ATC'20

Fewer Cores, More Hertz: Leveraging High-Frequency Cores in the OS Scheduler for Improved Application Performance

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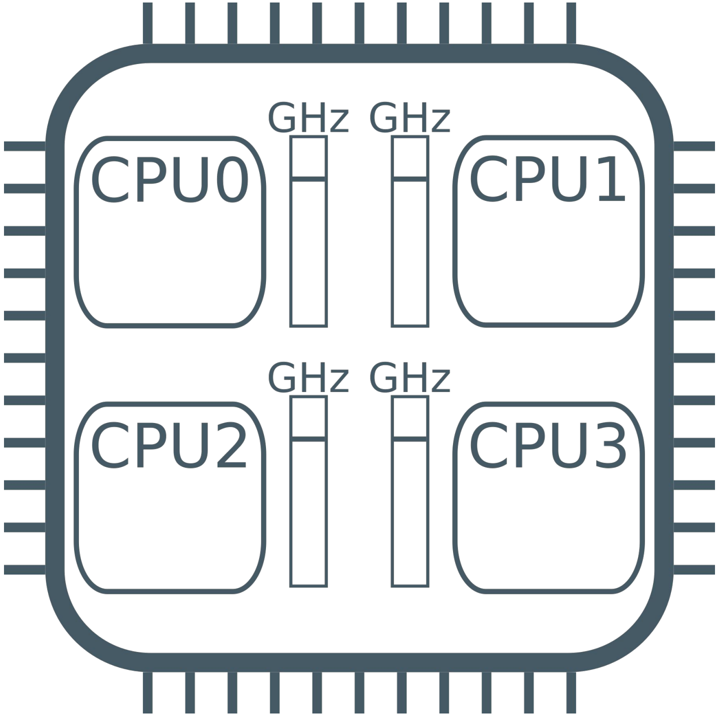
University of Sydney

J.-P. Lozi
Oracle

N. Palix
Université Grenoble Alpes

Dynamic Frequency Scaling Before



CPU frequency changes depending on load

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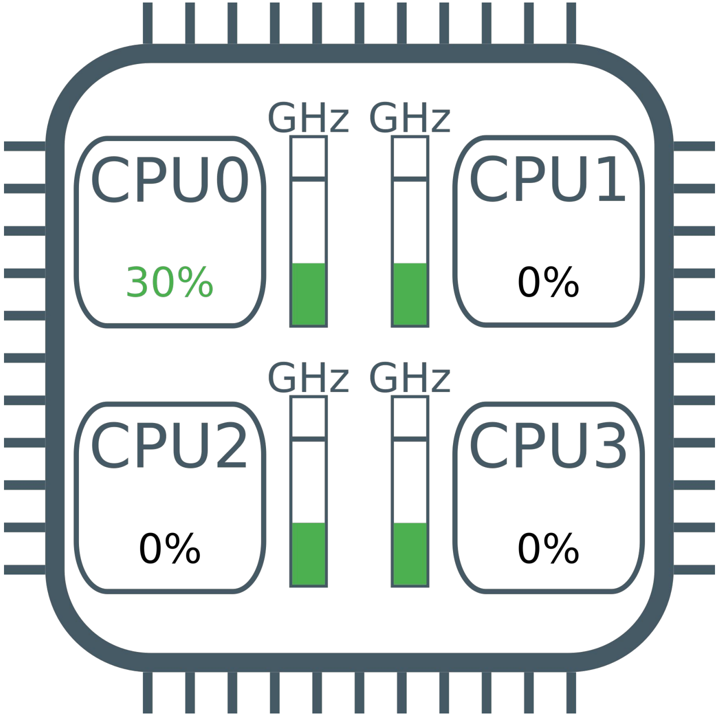

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Frequency is managed at **chip granularity**

The load of a single CPU impacts the frequency of all CPUs on the chip

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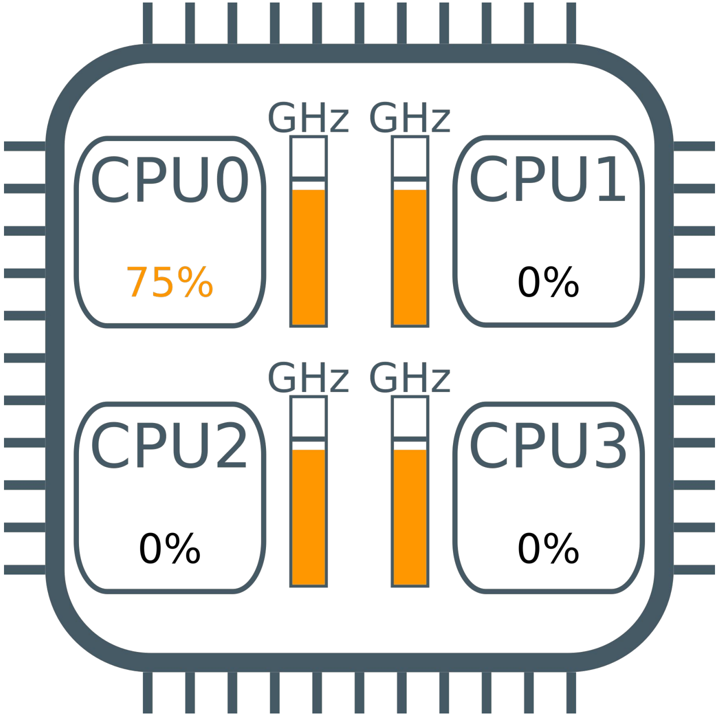

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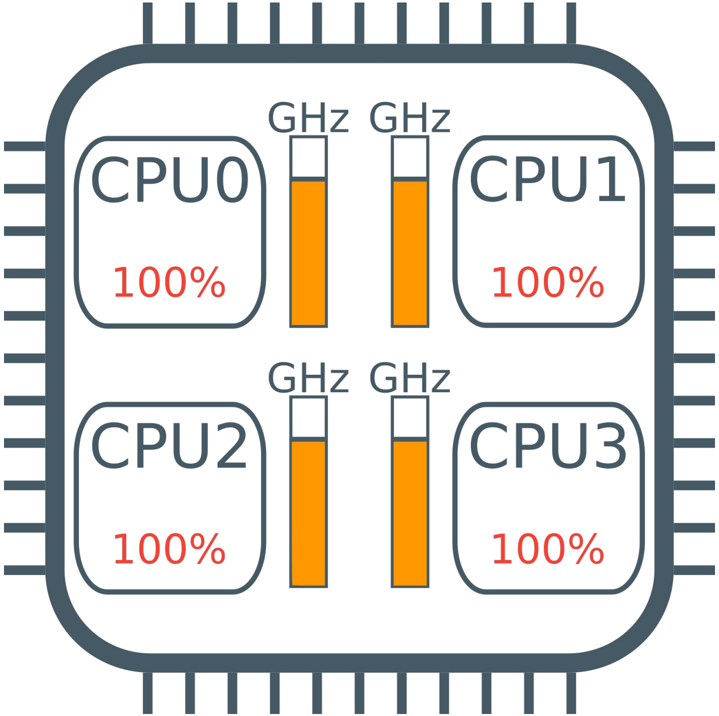

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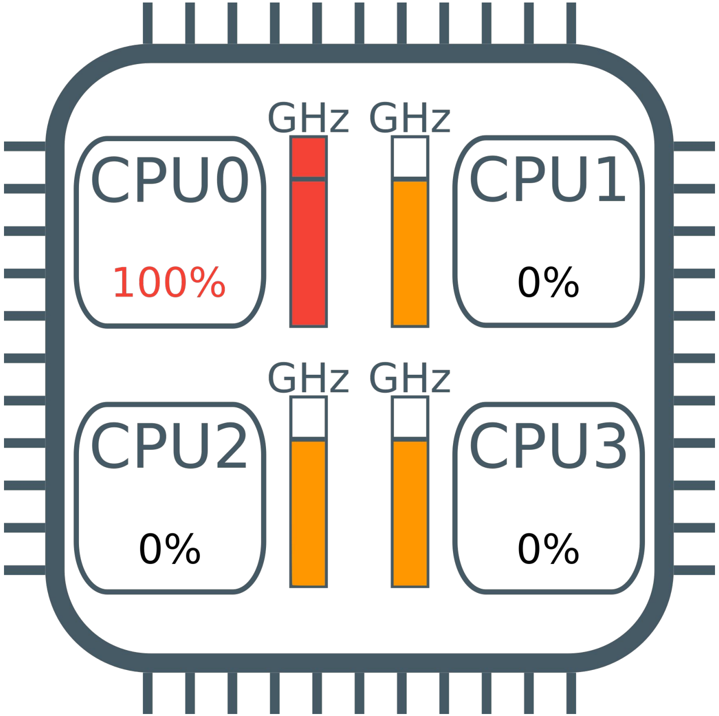

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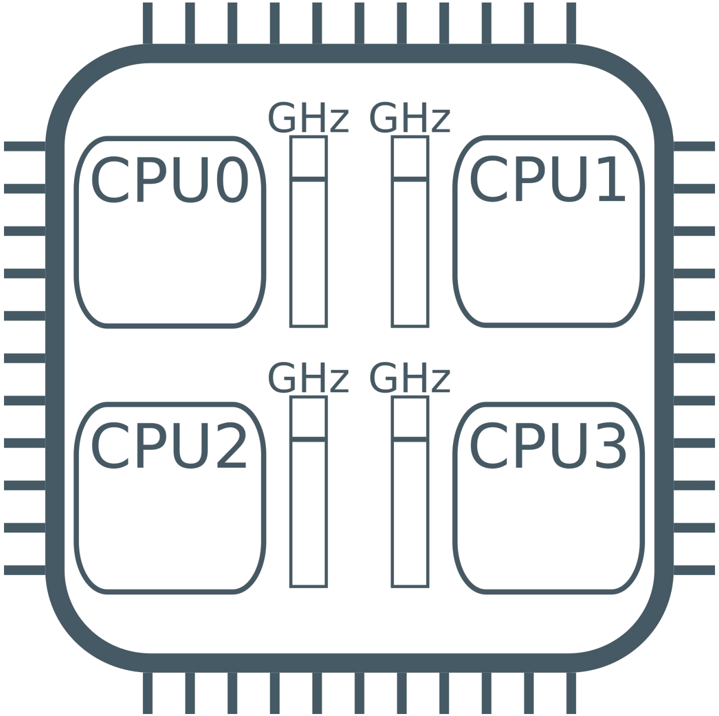
With all CPUs fully loaded, **nominal frequency** is guaranteed

Turbo mode: when some CPUs are idle, busy CPUs can use even higher frequencies

Dynamic Frequency Scaling Now



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At least since:

- Intel® Cascade Lake (2019)
- AMD® Ryzen (2019)

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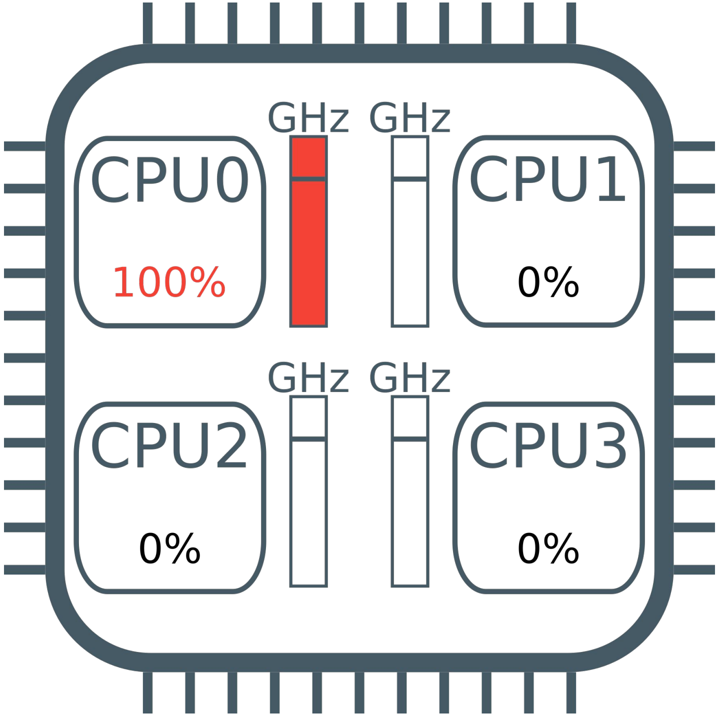

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Idle cores can run at minimal frequency while other cores run at maximal frequency

→ Energy savings

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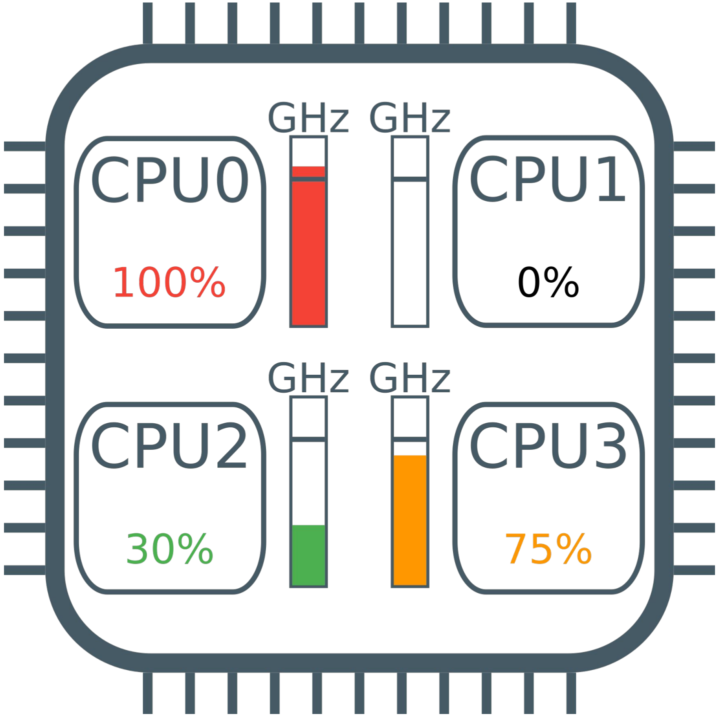

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Each core individually sets a frequency that matches **its** load

Previous Work

Focus on changing the frequency to match load

- Linux scaling governors (ondemand, schedutil)
- hardware frequency scaling (Intel)

Frequency scaling was used to

- maximize instructions per joule metric (Weiser’94)
- reduce contention (Merkel’10, Zhang’10)
- reduce energy usage (Bianchini’03)

Recent work by the Linux scheduler community

- TurboSched: small jitter tasks on Turbo cores
- support for heterogeneous architectures (big.LITTLE), ...

