Heterogeneous Scheduler

Scheduling support for heterogeneous hardware accelerators under linux[1]

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Abstract

During these days, computers are more often provided with dedicated graphic cards. Modern GPUs are designed to exploit an high level of parallelism and compared to a standard CPU are faster (sometimes more than 10X) and more expensive. A common user, that is not either playing or doing some graphic tasks, use the 10% of GPUs computational capacity. The main goal of this project is to fix, deploy and test an heterogeneous scheduler that allows linux to use both CPUs and GPUs at the same time. The implementation of this scheduler is in both kernel and user space and allows the tasks migration using the cuda libraries.

Introduction

Since the producers of GPUs has released the first version of API to program directly those components, researchers and industries has started to produce hybrid solution of scheduler. The main goal of these solutions is the performance improvement. What is analyzed in this project is a system that use the CUDA API[2] provided by NVIDIA and the linux kernel to create a huge scheduler being able to migrate tasks between GPUs/CPUs and viceversa. This report is organized in such a way that the first part provides an high level description of the architecture concepts (Partially taken by [3]). The second describes how this concepts has been implemented. The third figures out step by step the installation phases. The fourth is reserved to the testapplication.

1 Architecture concepts

1.1 Heterogeneous system definition and problems

The scheduling concepts presented in this project are based on heterogeneous systems that are those systems where there are non-uniform computing unit which include single- or multi-core CPUs operating in SMP mode and an arbitrary combination of additional hardware accelerators such as GPUs, DSPs or FPGA. Scheduling such systems is more difficult due to several reasons:
1) In general accelerator doesn't have shared memory space with CPU cores so every time two processes that are running on different computational unit, one on CPU and one on an accelerator, has to share some piece of data they are obligated to trasfer the information. The scheduler, in this case, has to consider the transfer time between them. These overheads have to be known and used as input for a scheduling decision in heterogeneous systems. Futhermore this problem introduces a course granularity in the scheduling due to the non-uniformity of communication bandwith between components, latency and performance characteristics.
2) Most accelerator architectures do not support preeption but assume a run-to-completion execution model. While computations on CPU cores can be easily preempted and resumed by reading and restoring well defined internal registers, most hardware accelerators do no even expose the complete internal state nor are they designed to be interrupted.
3) Heterogeneous computing resources have completely different architectures and ISAs. Hence, a dedicated binary is required for each combination of task and accelerator which prevents migrating tasks between arbitrary compute units. Even if a task with the same functionality is avaiable for several architectures and if the internal state of the architecture is accessible, misgrating a task between different architectures is far from trivial, because the represetnation and interpretation of state is completely different.

1.2 Design decisions

During the implementation phase some decision have been taken to design the framework.

The first was about the **Scheduler Component**:

