EAS Overview and Integration Guide

Version 1.3

Revision Information

The following revisions have been made to this document.

Date	Version	Confidentiality	Change
26 September 2016	1.1	Non-Confidential	LSK-3.18 16.09 release
14 November 2016	1.1a	Non-Confidential	LSK-3.18 16.10 release
31 March 2017	1.2	Non-Confidential	AOSP 4.4 release
26 July 2017	1.3	Non-Confidential	AOSP 4.4 update & AOSP 4.9 release for review

Confidentiality Status

This document is Non-Confidential.

Web Address

http://www.arm.com

Contents

1 Overview

1.1 Application of EAS

The mainline Completely Fair Scheduler (CFS) scheduler class implements a throughput oriented task placement policy. EAS adds an energy based policy to this scheduler class which optimizes energy saving managing task placement and the spare capacity of CPUs intelligently. EAS operates when the system has low/medium total utilization and the original CFS policy operates at full system utilization, as EAS offers no energy benefit when all CPUs are overutilized.

EAS targets dual-cluster big.LITTLE systems with non-overlapping power/performance curves for the two cpu core types and per-cluster and/or per-cpu power-down cpu-idle states. Such a topology allows EAS to clearly show its advantages over the vanilla mainline CFS scheduler for a wide range of workloads. Since EAS uses a generic energy model approach, it also supports more advanced CPU topologies such as DynamIQ based systems.

The current EAS implementation does not support Symmetric Multi-Threading (SMT) nor Non-Uniform Memory Access (NUMA) architectures.

1.2 Scope of the document

This document describes the architecture of EAS as present in the EAS product codeline. The intended audience for this document are developers interested in porting, tuning and evaluation of the product codeline.

This software release is suitable for product evaluation of the Energy-Aware Scheduler. It represents an extended, product-hardened version of the ongoing open-source EAS development taking place on Linux Kernel Mailing List.

https://developer.arm.com/open-source/energy-aware-scheduling

This document contains information about where the source code is hosted in chapter “Source Code”, explains the building blocks and the functionality of EAS in chapter “Functionality” and how to evaluate a new EAS integration on a new device in chapter “Integration”.

1.3 Changes in EAS 1.2

- Provide PELT in addition to WALT (intention to use PELT as default)
- Provide Schedutil in addition to sched-freq (intention to use Schedutil as default) (partial backport from 4.7, but not including cpufreq changes)
- Wakeup path changes to support big.LITTLE using generic code
- EAS restructured to be much closer to mainline version, but retain latency focus from EAS r1.1
- Incorporated upstream CFS fixes

- Added upstream capacity-based-scheduling

1.4 Changes in EAS 1.3

- Validation on real devices and additional development boards
- Increased test coverage
- Upstream schedutil backporting
- **Schedutil is now the recommended CPUFreq governor**
- General EAS refactoring improvements
- android-4.9 brought to EAS equivalence with android-4.4

1.5 EAS Overview

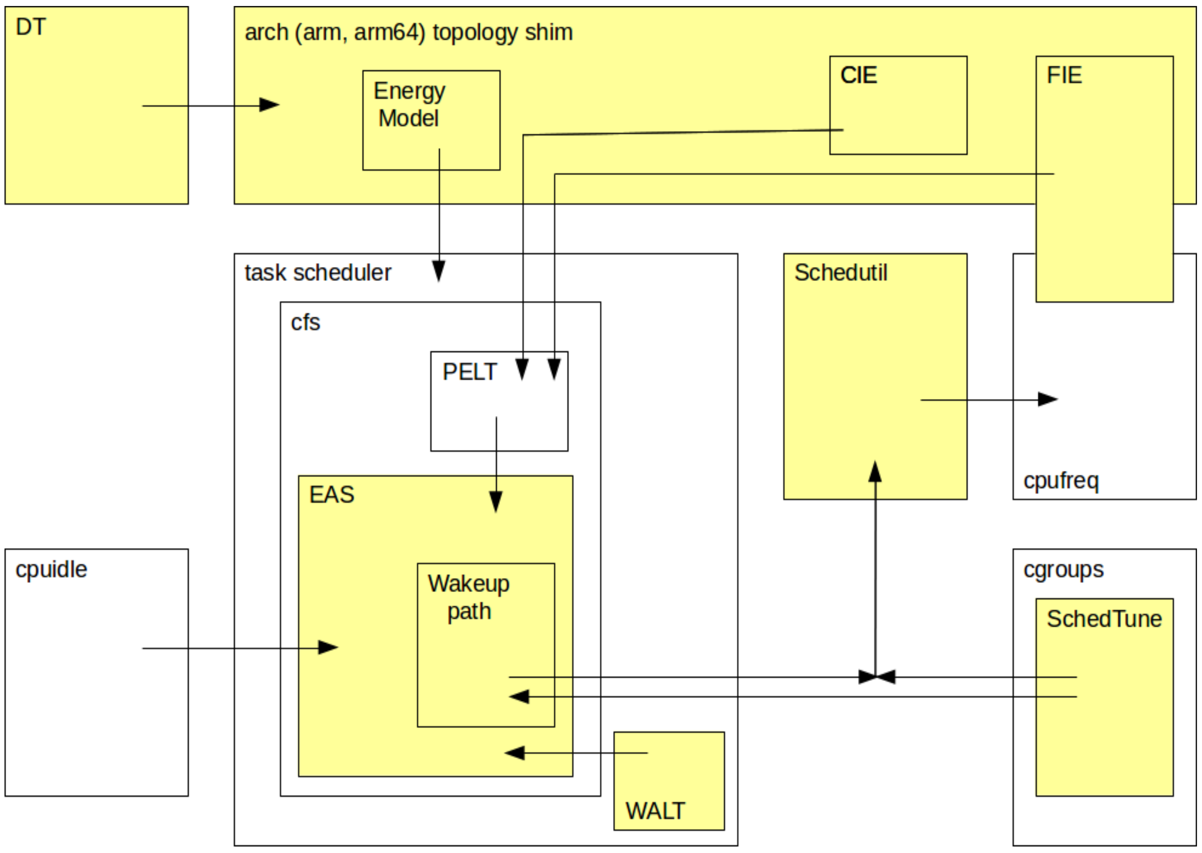


Figure 1 EAS building blocks in relation to Linux task scheduler, cgroups subsystem and related power management subsystems

EAS extends a few different subsystems present in the kernel. A major part of EAS is located in the file: `kernel/sched/fair.c` and is the algorithm responsible for task placement decisions. This module constructs necessary structures containing energy metrics which are used for calculating energy efficiency. The code extends commonly used

CFS scheduling policy and does not touch other policies. Some of the existing features in CFS have been made energy aware by factoring in the possible energy cost of scheduling tasks and managing the CPUs the tasks run on. EAS therefore impacts load balancing and task packing decisions. A key realisation was that it only makes sense to bias task placement in favour of energy efficient operation when there is spare CPU capacity available. In the absence of spare capacity, the system is usually in a state where throughput is the primary need. Intentionally biasing towards energy efficient operation in such cases could compromise throughput.

A set of heuristics have been introduced which enable under-utilized systems to run tasks in an energy efficient manner. When the system is over-utilized, EAS is effectively disabled, with the rules for task placement falling back to conventional CFS rules. EAS considers the system over-utilized when even one CPU's utilization is above a certain limit. This dynamic helps to spread work across CPUs when there is a real need for throughput while also giving the scheduler a chance to optimize task placement for energy efficiency when there is spare capacity available.

Enabling the scheduler to judge the power and performance requirements of tasks needs the introduction of new data structures centred around the concept of an energy model. Therefore, a common mechanism has been introduced for providing an energy model to the scheduler. This solution aspires to be universally beneficial for all platforms and use-cases.

The energy model data consists of:

- power consumption for each supported P-state (this is the DVFS Operating Performance Point (OPP) which is a tuple of frequency and the associated voltage)
- power consumption for each C-state (the idle power management state)
- wake-up energy cost for each C-state

The model only contains data for CPUs and clusters. The cluster maintenance energy, which can vary depending on specific architecture, is added to the energy related to each CPU to have accurate approximations.

Energy model data is provided to the kernel using the Flattened Device Tree (FDT) mechanism. Extensions to the FDT specification have been made that enable the expression of energy model data (see section Device Tree for further detail). A system specific FDT description is given to the kernel via a so called FDT blob as per the usual practice prevalent in Linux. The energy model data within the device tree is given to the scheduler via function present in `kernel/sched/energy.c`. Architecture specific code relevant to EAS includes a shim layer that builds a system topology for the scheduler. There are also some extensions for the main EAS algorithm such as FIE (Frequency Invariant Engine) and CIE (CPU Invariant Engine). These extensions help normalize the load calculations made by the scheduler and make these calculations invariant of the CPU frequency and micro-architecture. This scale-invariance improves the estimation of CPU utilization by factoring in the microarchitecture differences between CPUs as well as the current CPU frequency. Suitable scaling correction factors are provided for more accurate load-tracking.

Per-task load tracking in Linux (and by extension also EAS) is implemented using the Per-Entity Load Tracking (PELT) technique by the CFS scheduler class. The EAS product codeline introduces another load tracking mechanism known as Window Assist Load Tracking (WALT). WALT is used selectively in the product codeline at present. This is because when compared with PELT, WALT promotes faster reaction times when the behaviour of tasks changes. Faster reaction time is a key requirement for Android. WALT uses periodic calculations that are synchronized across all of the run queues, attempting to track the behaviour of all scheduling classes (while PELT is focused only on a single class - CFS). A big advantage of this approach is that the decisions can be made based on the information about the full state of the running system. The drawback is additional locking complexity and some additional delays in other pathways

Energy aware task placement decisions require the scheduler to estimate the energy impact in case of scheduling a specific task on a specific cpu. Sometimes it could be more energy efficient to wake up another cpu rather than alter the P-state of the current CPU where the given task runs. This calculation adds a small latency overhead to the scheduler. This feature is used at target run queue selection time for the task. At this point a decision needs to be taken to choose one of two possible pathways: energy efficient pathway or going to a sibling CPU.

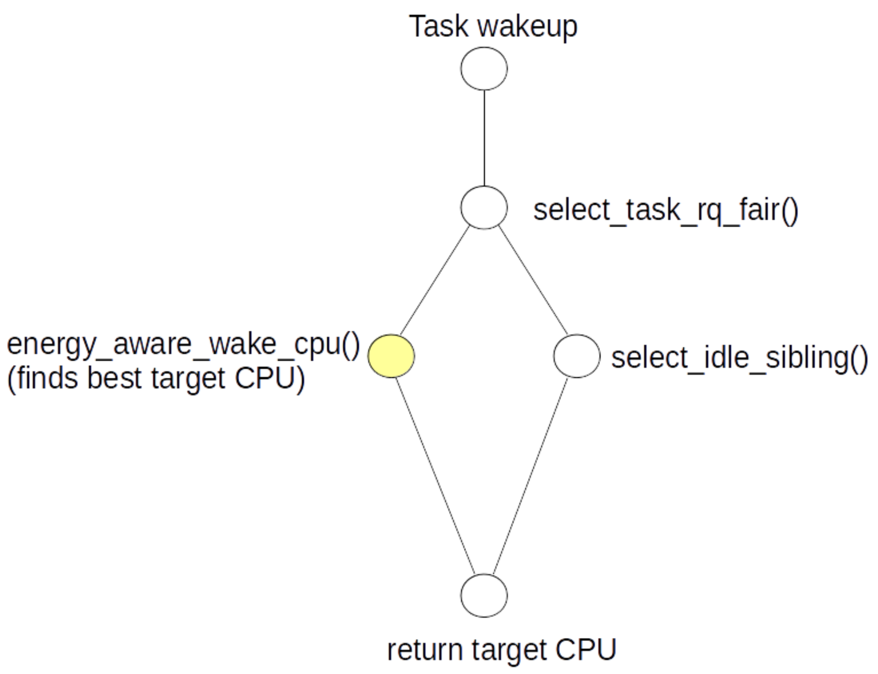


Figure 2 Task wakeup path modifications. (The yellow dots represent EAS functionality)

As mentioned previously, EAS is primarily targeted at promoting energy efficient operation when there is spare capacity present in the system. To assist with that style of operation, a new ‘utilization’ metric was introduced. The utilization metric, in addition to the load metric, simplifies energy-aware scheduling decisions. A CPU’s utilization corresponds to the CPU’s capacity. Therefore, CPU utilization can be compared with the currently available CPU capacity for CFS tasks.

EAS has a notion of over-utilization. The diagram below shows sites where the scheduler flags that the system is over-utilized.