Case Study: Compiling Linux

Setup:

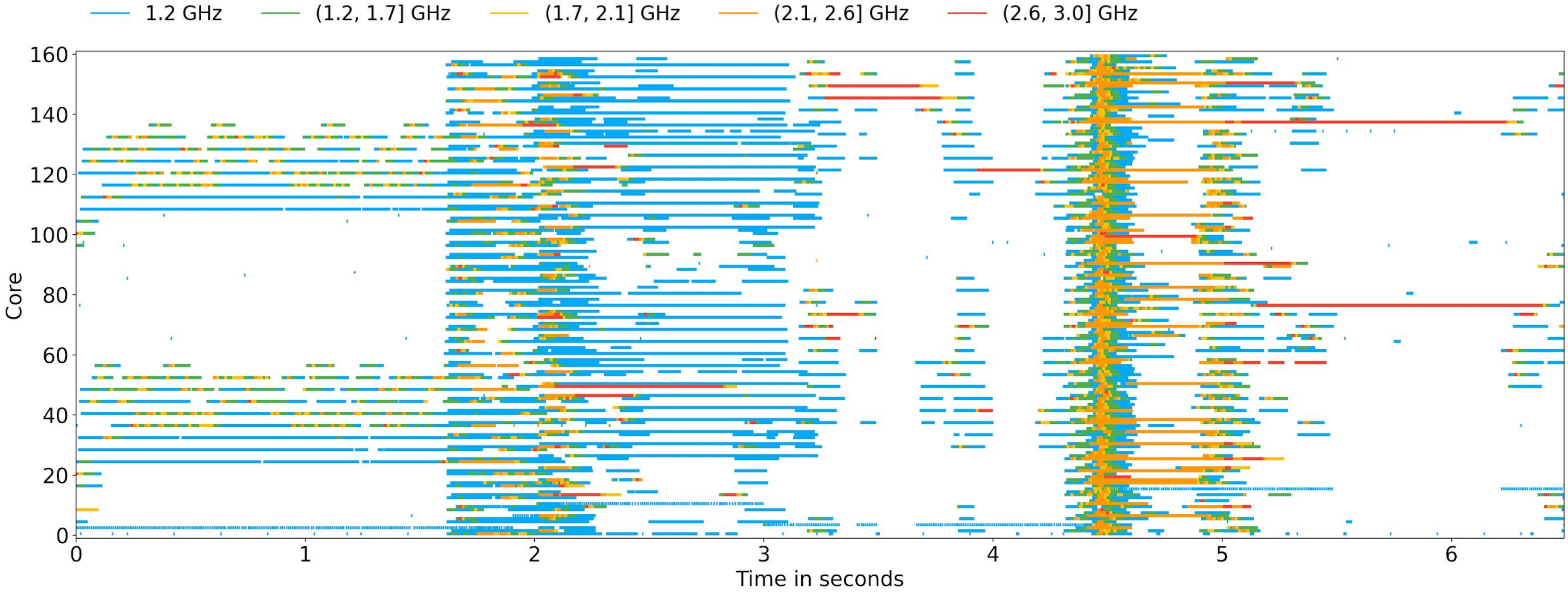
- 4x20-core Intel® Xeon E7-8870 v4 (160 HW threads with HyperThreading)
- 2.1 GHz nominal frequency, up to 3.0 GHz with Turbo Boost®
- Per-core frequency scaling
- 512 GB of RAM
- Debian 10 Buster with Linux 5.4

Maximum Turbo frequencies:

Active cores	1-2	3	4	5-8	>8
Max Turbo	3.0 GHz	2.8 GHz	2.7 GHz	2.6 GHz	2.1 GHz

For clarity, we only present the compilation of the scheduler subsystem

Case Study: Tracing the Frequency



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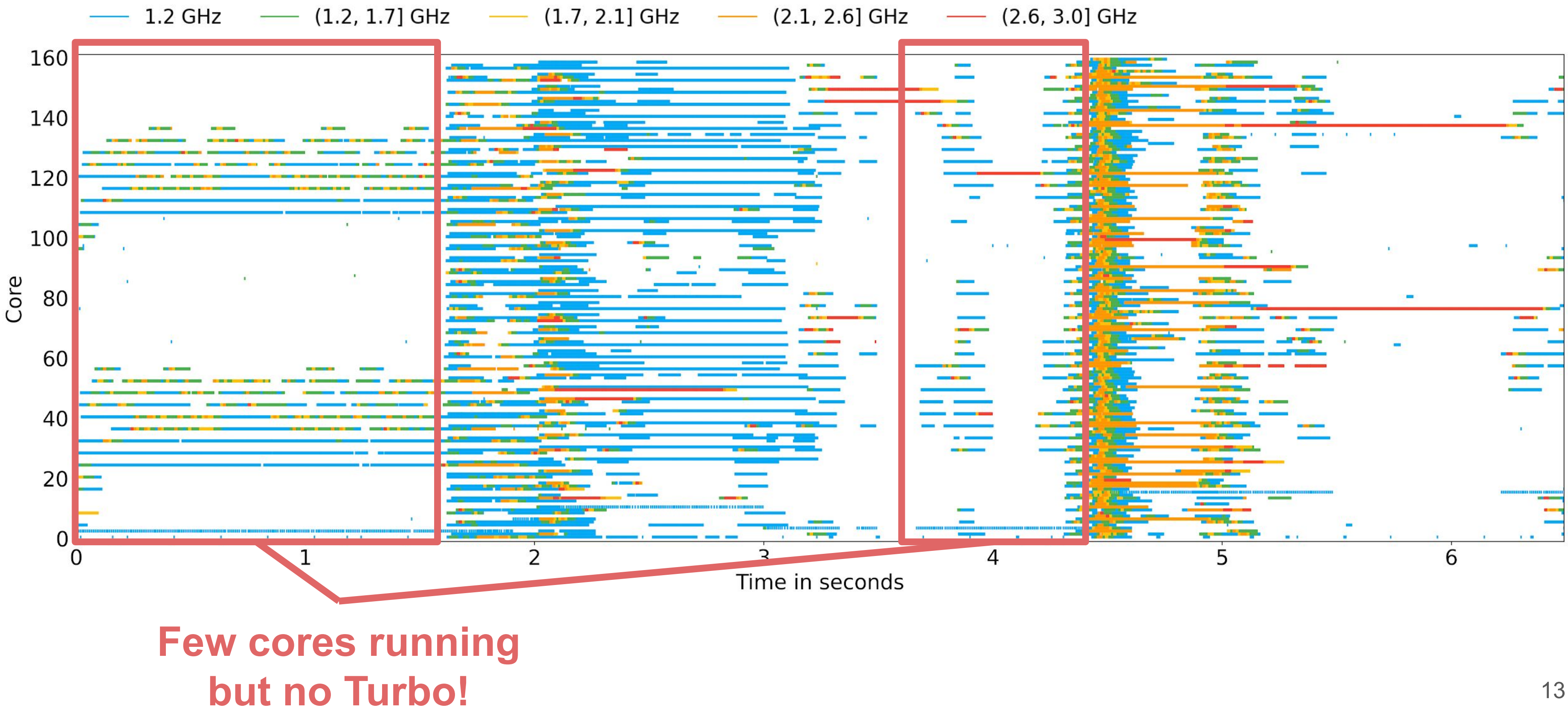

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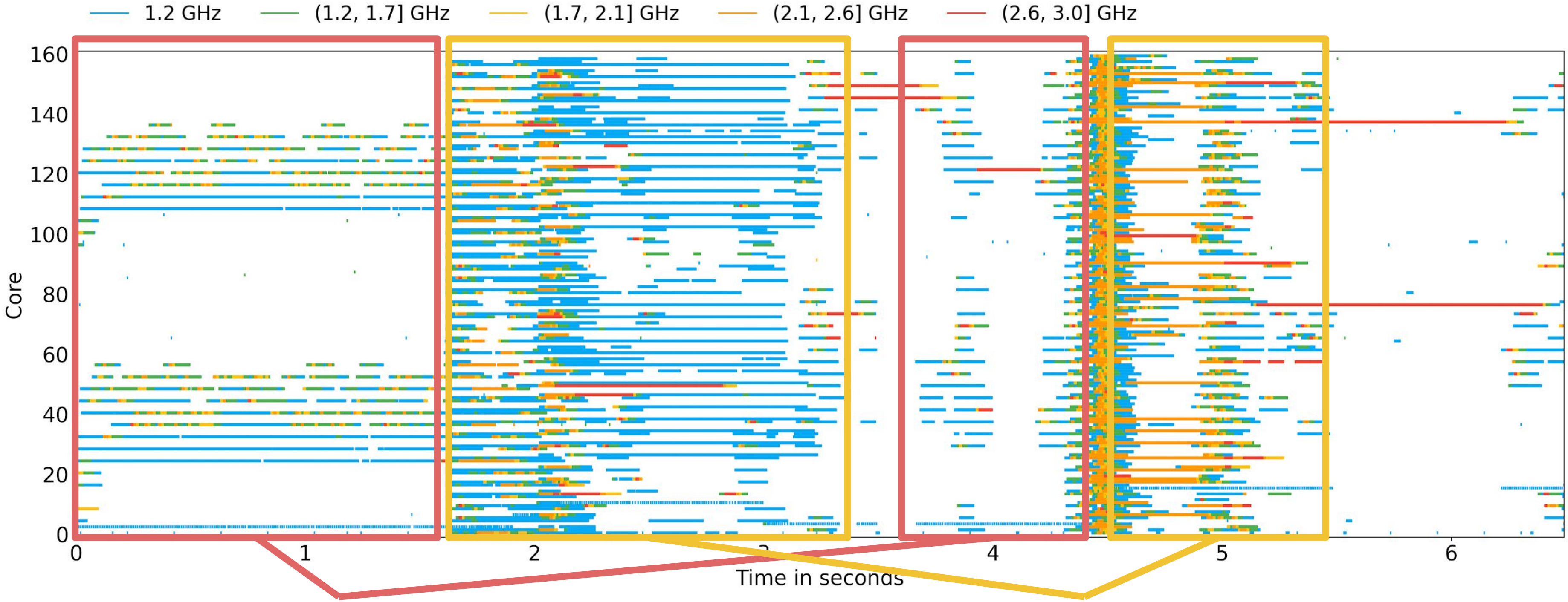
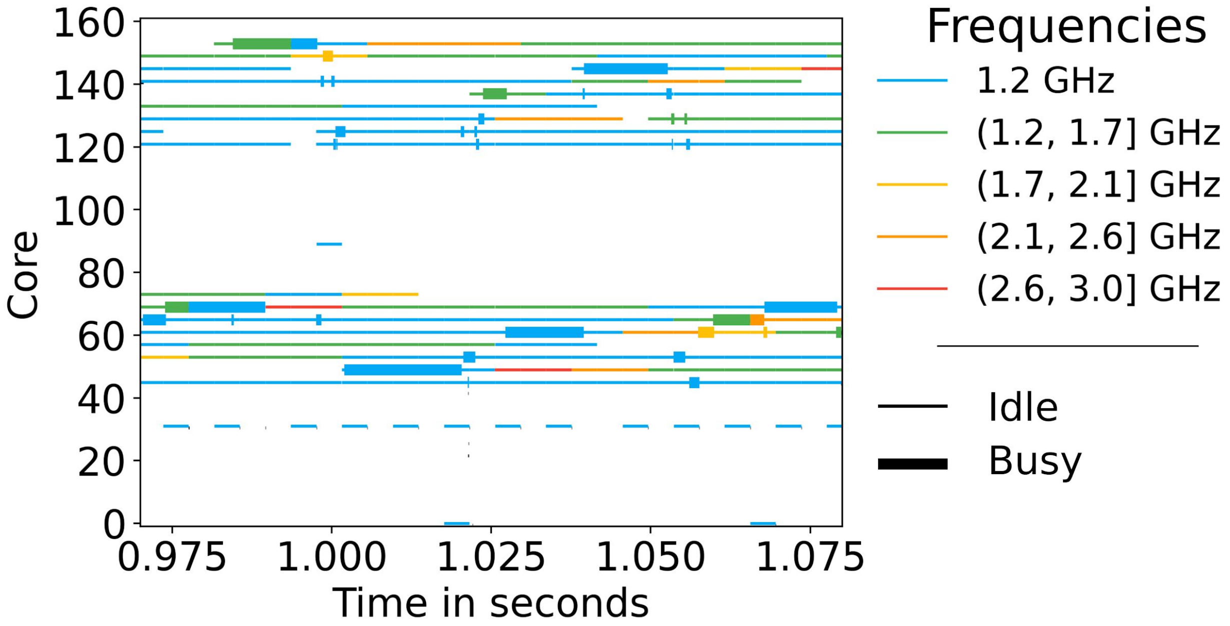


Few cores running but no Turbo!

