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—Computer Society, IEEEtran, journal, LaTeX, paper, template.

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.

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 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 [12] is evaluating the data transfer time between the host and the device.

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

However, GPUSync is implemented on the $LITMUS^{RT}$ [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 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 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 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 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, demonstrate 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

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.

GPU applications use a set of the API supported by the runtime environment such as CUDA, typically GPU application taking 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

A 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], [23] 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[24] and Earliest Deadline First[25]) with technique to prevent priority inversion, and the second is resource reservation based scheduling (e.g. Constant Bandwidth Server[26], Total Bandwidth Server[27]). 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[28], [29] 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[30], [31], several researches[32], [33] 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 platoform. 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], [34].

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

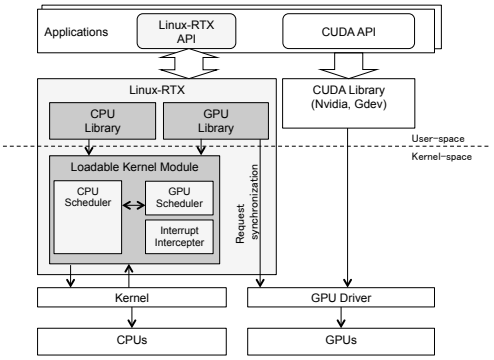


Fig. 1. Over view of the Linux-RTXG

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. GPU tasks may be provided with a function by calling an Linux-RTXG's API at strategic points.

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 awaken while the interrupt intercepter

TABLE 1
Basic Linux-RTXG APIs

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

Fig. 2. sample code of using rtxg scheduler

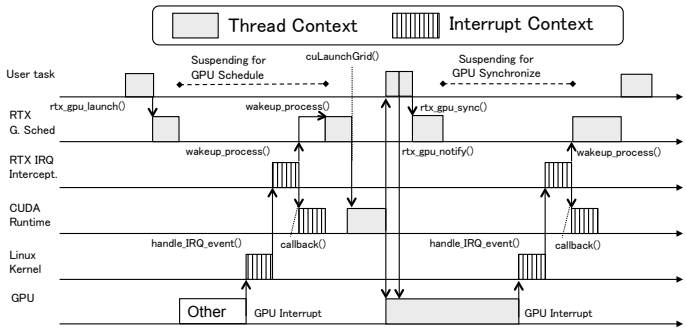


Fig. 3. GPU Scheduling control flow

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 the GPU task is requested GPU kernel launch issue. In $on_arrival$, 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.

