

# Coordinating CPU and GPU Resources with Loadable Real-Time Schedulers

Yusuke Fujii, *Member, IEEE*, Takuya Azumi, *Member, IEEE*,  
Nobuhiko Nishio, *Member, IEEE*, Tsuyoshi Hamada, *Member, IEEE*,  
Shinpei Kato, *Member, IEEE*,

**Abstract**—Graphics processing units (GPUs) easily provide the benefits of high-performance computing. However, GPU runtime environment is target to best-effort oriented application, these does not consider real-time. Previous work have contributed for real-time GPU, these have depends kernel. Dependence on the kernel and the device driver gives the burden developers and users. We present Linux-RTXG which is realized cpu-gpu realtime extending framework while kernel free. Linux-RTXG have a CPU real-time scheduler, a GPU real-time scheduler and a GPU reservation mechanisms. To achieve kernel free framework, we presents interrupt intercept mechanisms and independent interrupt mechanisms and to solved currently linux kernel real-time scheduling problem. Our experimental result, we indicate overhead of GPU scheduling using Linux-RTXG framework, and then, kernel free's approach performances of QoS management had kept equivalent performance as compared with the existing kernel-dependent approach.

**Keywords**—Computer Society, IEEEtran, journal, LATEX, paper, template.

## 1 INTRODUCTION

GPU is become common as a device to accelerate the general purpose application. Its range of application that are navigation[1] for autonomous drive, object detection[2], tokamak control for fusion reactor[3], user-interactive application[4] and databases[5]. And benchmarks[6] that contains a lot of applications has been provided. GPUs performance has been demonstrated by these research.

The past GPU applications should have been only "real-fast" since these were best-effort oriented. The recent GPU applications are required "real-time" and "real-fast" by the increasing real-time oriented application of targetting real-world. GPUs runtime environments such as CUDA[7] and OpenCL[8] are

provided by the vendor, however, these runtime environments made to target a best-effort applications, it is not support real-time. Therefore GPU runtime environments are required to have to support real-time.

We have already worked several research of GPU resource management. TimeGraph[9] provides GPU scheduling and reservation mechanisms at the device driver level to queue and dispatch GPU commands based on task priorities. RGEM[10] provides GPU kernel scheduling and data transferring scheduling, Gdev[11] is applied resource reservation. These work have weak point that is can not to provide fast supporting update architecture and full-function because these works is based on reverse engineering.

Some GPU functions are provided API, processing is issued to GPU via library and device driver from the user application. Thus if GPUs truly wants the real-time requirements, there is a need to manage host side task as well as GPU resource management. We have confirmed the fact that a large amount of latency occur, when other tasks appropriative resources in the host side at studies[12] is evaluating the data trans-

- Y. Fujii is with the Graduate School of Information Science and Engineering, Ritsumeikan University.
- T. Azumi is with the Graduate School of Information Science and Engineering, Osaka University.
- N. Nishio is with the College of Information Science and Engineering, Ritsumeikan University.
- T. Hamada is with the Advanced Computing Center, University of Nagasaki.
- S. Kato is with the School of Information Science, Nagoya University.

fer time between the host and the device.

GPUSync[13], [14] by Elliot et al. providing CPU task scheduling and budget enforcement on the proprietary runtime, and it is realized configurable framework in order to verify the combination of the policies of tasks allocation to multi-core cpu and the policies of GPU kernel allocation to multiple GPUs.

However, GPUSync is implemented on the *LITMUS<sup>RT</sup>*[15], it contains a large amount of changes to the kernel. Gdev also request a modification to the device driver. Many of these modifications are to required installation using patch to user. A big burden is given patch to both developer and user. Specifically, developers obligation that is maintenance of patch in order to catch up to the latest kernel release. However, software which is using basis in open source such as Linux are updated fast, in most cases, before developers to complete the porting work towards the latest kernel.

Linux have mechanism which is loadable kernel module (LKM). LKM is module that is able to load/unload between running for providing function foreign kernel. We work the real-time extension by LKM, is called RESCH. RESCH is providing real-time scheduling framework while it not modify the kernel and device drivers. RESCH is not support GPU resource.

**Contribution:** In this paper, we present linux real-time extension for cpu-gpu resource coordination called linux-rtxg for cpu and gpu coordinated resource management, this extension is able to more easily re-configure the resource management policy and the installation. Linux-RTXG's most contribution is to achieve real-time task scheduling on the using GPU environment while not kernel modification.

To achieve real-time task scheduling, Linux-RTXG provide the CPU task scheduler, GPU kernel scheduler, GPU kernel reservation mechanisms. TODO:moutyotto

**Organization** This rest of the paper is organized as follows. Section 2 discuss the GPU real-time scheduling by kernel free approach. Section 3 shows Linux-RTXG design and implementations, especially focus on GPU scheduling. Section ?? indicate Linux-RTXG's advantages and dis-advantages, furthermore, demon-

strate experimental results that are quantitative overheads and reservation performances. Section 5 discusses related work. We provide our concluding remarks in Section 6.

## 2 SYSTEM MODEL

In this section, we explain GPU task model on this paper while we discuss the gpu scheduling question and prior work. Next, we make available limitation for clearing the implementation of no patched gpu scheduling. This paper focus on a system composed of multiple GPU and multi-core CPU.

### 2.1 GPU Task Model

When using GPU in general-purpose way, CUDA and OpenCL can use much. In this paper, we only use CUDA, but it is possible the same approach even OpenCL.

GPU applications use a set of the API supported by the system, typically talking the following steps. (i) create GPU context (*cuCtxCreate*), (ii) allocate space to device memory (*cuMemAlloc*), (iii) The data and the GPU kernel are copied to the allocated device memory space from host memory (*cuMemcpyHtoD*), (iv) Launch the GPU kernel (*cuLaunchGrid*), (v) The GPU task is synchronized to the GPU kernel (*cuCtxSynchronize*), (vi) The resultant data transfer to host memory from device memory (*cuMemcpyDtoH*), (vii) release allocated memory space and context (*cuMemFree*, *cuModuleUnload*, *cuCtxDestroy*).

We define a GPU task which is to execute the GPU using above API flow, and define a GPU kernel that is unit of processing to executed on the GPU side.