Most cores used, but frequency is lower than nominal!

Case Study: Zooming In



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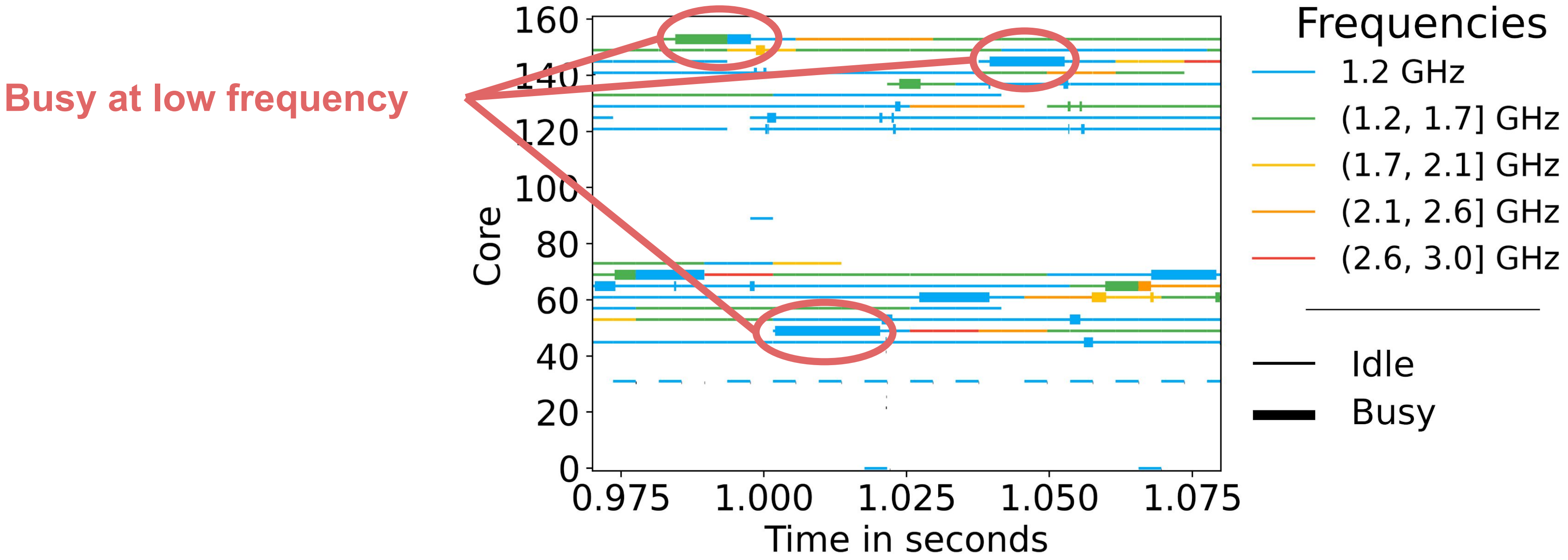

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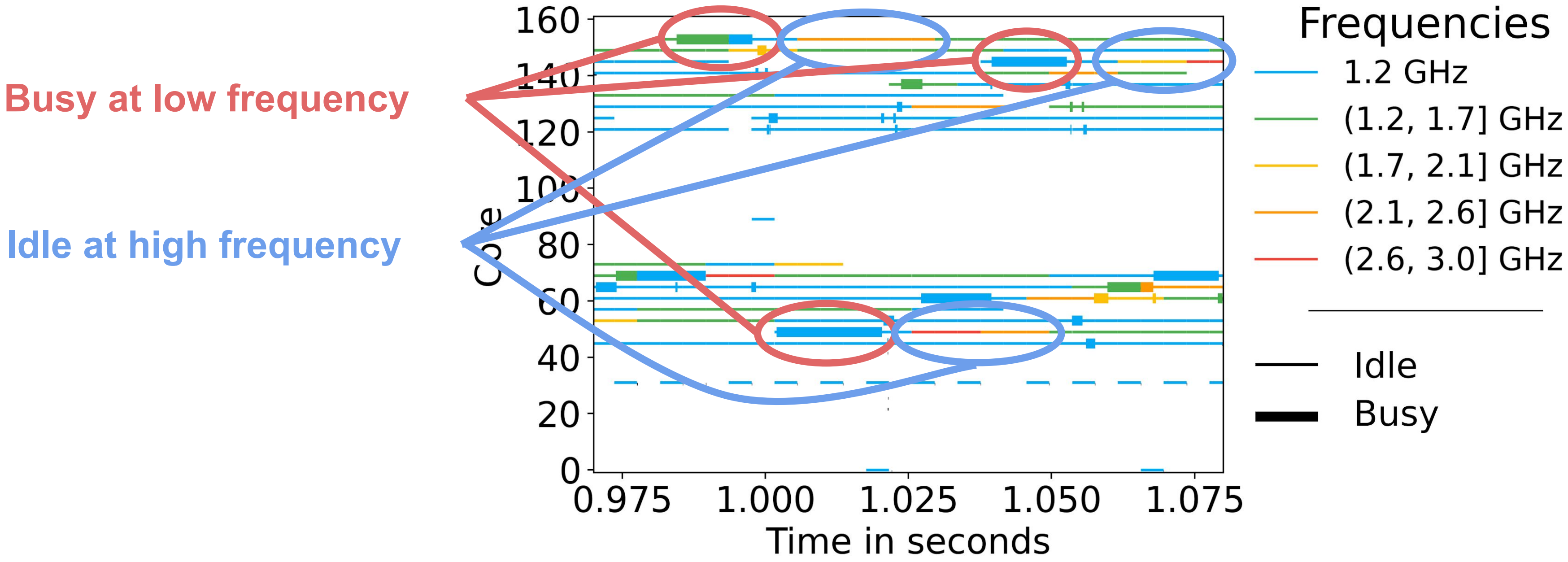

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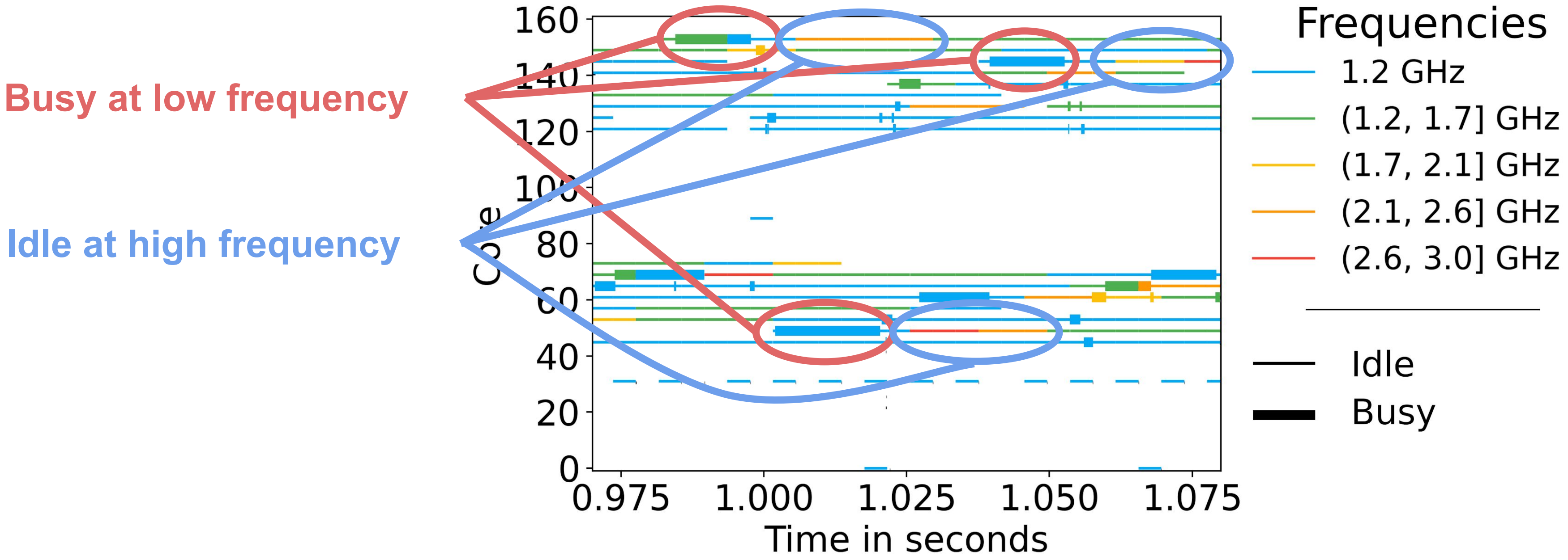

Frequency and load are mismatched!

Frequency Transition Latency

FTL: Latency between a change of load and change of frequency
We measure it from idleness to 100% load on our server

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0% → 100% : **29 ms**
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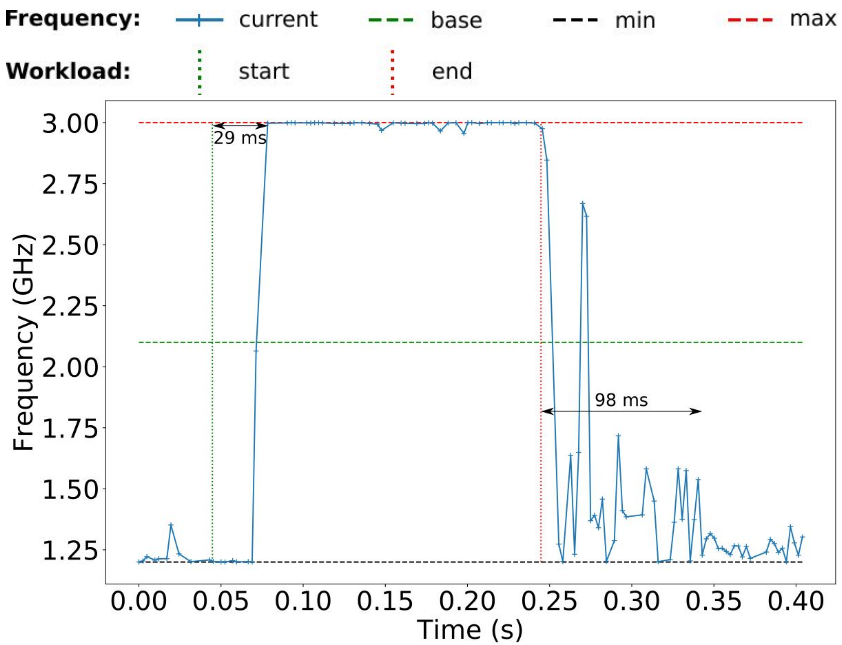

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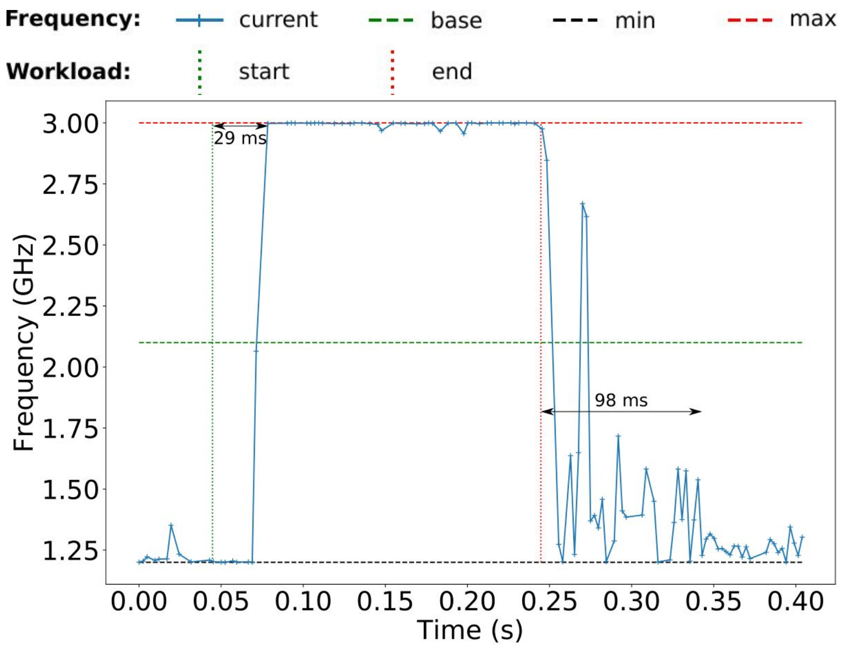
Changing frequency is not instantaneous!