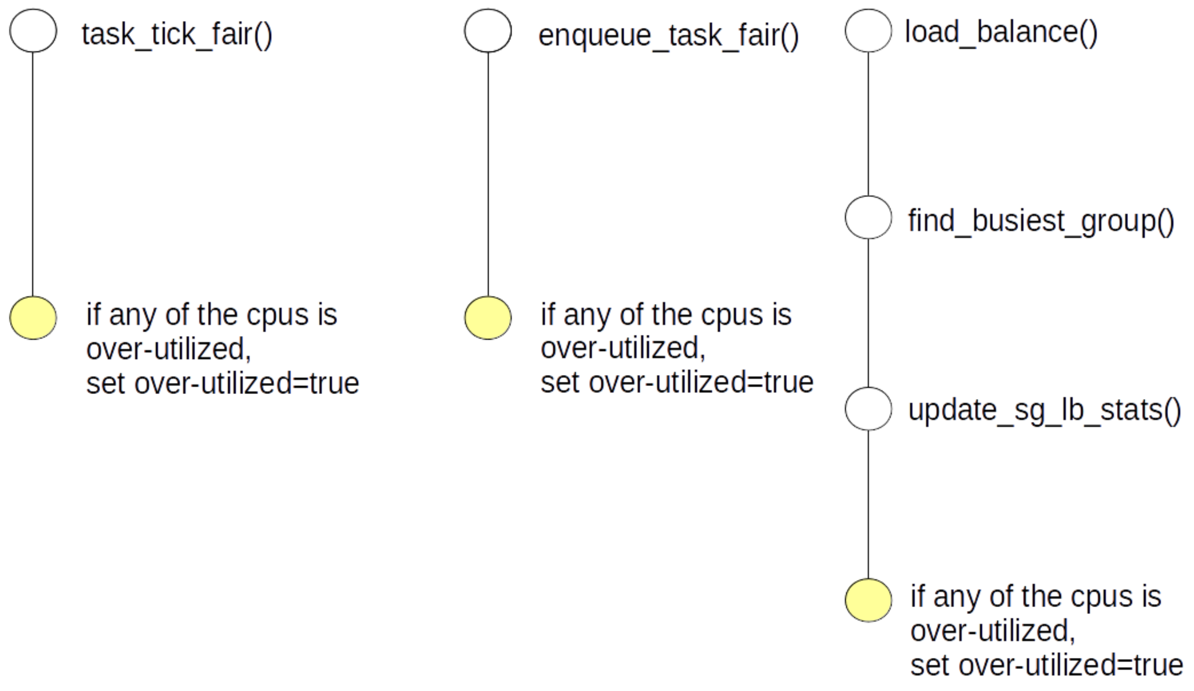

task_tick_fair()
if any of the cpus is over-utilized, set over-utilized=true
enqueue_task_fair()
if any of the cpus is over-utilized, set over-utilized=true
load_balance()
find_busiest_group()
update_sg_lb_stats()
if any of the cpus is over-utilized, set over-utilized=true

Figure 3 Places where the scheduler potentially marks the system as over-utilized

When one CPU is over-utilized, the whole system is considered as over-utilized. In this case the scheduler opts for a task spreading dynamic via conventional load balance pathways (as opposed to the new energy aware pathway). Note that the latter is implemented by the `energy_aware_wake_cpu()` function which promotes a task packing dynamic aimed at keeping CPUs idle).

The modification of the load balance subsystem is shown in the figure below:

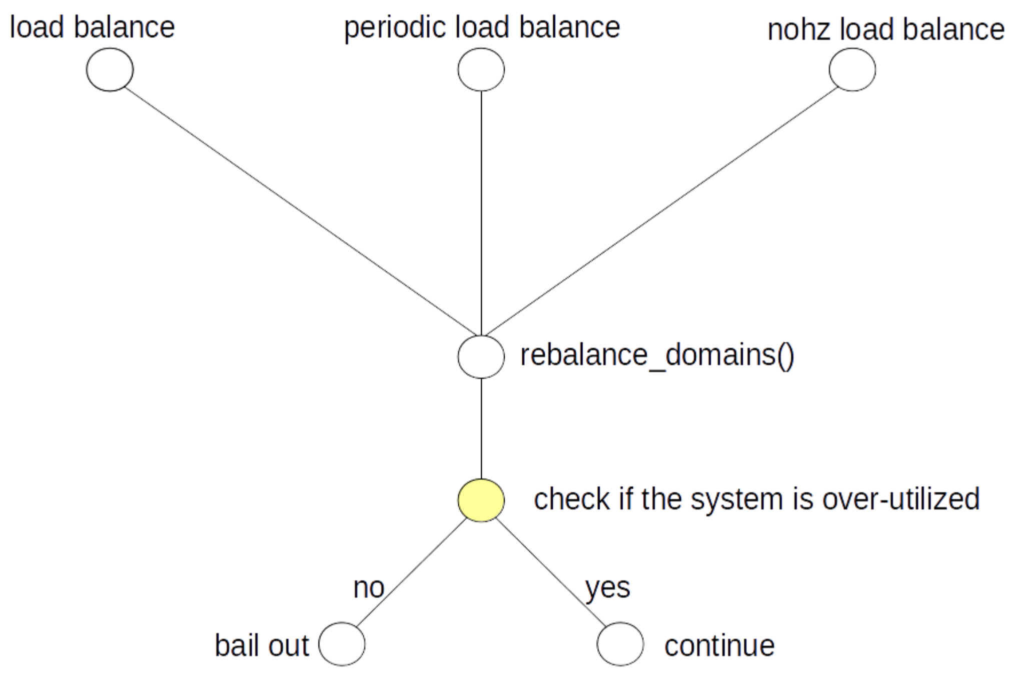


Figure 4 Load balance modifications and the check for an over-utilized system

Another subsystem which has been modified is cpufreq. This traditional architecture for DVFS management in Linux uses an average sampling driven design that is prone to sub-optimal OPP selection. For example, a given choice of sampling rate may be too high or too low for a task with a very specific load profile. Making a wrong estimation of load can result in needlessly high OPP selection (wasted energy) or a low OPP selection (poor responsiveness).

The Linux scheduler community has long asked for scheduler driven DVFS management. The rationale has been that the scheduler is best positioned to estimate the load profile of a task that is to run and can therefore request the necessary amount of compute needed on a per-task basis. Previous versions of EAS introduced an implementation of the scheduler-driven DVFS technique known as sched-freq. A newer implementation of the very same idea appeared in Linux kernel version 4.7 under the name of Schedutil; EAS currently adopts this solution by default (while still keeping sched-freq as an alternative for comparison). The most important improvement that Schedutil brings is that the scheduler can choose the frequency at which the CPU should run in the near future. This promotes more accurate frequency selection and therefore better servicing of the current load and utilisation.

The last module introduced by EAS is SchedTune, which uses the cgroups subsystem. SchedTune enables special case compute reservation for groups of tasks while also considering the energy impact. SchedTune is aimed for deployment in run-times with high visibility of compute requirements for tasks by way of a priori task classification. Middleware like Android fits very well in this category. Android knows which group of tasks require what compute for a given platform and at what point in time. SchedTune, by means of a cgroups exported interface, permits the Android run-time to efficiently move tasks between pre-created boost groups. SchedTune is aware of the platform specific energy model and works with the scheduler and Schedutil to ensure that the relevant tasks are serviced as needed.

UI/UX intensive jobs are given special attention to meet their latency requirements) in the most energy efficient manner for a given platform.

2 Requirements

2.1 Platform

1. The platform must have a working cpufreq implementation to allow EAS to manage spare CPU capacity correctly.
2. The platform must have a working cpuidle implementation to take energy savings due to turning off relevant parts of the CPU topology into consideration.
3. To be able to create the energy model there has to be infrastructure, on the board (e.g. Juno's (ARM development platform) energy meter) or external (e.g. ARM energy probe) to measure energy consumption.
4. Non-overlapping power/performance curves for the core types (big.LITTLE architecture) increase potential energy savings which can be achieved with EAS.

2.2 Operating System

The current EAS implementation is targeted for a v4.4 Linux kernel based Linux or Android Operating System, using the AOSP common kernel.

In the 1.3 release, we pushed an update for the android-4.9 branch of the AOSP common kernel to bring it to feature parity with the android-4.4 branch.

3 Source Code

The source code of the individual EAS components can be found here:

Linux Kernel:

- AOSP 4.4 common kernel:

  https://android.googlesource.com/kernel/common/+/android-4.4

- AOSP 4.9 common kernel:

  https://android.googlesource.com/kernel/common/+/android-4.9

  Note: android-4.9 changes are out for review at time of writing (26-July-2017). The changes tested here can be obtained at this URL: https://android-review.googlesource.com/#/c/444387/

  Once merged into android-4.9, the gerrit web interface will tell you that the patches have been merged however the changeset link will stay active.

Userspace:

- Linaro Android Userspace:

  http://releases.linaro.org/android/reference-lcr/juno/7.0-16.10/

Tooling:

- Lisa Tool (tagged for EAS 1.2)

  https://github.com/ARM-software/lisa/releases/tag/v17.03

EAS development has become more open. In order to see kernel patches being developed and take part in code reviews or experiment with early patches, please join the eas-dev mailing list hosted by Linaro.

Patches are being developed against the common kernel branches and reviewed in public on Google's Gerrit instance. Except for small uncontroversial fixes, these patches will be announced on eas-dev and partners are invited to contribute to the code review process.

4 Related Documentation Sources

Additional information and background on the Energy Aware Scheduling can be found on the ARM Developer website:

https://developer.arm.com/open-source/energy-aware-scheduling

5 Functionality

5.1 Linux Kernel

EAS Configuration Data

Device Tree

This section describes the structure of the energy model that EAS relies on. Specifically, the section focuses on the use of the Flattened Device Tree (FDT) as a means of expressing the energy model. FDT is an established specification intended to describe platform properties in a hierarchical data structure. This data structure is expressed in a Device Tree Source (DTS) file. DTS files are compiled into binary blobs which are provided as inputs to the kernel. FDT bindings are specifications that describe methods to describe particular system properties. A special set of FDT bindings were created in order to describe energy models for EAS. This makes it possible to have a single kernel image which can be deployed on multiple platforms with different FDT blobs containing the appropriate energy model.

EAS relies on a simple platform energy cost model to guide scheduling decisions. The model only considers the CPU subsystem. The energy cost model concept is applicable to any system so long as the cost model data is provided for those processing elements in that system's topology that EAS is required to service.

Processing elements refer to hardware threads, CPUs and clusters of related CPUs in increasing order of hierarchy. At present, EAS only supports CPUs and clusters of CPUs. Only two clusters of CPUs are supported.

EAS requires two key cost metrics - busy costs and idle costs. Busy costs comprise of a list of compute capacities for the processing element in question and the corresponding power consumption at each capacity. Idle costs comprise of a list of power consumption values for each idle state [C-state] that the processing element supports.

These cost metrics are required for processing elements in all scheduling domain levels that EAS is required to service. Given that these cost metrics are properties of the system and have close topological ties to the system, it made sense to use the well-established Flattened Device Tree specification as a means to express these cost metrics to the kernel. For a complete description of the FDT bindings introduced for the cost model, please see the binding document located at `Documentation/devicetree/bindings/scheduler/sched-energy-costs.txt` within the EAS kernel source.

The best way to understand the structure of the energy model as described using FDT is to look at an example. A working knowledge of FDT is assumed. A snippet from the DTS file of a system composed of a cluster of 2 ARM Cortex-A57 CPUs and a cluster of 2 ARM Cortex-A53 CPUs) is shown in the appendix subchapter “Example DTS file”.

EM data provisioning towards task scheduler

In the architecture specific topology shim layer the energy model data is constructed by calling `init_sched_energy_costs()`. Its interface towards the task scheduler is the scheduler domain topology level table (`arm64_topology[]`). It consists of `struct sched_domain_topology_level` entries each of which are extended by the function pointer `sched_domain_energy_f.` This points the task scheduler to the scheduler domain specific energy data. The pointer is set to `cpu_core_energy()` for the MC scheduler domain level and to `cpu_cluster_energy()` for the DIE scheduler domain level.

Data structures

The `struct sched_group_energy` represents the per scheduler group related data which is needed for Energy Aware Scheduling. It contains:

- Number of elements of the idle state array
- Pointer to the idle state array which comprises 'power consumption' for each idle state
- Number of elements of the capacity state array
- Pointer to the capacity state array which comprises 'compute capacity and power consumption' tuples for each capacity state

The `struct sched_group` contains a pointer to a `struct sched_group_energy` data structure.

EAS Load Tracking

Overview

Per-Entity Load Tracking (PELT) implements load-tracking for the SCHED_NORMAL scheduling policy a on per scheduling entity basis. Load stands for the actual load (a metric based on a sched-entity's runnable time, i.e. time spent on the run queue plus time spent running) and utilization (a metric based on a scheduling entity's running time).
The fact that historical behaviour of a scheduling entity becomes increasingly less relevant with age when trying to draw conclusions about its future compute requirements is incorporated by using a geometric series for each of the two metrics. This has the natural effect of decreasing the relevance of the accounted time in each time slice as they age.
PELT's bottom-up load-computation (scheduling entities contribute to the load of their parents' (run-queues or task groups) allows the correct migration of load for an entity along with its accompanying entities. This provides the right metric for intelligent load-balancing especially when task groups are involved.