### 2.2 GPU Scheduling

Real-time OS (RTOS) is a lot of research[16], [17], [18], [19] has been conducted for a long time. In among them have also been many studies[20], [21], [22], [15], [?] real-time OS, which is based on the Linux. OS available the GPU is limited to Windows, Mac OS and Linux, we selected Linux in order to achieve real-time on GPU environments.

Requirement that the scheduler the minimum required in carrying to realize the real-time multi-core environment is the following two:

- To use resources according to order.
- To limit the use of the shared resource

The basic approach to satisfy the first is priority-based scheduling (e.g. Rate-Monotonic[23] and Earliest Deadline First[24]) with technique to prevent priority inversion, and the second is resource reservation based scheduling (e.g. Constant Bandwidth Server[25], Total Bandwidth Server[26]). The GPU to handle the data transfer bandwidth and the processing core as a shared resource, it is necessary to satisfy the two requirements similar to above multicore environment. Our previous working only to scheduling GPU accesses. However, GPU kernel is driven by API is issued GPU task, to truly support the real-time scheduling, it is need to schedule GPU task; therefore, for realized real-time GPU, framework need to have CPU's priority-based scheduler, GPU's priority-based scheduler and restrict GPU resource by resource reservation mechanisms. Recently, GPUSync is to work the above interdependence of CPU scheduler and GPU scheduler.

GPUs have some problem on using real-time, except that scheduling mechanisms. GPUs runtime environments are black-box mechanisms results from GPU environments are provided only GPU vendors and these environments are closed-source. TimeGraph, Gdev and RGEM are solved this problem by ensuring transparency using reverse engineering and open-source driver. GPUSync is solved this problem too by GPU runtime resource management is disabled through the runtime access to single.

The other problem occurs by non-preemptive GPU executions and non-preemptive data transfers. several researches[27], [28] realize improvement the response time by preventing divides the kernel overrun. As these core problems are on the process of being resolved, however, real-time GPU is experimental-phase since have problem for practical realized. The most difficult problem is self-suspending due to GPU is treated as a I/O device. GPU task to suspended themselves until it receives

the results from issuing the processing to GPU, referred to as self-suspension. The self-suspension has been proven as a cause the NP-HARD problem in previous work[29], [30], several researches[31], [32] are working on the scheduling analysis for self-suspension task, but it has not been solved yet to complete.

Hence scheduling framework for the expansion and installation to aim in this study and easy is useful, it is argued that there is a demand.

**GPU Synchronization:** The synchronization matters for GPU system such as heterogeneous platform. GPU have two different synchronization techniques. The first techniques is memory map based synchronization which is called FENCE, it sends GPU commands after the command to take action, then GPU microcontrollers will write the any value to memory-mapped space after action is completed. GPU task monitors it mapped space value using such as polling, therefore task has an exclusive CPU resource, but response time will be the fastest. The other one techniques is interrupts based synchronization which is called NOTIFY, it sends GPU commands similar to FENCE, then GPU microcontrollers will rise the interrupt and write any value to GPU I/O registers. GPU task is suspending until interrupt, therefore task is able to share the CPU resources with other tasks, but response time will be the slow. Detailed architecture is omitted in this paper, it has been described in the previous documents[?], [11], [33].

Gdev use both techniques that are NOTIFY and FENCE for wakeup the waiting task, NOTIFY is used by scheduler, FENCE is used by kernel synchronization. Gdev's synchronization implementation is the additional commands sends to GPU and the modification of device driver's interrupt handler. GPUSync use NOTIFY techniques by using tasklet intercept[34] on the proprietary software. Tasklet is linux's soft-irq implementation. GPUSync identify the interrupt that is issued which kernel by callback pointer with a tasklet.

**kernel free scheduler:** To achieve "kernel free", we must not to modify the kernel code and the device driver code. GPU scheduler is required to receive notify the completion of

GPU kernel, for selection of next executing GPU kernel. It is realized by two methods that are API-driven method and Interrupt-driven method. The API-driven method is explicitly wakeup the scheduler after the synchronized by API such as *cuCtxSynchronize()* is provided runtime in the RGEM. The Interrupt-driven method is wakeup by trigger of the interrupt which is issued by using NOTIFY in the Gdev and TimeGraph. General utilized *cuCtxSynchronize()* synchronize completion of all GPU kernels, therefore, API driven is able to use when a GPU context have issued only single kernel. Thus if a GPU context issue multiple kernels, we must use the Interrupt-driven method for not to guarantee overrun due to reduction of the response time.

The Interrupt-driven method can be synchronized for each kernel, it is required to modification the kernel or the device driver's ISR. Gdev has been achieved independent synchronization mechanisms on the proprietary software, need to modify the kernel modification. The challenge is realize independent synchronization mechanisms by kernel free approach.

### 3 DESIGN AND IMPLEMENTATION

In this section, we present Linux-RTXG design and implementation. Linux-RTXG is an abbreviation of Linux Real-Time eXtension including GPU resource management, which is no patched Linux real-time gpu scheduling framework.

We describe main contribution of the GPU scheduler and the integration to CPU scheduler in this paper, while CPU scheduling description is to minimize by Linux-RTXG is base RESCH.

#### 3.1 Linux-RTXG

Figure 3.1 shows over-view of Linux-RTXG. Linux-RTXG is divided into two components that are loadable kernel module and library. Linux-RTXG library is interface of communicate between application and Linux-RTXG core component(kernel module). it is using system call that is ioctl.

The part of library included speciall method that is independent synchronization method. it method is used only on the nvidia driver.

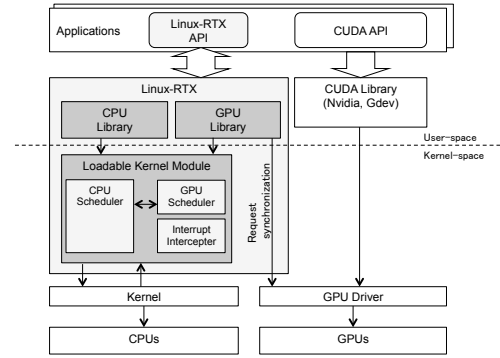


Fig. 1. Over view of the Linux-RTXG

if system use nouveau driver, runtime must use part of gdev. Gdev can happen arbitrary interrupt of gpu kernel in the user-space mode, and it have no need to be independent interrupt raised method.