Scheduling of homogeneous CPU cores is currently done in the kernel, as all needed input information for the scheduling decision is avaiable to the system, so that the scheduling problem can be completely hidden from the application programmer. The heterogeneous scheduling problem is more complicated, as more decision parameters affect the decision, which are partly not avaiable to the systems scheduler component.
Selecting an appropriate hardware architecture for a task to be scheduled dynamically at runtime is not trivial and has to be performed by a scheduler, which can be located at different locantions in the system, either in the application, in user space or in the system's kernel.
To allow a holistic view on the applications and its execution environment, the authors perform scheduling in the system's kernel by extending the CF scheduler. That way the scheduling principles are still hidden from the application developer and the OS can perform global decisions based on the system utilization. Application specific scheduling inputs still have to be provided by the application developer to incorporate application's needs. Therefore we use a hybrid user/kernel level approach to perform heterogeneous scheduling. A specific interface has to be provided to allow communication between application and scheduler.
The second was about the **Operating System Adapting**: Kernel space scheduling is the current standard in operating systems. To provide support for heterogeneous architectures one could either extend an existing OS or completely rewrite and fully optimize it towards the heterogeneity. While heterogenous systems will be more and more used in future and become standard in a foreseeable time, the authors believe that a complete rewrite of OS is not needed. An extension to the current system has several advantages: Providing a modular implemented extension to the CFS 1) keeps the management structures as well as the scheduler component exchangeable, 2) makes the changes easily applicable to other OS, and 3) reuses well established and well known functionalities of the current kernel that have been developed over years. That way authors kernel extension will help to explore new directions for future OS, but does not yet try to set a new standard.
The third decision was about **Delegate Threads**: Tasks that execute on heterogeneous resources may have no access to main memory and use a completely different instruction set or execution model than an equivalent task on a CPU. In order to schedule and manage these tasks whitout requiring a major OS rewrite, authors need to expose the tasks to the OS as known schedulable entities. Authors therefore represent each task executing on a hardware accelerator as a thread to the OS. This allows the authors to use and extend the existing data structures of the scheduler in the linux kernel. Authors denote each thread representing a task on a hardware accelerators as delegate thread.
Apart from serving as a schedulable entity, the delegate thread also performs all operating system interaction and managment operations on behalf of the task executing on the accelerator unit, such as trasferring data to and from the compute unit and controlling its configuration and execution. The delegate threads must be spawned explicitly by the application and thus can also be used for co-scheduling on different architectures. Once created, all threads are treated and scheduled equally by the operating system.
As a forth decision there is the **Cooperative Multitasking**: The CFS implements preemptive multitasking with time-sharing based on a fairness measure. Therefore, the authors scheduler has to include means to preempt a task and to migrate it to another computing unit. While non-voluntary preemption on FPGAs is possible, GPUs currently do not directly support it yet, even if it is planned for the future. Therefore authors use the delegate threads to forward requests from the kernel scheduler to the task on the accelerator. Nevertheless, even enabling preemption on GPUs does not solve the migration problem. The major difficulty is to find a way of mapping the current state of a compute unit to an equivalent state on a different compute unit. To allow preemption and subsequent migration of applications on heterogeneous systems, their delegate threads need to be in a state, which can be interpreted by other accelerators or by the CPU. As it is no possible to interrupt an accelerator at an arbitrary point of time and to assume that it is in such a state, the authors propose to use a cooperative multitasking approach using checkpoints to resolve these limitations. After reaching a checkpoint, an application voluntarily hands back the control to the OS, which then may perform scheduling decisions to suspend and migrate a thread at these points. The authors believe that this currently is the only way to simulate preemptive multitasking on heterogeneous hardware.

1.3 Scheduling Model

From the design decisions above the authors derive their scheduling model that is not restricted to a certain class of operating systems or scheduling algorithms. Applications using the scheduler may spawn several threads that may possibly run on diverse architectures. Thread information: As the scheduler needs information about the threads to be scheduled, the authors store this application provided information called meta information about each thread and submit it to the scheduler. The meta information can be individually set for an application. Currently the authors only use a type affinity towards a target architecture which can be determined dynamically depending on the input data.

Further application specific input data can possibly be determined using profiling prior to the first use of an application.
Scheduling: The scheduler component may be located in the kernel space as well as the user space. To assign tasks to certain hardware components, the scheduler has to provide a queue for each available hardware. The application provided meta information is used in a scheduling policy to map newly arriving tasks to one of the queues. Whenever a compute unit runs indle or the currently running task has used its complete time slice, the scheduler may dequeue a waiting task for that specific compute unit. In case this is a hardware task, the delegate thread receives the information that it may run its hardware counterpart. This includes using the proprietary drivers of the hardware, which are inevitable for the communication with some accelerators. As these currently may only be used from used space, this requires a combined approach using the kernel space and the user space. For CPUs, the standard Linux scheduler is used.
Checkpointing: Checkpointing has to be performed when the application can safely interrupt its execution and store its state in main memory. The state has to be stored by the application itself in data structures of the corresponding delegate thread, which then can be migrated to a different architecture. The checkpoint data of the delegate thread thus has to be readable by all target architectures. The Authors define a checkpoint as a struct of data structures that unambiguosisly defines the state of the application. The scheduler does not have any requirements concerning the checkpoint data. Hence, the application has to make sure that all needed data is available in these data structures and thus stored in accessible memory at the end of each thread's time slice. A checkpoint in most cases is a combination of 1) a set of data structures that define a minimum state that is reached several times during execution, and 2) a data structure that define the position in the code. The checkpoint data of an application is copied to the newly allocated accelerator and copied back to the host's main memory when the application's time slice is exhausted. Checkpoints are to be defined by the application developer or to be inserted by a compiler. One has to identify a preferably small set of data structures that 1) unambiguously define the state of a thread, and 2) are readable and translatable to corresponding data structures of other compute units. The size of checkpoints may vary to a large extend depending on the application used. While MD5[4][5] cracking only needs to store the current loop index and the given search-string, image processing algoritms require to store the complete intermediate results that might be of large extent. In general, a checkpoint could be simply defined by a list of already processed data sets. Therefore, the choice of the checkpoint is very important and influences the scheduling granularity. The checkpoint distance, i.e., the amount of work done between 2 checkpoints stored back, increases with the size of the checkpoint. We here assume all checkpoints to be small enough to fit into the host's memory. The introduced checkpoint size is known at definition time and may be used to re-determine the scheduling granularity for a task.