EAS introduces an additional PELT metric: PELT utilization. This metric is used for CPU frequency selection and wakeup task placement.

The Window Assisted Load Tracking scheme (WALT) offers an alternative load tracking mechanism to PELT. For mobile workloads there is evidence that using the window based approach of WALT for CPU frequency selection and wakeup task placement improves the performance/power ratio and responsiveness in comparison to the use of PELT.

FIE - Frequency Invariant Engine

The PELT implementation is prepared to be aware of frequency scaling to provide better estimates for cpu load and utilization by calling `arch_scale_freq_capacity()`. However the mainline kernel will only use the default implementation of `arch_scale_freq_capacity()` which always returns `SCHED_CAPACITY_SCALE` essentially not making PELT frequency scale-invariant.

Architectures interested in actual frequency scaling have to re-define `arch_scale_freq_capacity()` to point to their own frequency scaling solution.

The FIE is integrated into the cpufreq subsystem by scaling the per-cpu variable `freq_scale` with the current frequency of the cpufreq policy the CPU belongs to. Its interface function `cpufreq_scale_freq_capacity()` is used to provide the actual frequency-invariant scaling solution.

```
#define arch_scale_freq_capacity cpufreq_scale_freq_capacity
```

CIE - Cpu Invariant Engine

PELT is aware of CPU invariant scaling to provide better estimates for cpu utilization. CPU invariant scaling is necessary due to micro-architectural differences (i.e. instructions per cycles, for example) between CPUs and differences in the current maximum frequency supported by individual CPUs. However the mainline kernel will only use the default implementation of `arch_scale_cpu_capacity()` which always returns `SCHED_CAPACITY_SCALE` (1024) essentially not making PELT CPU scale-invariant.

The CIE is integrated into the architecture topology shim by scaling the per-cpu variable `cpu_scale` with the capacity value of the highest capacity state in the energy model of the CPU. Its interface function `scale_cpu_capacity()` is used to provide the actual CPU-invariant scaling solution.

```
#define arch_scale_cpu_capacity scale_cpu_capacity
```

WALT - Window Assisted Load Tracking

Window Assisted Load Tracking (WALT) provides a window based view of time in order to track the demand and CPU utilization of tasks. A *"window"* is a (compile time) configurable time duration, by default 20ms, which is used to collect a new *"sample"* for both task demand and CPU utilization. The start of a new window is synchronized across all the CPUs in the system. A "sample" measures:

- how long a task was RUNNING, within the corresponding window
- how long a CPU was BUSY, within the corresponding window

Samples are *normalized to 1024*, which represents the maximum utilization for both a task and a CPU. Thus, a 1024 sample means that a task was running for the whole duration of the corresponding window or, similarly, that a CPU was busy for the whole duration of the corresponding window.

Similar to PELT, WALT samples are also scaled such that they are architecture and frequency invariant. Architecture scaling compensates for the possibly different maximum capacity of CPUs while frequency scaling compensates for time spent running at different frequencies. Thus, for example a sample of value 512 is measured for a task running for the whole sample window duration but at a frequency which also provides half of the capacity of the CPU with the maximum capacity in the system.

The *demand of a task* is estimated by WALT considering the last N "non zero" collected samples, where N is a compile time configuration which is set to 5 by default. Thus, samples are collected for a task only for windows where the task had a chance to run. From all the collected samples the task utilization is estimated based on an "aggregation policy" which can be selected at compile time. By default the aggregation policy used is

`WINDOW_STATS_MAX_RECENT_AVG` which returns the maximum value between the average of all the collected samples and the most recent collected sample.

WALT estimates the *utilization of a CPU* by considering the sample measured during the **last** window. Thus, it's noteworthy that everything happening in the **current** window's time-frame is not affecting the view of CPU utilization.

Another main feature of WALT is that task demand and CPU utilization is tracked across all scheduling classes. The utilization metrics are associated with the `struct task_struct` for tasks and to the `struct rq` for cpus. The code to update these metrics is self-contained into a single source file (`kernel/sched/walt.c`) and functions exposed by this file are used only from the core scheduler code (`kernel/sched/core.c`). A custom set of "events" is defined which are used from specific call sites of the core scheduler to trigger updates of the metrics as well as to collect new samples.

Integration with EAS

It is possible to use WALT signals to drive EAS, for task placement as well as SchedFreq for OPP selection. The contact surface between WALT and EAS/SchedFreq is confined to a couple of functions: `cpu_util()` and `task_util()`. Both of these functions allow the transparent use of WALT signals instead of the corresponding PELT signal. When WALT is enabled at compile time via `CONFIG_SCHED_WALT`, a couple of control interfaces are exposed as procfs flags:

```
/proc/sys/kernel/sched_use_walt_cpu_util
/proc/sys/kernel/sched_use_walt_task_util
```

When set to 1, they force the previous functions to return the corresponding WALT signal.

NOTE: Although it's technically possible to enable the usage of WALT only for one of the two signals, such mixed configurations have not been tested and they should be considered highly experimental.

Userspace exposed control interfaces

A set of configuration controllers are exposed to tune the behaviour of WALT:

- `sysctl_sched_walt_init_task_load_pct`

  The initial utilization (in percentage) of a newly created task.

- `sysctl_sched_walt_cpu_high_irqload`

  Time spent serving IRQs (in ms, by default 10) to consider a CPU highly loaded by interrupt. This value is used in `find_best_target()` to skip CPUs which are currently under a high IRQ pressure:

- `sysctl_sched_use_walt_cpu_util`

  Enable usage of WALT estimated CPU utilization.

- `sysctl_sched_use_walt_task_util`

  Enable the usage of WALT estimated task utilization.

Initial Task Load

Newly created tasks have no previous history for which a corresponding utilization can be estimated. PELT and WALT differ in their approach to providing a suitable value. For WALT, a userspace control interface can be used to select the default initial task utilization for new tasks: `sysctl_sched_walt_init_task_load_pct`. The default value is 15%.

Since utilization influences both load balancing and clock frequency selection, choosing a particular value for this setting is a trade-off between potential performance gain experienced by the task in the early phases of its life and increased power consumption if tasks creation rate is too high.

Additional EAS related key concepts

Tipping Point - Over-Utilization

EAS is designed to save energy by managing spare capacity, i.e. CPU cycles, intelligently using a platform energy model. Without sufficient spare capacity, it is no longer feasible to optimize for energy and EAS optimizes solely for throughput instead. The tipping point at which EAS stops optimizing for energy is based on utilization.

A CPU is considered “over-utilized”, i.e. full, when its utilization leaves almost no capacity left:

```
capacity_of(cpu) * 1024 < cpu_util(cpu) * capacity_margin
```

`capacity_margin` is defined as 1280, i.e. 20%, by default. The entire system is considered over-utilized as soon as one CPU is over-utilized to ensure that no task is throughput constrained unnecessarily.

is_big_little

~~On a non big.LITTLE type of devices no simple heuristic exists to predict, before consulting the energy model, which cluster of CPUs is likely to be more energy efficient for wakeup load balancing decisions.~~

~~A tuning interface is exposed to user-space to be able to provide the scheduler such a high level topological information: `sched_is_big_little`.~~

Note: The `is_big_little` interface was removed in EASr1.2. The wakeup path which used this information has been refactored and updated in order to handle the differences automatically.

EAS functionality

Energy aware wakeup path

When the system is not over-utilized, all tasks will occasionally wake up hence most of the energy-aware scheduling decisions can be made in the task wake-up path in the scheduler. If the system is over-utilized, tasks will be placed only on CPUs that are currently idle.

When energy awareness is active (i.e. the system has not marked itself overutilized) tasks are generally placed according to the following steps:

1. Tasks which are woken with the sync flag are placed on the current cpu, if their affinity allows.

2. All other tasks go first through `find_best_target` to determine the 'best' cpu for them. This is the function where schedtune influences task placement decisions. Any CPUs where the task will not fit or which have high irqload (as defined by WALT) are discarded.

3. `find_best_target` will attempt to select two candidate CPUs for a task, a primary target and a backup target, except where a latency-sensitive task finds an idle CPU available. Tasks which are latency sensitive or have boosted utilization begin looking for a CPU in the group which contains the highest capacity CPUs. All other tasks begin looking starting from the group which contains the lowest capacity CPUs.

    a. Latency sensitive (schedtune.prefer_idle – see below) tasks will select the first idle CPU they find. If there is not an idle CPU available they will first select a CPU with the largest amount of spare compute capacity, and as an alternative they will also select a CPU with the lowest utilization once this task is placed there. These two options express the spread/pack dynamic for this class of tasks.

    b. Non latency sensitive tasks will select a primary target of an active CPU which has the smallest maximum capacity and the most spare capacity after adding the task to reflect a strategy which attempts to spread tasks within the most energy efficient cluster of CPUs. The backup CPU selected will be an idle CPU (if there is one) which has the lowest maximum capacity and the shallowest idle state.

4. If the task is latency sensitive, the task is placed on the first encountered idle CPU.

5. For all other tasks, candidate CPUs are evaluated for energy/performance tradeoffs before being used. The backup target is only evaluated if the primary target is not allowable,

6. If none of the candidate CPUs are allowable in the energy/performance tradeoff, the task will be placed on its previous CPU. If access to the `sched_domain` is not possible (for example, during hotplug sched domain structures are rebuilt), then the previous CPU will be used.

Misfit Task

Tasks that run for longer periods don't regularly come through the wake-up path and therefore don't get a chance of being placed on higher capacity CPUs through that route. These tasks have to be migrated as part of periodic load-balancing or idle load-balancing instead. CPUs with runnable tasks with a higher utilization than can be accommodated mark themselves as having one or more "misfit" tasks. In this scenario, the system is over-utilized and scheduling decisions consider only throughput.

During periodic or idle load-balancing, if no general overload issues are present, CPUs with misfit tasks are considered and misfit tasks are migrated to more appropriate CPUs if necessary.

Schedutil - Scheduler driven DVFS

Schedutil is a cpufreq governor that makes it possible to control CPU clock frequency selection directly from the scheduler. Schedutil works as a shim layer between the scheduler and the CPUFreq framework. This enables the scheduler to implement a CPUFreq policy governor by itself, basically replacing legacy governors such as ondemand, interactive, etc. The tight connection between the scheduler and clock frequency selection provides better system-wide policies and improves both performance and power savings.

Schedutil can be activated through the usual CPUFreq sysfs interfaces.

Up and down threshold configuration interfaces

Schedutil exposes to user-space an up and a down throttling threshold. Throttling thresholds (beyond the physical transition latency limit) are necessary to prevent too frequent (and potentially harmful) clock frequency transitions. In general it is required to be quick in responding to a sudden increase in utilization, and have a bit of hysteresis for brief drops. The actual values (in microseconds) can be configured via two governor sysfs files: `up_rate_limit__usec` and `down_rate_limit_usec`.