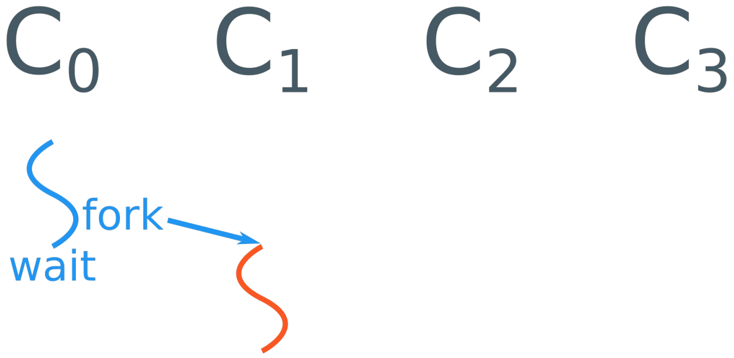


Tracing Scheduler Events

Behavior of Linux scheduler (**CFS**):

New and waking threads are placed on **idle** cores if available

→ **work conserving**



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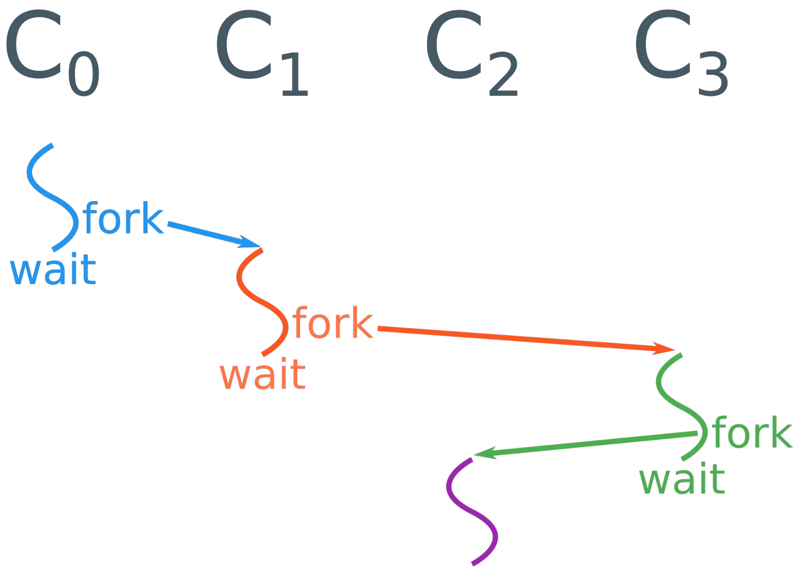
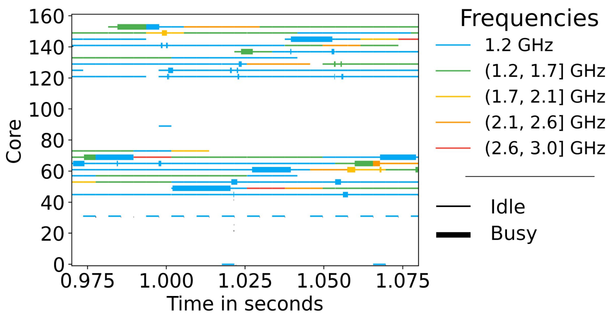
This repeated **fork/wait** pattern is a common occurrence in our case study.



Problem: Frequency Inversion

Long FTLs



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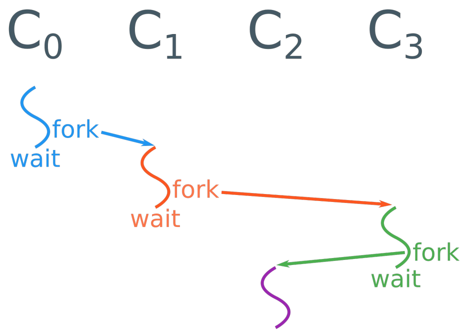
Work conserving scheduler



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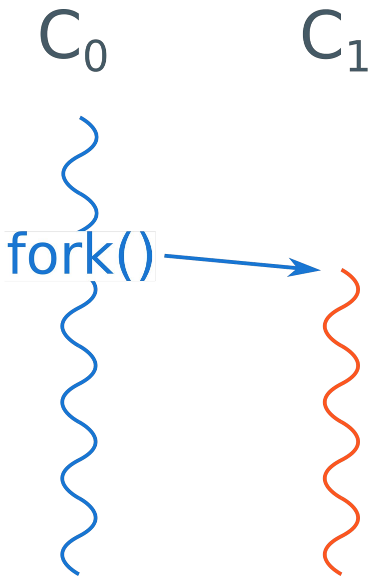
The frequencies at which two cores operate are inverted as compared to their load

Problem: With CFS



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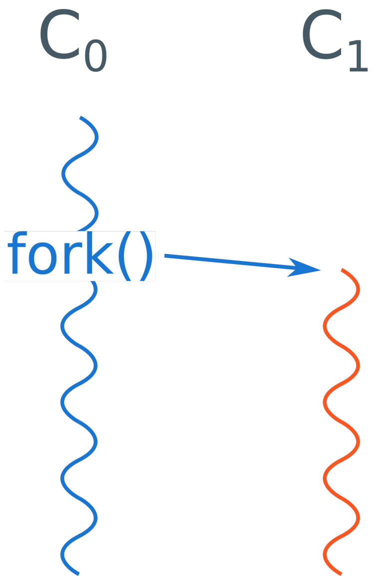

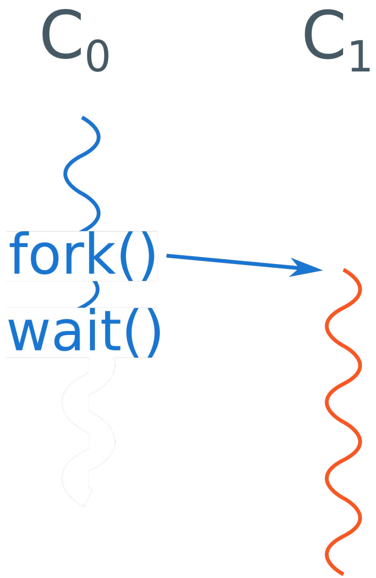

Ideal situation,
both cores are busy

Two cores used for a sequential work,
prone to **frequency inversion**

Solution 1: Local Placement

We propose local placement with $\mathbf{S}_{\mathbf{local}}$.

C_0 C_1

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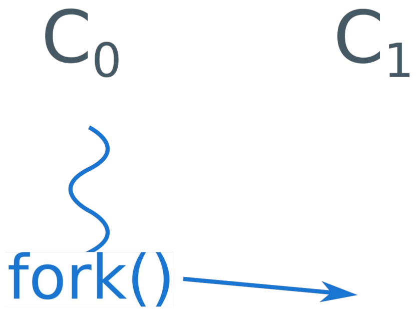

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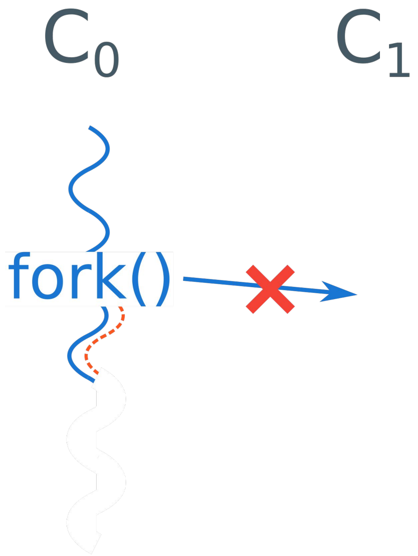

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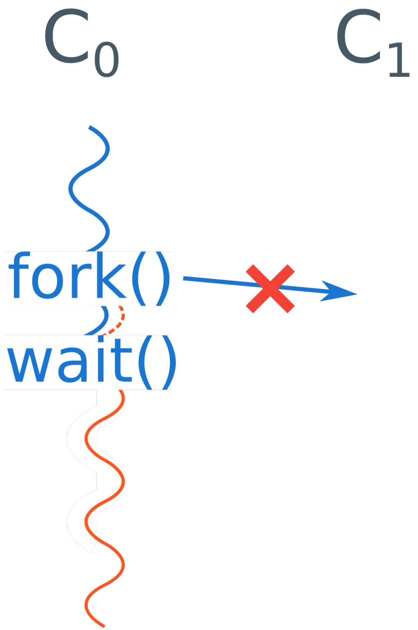
Parent thread calls the wait() syscall, the **child thread** is scheduled on C_0.

We use a **single** core for a sequential work.



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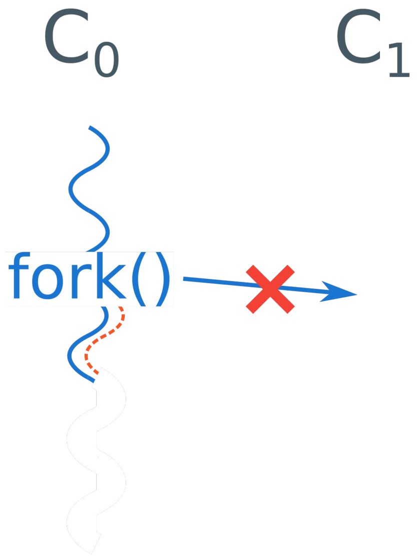

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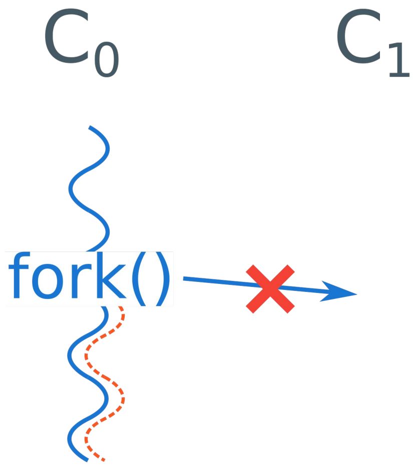

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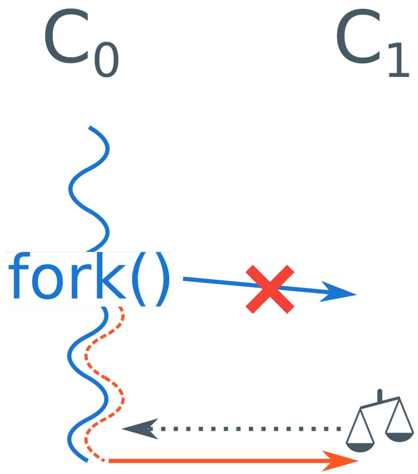

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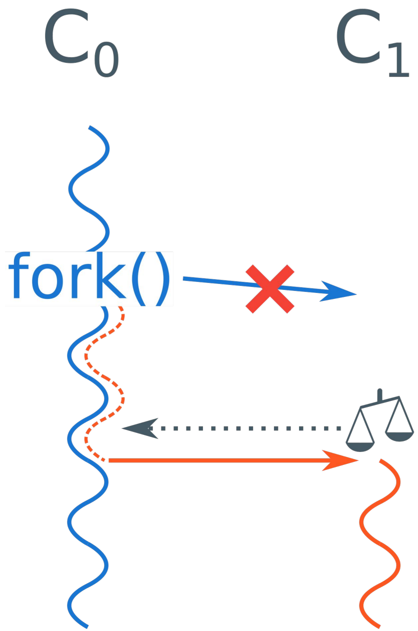
Both cores are used, but we lost tens of milliseconds of execution for the **child thread**.