2 Implementation

2.1 Kernel space modification

The creation of the scheduler partially has been done inside the kernel where have been modified components related to the CFS scheduler.

A)Data Structures
Following the goal to extend the current Linux scheduler, we have to make the kernel aware of existing heterogeneous hardware accelerators. The CFS uses its queue and statistics to ensure a fair treatment of all tasks with respect to their priorities. Its queue is ordered by the amount of unfairness, i.e., the time the task would have to execute undisturbed to be treated fair. We extend the kernel with a specific task struct for hardware threads and a semaphore protected queue for each of the available accelerators. The current implementation of the meta information in cludes the memory size to be copied and an array of type affinities. The higher a task's affinity to a compute unit is, the better is the estimated performance on this compute unit.

B)Scheduler API

With respect to the cooperative use of the scheduler, we provide an interface to the scheduler, which enables user space applications to request (allocate), rerequest and free compute units. The allocation call requests and acquires that compute unit, which matches the calling task best by enqueueing the task to the associated waiting queue. The assignment is done using an affinity-based approach, where the given affinity, as well as the current length of the waiting queues and the load of the compute units are included. Our CFS extension allows the migration of threads from one compute unit to another if the application provides implementations for both. Migration of a thread may be performed while it is blocked within a waiting queue or even if it is running on any of the available compute units. Since there are no means of directly migrating the tasks from one instruction set to another, migration is achieved by a combination of checkpointing and cooperative multitasking. If the program reaches a checkpoint, it requests (re-requests) to further use the compute unit, but offers to voluntarily release it (also compare Figure 2). The scheduler decides if the task on the compute unit should be replaced by another, which depends on the type of compute unit and on the cost of switching the task. Re-requests inside the time window of an accelerator-specific granularity are always successful and will only be denied after the granularity has expired and if other tasks are waiting for the resource. The time a task may run on an accelerator follows the CFS approach. It is the sum of the fairness delta, i.e., the time to compute until the (negative) unfairness is equalized, and the granularity, i.e., the "positive unfairness" for this task. To enable dynamic load balancing on CPU cores and GPUs, a load balancing component managing running and queued tasks was introduced. If the application has either finished its work or unsuccessfully re-requested its compute unit, it calls a free function. This releases the compute units semaphore and hands it to the next task or, in case no other tasks are waiting on this device, invokes the load balancer.

C) Control API

Using most of todays hardware accelerators involves using their proprietary user space APIs to copy code or data to and from the device and to invoke programs on it. Since there are virtually no implementations to communicate efficiently with these devices from the kernel, the extension leaves all interaction with the accelerators to the **user space**. It provides system calls to add a compute unit, to remove it afterwards, to iterate through all currently added units and to alter a device after it has been added.

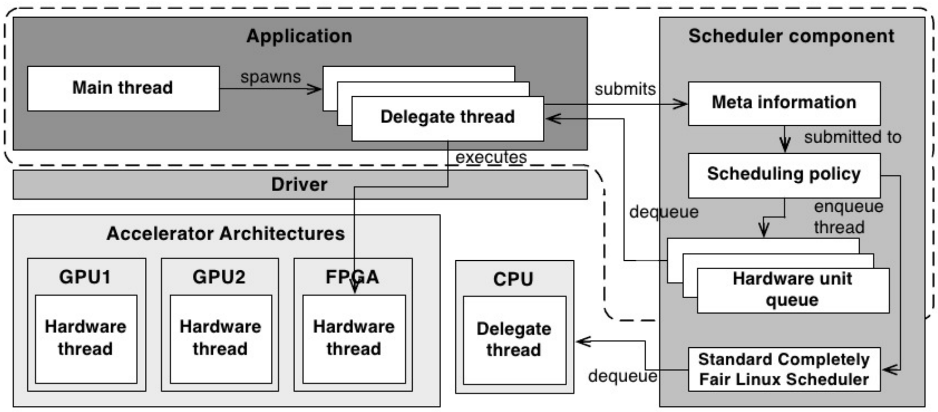


Figure 1: Novel scheduling model for heterogeneous systems. New part are sorrounded by dashed lines

