

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

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**Abstract**—Graphics processing units (GPUs) easily provide the benefits of high-performance computing. However, GPUs runtime environment is target to best-effort oriented application, and do not consider real-time. Previous work have contributed for real-time GPU, and 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 real-time extending framework without kernel modification. Linux-RTXG has a CPU real-time scheduler, a GPU real-time scheduler, and a GPU reservation mechanism. To achieve framework without kernel modification, 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**—GPU, resource managemenet, scheduling, real-time system, operating system

## 1 INTRODUCTION

Graphic Processing Units (GPUs) are 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 an fusion reactor [3], user-interactive application [4], databases [5], and benchmarks [6] that contains a lot of applications. GPUs performance has been demonstrated by these research.

The past GPU applications should have been only “real-fast” since they 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] mainly target a best-effort applications, they

do not support real-time requirements. Therefore, GPU runtime environments are required to support real-time scheduling.

In our previous work, we showed how to support GPU resource management. Time-Graph [9] provides GPU scheduling and reservation mechanisms at the device driver level to queue and dispatch GPU commands based on task priorities. Gdev [10] is applied resource reservation. These work have weak point that can not to provide fast supporting update architecture and full-funciton because these work 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 [11] is evaluating the data transfer time between the host and the device.

GPUSync [12], [13] 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 policies of tasks allocation to

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multi-core and multi-processor CPUs and policies of GPU kernel allocation to multiple GPUs.

However, GPUSync is implemented on the *LITMUS<sup>RT</sup>* [14], 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 users. A big burden is given patch to both developers and users. Specifically, developers obligation that is maintenance of patch in order to catch up to the latest kernel release. However, if software 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 supports a loadable kernel module (LKM) which 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 does not support GPU resource.

**Contribution:** In this paper, we present linux real-time extension for CPU/GPU resource co-ordination 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 without kernel modification.

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

**Organization** This rest of the paper is organized as follows. Section 2 discusses the GPU real-time scheduling by kernel free approach. Section 3 shows Linux-RTXG design and implementations, especially focus on GPU scheduling. Section 4 indicates Linux-RTXG's advantages and dis-advantages, furthermore, demonstrates 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 in this paper, and also we discuss the GPU scheduling and prior works. Next, we make available limitation for clearing the implementation of GPU scheduling without kernel modification. This paper focuses on a system composed of multiple GPUs and multi-core CPUs.

### 2.1 GPU Task Model

In case of General Purpose GPU computing (GPGPU), CUDA and OpenCL are used to implement GPU applications. This paper focuses on CUDA, but it is possible to adapt the same approach to OpenCL.

We define a GPU task as a process which executes GPU, which cyclic executes unit is called GPU job, and, a GPU kernel is a processing to be executed on the GPU side. We support that a GPU application has multiple tasks.

GPUs use a set of the API supported by the runtime environment such as CUDA, typically GPU application takes the following steps: (i) *cuCtxCreate* creates a GPU context, (ii) *cuMemAlloc* allocates memory spaces to device memory, (iii) *cuModuleLoad* and *cuMemcpyHtoD* copy the data and the GPU kernel to the allocated device memory spaces from host memory spaces, (iv) *cuLaunchGrid* invokes the GPU kernel, (v) *cuCtxSynchronize* synchronizes waiting GPU task to that is completion of kernel, (vi) *cuMemcpyDtoH* transfers resultant data to host memory from device memory, and (vii) *cuMemFree*, *cuModuleUnload*, and *cuCtxDestroy* release allocated memory spaces and the GPU context.

### 2.2 GPU Scheduling

Real-time OS (RTOS) researches [15], [16], [17], [18] have been conducted for a long time. In among them, there are many existing studies concerning RTOS based on Linux [14], [19], [20], [21], [22]. The available OS for GPUs are limited to Windows, Mac OS and Linux, we selected Linux in order to achieve real-time processing on GPU environments.

In order to meet real-time constraints on shared resource environment such as a multi-core environment, there are two requirements for the scheduler as follows:

- To use resources according to a specified order
- To limit the use of the shared resources

A basic approach of the previous works to satisfy the first requirement uses priority-based scheduling (e.g. Rate-Monotonic [23] and Earliest Deadline First [24]) with technique to prevent priority inversion, and the second one is resource reservation-based scheduling (e.g. Constant Bandwidth Server [25], Total Bandwidth Server [26]). GPUs need to handle a data transfer bandwidth and a processing core as a shared resource; thus, we satisfy the two requirements similar to above multicore environment. Our previous works schedule only GPU accesses. However, GPU kernel consumes CPU time because it driven by API. to truly support the real-time scheduling, it is need to schedule a GPU task; In order to truly support the real-time scheduling, scheduler is need to schedule GPU tasks of CPU side. therefore the framework needs to have CPU's priority-based scheduler, GPU's priority-based scheduler, and GPU's resource reservation mechanism to realize real-time GPU Recently, GPUSync target interdependence of CPU scheduler and GPU scheduler.