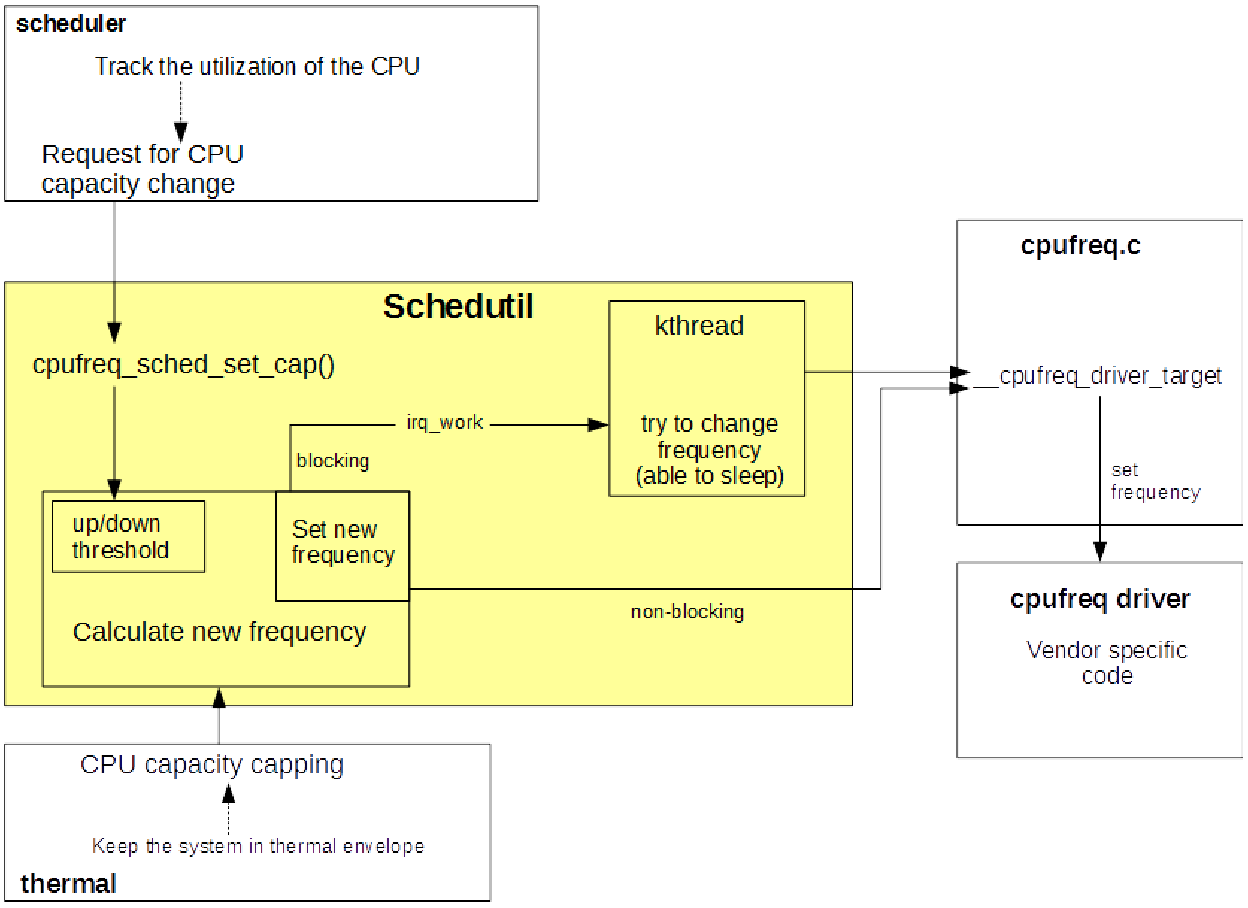


Figure 5 Schedutil block diagram showing connections between scheduler, thermal subsystem and existing CPUFreq

SchedTune - Task classification and control

SchedTune is an EAS module that implements a single (and simple) central tunable controller to balance energy-efficiency and performance-boosting. It extends the Schedutil CPUFreq governor, to bias the OPP selection, thus allowing this governor to provide behaviours similar to other governors; e.g. interactive, performance or powersave. It also integrates the energy-aware wakeup path of the EAS core, to bias tasks placement, thus allowing to trade-off energy-efficiency for performance-boosting.

From a user-space perspective, SchedTune fosters the collection of sensible information to better support the scheduler in its decisions. A simple yet powerful interface, based on the cgroups API, allows an easy integration with run-times available in platforms like Android. This interface is suitable to support task classifications, for example foreground vs background, which can then be managed according to different goals from the scheduling standpoint.

SchedTune is exposed to user-space via the cgroups interface, where the `schedtune` controller can be mounted to get access to the sysfs tunables it exposes. For example, Android mounts it by default under `/dev/stune`. This path represents the `root boostgroup`, which includes every task in the system. Additional `boostgroups` can be created (up to a maximum of 5 with the default kernel configuration), to represent different possible tasks classifications. All tasks within the same boostgroup are assigned a similar set of SchedTune parameters.

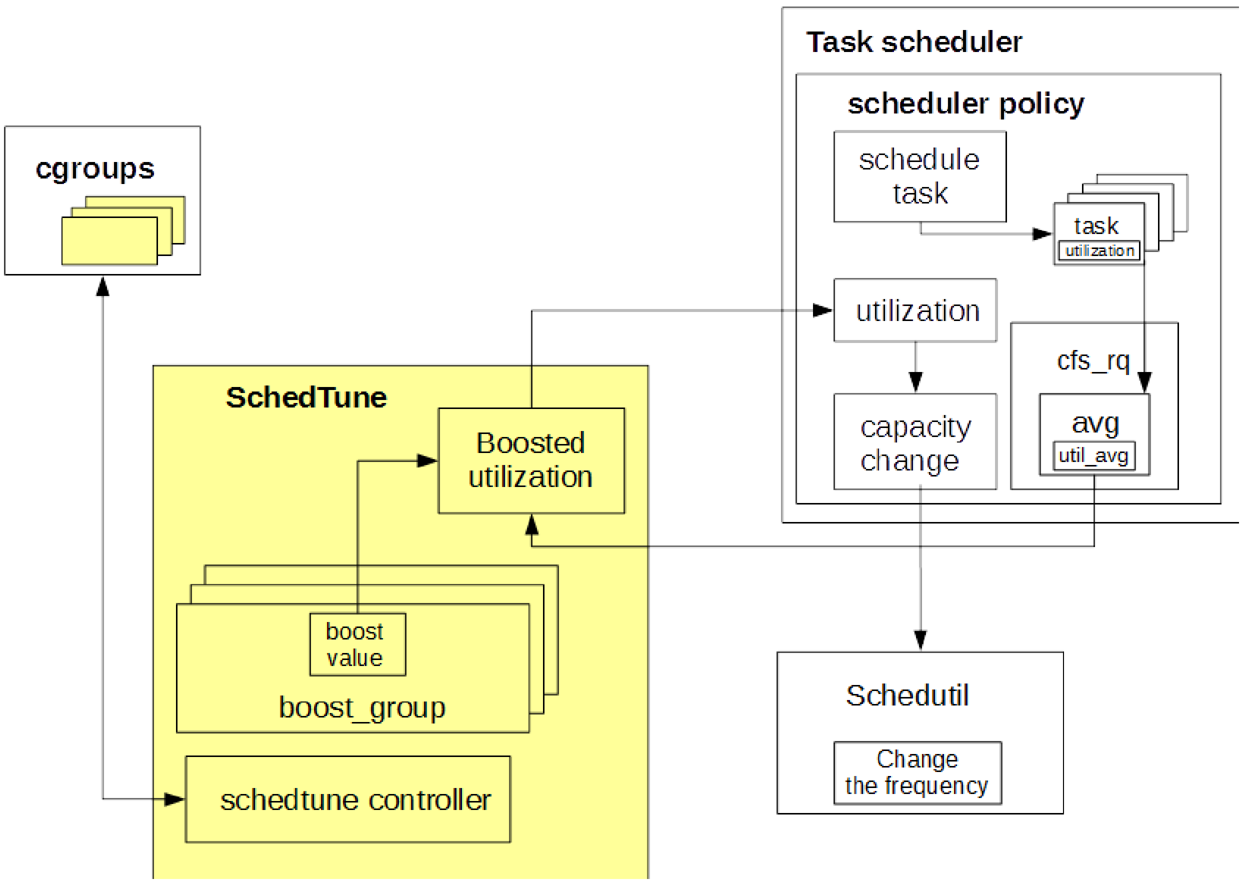


Figure 6 SchedTune block diagram showing components and connections between scheduler policy and boosted group's utilization concept.

Userspace exposed control interfaces

For each boostgroup, SchedTune currently exposes two tunables:

`1. schedtune.boost (int [-100..100])`

This parameter specifies the boost percentage value which is used for the tasks in this group.

This value is used to compute a "margin" to be added or removed to or from the utilization signal of a task/cpu. The value of the margin is calculated to provide a well-defined and expected user-space behaviour. For example, the following table reports the meaning of some specific boost values:

Boost value [%]	**Meaning (e.g. run the task at a frequency corresponding to)**
0	Minimum required capacity (max energy efficiency)
100	Maximum possible speed (min time to completion) (*)
50	Something in between the previous two configurations
-50	Half of the minimum required capacity
-100	Minimum available capacity (minimum OPP)

(*) minimum latency is not yet completely supported in the current ACK release, this feature is a work in progress and will be added in a following release.

The logic to convert the boost value into a proper margin is based on a "Signal Proportional Compensation" (SPC) policy which is implemented in:

`kernel/sched/fair.c::schedtune_margin(signal, boost)`

The parameter `signal` is the original task or CPU utilization to compensate and `boost` is the boosting percentage defined for the boostgroup the task is part of.

`2. schedtune.prefer_idle (int [0,1])`

This parameter specifies the "packing" vs "spreading" strategy to be used for tasks placement in the wake up path.

One of the first operations done in the energy aware wakeup path is the selection of a candidate CPU where the task should be executed. The prefer_idle flag reflects the desire for low-latency activation, possibly at the expense of increased energy consumption. Tasks belonging to boostgroups having this flag set are allocated (if available) on an idle CPU, thus reducing to the minimum their activation latency. When the flag is reset (or not IDLE CPUs are available) a more complex CPU selection heuristic is used, which targets tasks packing to optimize for energy consumptions.

The figure below shows the state of the kernel scheduler and SchedTune in time t0, t1. It narrows down the case when the boost is applied via SchedTune to the run queue utilization. Thanks to this enhancement, it is possible to request more capacity via SchedFreq.

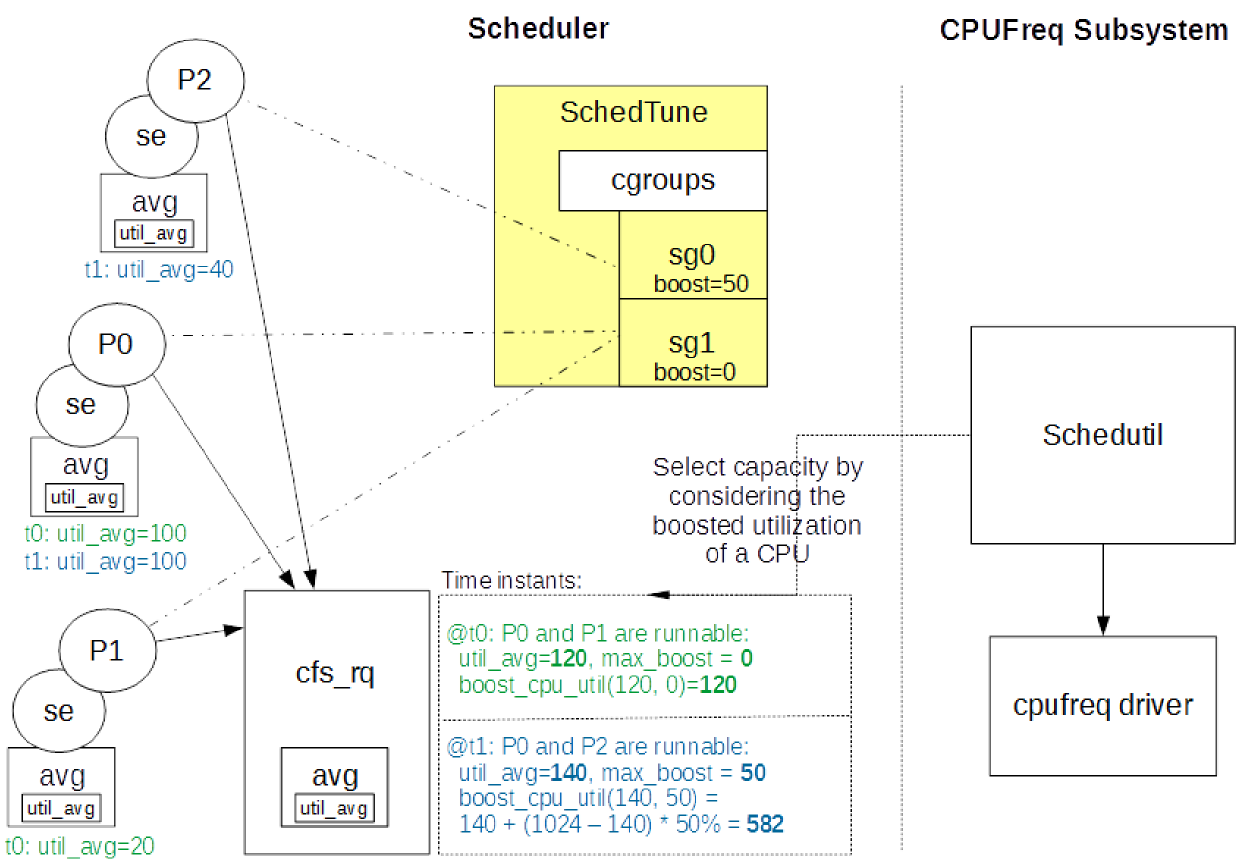


Figure 7 Flow diagram showing the state of the SchedTune and kernel scheduler in time: t0, t1.

Dynamic CPU capacity capping

The current maximum frequency of a core in a multi-core processor can be restricted to a value lower than its absolute maximum frequency. One of the reasons for this to happen is thermal management. It makes sure that the system always operates in the boundary of its power budget. This is normally achieved by reducing the maximum frequency of CPU cores. To make sure that the task scheduler knows about this new maximum frequency dynamic CPU capacity capping can be applied.