Linux-RTXG loadable kernel module is positioned kernel-space. Thus, module can use kernel exported function.

#### 3.2 GPU Scheduling

Linux-RTXG is API-driven where the scheduler invoked only when computation requests are submitted. The basic APIs supported by Linux-RTXG are listed in Table 1. Some APIs have arguments and others do not. Linux-RTXG APIs are not modification existing CUDA API to cope with proprietary software to be independent from the runtime. However, user have to add Linux-RTXG api to existing CUDA application for using Linux-RTXG scheduler.

The sample code of the using Linux-RTXG scheduler is shown in Figure 2, and to some extent omitted except GPU scheduling. The *gpu\_task()* is

Figure 3.2 shows control flow of run the Figure2's sample code. The configure is the Kernel issue that is restricted to single kernel. User task (GPU Task) can be control the timing of GPU kernel execution by called *rtx\_gpu\_launch()*. Task goes to sleep until the wakeup by interrupt why task is not permitted issuance of GPU kernel due to already execute other task in the GPU.

Once issued GPU kernel is finished, interrupt is awoken while the interrupt interceptor wakeup the GPU scheduler, GPU scheduler

TABLE 1  
Basic Linux-RTXG APIs

<code>rtx_gpu_open()</code>	To register itself to Linux-RTXG, and create scheduling entity. It will must call first.
<code>rtx_gpu_device_advice()</code>	To get the recommendation of GPU devices to be used
<code>rtx_gpu_launch()</code>	To control the GPU kernel launch timing, in other words it is scheduling entry point. It will must call before the CUDA launch API.
<code>rtx_gpu_sync()</code>	To wait for finishing GPU kernel execution by sleeping with TASK UNINTERRUPTIBLE status.
<code>rtx_gpu_notify()</code>	To send the notify/fence command to GPU microcontroller. The fence or the notify is selected flag is set by argument.
<code>rtx_gpu_close()</code>	To release scheduling entity.

```

void gpu_task(){
    /* variable initialization */
    /* calling RESCH API */
    dev_id = rtx_device_advice(dev_id);
    cuDeviceGet(&dev, dev_id);
    cuCtxCreate(&ctx, SYNC_FLAG, dev);
    rtx_gpu_open(&handle, vdev_id);
    /* Module load and set kernel function */
    /* Device memory allocation */
    /* Memory copy to device from host */
    rtx_gpu_launch(&handle);
    cuLaunchGrid(function, grid_x, grid_y);
    rtx_gpu_notify(&handle);
    rtx_gpu_sync(&handle);
    /* Memory copy to host from device */
    /* Release allocated memory */
}

```

Fig. 2. sample code of using rtxg scheduler

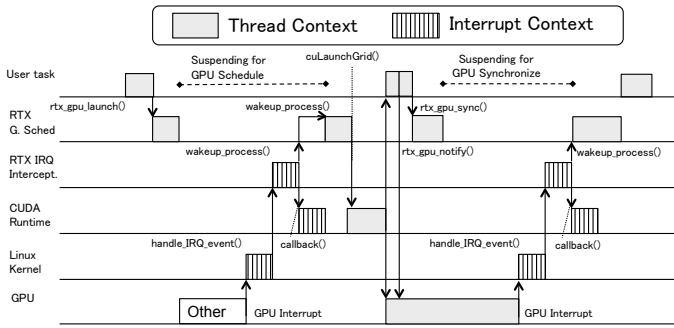


Fig. 3. GPU Scheduling control flow

wakeup the sleeping task. The wake-up task issue the GPU kernel via CUDA API such as `cuLaunchGrid()`. After the GPU kernel issued, task register the NOTIFY for occurring the interrupt, and task to sleep until it occurs interrupt. To pick up the next task is performed

by the GPU scheduler caused by interruption of GPU kernel finish. Linux-RTXG is doing the execution order control tasks in the above flow.

We present hierarchal scheduling which are group scheduling, GPU kernel scheduling. The group scheduling is a using resource reservation mechanism. The Context scheduling is a priority scheduling. Specifically, GPU kernel execution is associated to each scheduling entity while Linux-RTXG grouped the scheduling entity to VGPUs, these VGPUs belong to any of physical GPUs. In Linux-RTXG, resources are distributed in this group.

Figure 4 shows pseudo-code of scheduling mechanism. *onarrival* is called when the GPU task is requested GPU kernel launch issue. In *onarrival*, GPU task to check whether the given execute permission to group of task itself, and then, check the se permit. If it has not executing permission, GPU task is enqueued to wait\_queue and go to sleep, contrary to this, if it has executing permission, GPU task go to launch issue.

*oncompletion* is called by the scheduler thread, when the GPU kernel is completion. In *oncompletion*, scheduler thread pick up the next group,

### 3.3 GPU synchronization

We present implementation of the interrupt intercept is to get the interrupt for kernel free interrupt handling for realized interrupt-driven wakeup the scheduler, and present implementation of independent synchronization mechanism, in Section 2.

Linux-RTXG is use the independent synchronization mechanisms as much as possible, it because we do not want using black-box resource management for to realized truly real-time resource environments.

---

```

se: The scheduling entity
se->vgpu: The group that is belonged se
se->task: The task that is associated with se
vgpu->parent: The physical GPU identification

```

---

```

void on_arrival(se) {
    check_permit_vgpu(se->vgpu)
    while(!check_permit_se(se)) {
        enqueue(se->vgpu, se);
        sleep_task(se->task);
    }
}

void on_completion(se) {
    reset_the_permit(se->vgpu, se)
    n_vgpu = pick_up_the_next_vgpu(se->vgpu->parent)
    se = pick_up_the_next_se(n_vgpu)
    if(se) {
        dequeue(se->vgpu, se);
        wakeup_task(se->task);
    }
    set_the_permit(se->vgpu, se)
}

```

---

Fig. 4. High Level Pseudo-code of scheduling mechanisms

**Independent synchronization mechanism from runtime** We present independent synchronization of NOTIFY and FENCE, these are the to occur interrupt for NOTIFY and the write the fence value by microcontroller. NVIDIA's proprietary software use ioctl interface to communication between kernel-space and user-space. These ioctl interfaces are provided drivers function such as device memory allocation, get the gpu information and memory mapping. Gdev build infrastructure that is able to execute on the NVIDIA's driver using these ioctl interfaces.