GPUs have some problems on real-time environment, except 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 and Gdev address this problem by ensure transparency using reverse engineering and an open-source driver. GPUSync achieve closed-source compatible by GPU resource management that approaches are the interrupt handling and the arbitrate runtime access.

The other problem occurs by non-preemptive GPU executions and non-preemptive data transfers. Several researches [27], [28] have improved the response time by preventing overrun which occurs while dividing the kernel. However, these existing methods concerning real-time GPU are typically experimental, not practical enough. The most difficult problem is self-suspending because GPU is treated as an I/O device. GPU tasks suspend until it receives the results from invoking the pro-

cessing 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 completely.

Hence, the proposed scheduling framework aims at easier expansion and installation.

**GPU Synchronization:** The synchronization must be considered for GPU system such as heterogeneous platform. GPU have two different synchronization technique. 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. A 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 interruption 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. A GPU task is suspending until interrupt, therefore a task is able to share the CPU resources with other tasks, but a response time will be the slow. Detailed architecture is omitted in this paper, it has been described in the previous documents [9], [10], [33].

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

**kernel free scheduler:** We must not modify the kernel code and the device driver code to achieve "kernel free". GPU scheduler is required to receive a notice of GPU kernel completion, 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()* provided runtime in the RGEM. The Interrupt-driven method is woken up by a trigger of the interrupt which is issued by using NOTIFY in the Gdev and Time-Graph. 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 task invokes 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 modify the kernel or the device driver's ISR. Gdev has been achieved independent synchronization mechanisms on the proprietary soft-ware, it need to modify the kernel modification. The challenge is realizing independent synchronization mechanisms without kernel modification

### 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 Linux real-time GPU scheduling framework without kernel modification.

We describe the 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 based RESCH.

#### 3.1 Linux-RTXG

Figure 1 shows an overview of Linux-RTXG. Linux-RTXG is divided into two parts: a Linux-RTXG core component (a loadable kernel module) and a Linux-RTXG library. Its core component has features such as a CPU task scheduler, a GPU task scheduler, and a GPU resource reservation mechanism. These features use the kernel exported functions such as the *schedule()*, the *mod\_timer()*, the *wake\_up\_process()* and *set\_cpus\_allowed\_ptr()*, they are implemented on the loadable kernel module, its kernel module is positioned in kernel-space.

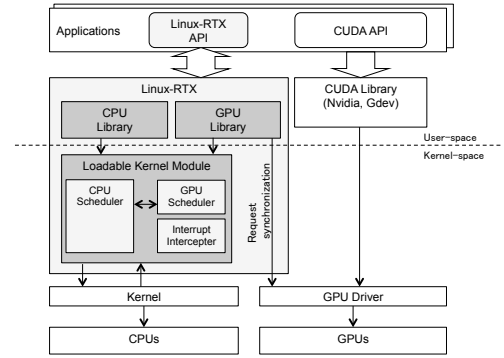


Fig. 1. Overview of the Linux-RTXG

The Linux-RTXG library is interface to communicate between application and Linux-RTXG core component(kernel module). These interface are implemented using an ioctl system call, which is a standard way of communicating to a driver.

The part of the library included a method that is an independent synchronization method. The independent synchronization method is used only on the Nvidia driver. If a GPU using system use Nouveau driver[35], GPU runtime must use part of Gdev. In that case, the GPU using system have not need the independent synchronization method because Gdev can manage arbitrary interrupt of the GPU kernel in the user-space mode,

#### 3.2 GPU Scheduling

Linux-RTXG is API-driven scheduler 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 the others do not. Linux-RTXG does not modify the 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. GPU tasks may be provided with a function by calling Linux-RTXG's API at strategic points.