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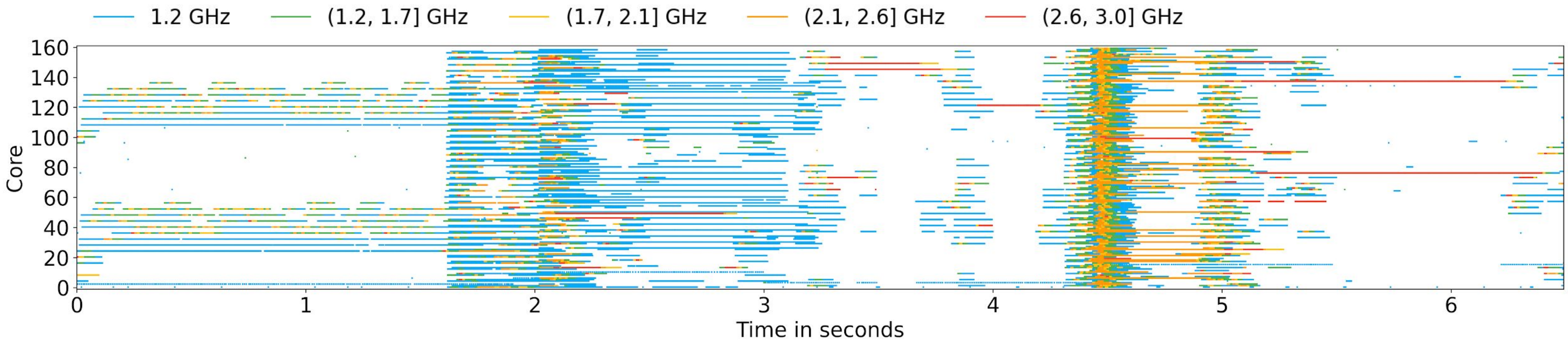

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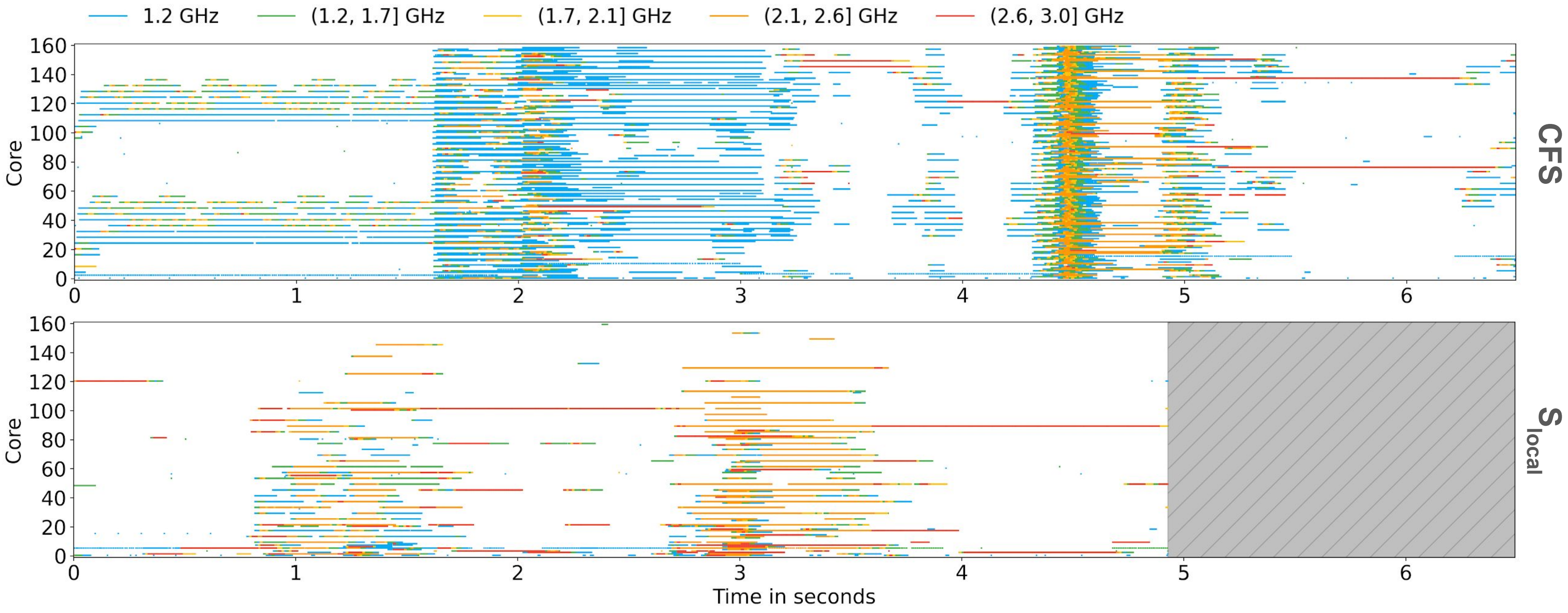

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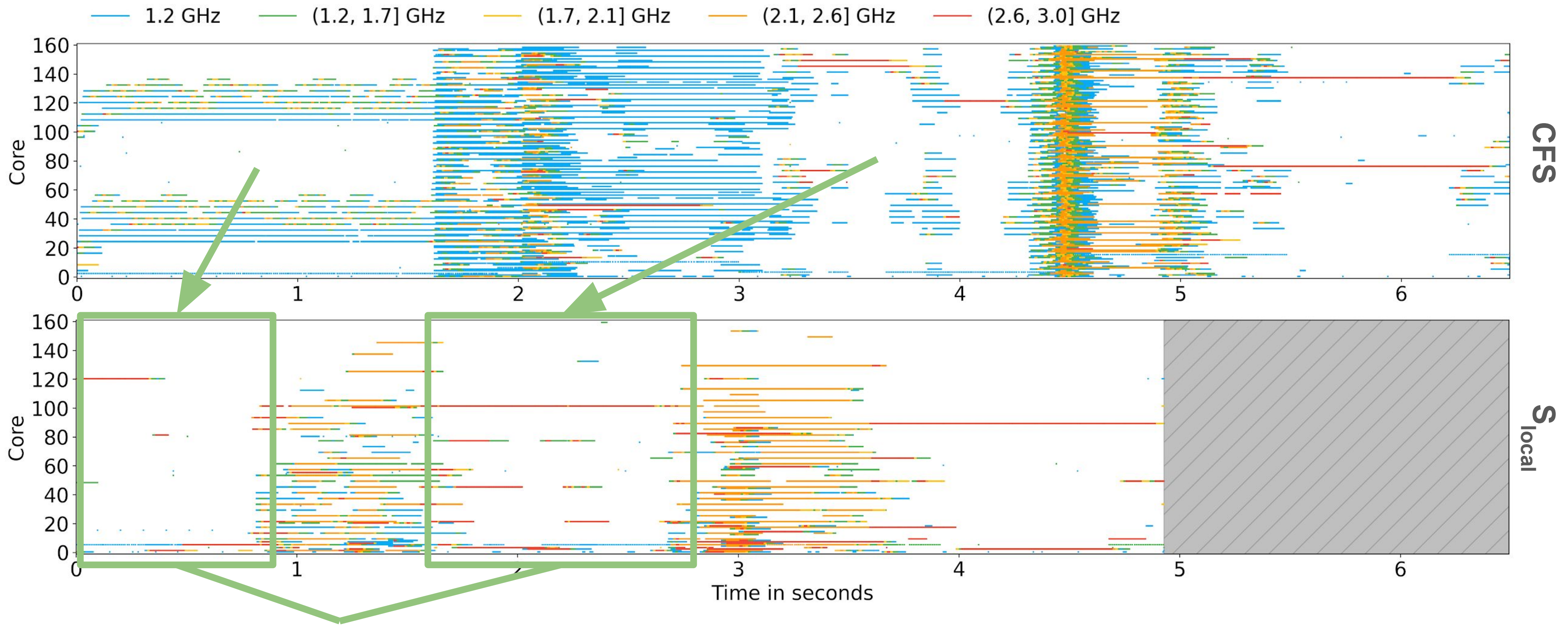

<5 cores used, more Turbo

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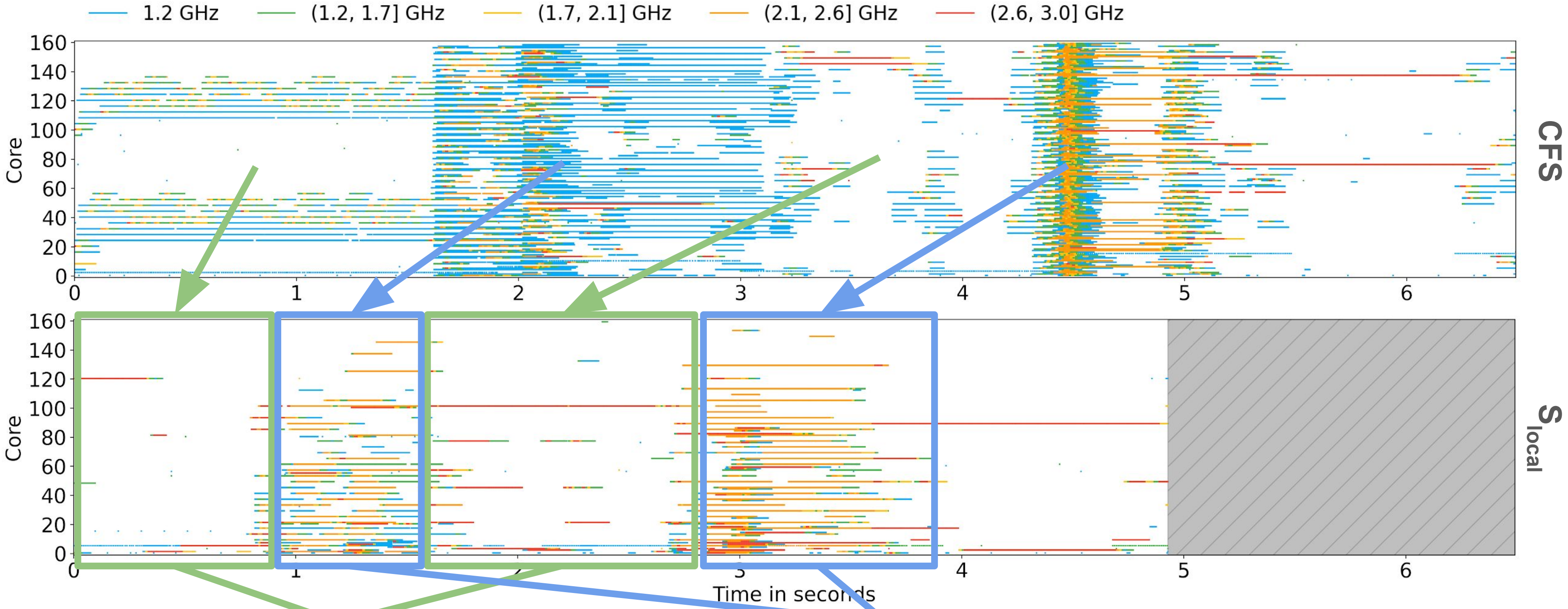

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Longer high frequency periods

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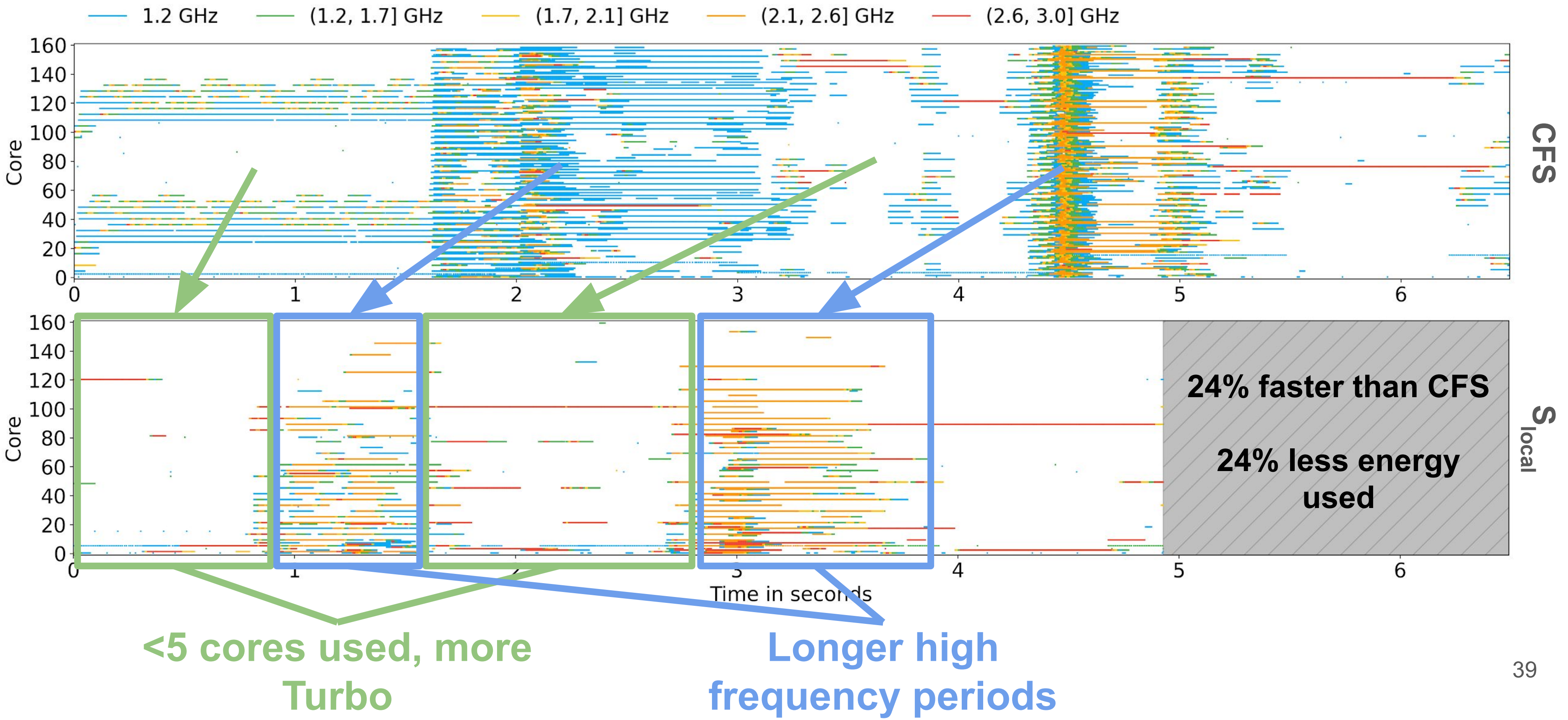