We also use this ioctl interface similar to Gdev's command sending method for our method. Specifically, our methods are two divided, the one is Initialize, the other one is Notify. Initialize processes for generating a context dedicated this method. These processes are including the create virtual address space and the allocate indirect buffer object for command sending and the create context object. The indirect buffer is an area for storing GPU commands

The Notify processes send commands to the compute engine or the copy engine that are This independent generate sign for synchronization method is using reverse engineering. However, It is the limit of implementation using the closed-source runtime environment.

**Interrupt interception:** Interrupts are handled by the ISR (Interrupt Service Routine) that is registered kernel by the device driver. In addition, scheduler require to identify the interrupt by using reading GPU status register, it must be done before original ISR is reset the GPU status register.

Linux kernel have structure that holds the interrupt parameters called `irq_desc` for each interrupt number. These structures have structures called `irq_action` including the ISR callback pointer. `irq_desc` is allocated to global memory space of the kernel, anyone is accessible from kernel space. Linux loadable kernel modules can get an `irq_desc` for running in kernel, while also can get an callback pointer of ISR. We retain getting callback pointer of GPU device driver's ISR, and then we register interrupt interception ISRs to kernel. So, we get the to intercept interrupt by it ISR and then call retaining callback pointer, In addition, I/O registers are mapped to kernel memory space by device driver from the PCIe base address registers (BARs)[12], [35]. Therefore Linux-RTXG remap the BAR0 to our allocated space by using `ioremap()` when the ISR initialize. The interrupt interception identify interrupt by read the mapped-space.

### 3.4 Scheduler Integration

Linux scheduler have various real-time scheduling policies that were SCHED\_DEADLINE, SCHED\_FIFO and SCHED\_RR. , SCHED\_DEADLINE is implementation the Constant Bandwidth Server and Global Earliest Deadline First, while it is including mainline of Linux 3.14.0 kernel. However, synchronization does not work well in a SCHED\_DEADLINE scheduling policy when using GPU tasks.

This problems are twofold. The first is implementation of `sched_yield`—in kernel space used `yield()`—. The second is implementation of return from sleeping state.

The first problem occurs by releasing the CPU using `sched_yield()` when waiting for I/O in polling. Polling (Spin) is the exclusive CPU, therefore task may once better to release the CPU can obtain good results. However, `sched_yield` will set 0 to polling task's runtime of remaining execution time treated as a parameter of `SCHED_DEADLINE`. Thereby, it task lose execute authority until runtime is replenished in the next period, therefore task is unable to call `sched_yield` between polling. `sched_yield` is used much by device drivers and library as well as GPU runtime. These software is affected by this problem. Even NVIDIA CUDA is affected depending on the setting. We support this problem by limit the GPU synchronization method to `NOTIFY` in the `SCHED_DEADLINE` policies.

The second problem is subjected to a check equation (1) when restore task from sleeping state. If equation (1) is true, runtime is replenished and absolute deadline is setted next cycle deadline.

$$\frac{Absolute\_Deadline - Current\_Time}{Remaining\_Runtime} > \frac{Relative\_Deadline}{Period} \quad (1)$$

We corresponding to this check by subtracting the GPU execution time from *Remaining\_Runtime* when task is restored by GPU kernel execution with the exception of the task is restored by period.

## 4 EVALUATION

We evaluate scheduling overhead and qos management performances.

・優先度スケジューリングの評価はしなくてよいのか

- ・GPUSync と比較しなくて良いのか
- ・実アプリで動かすとどうなるのか

本稿における評価では、本 Linux-RTXG を利用した際のオーバーヘッドを定量的に計測し、利用に伴ってどれだけのデメリットを含んでいるかを提示する。定性的な評価としては関連する研究と保持する機能や特徴の差について次章で discuss する。

### 4.1 Experimental Environment

Our experiments are conducted with the Linux kernel 3.16.0 on NVIDIA Geforce GTX680

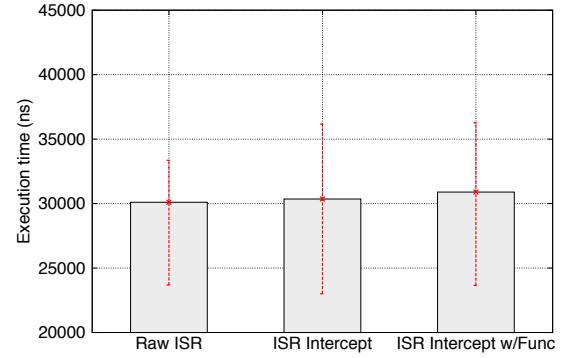


Fig. 5. Interrupt intercept overhead

graphics card and 3.40GHz Intel Core i7 2600, which contains 8 cores (including the two hyper-threading cores) and 8GB main memory. GPU programs are written in CUDA and compiled by NVCC v6.0.1. GPU drivers are used NVIDIA driver 331.62 and Nouveau driver linux-3.16.0. CUDA libraries are used NVIDIA CUDA-6.0 and gdev.

### 4.2 Interrupt intercept overhead

まず Interrupt intercept のオーバーヘッドの測定を行う。本評価では、GPU ドライバは nouveau を用いる。割り込み処理は、各割り込みの種類によって、処理時間が異なり、その分布は一樣ではないため、単に測定して平均をとっても比較ができない。そのため各割り込みの種類の判別のために Nouveau を用いて、割り込みの種類が同一のもので、カーネル内の `do_IRQ` 関数内でハンドラが呼ばれてから終了までの時間を測定しどの程度のオーバーヘッドで割り込みの盗聴及び、盗聴した割り込みがいずれのカーネルに関連したものであるかの識別ができるかどうかを測定する。

Figure ??は上記設定で測定した結果である。Raw ISR は通常のルーチンで実行される ISR、ISR Intercept は割り込みを盗聴するのみ、ISR intercept w/Func は盗聴した上でその割り込みが、いずれのカーネルに関連した割り込みか識別しスケジューラを立ち上げる機能を実行した場合である。それぞれ 1000 回の測定で平均値を取り、最小値と最大値についてエラーバーで示している。この図から見て取れるように、オーバーヘッドは確実に存在する。ISR Intercept だと 247ns のオーバーヘッドであり、ISR Intercept w/Func でも 790ns のオーバーヘッドである。この数値は直感的に考えると小さくシステム自体に影響を及ぼすほどではな