Dynamic CPU capacity capping provides PELT and the scheduler CPU capacity management with a maximum frequency scaling correction factor. This scaling factor describes the influence of running a CPU with a current maximum frequency lower than the absolute maximum frequency.

```
current_max_freq(cpu) << SCHED_CAPACITY_SHIFT / max_freq(cpu)
```

Dynamic CPU capacity capping is integrated into the cpufreq subsystem by scaling the per-cpu variable `max_freq_scale` with the current maximum frequency of the cpufreq policy the CPU belongs to. Its interface function `cpufreq_scale_max_freq_capacity()` is used in the CIE implementation making sure that Dynamic CPU capacity capping affects PELT and CPU capacity management.

EAS Trace

The EAS release contains several patches with additional trace events which help in verifying that the individual EAS building blocks such as load-tracking (PELT and WALT), FIE, CIE, SchedFreq and SchedTune are working correctly. These trace events are also required for the Interactive Test and Analysis part of the LISA toolkit to work correctly.

EAS Debug

There is support to evaluate the EAS energy model on a running system via the proc file-system. In case `CONFIG_SCHED_DEBUG` and `CONFIG_SYSCTL` are enabled the related files are placed under the subdirectory named `energy` inside the `/proc/sys/kernel/sched_domain/cpuX/domainY/groupZ` directory.

To be able to figure out the reason for a potential misbehaviour of a task while running the EAS verification tests the cause of each task migration is additionally provided with the existing `sched_migrate_task` trace event. Please refer to chapter “Evaluate per task behavior” for more information.

5.2 User-space

General policies to minimise energy use are not always suitable for some tasks in an interactive system. This is not a problem caused by EAS, but rather a feature of any system where performance is constrained to reduce energy consumption. There are often some tasks for which highest performance or minimum latency is more important than minimum energy to complete a job. Where you have heterogeneous multiprocessing, you also have to select a suitable CPU match for a task.

There have been attempts at controlling this behaviour for at least as long as systems have implemented DVFS - the interactive governor is a longstanding Android feature which links to user input to try and minimise latency. Some systems use cpusets to guide tasks to specific CPUs and they may use cpu bandwidth controls and/or task priority to control behaviour. There are also controls which modify scheduler parameters and hence change the frequency of load balance decisions etc. Usually a combination of all these tools is used to configure a system to provide an acceptable balance between energy use and performance. The previous (HMP or GTS) big.LITTLE MP support had some userspace controllable tuning parameters and it was not uncommon to see userspace daemons dynamically controlling those thresholds in response to specific system events or behaviours. All of these tools and techniques are a way to guide the kernel as to the desired response when scheduling.

Android userspace uses a combination of cpusets and schedtune to partition the system and optimise for responsiveness of user-facing tasks together with energy use for other tasks.

Android 7.1 AOSP changes for Google Pixel

The EAS/stune userspace integration, done as part of the Pixel program, has been made available in AOSP android_7.1.0_r1. These will make their way into Linaro Android when this release has been taken in. All integration points mentioned here are for the tag 'android_7.1.0_r1'. Linaro LCR Android release 16.10 is based on android_7.0 and has only basic support for foreground/background stune groups.

SchedTune CGroup layout

There are 4 groups defined for schedtune, commonly abbreviated to stune in AOSP commit messages.

/dev/stune	root group: anything not explicitly placed elsewhere goes here
/dev/stune/background	background group: this group holds tasks which the userspace designates as unimportant for interactive performance
/dev/stune/foreground [prefer_idle=1]	foreground group, this group holds tasks which the userspace designates as important for interactive performance **Includes: audioserver / mediaserver**
/dev/stune/top-app [prefer_idle=1] [boost=10]	top-app: holds tasks which belong to the application top-most of the display stack, which use SP_TOP_APP scheduling policy (defined for the Java side as THREAD_GROUP_TOP_APP in frameworks/base/core/java/android/os/Process.java, and the Android.ui thread of all running apps **Includes: cameraserver / bootanimation**

SchedTune CGroup usage for Services

Some system components have been placed directly into one of the stune groups. The init script sections for these services are updated to write the service PID into the relevant group at creation time.

1. /dev/stune/foreground
    a. audioserver
    b. mediaserver
2. /dev/stune/top-app
    a. cameraserver
    b. bootanimation

SchedTune CGroup usage for Application Tasks

All tasks in Android are mapped to specific scheduler policies by platform/system/core/libcutils/sched_policy.c. This includes assigning to specific cpuset groups as well as now assigning to the different schedtune groups. In order that sched_policy.c will include the schedtune group mappings, you must have USE_SCHEDBOOST defined when building. ActivityManager decides which tasks belong to a foreground app, a background app, or the top-app and passes the policy down through setProcessGroup etc. until eventually sched_policy.c writes the TIDs into the correct tasks file.

Further to this, each application has an android.ui thread which will have its thread group set to TOP_APP. This results in calling into sched_policy.c:set_sched_policy and should force that task to be added to the foreground cpuset group and the top-app schedtune group.

AOSP Commits adding EAS Integration

- https://android.googlesource.com/platform/system/core/+/11cde56 Mount schedtune cgroup as /dev/stune
- https://android.googlesource.com/platform/system/core/+/770ee49 & https://android.googlesource.com/platform/system/core/+/aa45cb8 Set stune groups from set_sched_policy
- https://android.googlesource.com/platform/system/core/+/5dcff8f Add support for background stune group
- https://android.googlesource.com/platform/system/core/+/481edfe & https://android.googlesource.com/platform/system/core/+/955694b Add support for the top-app stune group
- https://android.googlesource.com/platform/frameworks/av/+/64c1ce8 & https://android.googlesource.com/platform/frameworks/av/+/caba519 Put mediaserver and audioserver in the foreground stune group.
- https://android.googlesource.com/platform/frameworks/av/+/052c495 Put cameraserver in the top-app stune group.
- https://android.googlesource.com/platform/frameworks/base/+/1c14fbc &
- https://android.googlesource.com/platform/frameworks/base/+/5c52691 Put bootanimation in the top-app stune group.
- https://android.googlesource.com/platform/frameworks/base/+/fe51b8f & https://android.googlesource.com/platform/frameworks/base/+/4074ad0 Set android.ui to be in the fg stune group. (but uses top-app, so with later patches results in android.ui being in the top-app stune & fg cpuset group).

Userspace Integration required from OEMs

You will notice that there is no ‘interactive’ style responsiveness boosting implemented in the kernel for the schedutil CPUFreq governor. If you want this functionality on your device, then the place to implement this is in the PowerHAL - you can set minimum frequencies, change stune group boost levels and more in response to indications from Android about what activities are going on. We do not discuss the implementation of a PowerHAL, but there is a Hikey-specific PowerHAL available in the Hikey device project for AOSP. Since the Android 7.1 release in AOSP, the new hints for Android 7.1 are implemented in a Pixel-specific PowerHAL.

When looking at PowerHAL implementations for other devices please remember that the actions taken on receipt of hints from the middleware are normally device-specific tunings and should be carefully tested.

New Android 7.1 Power Hints

For more detail, refer to your Android PDK. For reference, the new hints are named like so:

- POWER_HINT_SUSTAINED_PERFORMANCE
- POWER_HINT_VR_MODE

6 Tuning

This chapter contains the description of task scheduler related configuration data which can be used to fine tune the EAS behaviour on a particular target device.

- sched_migration_cost

  This value describes the amount of time after the last execution of a task that this task is considered to be "cache hot" in load balancing decisions. The default value is 500000 ns.

  A "cache hot" task is not considered for periodic, idle or nohz-idle load balance as long as the scheduler domain `sd->nr_balance_failed` counter is smaller or equal then the `sd->cache_nice_tries` value (leave “cache hot” task for # tries on the current cpu) plus 2.

  If the idle time of a certain cpu or cluster is higher than desired when there are runnable tasks in the system, try to reduce this value.

  This task scheduler sysctl tuning variable is located in `/proc/sys/kernel/`.

- busy_factor

  In case a cpu is busy, i.e. the cpu is not idle, the load balancing operation interval is increased by multiplying the scheduler domain `sd->balance_interval` value with this factor.

  The time between consecutive load balancing procedures on a specific scheduler domain level of a busy cpu can be reduced by decreasing this value.

  This scheduler domain data is set to 32 during sched domain hierarchy bring-up in `sd_init()`.

7 Integration

7.1 An Overview of the LISA Toolkit

The Linux Interactive System Analysis (LISA) is a toolkit containing libraries and APIs that are suitable for `interactive analysis` of the behaviour of a Linux based system. The main goals of this toolkit are:

1. To support studying and understanding of existing behaviours, e.g. how PELT works
2. To support the analyses of new features to verify their impact on existing behaviours
3. To get possible insights on what's not working or not working well and possibly why
4. To establish a common framework and language to share easy to understand and reproducible experiments

LISA is available at: https://github.com/ARM-software/lisa

This toolkit is targeted at two main consumers: developers and integrators.

Developers are people involved in the creation of new features of a Linux based system, mainly on the kernel-space side but user-space developers may also be involved. Their goal is usually to run some experiment on a target platform, collect execution traces and use the collected data to generate plots and statistics which allow the comparison of existing behaviours with the new features that are being developed. This process is usually repeated multiple times during the development and testing of a new feature and involves the interaction of possibly multiple different target platforms.

Integrators are people mainly interested in running regression tests and performing analyses to verify how the behaviours of a system are changing across different release versions.

The working flow used by both of these customers is usually repeated multiple times and it may involve interactions with multiple different target platforms. Moreover, developers usually need to share their results and experiments with other developers in order to reproduce the same experiments or to cross-check conclusions.

The LISA toolkit addresses all these requirements and promotes re-use and cooperation among different people using different targets. LISA is a collection of python libraries which expose different sets of APIs at different abstraction levels as shown below:

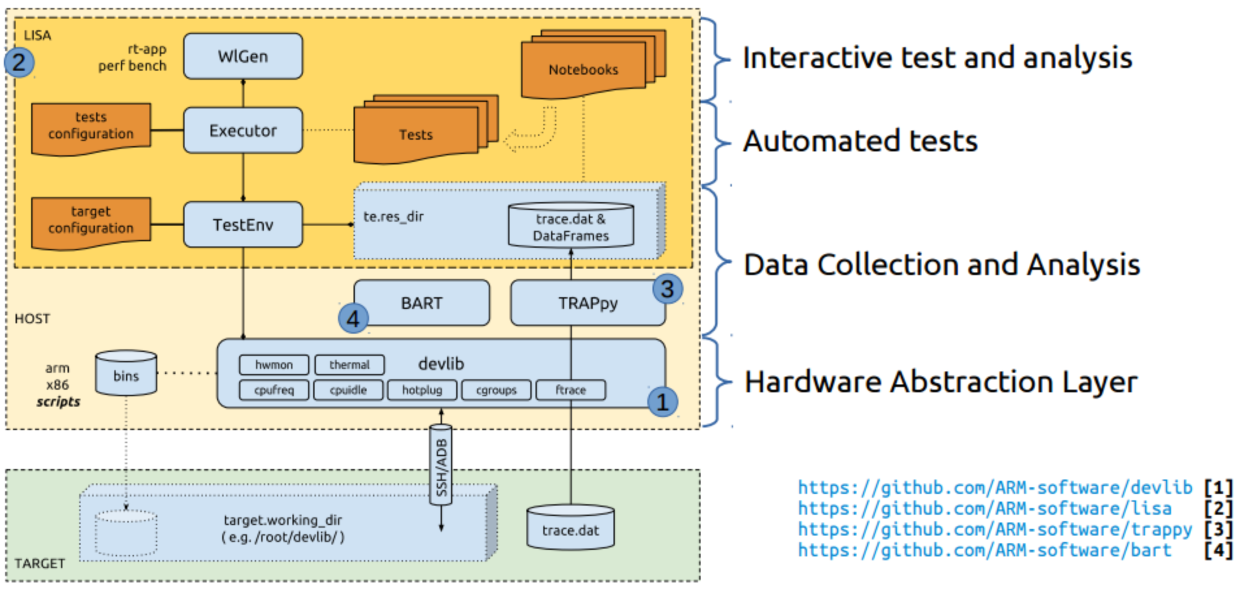


Figure 8 Bird's eye view on the LISA toolkit components

Hardware Abstraction Layer

The devlib library is used to abstract the access to a target device. A device can be either a remote machine, accessed via SSH or ADB, or the local one. The devlib library allows the configuration of an abstract communication channel to send commands to the device as well as exchange files with the device. On top of these basic APIs, devlib also provides a set of convenient libraries to access and control the main subsystems of a Linux based device, e.g.: cpufreq, cpuidle, hotplug, cgroups, ftrace, etc.

An example of the devlib APIs is available at this link:

http://github.com/ARM-software/lisa/blob/master/ipynb/tutorial/02_TestEnvUsage.ipynb

Data Collection and Analysis

A set of libraries are provided for processing collected trace data and for analysing system behaviours.