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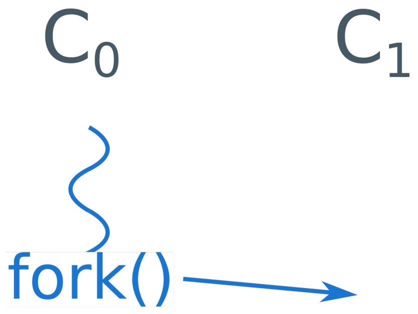

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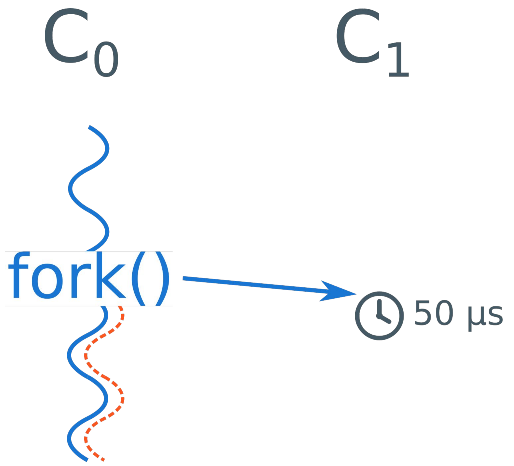

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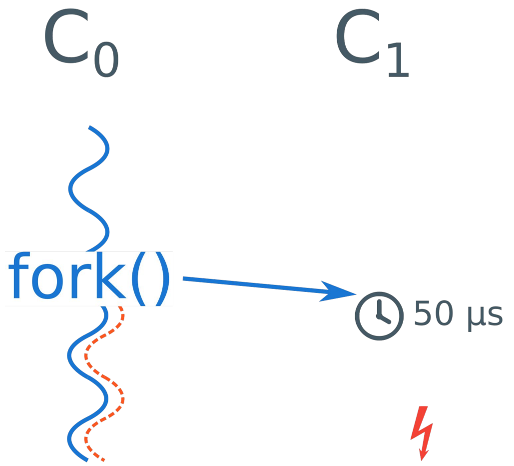
When the timer is **triggered** 50µs later,



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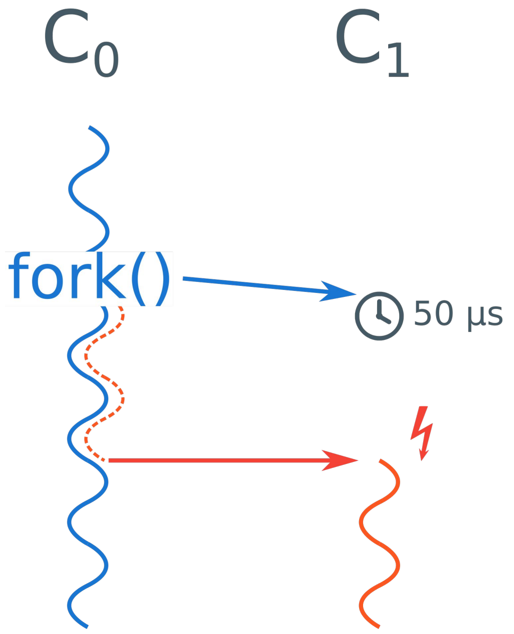
When the timer is **triggered** 50µs later, we migrate the **child thread** to C_1.
We only lose 50µs compared to CFS or S_{local}.



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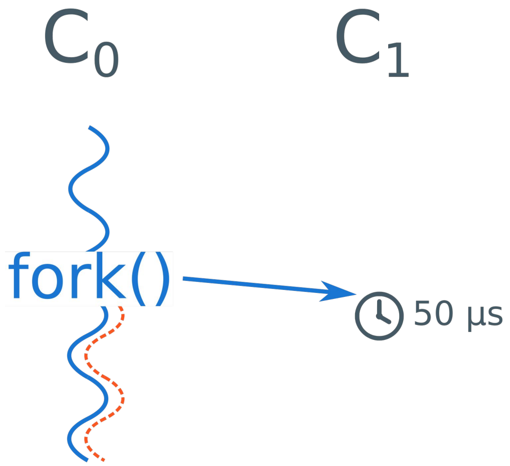

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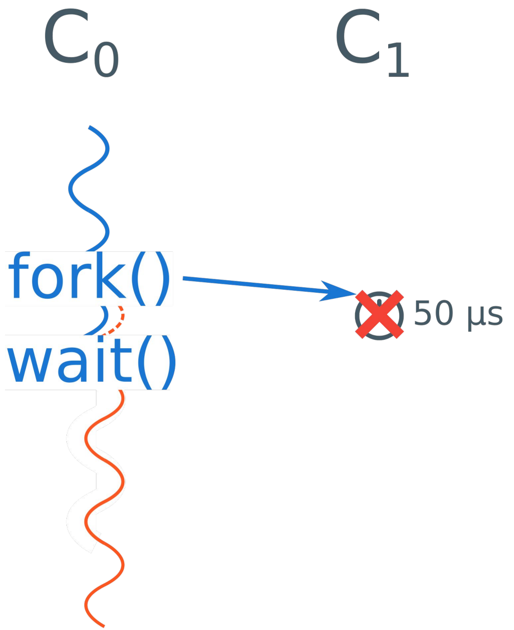

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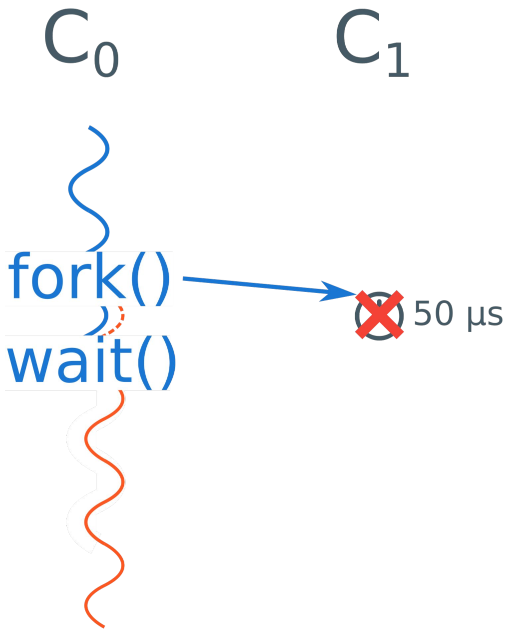
This sequential program uses a single core, running at a **high frequency**, and C_1 stays **idle**.



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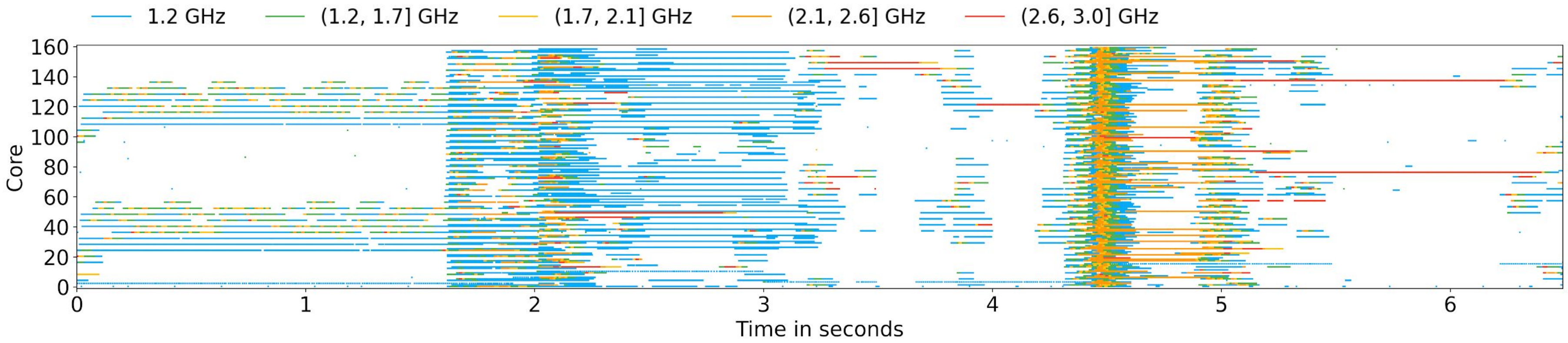

CFS

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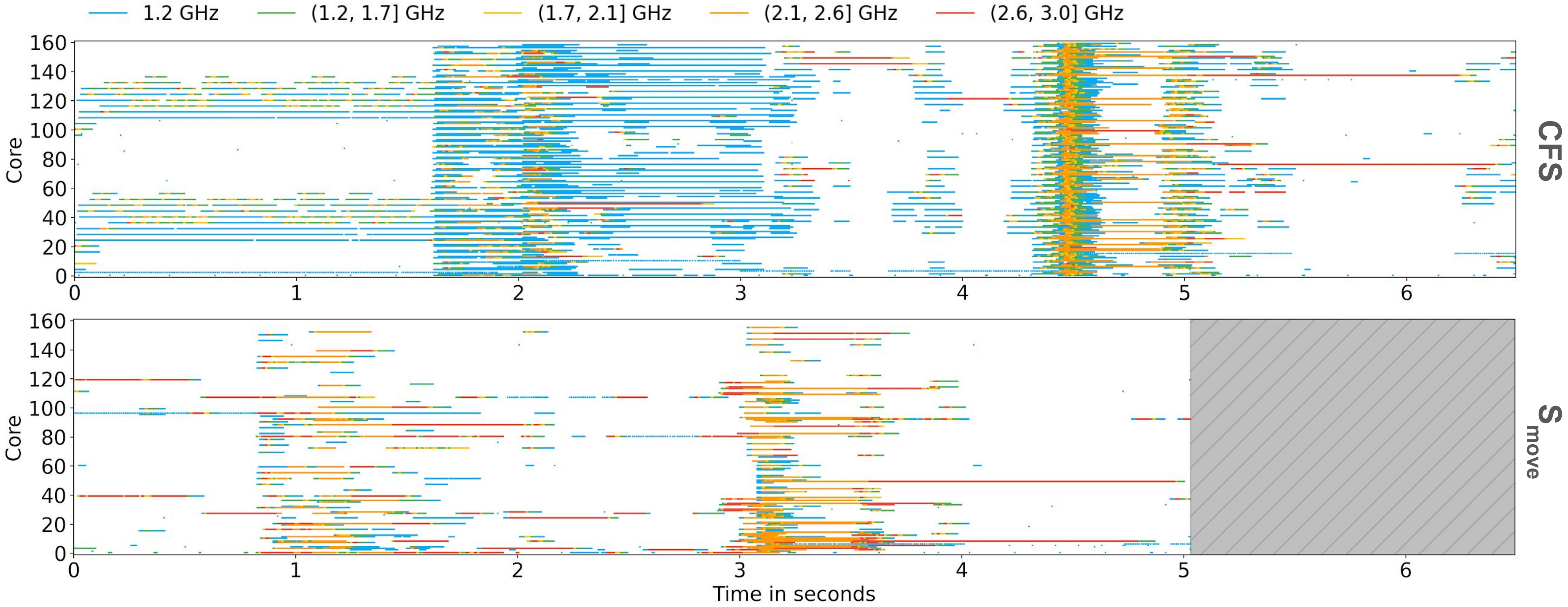