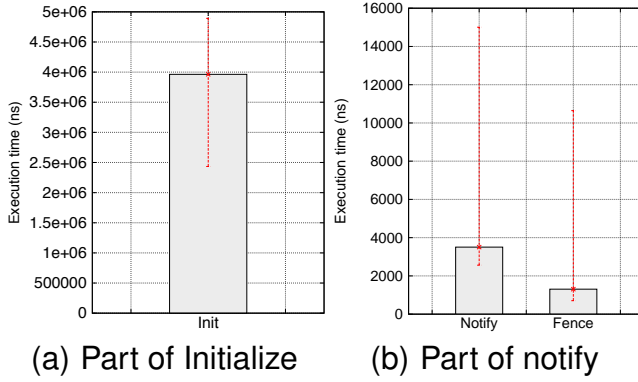


Fig. 6. Interrupt raised method overhead

いと考えられ、しかしその割込みが乱発することによる積み重ねによっては影響を与えることは、本手法のデメリットとして意識しなければならない。

### 4.3 Independent generate sign for Synchronization overhead

本稿では同期用サイン生成のためのオーバーヘッドを測定する。割込みの立ち上げは同期を求めるタイミング (e.g. カーネルラUNCH後) に `rtx_nvrml_notify()` を呼び出す必要がある。スケジューリングを行わない Vanilla な状態ではこれらの API は必要ではないものであるため、これらの API にかかった時間はすべてオーバーヘッドとなる。

そのためこれらのオーバーヘッドの計測を行う。計測は API の呼び出しから戻るまでを測定する。

結果を Figure 6 に示す。Initialize は Indirect Buffer はプロセスが立ち上がるたびに、コマンド送信用の Indirect Buffer の確保や各エンジンの登録のために呼び出される必要がある。Notify はカーネル実行後や非同期メモリコピー実行後のような実際に割込みを発生させたいタイミングで呼び出される。これらは `ioctl` システムコールによってユーザ空間とカーネル空間をまたいでいる影響か、実行時間のバラ付きが大きく出ている。

Initialize は比較的時間がかかっているが、1 プロセスにつき一度しか呼ばれないため、アプリケーション全体への影響は少ないと考えられる。Notify に関してはそれほど時間がかかっておらず、同期待ちの間に実行されるべき処理のため、こちらもアプリケーション全体への影響は少ないと考えられる。Fence についても Notify と同様に平均で 2000ns 以下とほぼ誤差といってもよい程度の時間である。

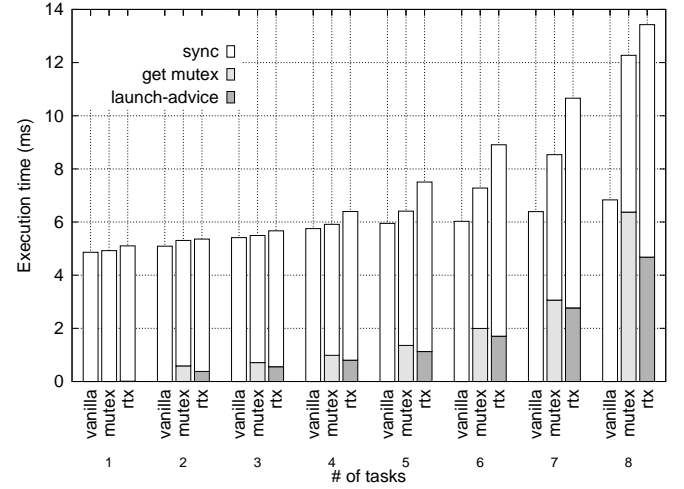


Fig. 7. Scheduling overhead(between GPU kernel launch request and synchronization)

### 4.4 Scheduling Overhead

rtx でスケジューリングした場合のオーバーヘッドを測定するために、“vanilla”, “mutex”, “rtx”の3種類のアプリケーションを用意した。全てに共通するのが、1個のアプリケーションに複数のタスクが存在しており、各タスクには10個のジョブが含まれることである。1個のジョブはGPUへのデータ転送、GPUカーネル実行、GPUからのデータ転送を含んでいる。GPUカーネルは単純な行列の計算を行う。

3種で異なる点として、まず mutex は同時に launch が発行されるのが1つに調停されるように mutex を用いてロックしたバージョンである。そして rtx は linux-rtxg を用いて実行したケースであり、vanilla はそれらの追加が無くスケジューリングや調停を一切行わないケースである。

CPUのスケジューリングはlinux-rtxを用いたシンプルな Fixed-priority スケジューリング (Linuxの SCHED\_FIFO と同様のポリシー、ジョブ管理のみを行う) を用いる。GPU側のスケジューリングは、Gdev で提案された BAND スケジューラ、Linux-RTX での同期は全て NOTIFY を用いて行う。

計測結果を Figure 4.4 に示す。アプリケーションに含まれるタスク数ごとにプロットしており、各ジョブ内のラUNCH要求から実行完了までにかかった時間の平均値を各処理毎に積み上げ式で示している。

TODO:結果について説明と、考察

launch\_advice は `rtx_gpu_launch` によって GPU 利用のためのリクエストを出してから、許



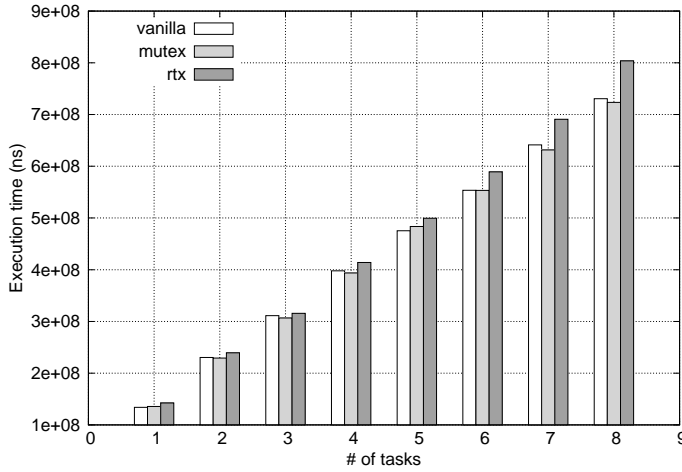


Fig. 8. Scheduling overhead (Time of entire task)