Figure 3 shows the control flow of run of the Figure 2 sample code. The configuration

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_gpu_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 Linux-RTXG scheduler

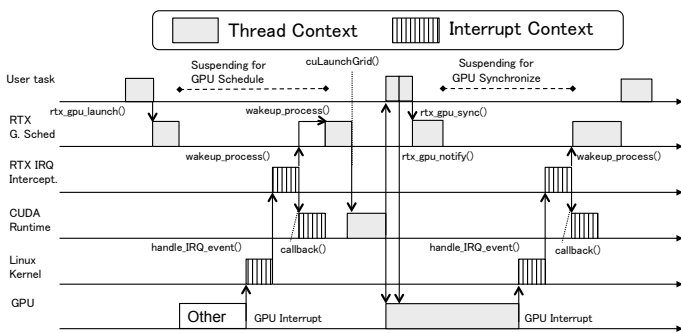


Fig. 3. GPU Scheduling control flow

is the Kernel issue that is restricted to single kernel. User task (GPU Task) can control the timing of GPU kernel execution by calling `rtx_gpu_launch()`. The task goes to sleep until the wakeup by interrupt why the 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 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. *on\_arrival* is called when a GPU task is requested GPU kernel launch issue. In *on\_arrival*, a 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, a GPU task is enqueued to wait\_queue and go to sleep, contrary to this, if it has executing permission, a GPU task go to launch issue.