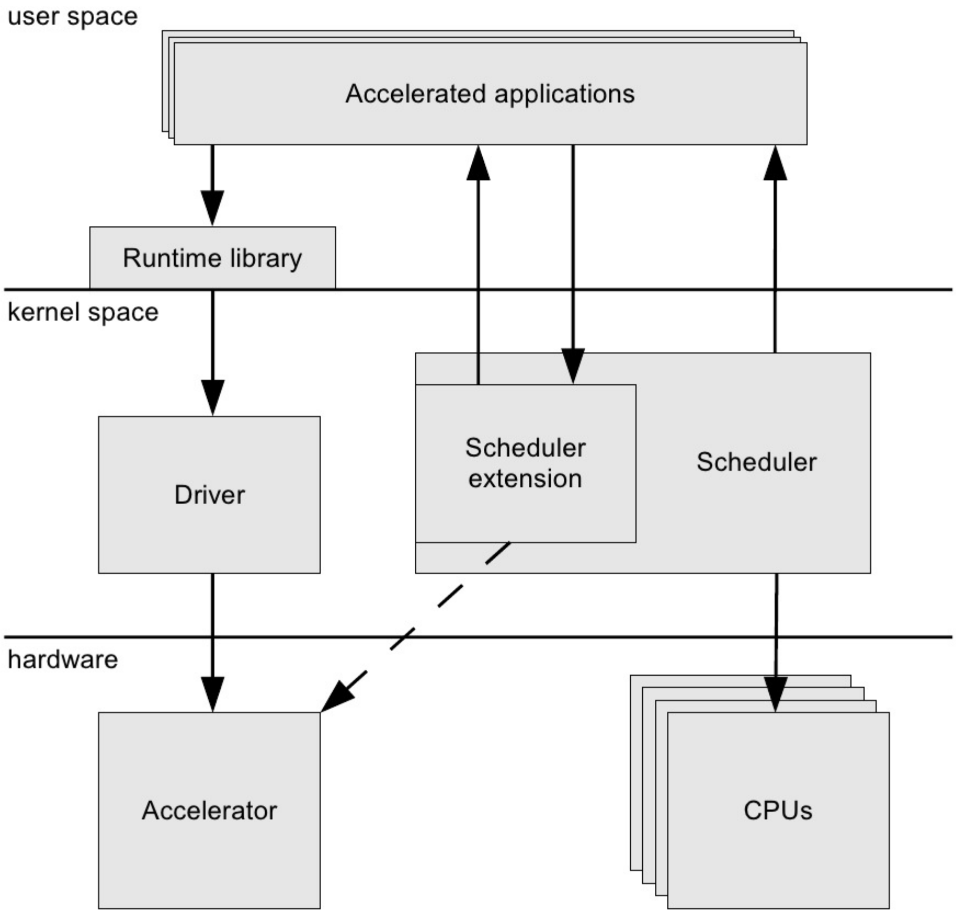


Figure 2: Schema of the architecture implemented

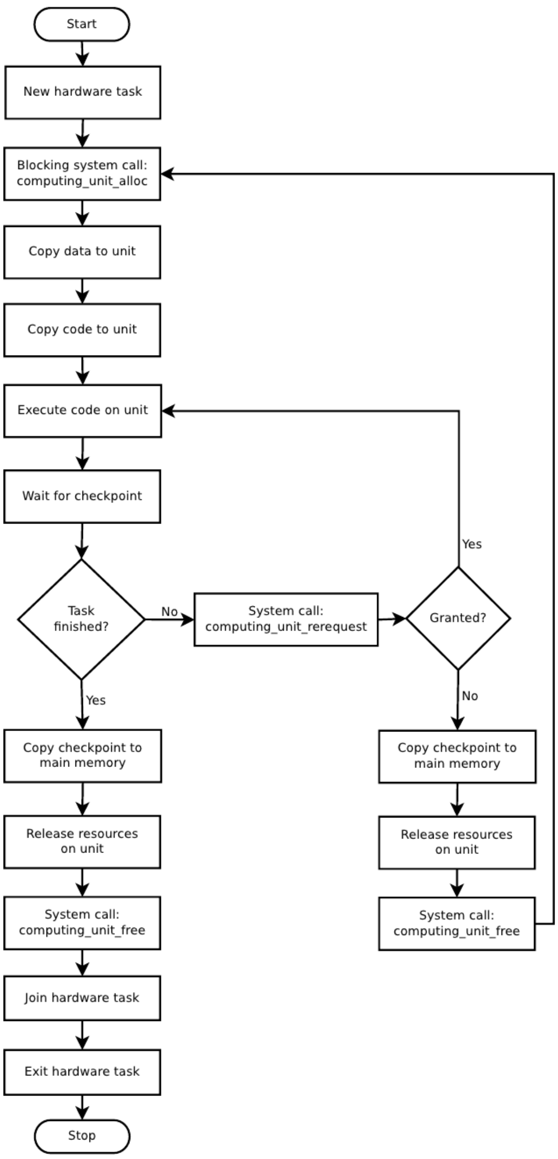


Figure 3: flowchart of the execution for each process

3 Installation Guide [6]

In this section we will see which steps are needed to setup our linux box to support accelerators. I will describe where take the files useful to the installation and which components have to be setuped. The authors released the code and the documentation on a github repository but during my setup I noticed that the code was not correct and it didn't compile. I requested to them a working patch for the kernel and I fixed the bug in the testapplication provided. I will give you all the links to the fixed version in the following subsections.

3.1 OS and drivers installation

Before everything, we have to install the OS. During my project I decided to test it on Gentoo linux 32 bit. I had problems with it because NVIDIA doesn't release official drivers for