可ができるまでを示しており、`get_mutex` は `mutex` によってロックを獲得するまでの時間、`launch`、`notify` はそれぞれコマンドを発行するまでにかかった時間で、`sync` は発行されてから同期完了するまでの時間である。全て、100 回のアプリケーション実行 (*numberoftasks*)

#### 4.5 QoS Management

次に GPU のバジェットエンフォースメントの性能を評価する。ここでは、今回同一アルゴリズムで QoS マネージメントを行っている Gdev との比較を行い、パッチを利用しない実装においても、性能をほぼ落とすことなくできていることを示す。

比較対象は、本 Linux-RTXG と同様のスケジューリングアルゴリズムが提供可能な Gdev のモジュール版とで比較する。評価に用いるスケジューリングポリシーは BAND スケジューラを用いる。実験に利用するアプリケーションとして、4.4 節で利用したものと同様のもの Task を 4 つ生成し、各タスク毎に 25% の GPU 利用権限を与える。これらのタスクの実行中の GPU 利用率を計測し、Gdev と同様のアルゴリズムを用いることで、今回提供する Linux - RTXG によるアプローチによってどれだけ QoS マネージメントについてのパフォーマンスに影響するかを示す。Gdev を用いることから、両者ともデバイスドライバは Nouveau ドライバを用いる。

Figure 4.5, 4.5 show gpu usage on the qos management by gdev and linux-rtxg. TODO: 結果に合わせて記述

Figure ?? shows

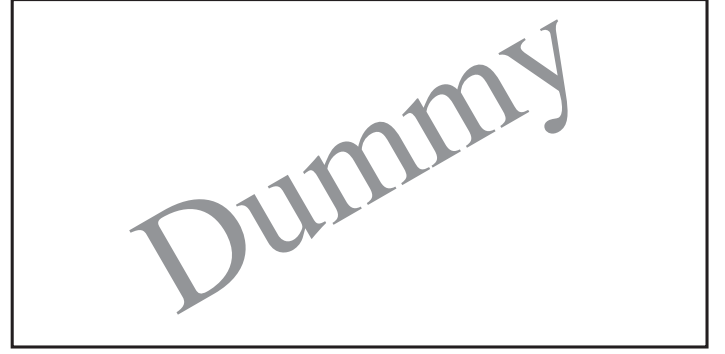


Fig. 9. Utilization of four tasks on the Linux-RTXG only priority scheduling. Each tasks are given different priorities.

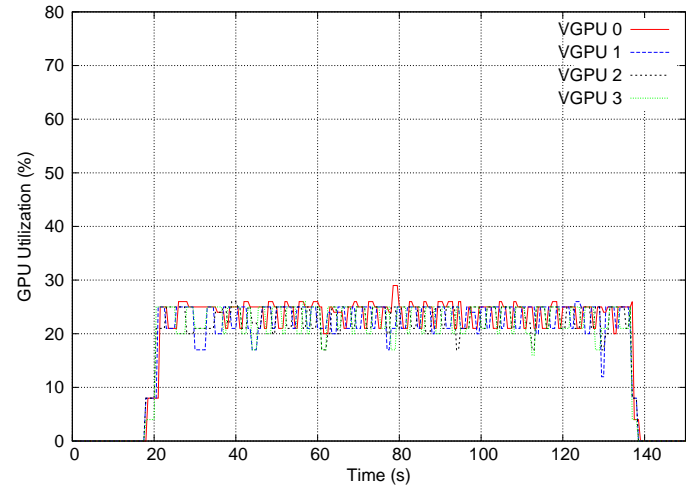


Fig. 10. Utilization of four tasks on the Linux-RTXG resource reservation. Each tasks are given different priorities and all tasks are fairly given resources which is 25%

## 5 RELATED WORK

### Comparison of prior work

我々の知る限り、カーネルやドライバを修正せずに GPU 資源管理に取り組んだ例は無い。2014 年では旧バージョンのマイナーアップデートも含め 172 個<sup>1</sup> のアップデートがリリースされている。

我々はこれまでいくつかの GPU の資源管理に関する研究 [9], [4], [10], [11] を行ってきた。Time-Graph は GPU に送信されるコマンドをスケジューリングすることで CUDA にかぎらず、OpenGL など、全ての GPU を利用に関する資源管理を行

1. kernel.org で提供されるカーネルのうち 2014 年に更新されたファイルの数

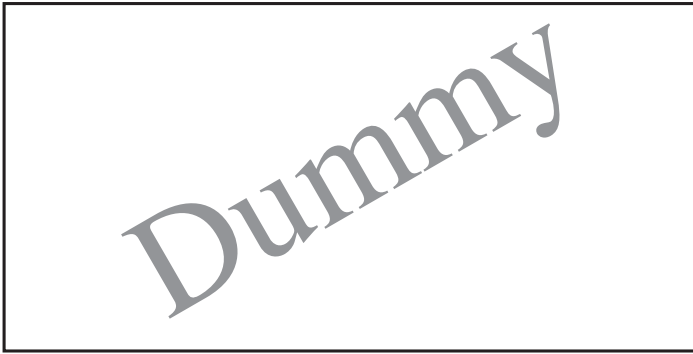


Fig. 11. Utilization of four tasks on the Gdev resource reservation. All tasks are fairly given resources which is 25%

っている。しかしながら GPU のコマンドは処理の実行だけでなく、データ転送、割込み処理登録などの処理時にも送信されており、本当にスケジューリングすべき単位でのスケジューリングには向いていないことがわかっている。そのため、RGEM は GPGPU に特化し、GPU カーネル実行単位でのスケジューリングを目指し、固定優先度でのスケジューリングを実現してる。加えて、データ転送のセグメント分けによってノンプリエンティブな特性にもたらされるデメリットを最小限にし、レスポンスタイムの向上を目指している。Gdev は RGEM の発展形であり、仮想 GPU と Resource Reservation による QoS 制御や、OS 空間での CUDA 実行などを実現している。加えてデータ転送とカーネル実行をオーバーラップさせることで実行時間自体の縮小を実現している。

PTask[36] is an OS abstraction for GPU applications that optimizes data transfers and GPU scheduler.