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

---

```

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

### 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 uses the independent synchronization mechanisms as much as possible, it because we do not want using black-box resource management to realize truly real-time resource environments.

**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 microcontrollers. NVIDIA's proprietary software uses ioctl interface to communicate 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 included a creating virtual address space, a allocating indirect buffer object for command sending, and a creating context object. The virtual address space is used for managing the GPU device memory space and kernel memory space (Host-side) such as indirect buffer. The indirect buffer is an area of storing GPU commands for sending GPU commands. The context object is need to use a FIFO engine that is microcontroller for receiving commands, specifically, creating context object does preparation for use the FIFO engine, such as allocating kernel memory object and mapping FIFO engine register to host memory space by memory-mapped I/O. The Notify processes send commands to the compute engine or the copy engine by iowrite commands to mapped FIFO register. This independent generating synchronization sign for synchronization mechanisms is using reverse engineering. However, the method has limitation because the method depends on the proprietary 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.

The Linux kernel has structures 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) [11], [36]. Therefore, Linux-RTXG remaps the BAR0 to our allocated space by using *ioremap()* when the ISR is initializes. The interrupt interception identifies interrupt by reading the mapped-space.

### 3.4 Scheduler Integration

Linux scheduler has 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 scheduling performance. Scheduling experiments are limited on the GPU scheduling since CPU scheduling performance is already experiments [22]. In this evaluation, we focus two point. The one is to indicate the Linux-RTXG disadvantages. The other one is demonstrating QoS performance.

GPU using Real-world oriented applications[2], [3] are executed cyclic. These evaluation applications are equivalent to the real-world oriented applications because GPU applications characteristics are these application on the single GPU kernel. We will discuss for the difference between the functions and features to hold to it with a qualitative evaluation in the next chapter.

TODO:GPUSyncと比較しなくて良いのか

### 4.1 Experimental Environment

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

We measurement overhead due to interrupt interception. This experiment use GPU driver which is used the Nouveau in order to compare and identify the type of interrupt. We compare consumption time from the start ISR until ISR is completion, it consumption time is average time of 1000 times.

Figure 4.2 shows results of measurements in the above setting. Raw ISR is execute ISR in the

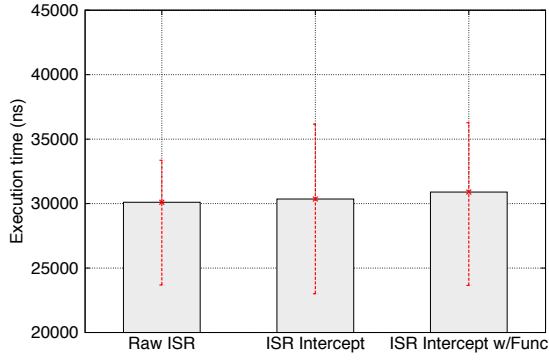


Fig. 5. Interrupt intercept overhead

normal routine, ISR Intercept is only intercept our approach, ISR intercept w/Func is interception and processing functions that are identify the ISR and wakeup the scheduler thread. These are showed the average times with error bar is indicate minimum and maximum.