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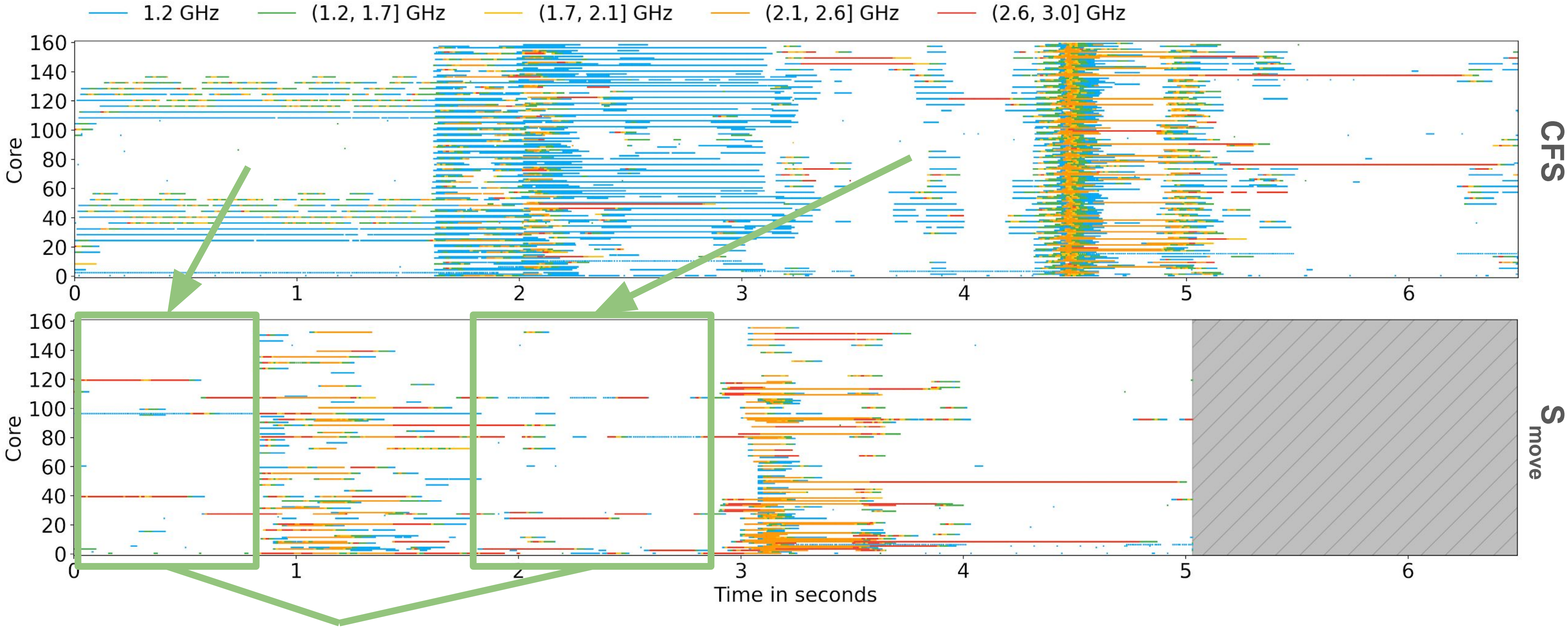

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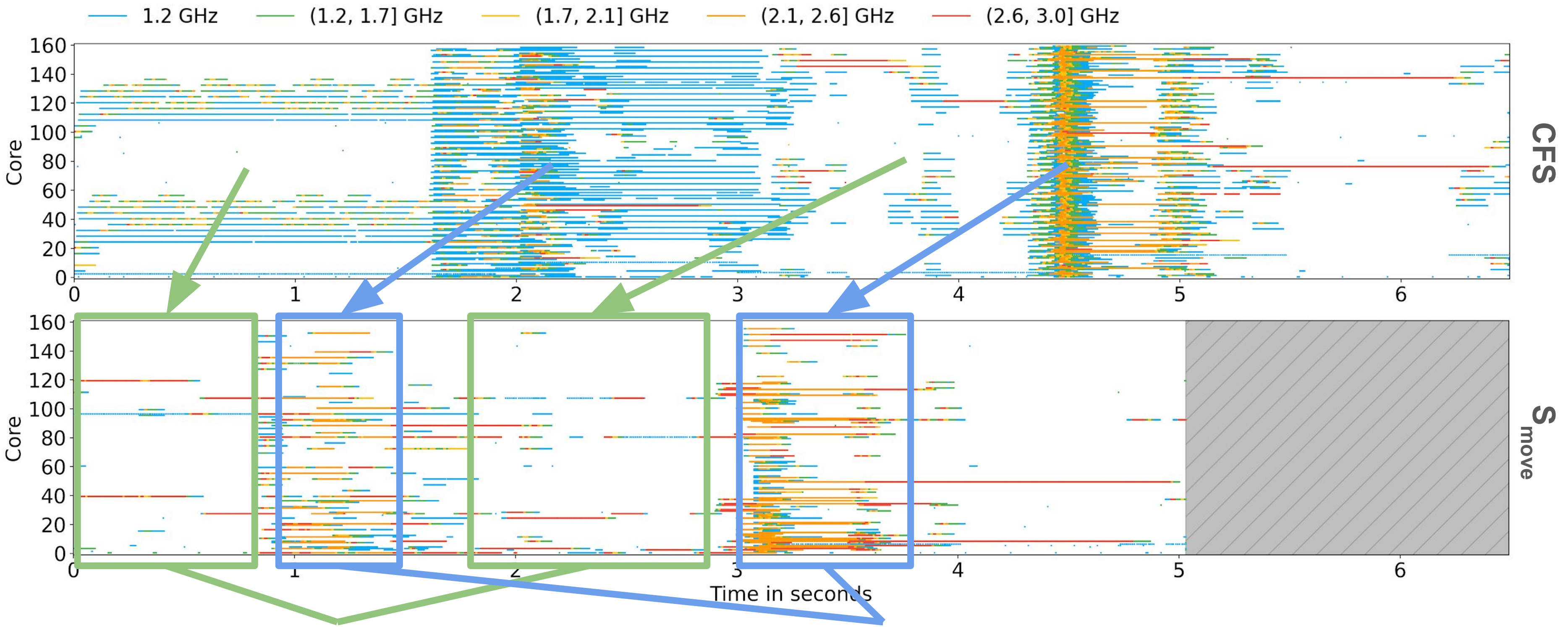

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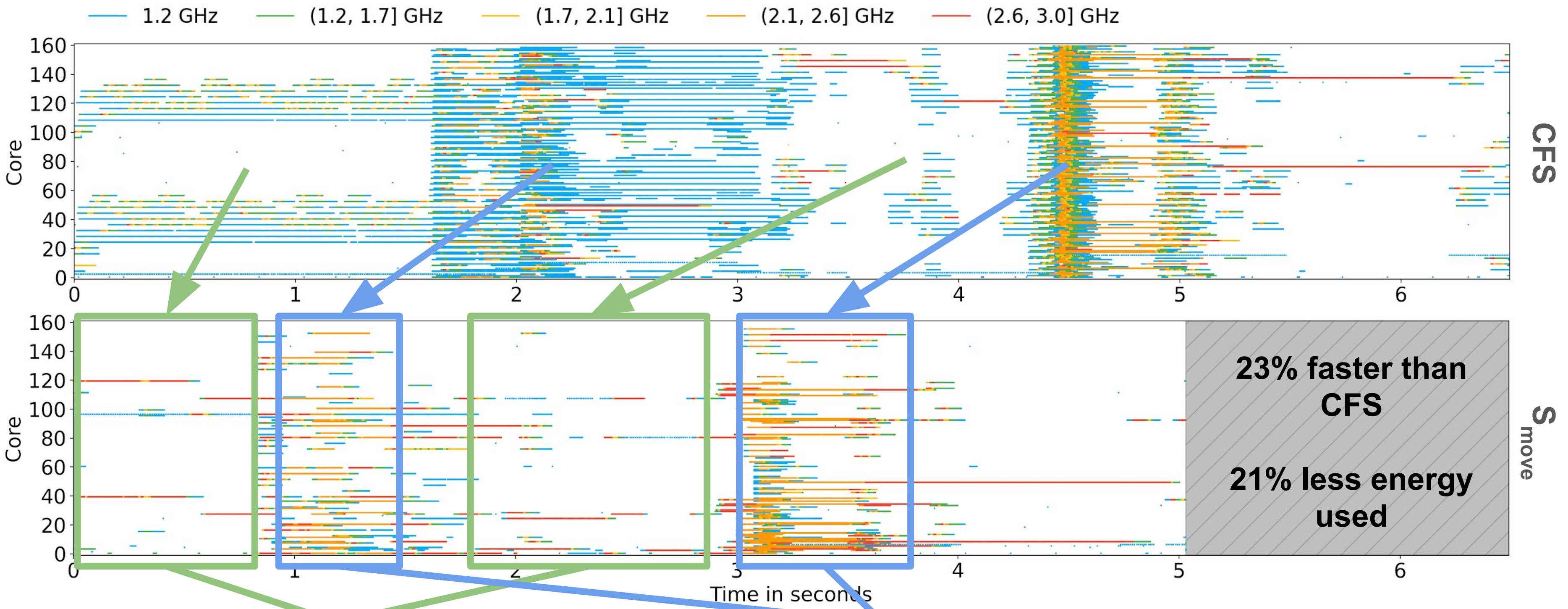

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Longer high frequency periods

Our Solutions: S_{local} and S_{move}

Both solutions behave similarly on **our case study**

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S_{move} is more balanced, and accounts for **frequency**,
more complicated (124 lines of code, timers), but keeps the overall ideas of CFS

Performance and Energy Evaluation

60 applications from:

- NAS: HPC applications,
- Phoronix: web servers, compilations, DNN libs, compression, databases, ...
- hackbench & sysbench OLTP

2 machine markets:

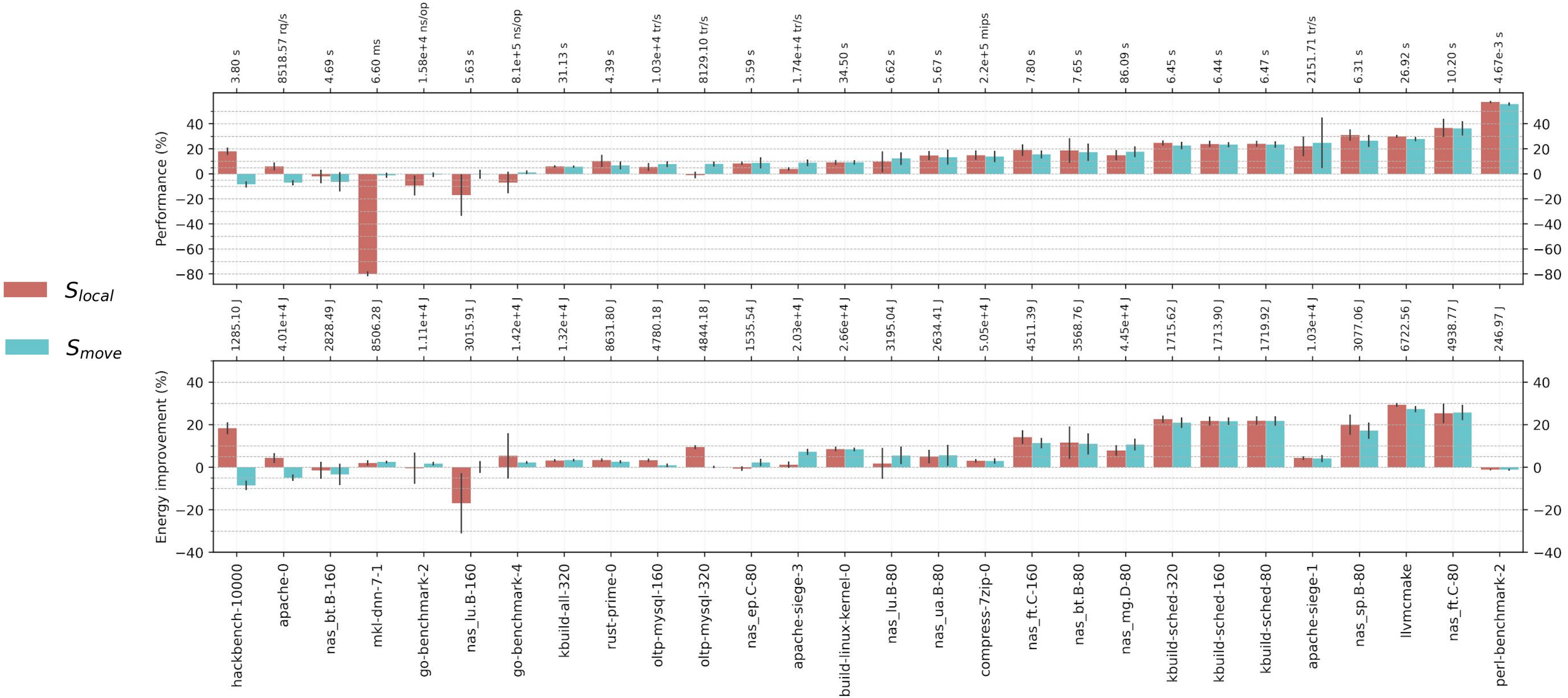
- **Server**: 80-core Intel® Xeon E7-8870 v4 (160 HW threads)
- **Desktop**: 4-core AMD® Ryzen 5 3400G (8 HW threads)