Elliott et al. present GPUSync[37], [14]. GPUSync ではホストから GPU へのデータ転送開始から、GPU での処理、GPU からホストへのデータ転送までをクリティカルセクションと設定し、runtime へのアクセスはクリティカルセクションを区切りとして単一のアクセスとなるように調停を行っている。これによってクローズドソースなランタイムを利用しつつ、自身の GPU 資源管理を実現可能としている。GPUSync はアクセス調停の手法として k-exclusion lock の拡張を利用している。加えて各 GPU ごとに Resource Reservation による QoS 担保を行っており、各 GPU 間の P2P migration も実現しており、MultipleGPU への自動割り当ても行っている。

Han et al. show GPU-SPARC[28]. GPU-Sparc support to automatically split and run the GPU kernel concurrently over multi-GPU, and then they supported priority queue based scheduling.

We show the table2 that is result of comparing the Linux-RTXg and prior work.

## 6 CONCLUSION

In this paper, we present linux real-time extension for cpu-gpu resource coordination called linux-rtxg for cpu and gpu coordinated resource management. We focus on that are specifically not modify the kernel, worked for GPU resource management. GPU をよりリアルタイムにするために必要と考えた、GPU タスク (running on the CPU) のスケジューリング拡張、GPU カーネルのスケジューリング拡張について取り組んでおり、GPU の同期に用いられる割込みの top-half を傍聴することで実現した。今回実現したフレームワークは、ジョブ一個あたりのオーバーヘッドは約  $x\%$  (sleep している時間も含む) になり、task あたりのオーバーヘッドは約  $x\%$  に収まることを示した。加えて既存フレームワークである Gdev と同一アルゴリズムを用いて、割込み傍聴を用いた QoS Management の性能を検証したところ、約  $x\%$  のオーバーヘッドに収まることを示した。

フレームワークとしては、GPUSparc などでも用いられるカーネル分割による擬似プリエンティブスケジューリングへの対応などのアプローチを統合することでより完成度を高めることができる。本フレームワークはリアルタイム GPU を実現するための基盤としてメリットを持っているが、リアルタイム GPU を完全に実現しているわけではない。今後本フレームワークを利用してどれだけの成果を得られるかが重要である。

## ACKNOWLEDGMENTS

The authors would like to thank...

## REFERENCES

- [1] M. McNaughton, C. Urmson, J. Dolan, and J.-W. Lee, "Motion planning for autonomous driving with a conformal spatiotemporal lattice," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, May 2011, pp. 4889–4895.

TABLE 2  
Linux-RTXG vs prior work

	CPU		GPU		Budget Enforcement	Data/Comp. Ovlp.	Auto GPU Allocate	Closed Src. Compatible	Kernel Free	Configurable
	FP	EDF	FP	EDF						
RESCH	x	x							x	x
RGEM			x						x	
Gdev			x		x	x				
PTask					x	x	x	x		
GPUSync	x	x	x		x	x	x	x	x	
GPUSparc			x			x				
Linux-RTXG	x	x	x		x	x		x	x	x