that specific distro and the drivers provided by the gentoo developers did not work properely to this kind of application. So I decided to move everything on the Operating System used by the authors. This hybrid scheduler has been built on a Ubuntu 10.04.4 LTS. You can download the ISO image from the following link:
Ubuntu ISO Image.
Either burn it on a cd-rom (using eg. k3b, brazero) or create a bootable pendrive (look at this guide FromUSBStick).
Install the Ubuntu distro on a either a laptop or a PC where is plugged in an accelerators (in our specific case an NVIDIA graphics card) To do so look at the Ubuntu 10.04 Installation Guide.
Ubuntu as default installs non-proprietary drivers

(nouveou) that don't allow to program the graphic card. We have to remove them and install the proprietary driver provided from nvidia.

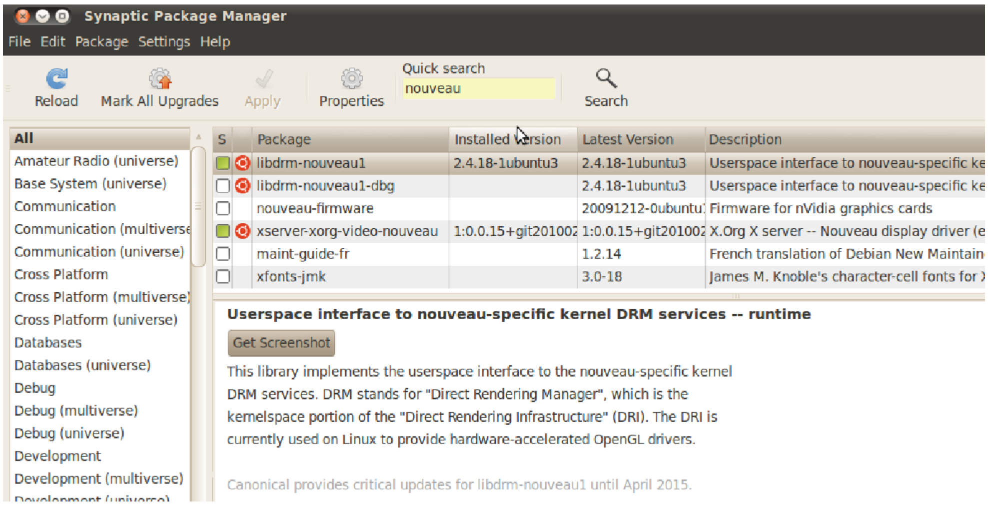


Figure 4: Disinstalling nouveou driver (nouveau-firmware package) using the Synaptic Packege Manager