As a result, the overhead exist certainly. ISR Intercept has overhead that is about 247 nano seconds. ISR Intercept w/Func also has overhead that is about 790 nano seconds.

Intuitively, it value does not affect system since very small values, however, interrupt is occur frequently including such as timer interrupt, should be aware as disadvantages.

In addition, we evaluate comparing the response time of the ISR (top-half) and the tasklet (bottom-half) in an environment with noCPU load, it evaluate does measurement time until the responsible timing from the start of interrupt process which is *do\_IRQ* function is called). it measurement result is shown in Figure 4.2.

GPUSync bypass the *tasklet\_schedule()* if it function is called from the nvidia driver. The tasklet is generally called after the important procesing in ISR. It approach has robustness, but response is worse than ISR, it response can be seen from Figure 4.2.

### 4.3 Independent Synchronization mechanism overhead

We evaluate the overhead according to using independent synchronization mechanism. The our method is need to call the *rtx\_nvrn\_notify()* at the timing of requested

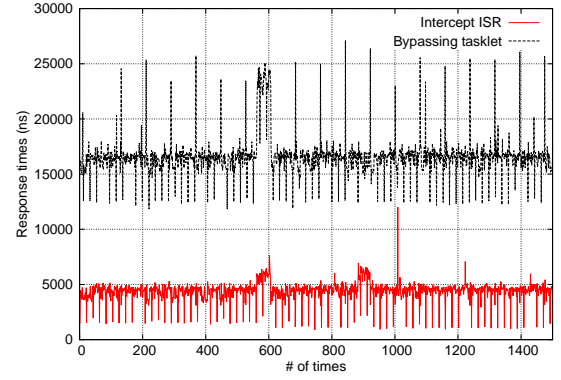


Fig. 6. Comparison of the response time of the interrupt top-half and bottom-half

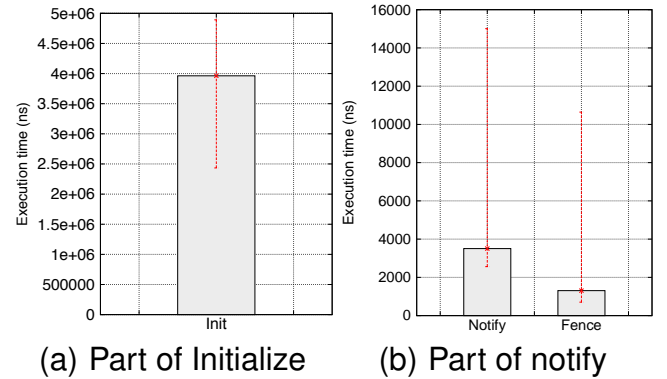


Fig. 7. Interrupt raised method overhead

synchronization (e.g. after the kernel launch issue). In vanilla environment, these api is not necessary, therefore, time the API consumed is overhead.

We measured overhead by measuring the API consumed time between API call and return.

As a result shown in Figure 7. Initialize is need to called the at awaken a linux process for allocating a indirect buffer and register several compute engine to the device driver. Notify and Fence areGPU command sending to GPU devices which called at timing of the need to synchronization such as after the kernel launch issues. These methods execution time is variants occurred affected by ioctl system call.

Initialize average time is about 4 mill seconds, however, application is not affected too much because above characteristics is only called once. Notify is not takes much time that



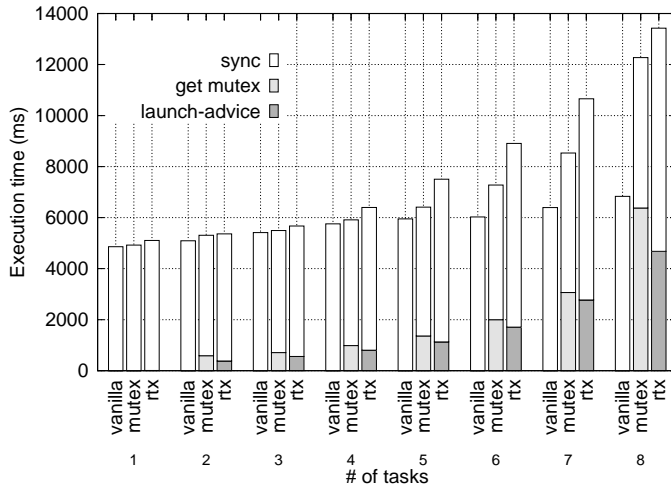


Fig. 8. Scheduling overhead(between GPU kernel launch request and synchronization)

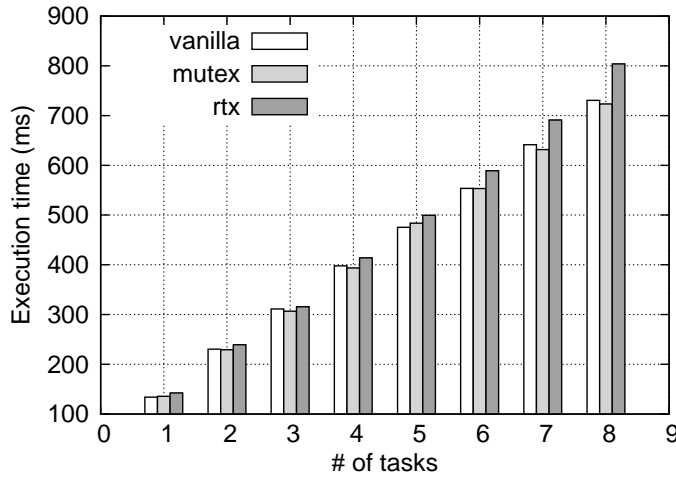


Fig. 9. Scheduling overhead (Time of entire task)

is about 3.5s. Fence likewise be not takes much time that is about 2s. Although may be not have to worry about for most applications, it is necessary to consider the overhead in a cycle of short application.

#### 4.4 Scheduling Overhead

We will evaluate scheduling overhead by using Linux-RTXG scheduler. We prepared three applications that are "vanilla", "mutex", and "rtx" for measurement overheads. These applications is based common application based on Gdev's microbenchmark which has GPU looping function. Changes are arranged to generate multiple

GPU tasks by the fork. Each tasks have 10 jobs, a job is included GPU data transferring and a GPU kernel execution.

The "rtx" application is scheduled by rtx. The "mutex" application is limited to single kernel issue similar to scheduling environment. The "vanilla" application is not to change the base application.

CPU scheduling policies is using the simple fixed-priority scheduling by Linux-RTXG similar to Linux's **SCHED\_FIFO** that difference is the presence or absence of the job management. GPU scheduling policies is fixed-priority scheduling with resource reservation which is BAND scheduling policy. The synchronization is using NOTIFY of independent synchronization mechanism.