- [2] M. Hirabayashi, S. Kato, M. Edahiro, K. Takeda, T. Kawano, and S. Mita, "Gpu implementations of object detection using hog features and deformable models," in *Cyber-Physical Systems, Networks, and Applications (CP-SNA), 2013 IEEE 1st International Conference on*. IEEE, 2013, pp. 106–111.
- [3] N. Rath, S. Kato, J. Levesque, M. Mauel, G. Navratil, and Q. Peng, "Fast, multi-channel real-time processing of signals with microsecond latency using graphics processing units," *Review of Scientific Instruments*, vol. 85, no. 4, p. 045114, 2014.
- [4] S. Kato, K. Lakshmanan, Y. Ishikawa, and R. Rajkumar, "Resource sharing in gpu-accelerated windowing systems," in *Real-Time and Embedded Technology and Applications Symposium (RTAS), 2011 17th IEEE*. IEEE, 2011, pp. 191–200.
- [5] P. Bakkum and K. Skadron, "Accelerating sql database operations on a gpu with cuda," in *Proceedings of the 3rd Workshop on General-Purpose Computation on Graphics Processing Units*. ACM, 2010, pp. 94–103.
- [6] S. Che, M. Boyer, J. Meng, D. Tarjan, J. W. Sheaffer, S.-H. Lee, and K. Skadron, "Rodinia: A benchmark suite for heterogeneous computing," in *Workload Characterization, 2009. IISWC 2009. IEEE International Symposium on*. IEEE, 2009, pp. 44–54.
- [7] "Cuda zone," <https://developer.nvidia.com/category/zone/cuda-zone>, accessed January 12, 2015.
- [8] J. E. Stone, D. Gohara, and G. Shi, "Opencl: A parallel programming standard for heterogeneous computing systems," *IEEE Des. Test*, vol. 12, no. 3, pp. 66–73, May 2010.
- [9] S. Kato, K. Lakshmanan, R. R. Rajkumar, and Y. Ishikawa, "Timegraph: Gpu scheduling for real-time multi-tasking environments," in *2011 USENIX Annual Technical Conference (USENIX ATC '11)*, 2011, p. 17.
- [10] S. Kato, K. Lakshmanan, A. Kumar, M. Kelkar, Y. Ishikawa, and R. Rajkumar, "Rgem: A responsive gpgpu execution model for runtime engines," in *Real-Time Systems Symposium (RTSS), 2011 IEEE 32nd*. IEEE, 2011, pp. 57–66.
- [11] S. Kato, M. McThrow, C. Maltzahn, and S. A. Brandt, "Gdev: First-class gpu resource management in the operating system," in *USENIX Annual Technical Conference*, 2012, pp. 401–412.
- [12] Y. Fujii, T. Azumi, N. Nishio, S. Kato, and M. Edahiro, "Data transfer matters for gpu computing," in *Parallel and Distributed Systems (ICPADS), 2013 International Conference on*. IEEE, 2013, pp. 275–282.
- [13] G. A. Elliott, B. C. Ward, and J. H. Anderson, "Gpusync: A framework for real-time gpu management," in *Real-Time Systems Symposium (RTSS), 2013 IEEE 34th*. IEEE, 2013, pp. 33–44.
- [14] G. A. Elliott and J. H. Anderson, "Exploring the multitude of real-time multi-gpu configurations," 2014.
- [15] J. Calandrino, H. Leontyev, A. Block, U. Devi, and J. Anderson, "Litmus rt : A testbed for empirically comparing real-time multiprocessor schedulers," in *Real-Time Systems Symposium, 2006. RTSS '06. 27th IEEE International*, Dec 2006, pp. 111–126.
- [16] J. A. Stankovic and K. Ramamritham, "The spring kernel: A new paradigm for real-time systems," *Software, IEEE*, vol. 8, no. 3, pp. 62–72, 1991.
- [17] T. Yang, T. Liu, E. D. Berger, S. F. Kaplan, and J. E. B. Moss, "Redline: First class support for interactivity in commodity operating systems," in *OSDI*, vol. 8, 2008, pp. 73–86.
- [18] H. Monden, "Introduction to itron the industry-oriented operating system," *Micro, IEEE*, vol. 7, no. 2, pp. 45–52, 1987.
- [19] R. Rajkumar, K. Juvva, A. Molano, and S. Oikawa, "Resource kernels: A resource-centric approach to real-time and multimedia systems," in *Photonics West'98 Electronic Imaging*. International Society for Optics and Photonics, 1997, pp. 150–164.
- [20] S. Oikawa and R. Rajkumar, "Portable rk: A portable resource kernel for guaranteed and enforced timing behavior," in *Real-Time Technology and Applications Symposium, 1999. Proceedings of the Fifth IEEE*. IEEE, 1999, pp. 111–120.
- [21] P. Mantegazza, E. Dozio, and S. Papacharalambous, "Rtai: Real time application interface," *Linux Journal*, vol. 2000, no. 72es, p. 10, 2000.
- [22] V. Yodaiken *et al.*, "The rtlinux manifesto," in *Proc. of the 5th Linux Expo*, 1999.
- [23] C. L. Liu and J. W. Layland, "Scheduling algorithms for multiprogramming in a hard-real-time environment," *J. ACM*, vol. 20, no. 1, pp. 46–61, Jan. 1973. [Online]. Available: <http://doi.acm.org/10.1145/321738.321743>
- [24] —, "Scheduling algorithms for multiprogramming in a hard-real-time environment," *Journal of the ACM (JACM)*, vol. 20, no. 1, pp. 46–61, 1973.
- [25] L. Abeni and G. Buttazzo, "Integrating multimedia applications in hard real-time systems," in *Real-Time Systems Symposium, 1998. Proceedings., The 19th IEEE*. IEEE, 1998, pp. 4–13.
- [26] M. Spuri and G. Buttazzo, "Scheduling aperiodic tasks

in dynamic priority systems,” *Real-Time Systems*, vol. 10, no. 2, pp. 179–210, 1996.

- [27] C. Basaran and K.-D. Kang, “Supporting preemptive task executions and memory copies in gpgpus,” in *Real-Time Systems (ECRTS), 2012 24th Euromicro Conference on*, July 2012, pp. 287–296.
- [28] W. Han, H. Bae, H. Kim, J. Lee, and I. Shin, “Gpu-sparc: Accelerating parallelism in multi-gpu real-time systems,” 2014.
- [29] F. Ridouard, P. Richard, and F. Cottet, “Negative results for scheduling independent hard real-time tasks with self-suspensions,” in *Real-Time Systems Symposium, 2004. Proceedings. 25th IEEE International*. IEEE, 2004, pp. 47–56.
- [30] K. Lakshmanan, S. Kato, and R. R. Rajkumar, “Open problems in scheduling self-suspending tasks,” in *Proc. Real-Time Scheduling Open Problems Seminar*, 2010.
- [31] B. Chattopadhyay and S. Baruah, “Limited-preemption scheduling on multiprocessors,” in *Proceedings of the 22nd International Conference on Real-Time Networks and Systems*. ACM, 2014, p. 225.
- [32] J. Kim, B. Andersson, D. d. Niz, and R. R. Rajkumar, “Segment-fixed priority scheduling for self-suspending real-time tasks,” in *Real-Time Systems Symposium (RTSS), 2013 IEEE 34th*. IEEE, 2013, pp. 246–257.
- [33] Y. Fujii, T. Azumi, N. Nishio, and S. Kato, “Exploring microcontrollers in gpus,” in *Proceedings of the 4th Asia-Pacific Workshop on Systems*. ACM, 2013, p. 2.
- [34] G. A. Elliott and J. H. Anderson, “Robust real-time multiprocessor interrupt handling motivated by gpus,” in *Real-Time Systems (ECRTS), 2012 24th Euromicro Conference on*. IEEE, 2012, pp. 267–276.
- [35] S. Kato, J. Aumiller, and S. Brandt, “Zero-copy i/o processing for low-latency gpu computing,” in *Proceedings of the ACM/IEEE 4th International Conference on Cyber-Physical Systems*. ACM, 2013, pp. 170–178.
- [36] C. J. Rossbach, J. Currey, M. Silberstein, B. Ray, and E. Witchel, “Ptask: Operating system abstractions to manage gpus as compute devices,” in *Proceedings of the Twenty-Third ACM Symposium on Operating Systems Principles*. ACM, 2011, pp. 233–248.
- [37] G. A. Elliott, B. C. Ward, and J. H. Anderson, “Gpusync: A framework for real-time gpu management,” in *Real-Time Systems Symposium (RTSS), 2013 IEEE 34th*. IEEE, 2013, pp. 33–44.

PLACE  
PHOTO  
HERE

**Takuya Azumi** Biography text here.

PLACE  
PHOTO  
HERE

**Nobuhiko Nishio** Biography text here.

PLACE  
PHOTO  
HERE

**Tuyoshi Hamada** Biography text here.

PLACE  
PHOTO  
HERE

**Yusuke Fujii** Biography text here.

PLACE  
PHOTO  
HERE

**Shinpei Kato** Biography text here.