The TRAPpy library (TRace Analysis and Plotting in Python) provides support for parsing a trace of system events, collected using either ftrace or systrace and converting them into PANDAS dataframes. This conversion gives access to rich PANDAS (http://pandas.pydata.org) APIs for analysis of the collected data.

An example of the TRAPPy APIs is available at this link:

http://github.com/ARM-software/lisa/blob/master/ipynb/tutorial/05_TrappyUsage.ipynb

The BART library (Behavioural Analysis and Regression Toolkit) provides support for analysing system behaviours and assertion based testing for specific behaviours of interest. The API exposed by this library is mainly intended for the development of regression tests.

An example the BART APIs is available in the "Behavioural Analysis" section of this link:

https://github.com/ARM-software/lisa/blob/master/ipynb/tutorial/UseCaseExamples_SchedTuneAnalysis.ipynb

Interactive Test and Analysis

One of the main advantages of LISA is the ability to define a convenient workflow to define new tests and experiments, execute them on multiple targets, process the collected data and share all of these with other developers. This greatly simplifies the reproduction and verification of the results.
This flow is based on (but not limited to) the usage of IPython notebooks as the primary environment where experiments are coded and results produced. An IPython notebook is just an interactive Python shell, running within a browser, which makes it easy to mix code which produces results and additional comments, thus making it a suitable environment to support the "interactive analysis" which LISA is fostering. Notebooks are not only a playground to design and run experiments but they are also a native exchange format which can be both used to share reproducible results or simply to publish an analysis report.

An example usage of the LISA's APIs to perform an interactive analysis is available at this link:

https://github.com/ARM-software/lisa/blob/master/ipynb/tutorial/UseCaseExamples_SchedTuneAnalysis.ipynb

Automated Tests

If needed, notebooks can be easily converted into standalone tests. For this purpose, LISA provides an API which allows the user to encapsulate the code of a notebook into a standard python nosetest class. These tests are useful for example to run regression analyses across different versions and releases of a code base.

A collection of tests. which allows to verify EAS specific features, are available here:

https://github.com/ARM-software/lisa/tree/master/tests/eas

Specifically:

- **preliminary**: checks that the configuration of a given device is suitable for running EAS
- **load_tracking**: checks that the main signals used by EAS are properly tracked and updated
- capacity_capping: Verify that dynamic CPU capacity capping works in the system
- **generic**: checks that some basic EAS scheduling features are working as expected
- heavy_load: Test an EAS system under heavy load

These tests can be executed from within a LISA Shell by:

- properly setup the target.conf file according to the target in use
- running the test with the command:
  [LISAShell lisa] \> lisa-test tests/eas/TEST_NAME.py

For more details on how to verify EAS features refer to section "Verify EAS Functionality"

Android Workloads

A set of Android benchmarks are now supported by the LISA framework which can be executed to collect energy and performance metrics. All the supported tests requires the device to be pre-configured to run a test, which implies for example to install by hand the APK required by the test.

The list of supported Android benchmarks is available at this link:

https://github.com/ARM-software/lisa/tree/master/tests/benchmarks

These benchmarks can be executed from within a LISA Shell by:

- properly setup the target.conf file according to the target in use
- running the benchmark with the command:

```
[LISAShell lisa] \> python tests/benchmarks/BENCHMARK_NAME.py \
                    --android-home /path/to/your/android-sdk \
                    --results-dir RESULTS_FOLDER
```

Each test provides a detailed list of supported configuration parameter which is printed via the "help" option.

7.2 Integrating a board into LISA

A few steps are required to integrate a new board with LISA. First of all, we have to distinguish between what we call a platform and a board in the LISA configuration. A board is the target device intended for analysis; whereas the platform identifies the type of system running on that device. For example, if Linux is running on a Juno development board that is to be experimented with, from the point of view of the LISA configuration, the board is Juno and the platform is Linux

That said, in order to integrate a board, LISA requires the following information in a JSON file:

A board description containing:

- A list of CPU names
- The name of the big core in the system
- An energy model that can be generated later as described in the following section

Refer to the following link for more details on the format of the JSON file:

https://github.com/ARM-software/lisa/wiki/Integrating-a-new-board-in-LISA

Note that currently LISA only supports devices with up to two clusters while designs with more than two clusters are only partially supported (some functionality may not be available).

For energy and power measurements, LISA supports three different energy meters: Linux Hardware Monitors (HWMON), ARM Energy Probe (AEP), BayLibre ACME Cape (ACME). For integrating a new energy meter, please refer to the following Wiki page:

https://github.com/ARM-software/lisa/wiki/Energy-Meters-Requirements

7.3 Building an Energy Model

LISA provides an energy model building feature for platforms where energy can be measured either at cluster level or at system level (for example, battery energy or the CPU's nearest measurement point).

In order to use this feature, the following requirements must be satisfied:

5. The desired energy probe must be integrated with LISA
6. For each cluster that is intended to be profiled, the following information must be provided:
    - cluster name
    - energy probe channel name
    - name of the core in the cluster
    - list of CPU IDs belonging to the cluster
    - list of frequencies available in the cluster
    - list of idle states available in the cluster
7. A mapping between cluster names and cluster Ids used in the kernel must be provided

For a more detailed description of how to use this feature as well as reference examples, please have a look at the notebooks section available in LISA:

https://github.com/ARM-software/lisa/tree/master/ipynb/energy

7.4 Verifying EAS functionality

A set of automated tests for verifying EAS are provided in LISA under the tests/eas/ directory. These tests are not designed as formal acceptance tests: kernel behaviour is inherently non-deterministic and platform variation cannot be fully accounted for. Therefore these tests should be considered a starting point for verification. They can highlight obvious issues but ultimately it is generally necessary to manually inspect trace files, benchmark results, and energy measurements before deciding whether EAS' behaviour is satisfactory. Sometimes the tests may produce failures where a manual inspection shows that behaviour was in fact acceptable. It is therefore recommended to run tests multiple times and consider the *proportion* of pass and fail results. Executing multiple iterations can be specified on the command line by using the '`--iterations`' parameter. A value of 10 iterations is considered a safe minimum for which we generally expect at least an 80% pass rate.

'Generic' EAS tests

The 'generic suite can be run with:

lisa-test tests/eas/generic.py

These tests require data about the platform topology and energy model. LISA is able to extract this information from the target filesystem so long as:

- CONFIG_SCHED_DEBUG is enabled in the kernel, so that /proc/sys/kernel/sched_domain/ exposes the scheduler's topology & energy data.
- The cpufreq and cpuidle devlib modules are enabled by LISA. To ensure this is the case, add “cpufreq” and “cpuidle” to the “modules” field in your target.config.

Goal

Verify energy-aware **task placements**.

Detailed Description

These tests use information about the target platform – namely the CPU topology and energy model – to determine the assertions that are made about scheduler behaviour. They are therefore named 'generic' because they can be used with any target platform, be it big.LITTLE or a different type of topology.

The 'generic' suite uses a set of rt-app synthetic workloads. The workloads are viewed by this suite as consisting of a set of *tasks,* each of which contains a set of *phases*, each phase having a given *duty cycle.* For example one of the workloads (used by the EnergyModelWakeMigration test) consists of two *tasks,* each with four *phases*, where both task has a *duty cycle* of 10% in its first and third phases, and 50% in its second and fourth. This example represents a workload that alternates between providing using 20% and 100% of the maximum compute bandwidth of the system's most capable CPUs. Another example (used by the RampUp test) contains a single task with several phases – the first having a 5% duty cycle, the last having 70%, and the intermediate phases having gradually increasing duty cycles. This represents a workload that increases its compute demand over time – here a “continuous” variation in capacity is modelled by using a set of discrete steps.

Those familiar with rt-app will be aware that this tool can describe many more parameters of a task, in particular its *period*. However **this test suite does not consider the period of a task.** In fact it **doesn't consider at which moment a task wakes up and goes to sleep**, but instead views a task as an abstract consumer of a portion of compute bandwidth, and views the size of this portion as fixed for each of the task's phases.

Using the information about the workload' and the platform data, the tests are able to estimate the amount of energy that the CPUs will use under any given task placement for each phase. Since the tests are aware of the workload parameters, they have advance knowledge of each task's utilisation in a given phase, so this test assumes a perfect load-prediction system (an “oracle” instead of the real scheduler's load-tracker). It further assumes a “perfect” scheduler-driven cpufreq governor that always immediately selects the minimum frequency to satisfy bandwidth requirements. Thus **this suite aims to test energy aware task placement, but not OPP selection**.

For each phase of the workload in question, the test uses this estimation to find the ideal (most energy-efficient) task placement that provides the required bandwidth to all tasks. The workload is run on the target, and a trace captured. The trace is used to find the real task placements that were selected. The energy estimation is repeated for the observed task placements, and compared with estimation for the ideal placements. If the observed task placements were estimated to use at least 5% more energy than the ideal task placement, then a failure is declared.

We have now asserted that the task placement was energy-efficient. However a second test is required to ensure that the placement provided the required bandwidth. Otherwise this test could be passed, for example, when two tasks with 55% duty cycles were placed on a single CPU – this may use less energy than placing them on different CPUs but is clearly undesirable as the tasks will not receive enough bandwidth. A second assertion is therefore required. The rt-app tool's output log is analysed and its 'Slack' measure is used to detect whether the required compute bandwidth was provided.

Thus two types of test failures can result from these tests:

1. **test_task_placement** asserts that the placement was energy efficient. In a big.LITTLE system, if a low-utilisation task was placed on a big CPU then this test should be expected to fail.
2. **test_slack** asserts that the required bandwidth was provided. In a big.LITTLE system if a high-utilization task was placed on a LITTLE CPU then this test should be expected to fail.

Workloads in 'generic' suite

This suite contains a set of sub-tests, each of which contains a single workload for which the task placement test is executed.

- OneSmallTask – a single 20% task lasting 2 seconds.
- ThreeSmallTasks – 3 20% tasks lasting 2 seconds
- TwoBigThreeSmall – 2 70% tasks and 3 10% tasks lasting 2 seconds
- RampUp – A single task ramping from 5% to 70% over 2 seconds
- RampDown – A single task ramping from 70% to 5% over 2 seconds
- EnergyModelWakMigration – Two tasks each alternating between 10% and 50% over 2 seconds, 500ms for each phase.

Users can add additional rt-app workloads to the suite, without needing to write more analysis code, by editing tests/eas/generic.py. The details of how to do so are outside the scope of this document, however.

Expected Behaviour

The workloads are placed onto CPUs in the most energy-efficient way that provides enough compute bandwidth for each task. The details of this expected placement differ from platform to platform and depend on the energy model data.

Capacity capping testing

Similar to the acceptance tests, this test is part of lisa. To run it configure your target in target.config and run:

lisa-test -v tests/eas/capacity_capping.py

Goal

Verify that dynamic CPU capacity capping works in the system.

Detailed Description

The maximum frequency of a core can be restricted to a lower value than its absolute maximum frequency. This may happen because of thermal management or as a request from userspace via sysfs. Dynamic CPU capacity capping provides PELT and the scheduler CPU capacity management with a maximum frequency scaling corrector which describes the influence of running a CPU with a current maximum frequency lower than the absolute maximum frequency.

The test creates as many busy threads as there are big cpus. These busy threads have high load and should run in the CPUs with highest capacity. The test has three phases of equal length. In the first phase, the system runs unconstrained. In the second phase, the maximum frequency of the big cpus is limited to the lowest frequency that the big frequency domain can run at. Finally, in the third phase, the maximum frequency of the big cpus is restored to its absolute maximum, i.e. the system is unconstrained again.

This test assumes that the lowest OPPs of the big cpus have less capacity than the highest OPP of the little cpus. If that is not the case, this test will fail. Arguably, capacity capping is not needed in such a system.

Expected Behaviour

The threads have high load, so they should always run in the CPUs with the highest capacity of the system. In the first phase the system is unconstrained, so they should run on the big CPUs. In the second phase, the big cluster's maximum frequency is limited and the little CPUs have higher capacity. Therefore, in the second phase of the test, the threads should migrate to the little cpus. In the third phase the maximum frequency of the big cpus is restored, so they become again the CPUs with the highest capacity in the system. The busy threads must run on the big cpus in the third phase.

Other EAS-related tests in LISA

LISA now provides some tests that do not directly test EAS, but are intended for diagnosing common problems that could prevent EAS from working.

Load tracking tests

In tests/eas/load_tracking.py are tests for load tracking features that EAS requires.

- **FreqInvarianceTest** runs a single workload multiple times, each time at a different CPU frequency. It collects a trace for each run, and asserts that the scheduler's load_avg and util_avg signals were scaled according to the frequency that the workload ran at.
- **CpuInvarianceTest** runs a single workload multiple times, each time pinned to a CPU of a different type. It collects a trace for each run, and asserts that the scheduler's util_avg signal was scaled according to the capacity of the CPU the workload ran on. The load_avg signal is not CPU invariant so is not tested here. This test is not relevant for symmetric systems.