We measured the average time in each part of each job of, 100 times GPU task execution (1000 jobs). As a result show in Figure 4.4. The "launch\_advice" is time of until GPU kernel launch request is accept on the Linux-RTXG. The "mutex" is time to get the mutex lock. The "sync" is time of until synchronization from issued the GPU kernel launch issue.

#### 4.5 Performance of QoS management

Next experiments are evaluating QoS management performance. In this evaluate, we measure the utilization of each tasks on the several environments. Thereby, we indicates performance that is not falling by not modify kernel.

The application utilizes the same as those used in the previous experiment. In the performing QoS management, tasks are four generated as a setting. E

each tasks assigned to VGPU one by one, and each VGPU is provided a GPU resource 25%.

The first, we experiment the utilization using only priority scheduling, we prepare four different priorities GPU task. As a result is showed in Figure ???. We can see the the task has been used in order of priority in Figure ??.

The second, we demonstrate performance of Linux-RTXG QoS management by using NVIDIA's proprietary software. Maximum utilization is Minimum

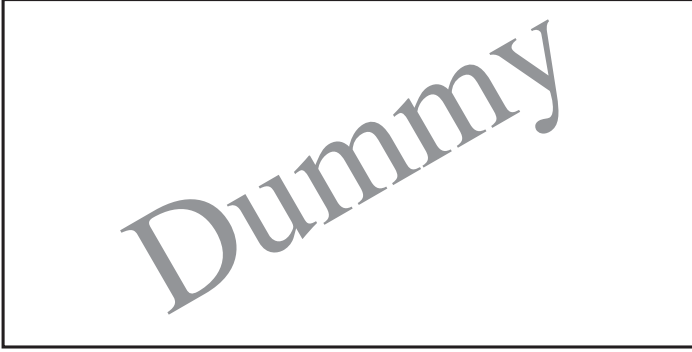


Fig. 10. Utilization of two tasks on the Linux-RTXG's FIFO VGPU scheduling and the using Nvidia drivers. Each tasks have a different workload.

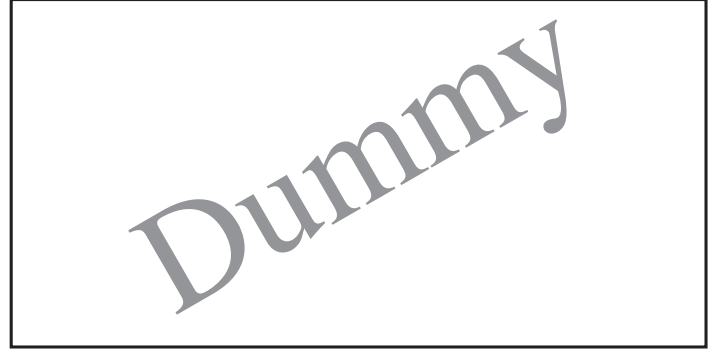


Fig. 12. Utilization of two tasks on the Linux-RTXG's FIFO VGPU scheduling. Each tasks have a different workload.

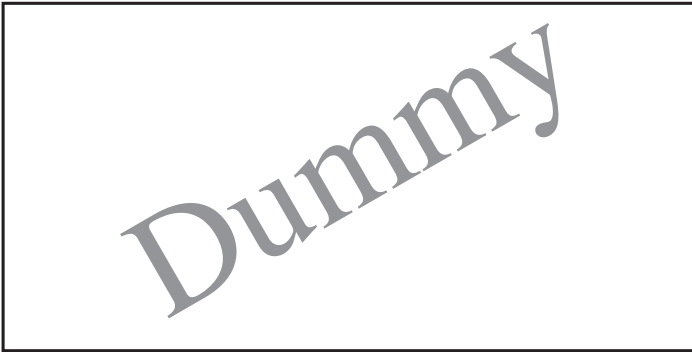


Fig. 11. Utilization of two tasks on the Linux-RTXG's BAND VGPU scheduling and the using Nvidia drivers. Each tasks have a different workload and a different resources.

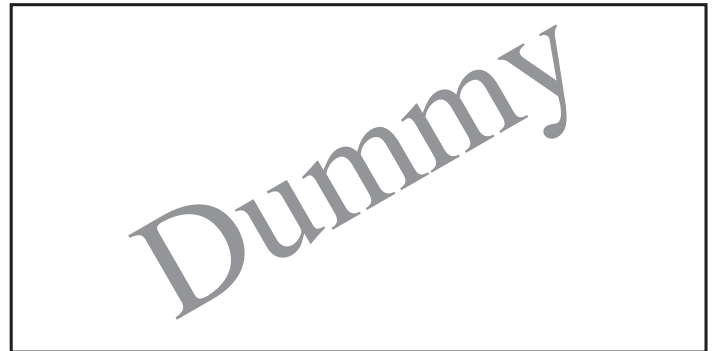


Fig. 13. Utilization of two tasks on the Linux-RTXG's BAND VGPU scheduling. Each tasks have a different workload and a different resources.

Next then, we demonstrate and compare the performance of the Linux-RTXG QoS management and the Gdev's QoS management by using Gdev's library and Nouveau's open-source driver. Figure ?? show experimental results of each tasks utilization on the Linux-RTXG QoS management and the Gdev QoS management.

A maximum utilization of Linux-RTXG is less than to  $x\%$ , while a minimum utilization of Linux-RTXG is more than to  $x\%$ . A maximum utilization of Gdev is less than to  $x\%$ , while a minimum utilization of Gdev is more than to  $x\%$ . Distribution of Linux-RTXG is  $x$ . Therefore, the synchronization mechanism of Linux-RTXG excluding kernel modification, it is show that possible scheduling without sacrificing perfor-

mance.

## 5 RELATED WORK

RGEM and GPU-Sparc [28] have GPU resource management without modification of the kernel and device drivers. However, synchronization mechanism of these work depends on proprietary-software. TimeGraph, Gdev, Ptask, and GPUSync are realized independent synchronization mechanisms for modifying the kernel and devie drivers. To our knowledge, Linux-RTXG is the only real-time GPU framework using a synchronization mechanism that is independent of the runtime while it was not modified the kernel and device drivers.

TABLE 2  
Linux-RTXG vs prior work

	CPU		GPU		Budget Enforcement	Data/Comp. Ovlp.	Closed Src. Compatible	Kernel Free	OS independent	GPU Runtime independent