This scheduler has been developed in 2010 when the driver version was 3.1. I tried to use it with the most recent 5.0 but given a possible change to the APIs it returns a runtime error. The driver that I used are downloadable from NVIDIA dev-driver 3.1.
To install it run in a terminal as root the commands (NB the X server has to be shutted down)

```
#chmod u+rx devdriver_3.1_linux*.run
#./devdriver_3.1_linux_32_256.40.run
```

The second step to have our cuda framework working is to install the NVIDIA SDK.
The commands to install it are:

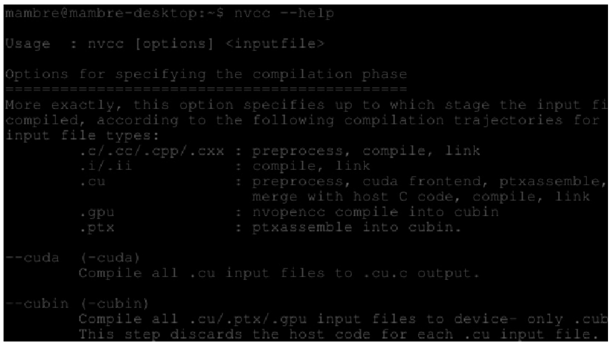
```
#chmod u+rx gpucomputingsdk*.run
#./gpucomputingsdk_3.1_linux.run
```

Are useful but not necessarily the toolkits provided by nvidia, downloadable from Toolkits.
As before to install the toolkits run the commands:

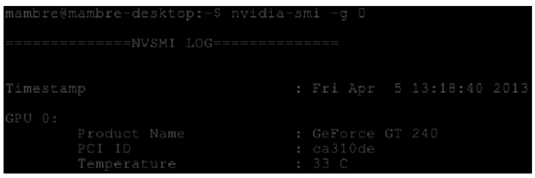
```
#chmod u+rx cudatoolkit_3.1*.run
#./cudatoolkit_3.1*.run
```

We can use the following commands to check if the drivers and the tools are correctly installed:

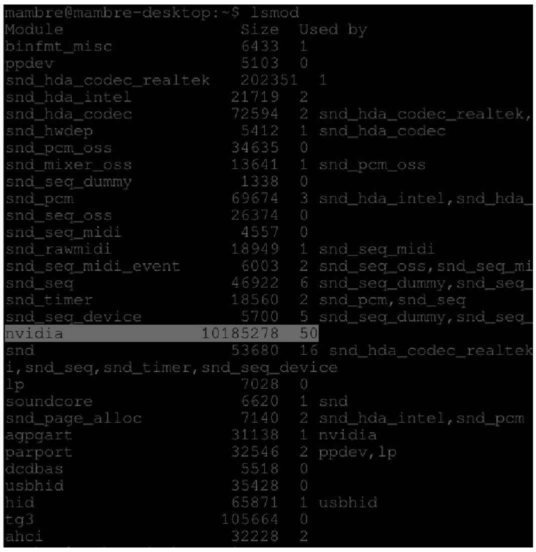
- **nvcc** is the most important tool. It's the NVIDIA compiler for cuda.



- **nvidia-smi** allow us to see which graphic units are installed on our machine.



- **lsmod** program let us know if the kernel module 'nvidia' is loaded and used by the linux kernel.



3.2 Kernel download and patching [7]

Now that we have the OS properely installed and configured we have to download the kernel
Either we download the tar.gz of the right version (2.6.32.57, skip the first list of commands look at only the patch) or we clone the kernel git repository running the following commands (The hardest way):

```
#cd /usr/src/
#git clone git://git.kernel.org/pub/scm/linux
    /kernel/git/stable/linux-stable.git
    linux-stable
#git checkout v2.6.32.57
#rm /usr/src/linux && ln -s /usr/src/linux-
    stable /usr/src/linux
```

With the last command above we move our history at the tag of the right version for the patch provided by the author. Now we have to download in the /usr/src/linux-stable/ folder the patch. Use this link to retrive the patch The command below apply the patch to the kernel:

```
#patch -p1 < kss_2.6.32.57.patch
```