If these tests fail, EAS may misbehave. The two most likely causes of this problem are

- The CPU capacity data in the EAS energy model, which the scheduler uses to scale load tracking signals, are inaccurate.
- The patches introducing scale invariance to your kernel tree have been wrongly integrated.

Preliminary tests

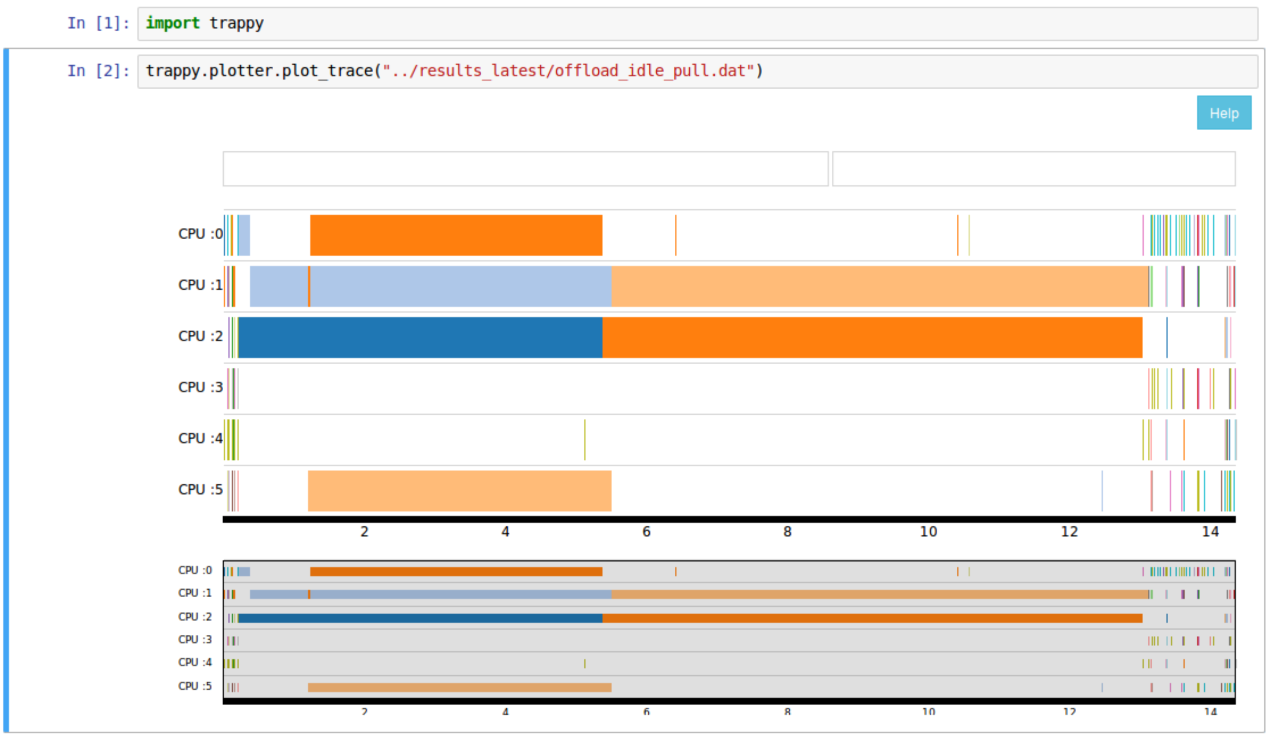
In tests/eas/preliminary.py are tests for checking that certain pre-requisites for the target platform are in place. They are not intended to verify EAS behaviour but rather to highlight areas that may require investigation, in advance of debugging EAS itself.

- **TestSchedGovernor** asserts that the 'sched' or 'schedutil' governor is available on the system. If it fails, this likely means the kernel was configured without these governors, which EAS is designed to work alongside.
- **TestKernelConfig** reads the kernel config from the target and asserts that certain kernel features, which EAS is designed to work with, are enabled.
- **TestWorkThroughput** ensures that cpufreq works as expected. It runs a simple workload multiple times, each at a different frequency, and ensures that it runs faster at higher frequencies. If this test fails, the platform's cpufreq driver may not be working. This will likely result in EAS misbehaving.

Analyze test failures

Fully debugging why a test has failed is outside the scope of this document. However, the first step is usually to plot the trace and have a look at the scheduling decisions. We can do this with trappy using an ipython notebook. For example:

```
import trappy

trace_file = "../results_latest/offload_idle_pull.dat"

trappy.plotter.plot_trace(trace_file)
```



```
In [1]: import trappy
In [2]: trappy.plotter.plot_trace("../results_latest/offload_idle_pull.dat")
```

Figure 9 Lisa example plot

The trace files for the different tests are:

- Fork Migration: fork_migration.dat
- Small Task Packing: small_task_packing.dat
- Offload migration and idle pull: `offload_idle_pull.dat`
- Wake Migration: wake_migration.dat

Evaluate per task behavior

During EAS integration on a new platform a test case might fail due to misbehaviour of one of the test tasks. This misbehaviour is normally characterized by an unexpected task migration during the test run, i.e. there are occurrences in which the test task is not scheduled on the designated cpu core type.

To be able to analyse during trace file post processing which scheduler core path (e.g. EAS wakeup or periodic load balance) led to this misbehaviour `CONFIG_SCHED_DEBUG_EAS_MIGRATION` can be enabled so that the migration cause is additionally provided with `each sched_migrate_task` trace event:

```
ksoftirqd/1-17 [001] 49.672428: sched_migrate_task: comm=usb-
storage pid=1048 prio=120 orig_cpu=1 dest_cpu=2
cause=select_idle_sibling:idle_cpu
```

```
ksoftirqd/1-17 [001] 49.685420: sched_migrate_task: comm=bash
pid=2074 prio=120 orig_cpu=1 dest_cpu=2
cause=select_idle_sibling:default
```

```
hackbench-2074  [002] 49.697317: sched_migrate_task:
comm=hackbench pid=2112 prio=120 orig_cpu=5 dest_cpu=2
cause=select_task_rq_fair:find_idlest_group/cpu
```

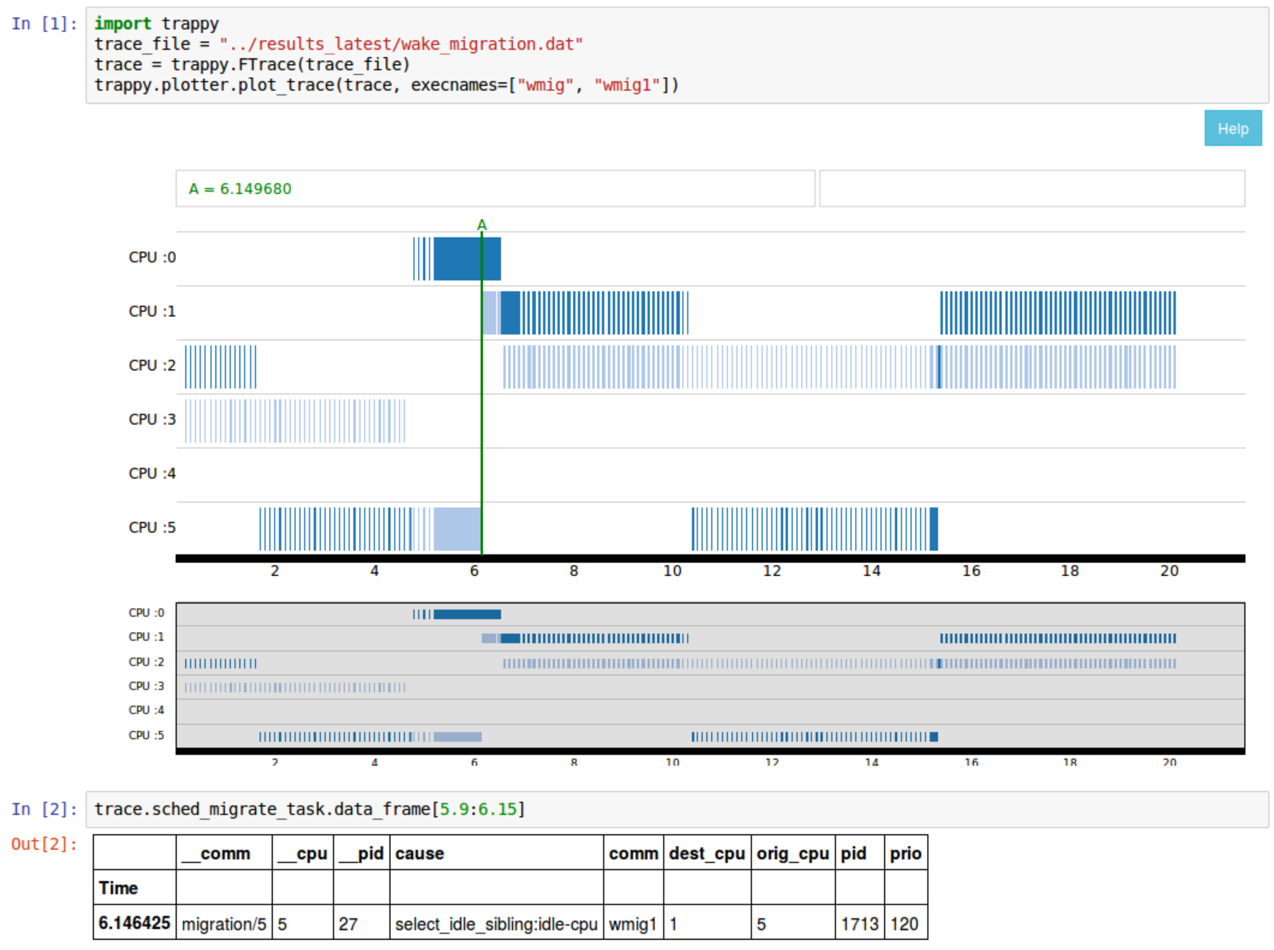
The set of individual task migration causes is defined in `include/trace/events/sched.h`.

You can visualize the events by using trappy in an ipython notebook. For example, if we want to analyse the result of the wake migration test we would do:

```
import trappy

trace_file = "../results_latest/wake_migration.dat"

trace = trappy.FTrace(trace_file)

trappy.plotter.plot_trace(trace, execnames=["wmig", "wmig1"])
```

This plot shows the scheduling decisions for the two tasks that comprise the test in this platform: `wmig` and `wmig1`. If we want to know the reason behind, for example, the migration in cycle 6.039334, we can do so by showing the events that happened around that time with this code:

```
trace.sched_migrate_task.data_frame[5.9:6.15]
```



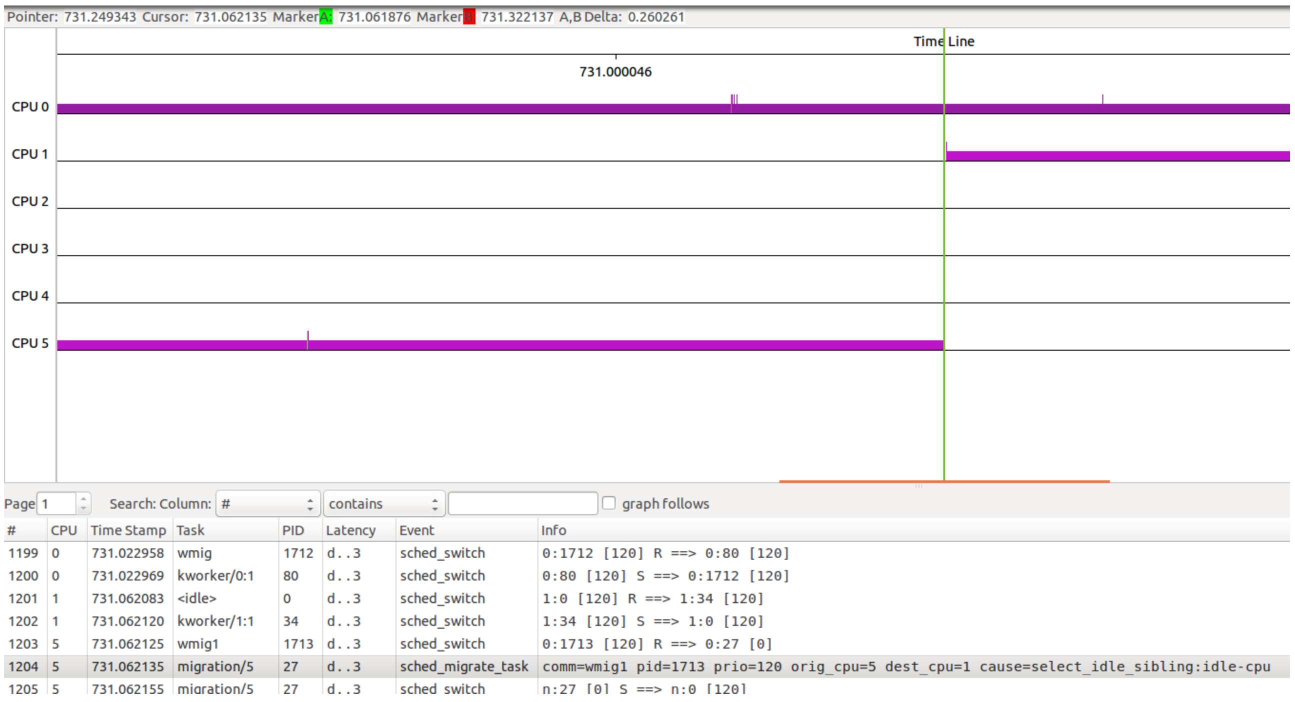
```
In [1]: import trappy
        trace_file = "../results_latest/wake_migration.dat"
        trace = trappy.FTrace(trace_file)
        trappy.plotter.plot_trace(trace, execnames=["wmig", "wmig1"])
```

```
In [2]: trace.sched_migrate_task.data_frame[5.9:6.15]
```

