scenarios:
  1. Higher frequency for slow tempo.
  2. Lower frequency for slow tempo.

Results

Effect of Frequency Selection

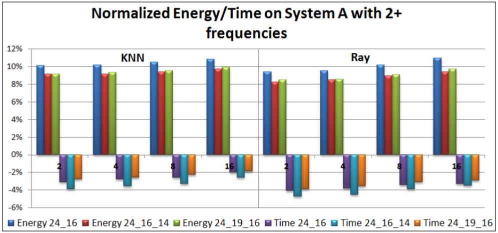
- Two scenarios:
  1. Higher frequency for slow tempo.
  2. Lower frequency for slow tempo.
- Optimal combination:
  - Frequency of slow tempo should be 60% of that of fast tempo.

Outline

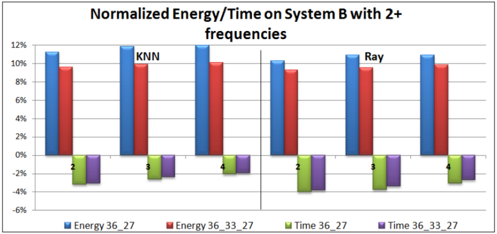
Results

N-Frequency Tempo Control

- We study how the number of frequencies impact the results.



Normalized Energy/Time on System A with 2+ frequencies
12%
10%
8%
6%
4%
2%
0%
-2%
-4%
-6%
KNN
Ray
2
4
8
16
Energy 24_16
Energy 24_16_14
Energy 24_19_16
Time 24_16
Time 24_16_14
Time 24_19_16



Normalized Energy/Time on System B with 2+ frequencies
12%
10%
8%
6%
4%
2%
0%
-2%
-4%
-6%
KNN
Ray
2
3
4
Energy 36_27
Energy 36_33_27
Time 36_27
Time 36_33_27

Results

N-Frequency Tempo Control

- A 3-frequency tempo control can sometimes incur less loss on performance.

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- But the 2-frequency tempo control has a slight edge on energy savings.

Results

N-Frequency Tempo Control

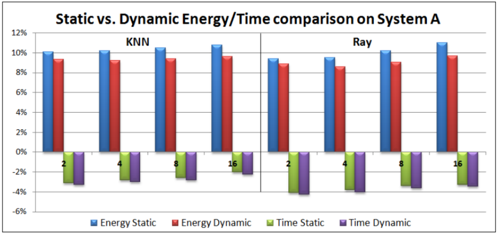
- A 3-frequency tempo control can sometimes incur less loss on performance.
- But the 2-frequency tempo control has a slight edge on energy savings.
- Maybe due to lesser overhead on DVFS.

Outline

- We study the effectiveness of HERMES under static scheduling and dynamic scheduling.

Results

N-Frequency Tempo Control



- Following figures show a more detailed analysis.
- Time series plot of power consumption.

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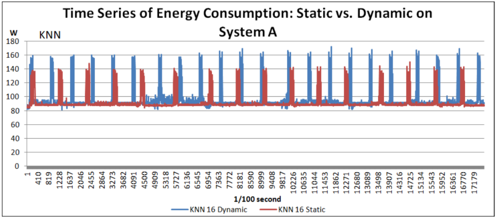
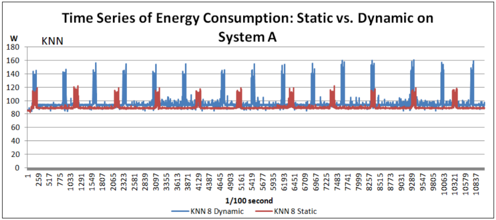
- Time series plot of power consumption.
- The shape of the time series are dependent on the type benchmarks and their settings (such as number of workers).

Results

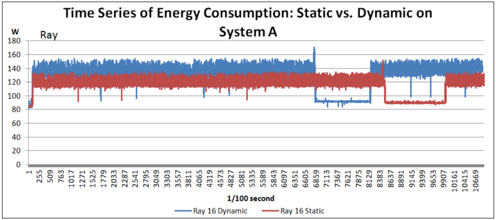
N-Frequency Tempo Control

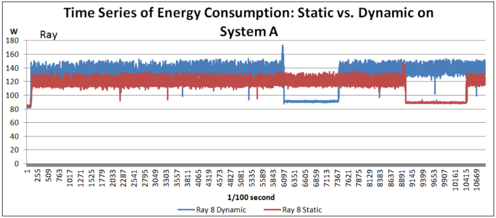




Results

N-Frequency Tempo Control





Static vs Dynamic Scheduling

- For each benchmark with the same number of workers, the executions of static scheduling vs. dynamic scheduling display similar patterns.

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- Dynamic scheduling incurs a slightly higher level of energy consumption.

Results

Static vs Dynamic Scheduling

- For each benchmark with the same number of workers, the executions of static scheduling vs. dynamic scheduling display similar patterns.
- Dynamic scheduling incurs a slightly higher level of energy consumption.
- Maybe due to the overhead of setting/re-setting the affinity of workers.

Outline

- Finally, we investigate the impact of naively applying frequency scaling.

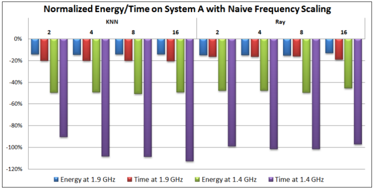
Results

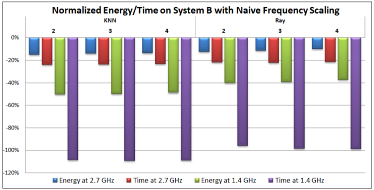
Naive Frequency Scaling

- Finally, we investigate the impact of naively applying frequency scaling.
- CPU frequencies are naively scaled down at a fixed frequency throughout the program execution.

Results

Naive Frequency Scaling





Outline

Conclusion

- Proposed HERMES – a novel and practical solution for improving energy efficiency of work-stealing applications.

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- Solution addresses the problem through judicious tempo control over workers, guided by a unified algorithm.
- Solution is scalable as it only makes minor changes to existing work-stealing runtimes.
- HERMES is a language-level solution without the need of characterizing program executions on a per-application basis.

Outline

COTTON Integration

Work-First vs Help-First

- The COTTON runtime is help-first work-stealing runtime.
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    - HERMES follows the work-first principle.
- The sequence of tasks pushed in the deque remains the same.
- No scenario yet identified where HERMES may show rogue behaviour in a help-first environment.

COTTON Integration

New Worker structure

- Member variables
  - Deque pointer
  - Linked list to maintain victim-thief and immediacy relationships
  - Frequency thresholds
- Member functions
  - `Up`(worker)
  - `Down`(worker)
  - `Down`(worker, victim)

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Modified methods

- Worker routine
- Deque Push
- Deque Pop
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- The corresponding modifications have been covered in the Implementation section.