We have done with the hardest way to do that. I have already done all those things and are stored in my github repo so easily you can choose to clone my repo with the patch already applied:

```
#cd /usr/src/
#git clone https://github.com/m4mbr3/
    RTOS_kernel.git linux-patched
#rm /usr/src/linux && ln -s /usr/src/linux-
    patched /usr/src/linux
```

3.3 Kernel setting, compilation and installation

In this phase we have the kernel correctly installed but it is not configured. I have copied the .config file precreated by ubuntu. It is general with all the most common modules. If you want to create your own kernel config file run:

```
#make menuconfig
```

Select all the components of your machine. Save it. Before 'make' starts to compile it asks you to set some variables releated to the extension. It asks to set the following parameters:

```
1) CU_HW_QUEUE_LIMIT
2) CU_HW_LOAD_BALANCER_FILLS_QUEUE
3) CU_HW_KEEP_QUEUE_FULL
```

They are also tunable in

```
'include/linux/sched_hwaccel.h'
```

The firt one sets the limit, the second one controls if the load balancer should refill the queue once it runs and the third one controls if the load balancer is invoked when the accelerator is idle or when the queue is not full. These parameters are linked to migration modes. Listed below the different cases:

- **Migration without queue limit:**

```
#define CU_HW_QUEUE_LIMIT 99999
//#define CU_HW_LOAD_BALANCER_FILLS_QUEUE
//#define CU_HW_KEEP_QUEUE_FULL
```

- **Migration without queue limit 5 and fixed set of tasks**

```
#define CU_HW_QUEUE_LIMIT 5
#define CU_HW_LOAD_BALANCER_FILLS_QUEUE
#define CU_HW_KEEP_QUEUE_FULL
```

- **Migration without queue limit and variable set of tasks**

```
#define CU_HW_QUEUE_LIMIT 5
#define CU_HW_LOAD_BALANCER_FILLS_QUEUE
#define CU_HW_KEEP_QUEUE_FULL
/* Also for this mode is needed  a
    modification in the file sched_hwaccel.c
     from */
if (is_cpu_cui(cui)||
    cui->cfs_rq.nr_running <
        CU_HW_QUEUE_LIMIT - 1)
/* To */

if (is_cpu_cui(cui) ||
    cui->cfs_rq.nr_running <
        CU_HW_QUEUE_LIMIT)
```

There is also another tunable parameters inside the 'kernel/sched_hwaccel.c' file. You will find the basic granularity setting per type:

```
static u64 type_granularities_sec[
    CU_NUMOF_TYPES]
```

Alternatively you can define

```
#define APPLICATION_CONTROLLED_GRANULARITY
```

in the previosly discussed header file and thereby extend the signature of the allocation system call. Now you are ready to compile the kernel. Run:

```
#make -jX
```

The X has to be changed with the number of your cores + 1. It makes the compilation faster. If you prefer to have a one core compilation just remove it. In this case only one thread will be sponed at a time.
After the end of the compilation we have to install the kernel and set the grub configuration. It is feasible running the commands:

```
sudo make modules_install
sudo make install
sudo update-initramfs -c -k 2.6.32.57
sudo update-grub
```

To check if everything is gone ok reboot the system and select the new voice in the list. If you get either a kernel panic or something that doesn't work try a new kernel configuration to include the missing parts. Instead, if everything seems to go normal go ahead in the configuration.

3.4 Testapplication installation and setting

Now that we have the kernel properely configured with the syscall needed by the heterogeneous scheduler we have to install the applications that use it. The authors released two application. They are dowlodable, like the kernel, from my github repository. In this repo you will find a doc folder with the Testapp guide [6] resumed partially here and another folder with the source code. To clone it as above use the following commands:

```
>cd ~
>git clone https://github.com/m4mbr3/
    RTOS_application.git testapplication
```

In the repository there are three subdirectory :

- **linux-source-2.6.32**

This is the subdir with all the kernel modification. As mentioned before they don't work and also are not in the .patch format so the application is painful with them. Fortunately the authors send me the patch that we used in the previous chapter so this folder up to now is useless.