	FP	EDF	FP	EDF						
RGEM			x				x	x	x	
Gdev			x		x	x				
PTask			x		x	x	x			x
GPUSync	x	x			x	x	x			x
GPUSparc			x			x	x		x	
Linux-RTXG	x	x	x		x	x	x	x	x	x

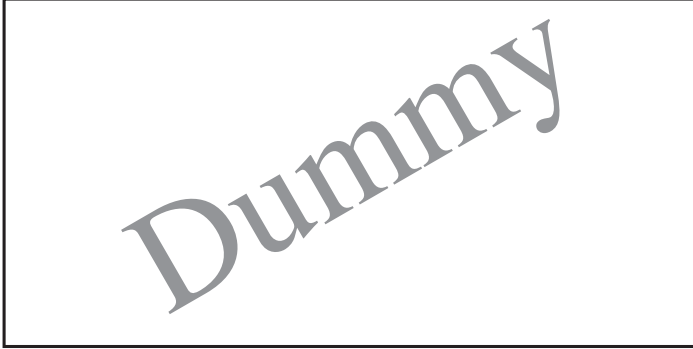


Fig. 14. Utilization of four tasks on the Linux-RTXG's BAND VGPU scheduling. Each tasks have a fair workload and a fair resources.

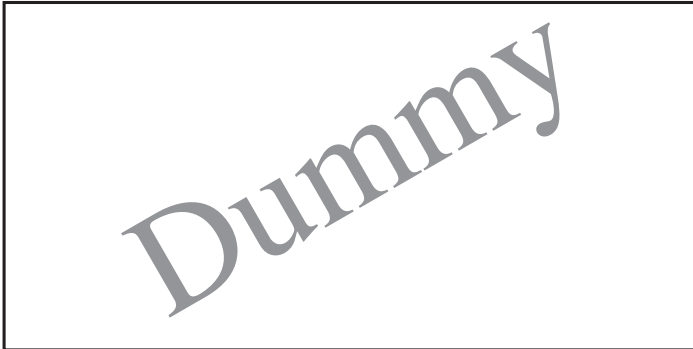


Fig. 15. Utilization of four tasks on the Linux-RTXG's BAND VGPU scheduling. Each tasks have a different workload and a different resources.

Table 2 shows that result of comparing the Linux-RTXG and prior work. GPUSync mentioned that GPU task dependent to CPUs scheduling, and supports CPU scheduling policies that are the Fixed-Priority scheduling and the EDF scheduling. GPUSparc have setting

of scheduling priorities that is Linux scheduling policies of *SCHED\_FIFO*. All exsisting researchs support to FP scheduling, but not support EDF. Linux-RTXG is meet the all of things except the GPU. Specially, Linux-RTXG's contribution is meet to both GPU runtime independent and OS independent.

The more-depth resource management would require the detail executing mechanisms in the black-box GPU stack. Menychtas et al. present enabling GPU using OS research by inferring interaction in the black-box GPU stack [37]. We present information of GPU microcontrollers [33] and an open-source GPGPU runtime [10]. GPUSync presents details verification information on the proprietary runtime mechanisms. Nouveau project provides an open-source GPU driver [35]. These works are very important, and we will also views of the further development of resource management their researches.

## 6 CONCLUSION

This paper has presented Linux real-time extension for CPU-GPU resouce coordination is called Linux-RTXG for CPUs and GPUs coordinated resource management. We focus on that are specifically not modify the kernel, worked for GPU resource management. Linux-RTXG presented the CPU task scheduling, the GPU task sheduling and the GPU resource reservation mechanisms. The CPU task scheduling is based on RESCH. The GPU task scheduling provides prioritized scheduling by our synchronization mechanisms. Our synchronization mechanisms are not need to modify the kernel and device drivers, presented by intercept interrupt top-half ISRs.

We indicated a unit of job overhead met within about  $x\%$ , and unit of task met overhead within  $x\%$ . In addition, we the evaluations demonstrated that the QoS management performance without kernel modification by comparing Linux-RTXG and Gdev. The basic scheduling framework has already completed to realized real-time GPU computing. Future work will address GPU execution such as pre-emption, and p2p migration to deal with more complex real-time problems.

## REFERENCES

- [1] M. McNaughton, C. Urmson, J. Dolan, and J.-W. Lee, "Motion planning for autonomous driving with a conformal spatiotemporal lattice," in *Proc. ICRA*. IEEE, 2011, pp. 4889–4895.
- [2] M. Hirabayashi, S. Kato, M. Eda Hiro, K. Takeda, T. Kawano, and S. Mita, "GPU implementations of object detection using HOG features and deformable models," in *Proc. Int. Conf. CPSNA*. 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 *Proc. RTAS*. IEEE, 2011, pp. 191–200.
- [5] P. Bakum and K. Skadron, "Accelerating SQL database operations on a GPU with CUDA," in *Proc. Workshop GPGPU*. 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 *Proc. IISWC*. 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. Comput.*, vol. 12, no. 3, pp. 66–73, 2010.