2 frequency scaling governors:

- **powersave**
- **schedutil**

Performance and Energy Evaluation

Compared to CFS, server machine, powersave governor, higher is better



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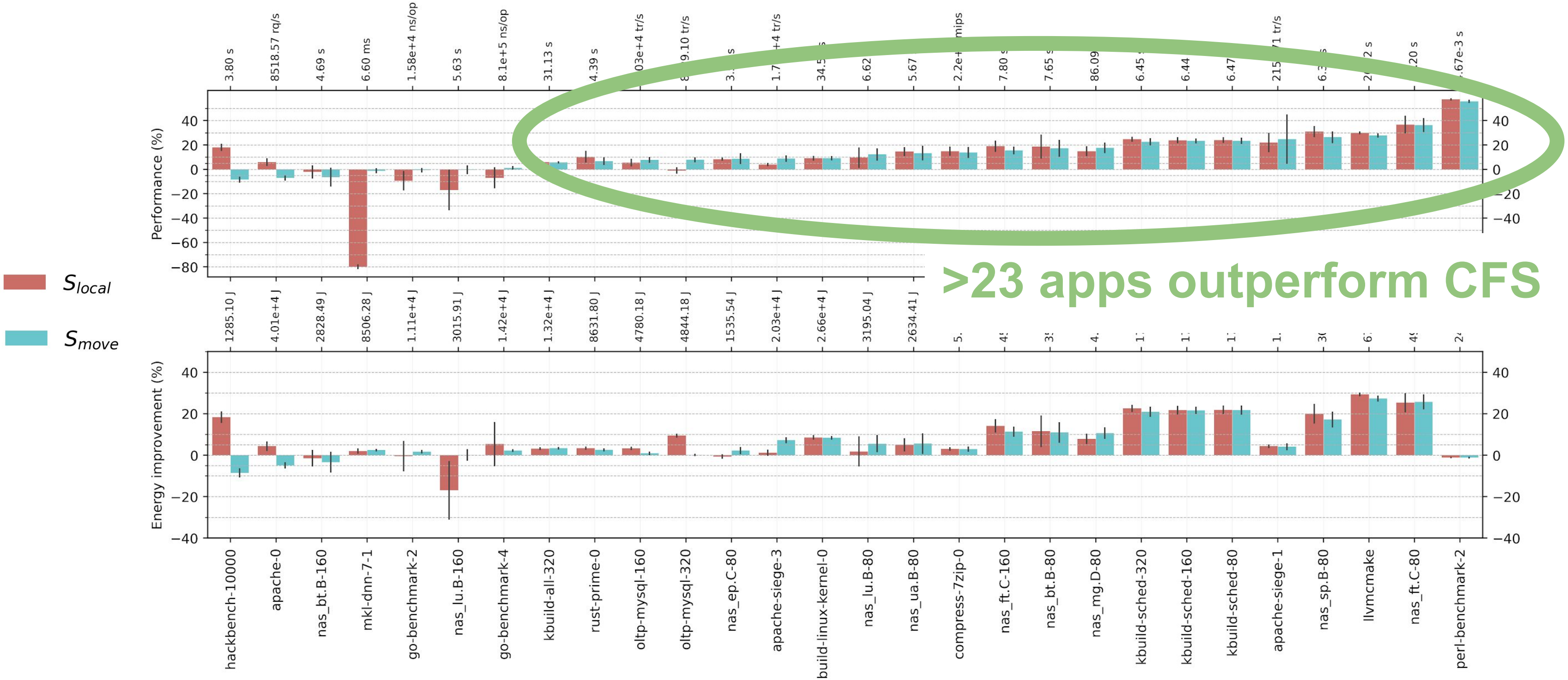

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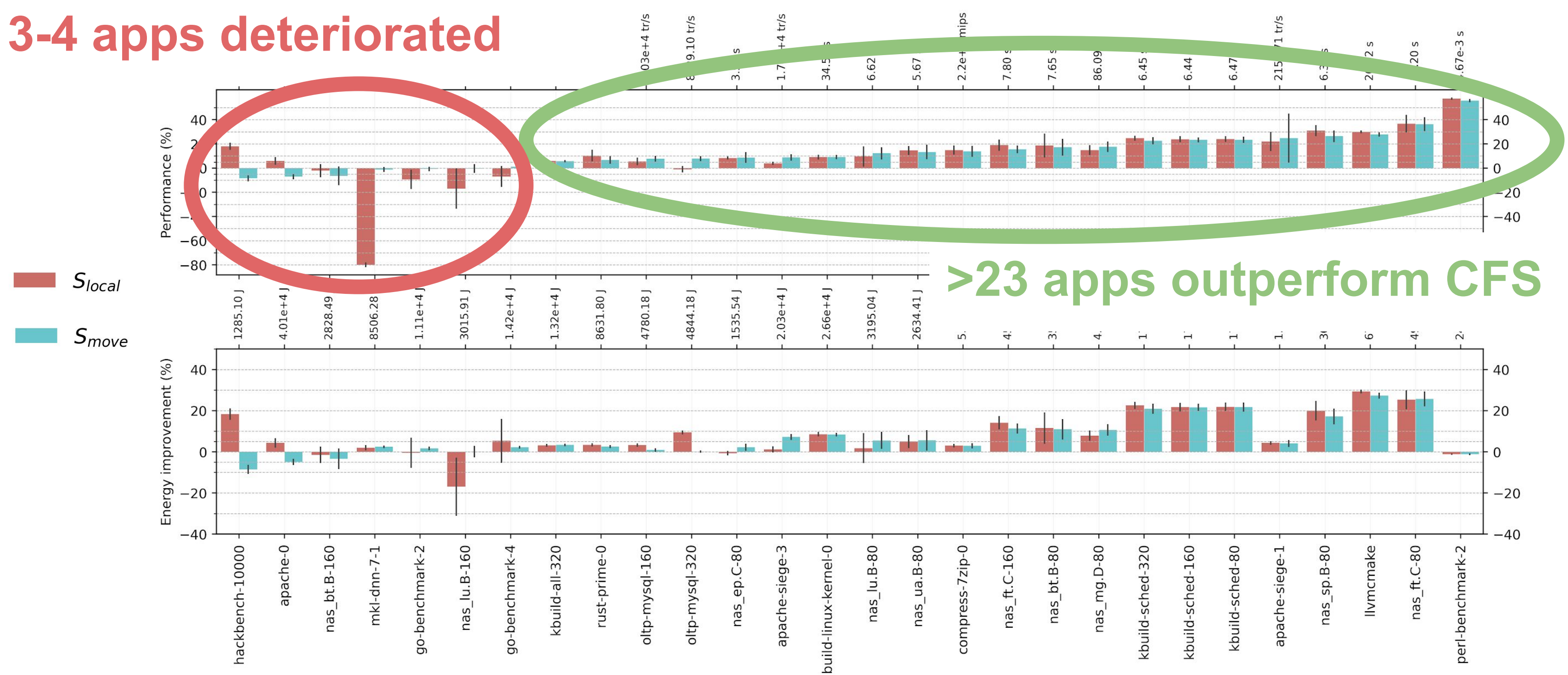


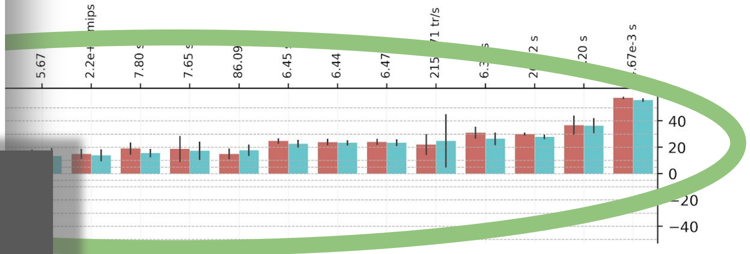
Performance and Energy Evaluation

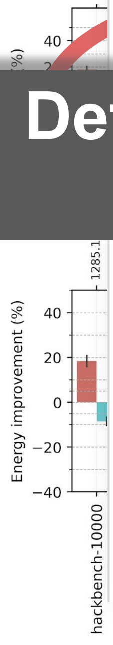
Compared to CFS, server machine, powersave governor, higher is better

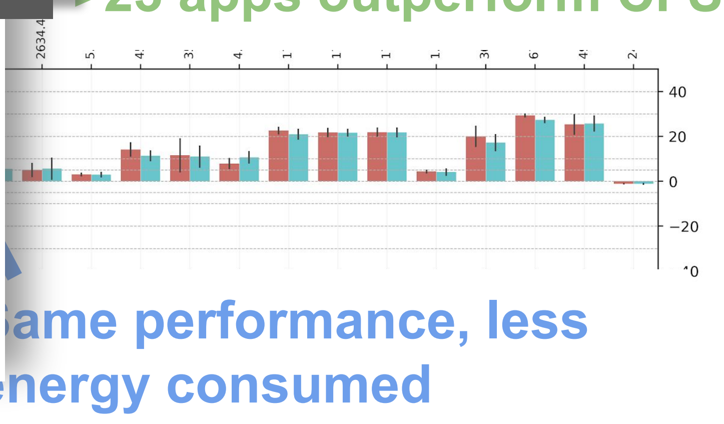
Perform… …valuation

Compared … …ave governor, higher is better

3-4 apps d…







$S_{lo…}$

S_{move}

Fewer Cores, More Hertz: Leveraging High-Frequency Cores in the OS Scheduler for Improved Application Performance

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Jean-Pierre Lozi — *Oracle Labs*
Julien Sopena — *Sorbonne University, LIP6, Inria*
Baptiste Lepers, Willy Zwaenepoel — *University of Sydney*
Nicolas Palix — *Université Grenoble Alpes*
Julia Lawall, Gilles Muller — *Inria, Sorbonne University, LIP6*

Abstract

In modern server CPUs, individual cores can run at different frequencies, which allows for fine-grained control of the performance/energy tradeoff. Adjusting the frequency, however, incurs a high latency. We find that this can lead to a problem

…

for 23 applications, and worsens performance by more than 5% (at most 8%) for only 3 applications. On a 4-core AMD Ryzen we obtain performance improvements up to 56%.

1 Introduction

Striking a balance between performance and energy consumption has long been a battle in the development of computing systems. For several decades, CPUs have supported Dynamic Frequency Scaling (DFS), allowing the hardware or the software to update the CPU frequency at runtime. Reducing CPU frequency can reduce energy usage, but may also decrease overall performance. Still, reduced performance may be acceptable for tasks that are often idle or are not very urgent, making it desirable to save energy by reducing the frequency in many use cases. While on the first multi-core machines, all cores of a CPU had to run at the same frequency, recent server CPUs from Intel® and AMD® make it possible to update the frequency of individual cores. This feature allows for much finer-grained control, but also raises new challenges.

One source of challenges in managing core frequencies is the *Frequency Transition Latency (FTL)*. Indeed, transitioning a core from a low to a high frequency, or conversely, has an FTL of dozens to hundreds of milliseconds. FTL leads to a problem of *frequency inversion* in scenarios that are typical of the use of the standard POSIX fork() and wait() system

…

until recently, and C_{CFS}, on which T_{woken} is running, is likely to be executing at a low frequency because it was previously idle. Consequently, the frequencies at which C_{waker} and C_{CFS} operate are *inverted* as compared to the load on the cores. This frequency inversion will not be resolved until C_{waker} reaches a low frequency and C_{CFS} reaches a high frequency, *i.e.*, for the duration of the FTL. Current hardware and software DFS policies, including the schedutil policy [9] that was recently added to CFS cannot prevent frequency inversion as their only decisions consist in updating core frequencies, thus paying the FTL each time. Frequency inversion reduces performance and may increase energy usage.

In this paper, we first exhibit the problem of frequency inversion in a real-world scenario through a case study of the behavior of CFS when building the Linux kernel on a Intel® Xeon-based machine with 80 cores (160 hardware threads). Our case study finds repeated frequency inversions when processes are created through the fork() and wait() system calls, and our profiling traces make it clear that frequency inversion leads to tasks running on low frequency cores for a significant part of their execution.

Detailed analysis in the paper!

>23 apps outperform CFS

Same performance, less energy consumed

Take away

Frequency inversion problem

- FTL + frequency agnostic scheduler
- New because of per-core dynamic frequency scaling

Solutions implemented in Linux

- S_{local}: simple, aggressive, relies on load balancing
- S_{move}: frequency-aware, more balanced
- Both are available at: https://gitlab.inria.fr/whisper-public/atc20

Possible extensions:

- Fully frequency aware scheduler
- Modeling the frequency behavior of a CPU (#active cores, temperature, instruction set, …)
- Shortening FTL with faster frequency reconfiguration