- **testapplication**

This is the folder with the testapplication framework. I patched the makefile to make it compilable. You will not have any problem to do that. To see which modification I applied you can use the git diff command as follow:

```
#git diff 960
    b8724bc252a8fe2662a470a600a2a4dc7142a
    fe403b2eb919be7ac3ebec7a62dbf37ffe3722af
```

The first one sha1 is related to my last commit, the second one is related to the last Author commit. The testapplication, as the kernel extension, could be customized. Inside the 'testapp.h' file you will be able to tune some modes:

```
/* types of ghosts...first defined one is
    taken */
#define MODE_ONLY_MD5
#define MODE_ONLY_PF
#define MODE_MD5_AND_PF
#define MODE_1_MD5_AND_2_PF
```

Choose one of the modes (only MD5 cracking workers, only prime factorization workers, both workers in equal amount, or both workers with twice as many PF workers than MD5 workers) with these preprocessor macros. In "num_of_ghosts.h" you can define the number of concurrent "test applications" you want to have, and in "kernel_granularity.h" you can define the granularity that will be used if you enabled the application controlled granularity in the kernel. The framework allows you to calibrate singularly MD5 or PF application. To adjust the MD5 application edit the file "worker_md5.h":
ORIGINAL_WORD_LENGTH is the word length of the target word and **MD5POOL** is the alphabet.
WORDS_PER_BATCH it the checkpoint distance of the CPU implementation and **WORDS_PER_BATCH_CPU** the distance of the GPU version.
The target string generation can be found in 'worker_md5.cpp'.
Instead to adjust the PF application edit the file 'worker_prime.h':
BASE_NUMBER is the starting number of the number generation for the PF threads.
CANDIDATES_PER_BATCH is the checkpoint distance of the CPU implementation and **CANDIDATES_PER_BATCH_GPU** the distance of the GPU version.
The number generation can be found in 'worker_prime.cpp'
To compile the testapplication you have to just run :

```
>make clean
>make
```

NB: the testapplication has to be compiled only after the compilation of the library that we will see in a while.

- **userspacecontrol**

In this subfolder we can find both the directory to the frontend and the directory to the library. First of all we need to compile the library running:

```
>cd ~/testapplication/kernel_space/src/
    userspacecontrol/library/
>make
```

to compile it. Then I suggest to copy it into the /lib/ directory using:

```
>sudo cp libhwaccel_uc.so /lib/
```

After that we go in the frontend folder and we compile also that tool. The result of this compilation will be a tool named accelerator-ctl. It allows us to control our scheduler recording new accelerator in the system and list them when the testapplication is running to control how the tasks are distributed thoughout the system. Now that you have compiled the library go back to the previous chapter to compile the testapp.

4 How use and evaluate the test application

In the previous section we have seen how is composed the testapplication repository. In this section, instead, we will see how the components above described works.

4.1 Control the scheduler

Firtst of all we have to notify all our accelerators to the scheduler. To do so, the authors provided us the tool 'accelerator-ctl' which is our user-space tool to control the scheduler. The operations provided are:

- **Add** a new accelerator

```
>/accelerator-ctl -c X
```

The X has to be changed with the number of the device. If you have only one accelerator it will be 0.

- **List** the units recognized by the accelerator

```
>./accelerator-ctl -l
```

- **Remove** a selected unit from the scheduler

```
>./accelerator-ctl -d
```

It will ask to you which accelerator you want to delete.

4.2 Run the test

Now we have to run the test so we need to compile the testapplication as described above and then we can run the bash script provided in the same folder to take in count the time of the execution. We will notice a lot of output on the screen. It's the description of what is appening. In function of the number of batch defined for the specific worker. The batch number means the distance between two checkpoints. Defines how many generated brute-force strings two adjacent checkpoints of this worker are apart on a GPU. If we, during the testapplication execution, list the units registered by the scheduler we will notice that close to the type of units there is the number of tasks running for each unit. To have information about the time we can use the bash script provided to run the test:

```
>chmod u+rx timeTestapp.sh
>./timeTestapp.sh
```

5 Conclusions and future work

This work main goal was to provide a detailed guide to the installation of the this hybrid scheduler. To give a visible view of the working scheduler I also published a youtube video . This work also include fixes to the original project to allow an happyful installation to who wants to extend it. As future works we have the porting to a more recent version of both kernel and cuda sdk, we have the integration and test with also other kind of accelerators (such as FPGA).

References

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[2] NVIDIA: Cuda documentation

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