Out[2]:

	__comm	__cpu	__pid	cause	comm	dest_cpu	orig_cpu	pid	prio
Time									
6.146425	migration/5	5	27	select_idle_sibling:idle-cpu	wmig1	1	5	1713	120

Figure 10 Ipython notebook example plot



Pointer: 731.249343 Cursor: 731.062135 MarkerA: 731.061876 MarkerB: 731.322137 A,B Delta: 0.260261

Page 1 Search: Column: # contains graph follows

```
#     CPU  Time Stamp   Task          PID   Latency  Event               Info
1199  0    731.022958   wmig          1712  d..3     sched_switch        0:1712 [120] R ==> 0:80 [120]
1200  0    731.022969   kworker/0:1   80    d..3     sched_switch        0:80 [120] S ==> 0:1712 [120]
1201  1    731.062083   <idle>        0     d..3     sched_switch        1:0 [120] R ==> 1:34 [120]
1202  1    731.062120   kworker/1:1   34    d..3     sched_switch        1:34 [120] S ==> 1:0 [120]
1203  5    731.062125   wmig1         1713  d..3     sched_switch        0:1713 [120] R ==> 0:27 [0]
1204  5    731.062135   migration/5   27    d..3     sched_migrate_task  comm=wmig1 pid=1713 prio=120 orig_cpu=5 dest_cpu=1 cause=select_idle_sibling:idle-cpu
1205  5    731.062155   migration/5   27    d..3     sched_switch        n:27 [0] S ==> n:0 [120]
```

Figure 11 Analysis within kernelshark

7.5 EAS test coverage

EASr1.2

This early software release has been has been tested using synthetics (only) on Juno r2, prior to more platform testing.

Note due to the non-deterministic nature of the Linux scheduler, behavioural test results cannot be guaranteed.

Workload	Result
Generic (task placement) tests	
OneSmallTask	PASS – less reliable
ThreeSmallTasks	PASS – less reliable
TwoBigTasks	PASS – less reliable
TwoBigThreeSmall	PASS – less reliable
RampUp	PASS – less reliable
RampDown	PASS – less reliable
EnergyModelWakeMigration	PASS – less reliable
heavy_load	FAIL
capacity_capping	PASS – less reliable
load_tracking	
CpuInvarianceTest	PASS
FreqInvarianceTest	PASS

EASr1.3 device testing

EASr1.3 is in use on a device with big.LITTLE hardware based upon an android-4.4 kernel however we cannot disclose any information about the device or partner involved. We have also tested this release using Juno and Hikey960, results of which are recorded below.

EASr1.3 android-4.4 on Juno

Workload	Result
Generic (task placement) tests	
OneSmallTask	PASS (50%)*
ThreeSmallTasks	PASS (90%)
TwoBigTasks	PASS (100%)
TwoBigThreeSmall	PASS (80%)
RampUp	PASS (100%)
RampDown	PASS (100%)
EnergyModelWakeMigration	PASS (80%)
heavy_load	
TaskSpread	PASS (80%)
capacity_capping	FAIL (0/1)*
load_tracking	
CpuInvarianceTest	PASS (100%)
FreqInvarianceTest	PASS (100%)

* Known issue: Juno platform cannot always change frequency when asked – not related to EAS.

EASr1.3 android-4.9 on Juno

Workload	Result
Generic (task placement) tests	
OneSmallTask	PASS (100%)
ThreeSmallTasks	PASS (100%)
TwoBigTasks	PASS (100%)
TwoBigThreeSmall	PASS (100%)
RampUp	PASS (100%)
RampDown	PASS (100%)
EnergyModelWakeMigration	PASS (100%)
heavy_load	PASS (90%)
capacity_capping	PASS (1/1)
load_tracking	
CpuInvarianceTest	PASS (100%)
FreqInvarianceTest	PASS (100%)

EASr1.3 android-4.4 on Hikey960

Workload	Result
Generic (task placement) tests	
OneSmallTask	PASS (100%)
ThreeSmallTasks	PASS (80%)
TwoBigTasks	PASS (100%)
TwoBigThreeSmall	PASS (90%)
RampUp	PASS (100%)
RampDown	PASS (100%)
EnergyModelWakeMigration	PASS (50%)*
heavy_load	
capacity_capping	
load_tracking	
CpuInvarianceTest	
FreqInvarianceTest	

* Under investigation – work on Hikey960 Energy model is not complete yet.

8 Glossary

Scheduling Entity

A scheduling entity (`struct sched_entity`) describes the unit which can be scheduled by the task scheduler. It can represent a task as well as a task group.

Task Group

A task group (`struct task_struct`) is an abstraction for a group of tasks which is represented by a single scheduling entity. The scheduler normally operates on tasks but in certain configurations it may be desirable to group tasks and provide fair CPU time to each such task group rather than to each individual task.

Scheduling Domain

A scheduling domain (`struct sched_domain`) is a set of CPUs which share properties and scheduling policies and which can be balanced against each other. Scheduling domains are hierarchical. A multi-level system will have multiple levels of domains.

E.g. the multi-cluster level (`MC` level) contains all the cpus belonging to a certain cluster whereas the physical processor level (`DIE` level) spans all the cpus of the processor.

Scheduling Group

Each scheduling domain contains two or more scheduling groups (`struct sched_group`) which are treated as a single unit by the scheduling domain. When the scheduler tries to balance the load within a scheduling domain, it tries to even out the load carried by each scheduling group without worrying directly about what is happening within the scheduling group.

Frequency Invariance

Frequency invariance makes the load and utilization signal of Per-Entity Load-Tracking (PELT) aware of CPU frequency scaling.

Without frequency invariance a task with 25% load on a CPU operating at 100% of its maximum frequency would change its load to 50% in case the frequency decreases to 50% of the maximum frequency. With frequency invariance the load of the task remains 25% regardless of the CPU frequency. The same is true for the utilization signal.

CPU Invariance

CPU invariance makes the utilization signal of Per-Entity Load-Tracking (PELT) and task scheduler CPU capacity management aware of CPU micro-architectural differences and/or differences in the maximum frequency supported by the CPUs.

Without CPU invariance a task with 25% utilization on a CPU with a capacity of 100% of the system-wide maximum CPU capacity would change its utilization to 50% in case it migrates to a CPU with a capacity of 50% of the system-wide maximum CPU capacity. With CPU Invariance the utilization of the task remains 25% regardless of the CPU the task is running on.

Utilization

The utilization of a scheduling entity is the amount of time the scheduling entity is running on a cpu over an elapsed period of time.

Load

The load of a scheduling entity is the amount of time the scheduling entity is ready to run on a CPU (i.e. it is runnable) multiplied by its weight (e.g. the weight of a task is its priority) over an elapsed period of time.

Spreading

The goal of the CFS task scheduler on an SMP platform is to distribute (hence to spread) work evenly across all available CPUs to guarantee maximum performance and minimum latency. This behaviour is characteristic for a work-conserving scheduler which tries to keep all scheduled resources busy as long as there are scheduling entities ready to be scheduled.

Packing

The goal of the EAS enhancement of the CFS task scheduler on an SMP platform is to maximize the power efficiency without harming the overall system throughput. EAS tries to distribute scheduling entities on the smallest number of suitable CPUs (hence to pack) while still meeting their compute requirements. This allows the power management subsystems to potentially save energy by turning off unused parts of the processor.

9 Appendix

9.1 Example DTS file

```
cpus {
     #address-cells = <2>;
     #size-cells = <0>;
     .
     .
     .
     A57_0: cpu@0 {
          compatible = "arm,cortex-a57","arm,armv8";
          reg = <0x0 0x0>;
          device_type = "cpu";
          enable-method = "psci";
          next-level-cache = <&A57_L2>;
          clocks = <&scpi_dvfs 0>;
          cpu-idle-states = <&CPU_SLEEP_0 &CLUSTER_SLEEP_0>;
          sched-energy-costs = <&CPU_COST_0 &CLUSTER_COST_0>;
     };
     A57_1: cpu@1 {
          compatible = "arm,cortex-a57","arm,armv8";
          reg = <0x0 0x1>;
          device_type = "cpu";
          enable-method = "psci";
          next-level-cache = <&A57_L2>;
          clocks = <&scpi_dvfs 0>;
          cpu-idle-states = <&CPU_SLEEP_0 &CLUSTER_SLEEP_0>;
          sched-energy-costs = <&CPU_COST_0 &CLUSTER_COST_0>;
     };
```

```
A53_0: cpu@100 {
        compatible = "arm,cortex-a53","arm,armv8";
        reg = <0x0 0x100>;
        device_type = "cpu";
        enable-method = "psci";
        next-level-cache = <&A53_L2>;
        clocks = <&scpi_dvfs 1>;
        cpu-idle-states = <&CPU_SLEEP_0 &CLUSTER_SLEEP_0>;
        sched-energy-costs = <&CPU_COST_1 &CLUSTER_COST_1>;
};
A53_1: cpu@101 {
        compatible = "arm,cortex-a53","arm,armv8";
        reg = <0x0 0x101>;
        device_type = "cpu";
        enable-method = "psci";
        next-level-cache = <&A53_L2>;
        clocks = <&scpi_dvfs 1>;
        cpu-idle-states = <&CPU_SLEEP_0 &CLUSTER_SLEEP_0>;
        sched-energy-costs = <&CPU_COST_1 &CLUSTER_COST_1>;
};
energy-costs {
        CPU_COST_0: core-cost0 {
                busy-cost-data = <
                        417   168
                        579   251
                        744   359
                        883   479
                        1024  616
                >;
        idle-cost-data = <
            15
            0
        >;
    };
    CPU_COST_1: core-cost1 {
        busy-cost-data = <
            235 33
            302 46
            368 61
            406 76
            447 93
        >;
        idle-cost-data = <
            6
            0
        >;
    };
    CLUSTER_COST_0: cluster-cost0 {
        busy-cost-data = <
            417   24
            579   32
            744   43
            883   49
            1024  64
        >;
        idle-cost-data = <
            65
            24
```

```
                >;
            };
            CLUSTER_COST_1: cluster-cost1 {
                busy-cost-data = <
                    235 26
                    303 30
                    368 39
                    406 47
                    447 57
                >;
                idle-cost-data = <
                    56
                    17
                >;
            };
        };
    };
```

The first CPU node in the example above labelled `A57_0: cpu&0` represents a Cortex-A57 CPU and follows standard conventions as described in the traditional CPU bindings document. A new property called `sched-energy-costs'` is introduced which is a list of phandles to cost nodes. The order of phandles in the list is significant. The first phandle is to the current processing element's own cost node. Subsequent phandles are to higher hierarchical level cost nodes up until the maximum level that EAS is to service. All cpu nodes must have the same highest level cost node. The phandle list must not be sparsely populated with handles to non-contiguous hierarchical levels.

In the example above, the Cortex-A57's `sched-energy-costs` node lists phandles labelled `'&CPU_COST_0'` and `'&CLUSTER_COST_0'`. Following the convention described in the previous paragraph, this is an ordered list with the first element being a phandle to a `cost` node that describes costing data for Cortex-A57 CPUs. The second element in the list is a phandle to a cost node that describes costing data for a cluster of Cortex-A57 CPUs.

Cost nodes are children of a special `energy-costs` parent node. Cost nodes contain two properties: a `busy-cost-data` property and an `idle-cost-data` property. These describe the previously introduced busy costs and idle costs. A `busy-cost-data` property is an array of 2-item tuples, each of type u32. The first item in the tuple is a capacity value and the second item in the tuple is the energy cost value associated with that capacity. An `idle-cost-data` property is an array of 1-item tuples, each of type u32. The item in the tuple is the energy cost value associated with the idle state the item refers to.

The scheduler has been suitably extended to process the relevant portions of the FDT and extract the costing data. The data is then supplied to the EAS core code for further processing as described in the next section.

For a detailed specification of the bindings referred to here, see: `Documentation/devicetree/bindings/scheduler/sched-energy-costs.txt`.