- [9] S. Kato, K. Lakshmanan, R. R. Rajkumar, and Y. Ishikawa, "TimeGraph: GPU scheduling for real-time multi-tasking environments," in *Proc. USENIC ATC*, 2011, p. 17.
- [10] S. Kato, M. McThrow, C. Maltzahn, and S. A. Brandt, "Gdev: First-Class GPU Resource Management in the Operating System," in *Proc. USENIC ATC*, 2012, pp. 401–412.
- [11] Y. Fujii, T. Azumi, N. Nishio, S. Kato, and M. Eda Hiro, "Data transfer matters for GPU computing," in *Proc. ICPADS*. IEEE, 2013, pp. 275–282.
- [12] G. A. Elliott, B. C. Ward, and J. H. Anderson, "GPUSync: A framework for real-time GPU management," in *Proc. RTSS*. IEEE, 2013, pp. 33–44.
- [13] G. A. Elliott and J. H. Anderson, "Exploring the Multi-tude of Real-Time Multi-GPU Configurations," in *Proc. RTSS*. IEEE, 2014.
- [14] J. Calandrino, H. Leontyev, A. Block, U. Devi, and J. Anderson, "LITMUS RT : A Testbed for Empirically Comparing Real-Time Multiprocessor Schedulers," in *Proc. RTSS*, 2006, pp. 111–126.
- [15] J. A. Stankovic and K. Ramamritham, "The spring kernel: A new paradigm for real-time systems," *IEEE Softw.*, vol. 8, no. 3, pp. 62–72, 1991.
- [16] 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 *Proc. OSDI*, vol. 8, 2008, pp. 73–86.
- [17] H. Monden, "Introduction to ITRON the industry-oriented operating system," *IEEE Micro*, vol. 7, no. 2, pp. 45–52, 1987.
- [18] 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.
- [19] S. Oikawa and R. Rajkumar, "Portable RK: A portable resource kernel for guaranteed and enforced timing behavior," in *Proc. RTAS*. IEEE, 1999, pp. 111–120.
- [20] P. Mantegazza, E. Dozio, and S. Papacharalambous, "RTAI: Real time application interface," *Linux J.*, vol. 2000, no. 72es, p. 10, 2000.
- [21] V. Yodaiken, "The RTLinux Manifesto," in *Proc. Fifth Linux Expo*, 1999.
- [22] S. Kato, R. Rajkumar, and Y. Ishikawa, "A loadable real-time scheduler suite for multicore platforms," Tech. Rep. CMU-ECE-TR09-12, Tech. Rep., 2009.
- [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, 1973.
- [24] —, "Scheduling algorithms for multiprogramming in a hard-real-time environment," *J. ACM*, vol. 20, no. 1, pp. 46–61, 1973.
- [25] L. Abeni and G. Buttazzo, "Integrating multimedia applications in hard real-time systems," in *Proc. RTSS*. 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 *Proc. ECRTS*, 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," Tech. Rep., 2014.
- [29] F. Ridouard, P. Richard, and F. Cottet, "Negative results for scheduling independent hard real-time tasks with self-suspensions," in *Proc. RTSS*. 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 *Proc. Int. Conf. RTNS*. 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 *Proc. RTSS*. IEEE, 2013, pp. 246–257.
- [33] Y. Fujii, T. Azumi, N. Nishio, and S. Kato, "Exploring

microcontrollers in GPUs,” in *Proc. APSys*. ACM, 2013, p. 2.

- [34] G. A. Elliott and J. H. Anderson, “Robust real-time multiprocessor interrupt handling motivated by GPUs,” in *Proc. ECRTS*, 2012, pp. 267–276.
- [35] “Nouveau,” <http://nouveau.freedesktop.org/wiki/>, accessed January 12, 2015.
- [36] S. Kato, J. Aumiller, and S. Brandt, “Zero-copy I/O processing for low-latency GPU computing,” in *Proc. Int. Conf. ICCPS*. ACM, 2013, pp. 170–178.
- [37] K. Menychtas, K. Shen, and M. L. Scott, “Enabling OS Research by Inferring Interactions in the Black-Box GPU Stack.” in *Proc. USENIX ATC*, 2013, pp. 291–296.

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