$on_completion$ is called by the scheduler thread, when the GPU kernel is completion. In $on_completion$, 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 re-

```
  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

source management for to realized 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 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 readling 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], [36]. Therefore Linux-RTXG remap the BAR0 to our allocated space by using $ioremap()$ when the ISR initizalize. 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 scheduling performance.

Scheduling experiments are limited on the GPU scheduling since CPU scheduling performance is already experiments[**?**].

In this paper, we experiments

本稿における評価では、本Linux-RTXGを利用した際のオーバ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。

TODO:GPUSync と比較しなくて良いのか

TODO:実アプリで動かすとどうなるのか

We will discuss in the next chapter for the difference between the functions and features to hold to it with a qualitative evaluation.

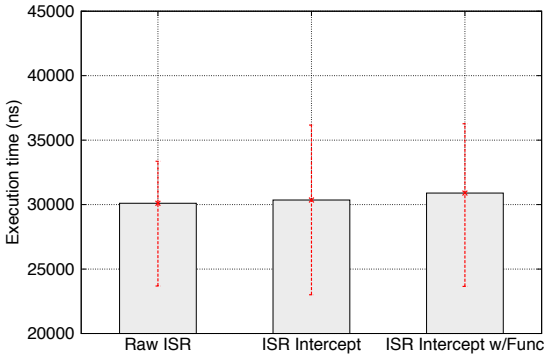


Fig. 5. Interrupt intercept overhead

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.

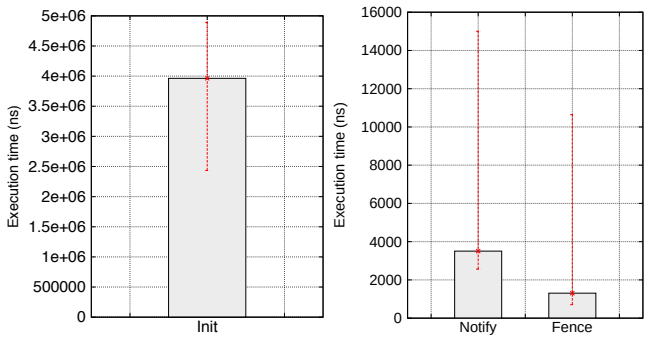
4.2 Interrupt intercept overhead

We mesurement 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 **??** shows results of mesurements in the above setting. Raw ISR is execute ISR in the normal routine, ISR Intercept is only intercept our approach, ISR intecept 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



(a) Part of Initialize (b) Part of notify

Fig. 6. Interrupt raised method overhead

occured frequently including such as timer interrupt, should be aware as disadvantages.

In addition, we measure the response time of the ISR (top-half) and the tasklet (bottom-half) in an environment with no load, it mesasurement result is shown in Figure **??**.

4.3 Independent Synchronization mechanism overhead

We evaluate the overhead according to using independent synchronization mechanism. The our method is need to call the $rtx\_nvrm\_notify()$ at the timing of requested 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 6. 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 is 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 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なため、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。

4.4 Scheduling Overhead

rtx でスケジューリングした場合のオーバ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 linxu-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、各ジョブ内のラウンチ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、許可がで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 Performance of 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無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

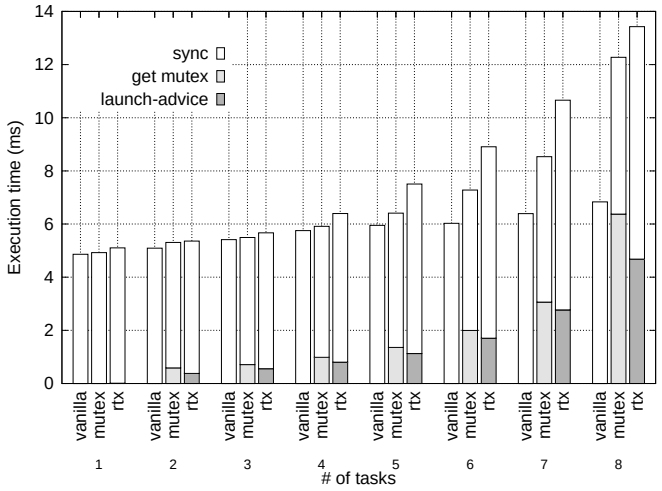


Fig. 7. Scheduling overhead(between GPU kernel launch request and synchronization)

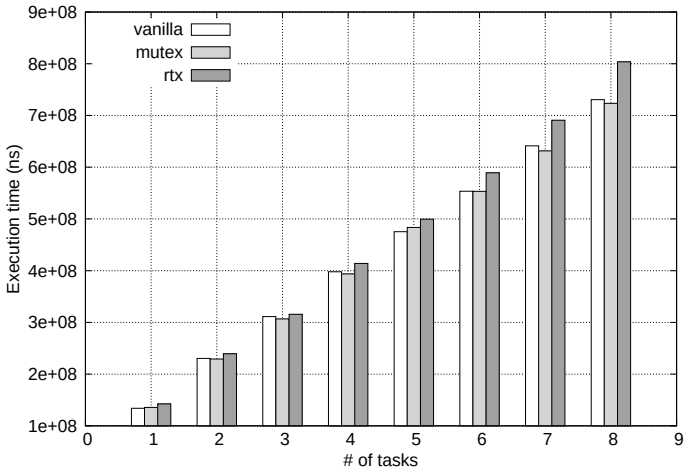


Fig. 8. Scheduling overhead (Time of entire task)

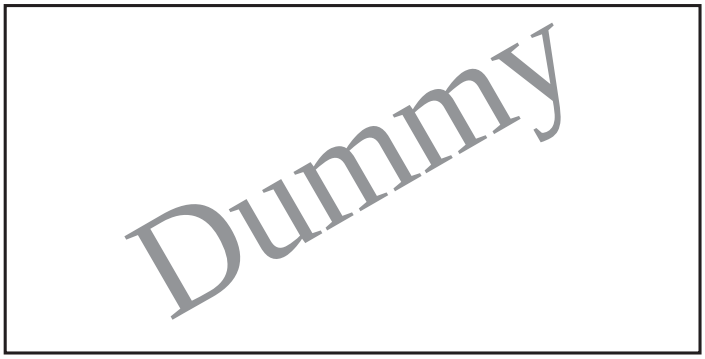


Fig. 9. Utilization of four tasks on the Linux-RTXG only priority scheduling. Each tasks are given different priorities.

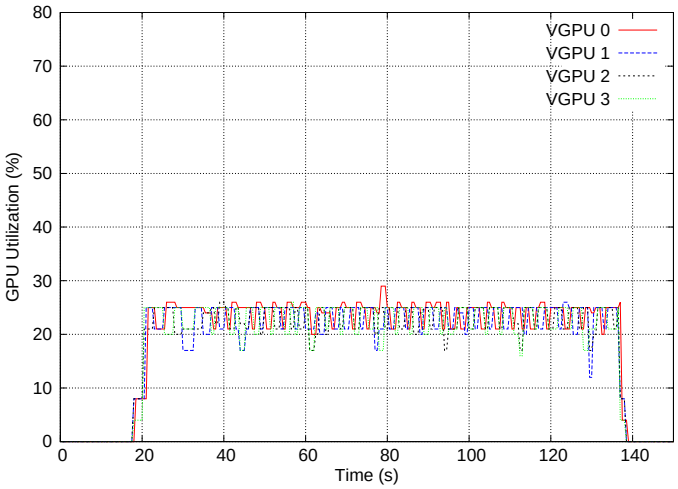


Fig. 10. Utilization of four tasks on the Linux-RTXG resource reservation. Each tasks are given different priorities and all tasks are fairly given resources which is 25%

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で 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.

The first, we experiment the utilization using only priority scheduling, we prepare four different priorities GPU task. It experiments result show in Figure 4.5.

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

5 Related Work

Comparison of prior work: RGEM and GPU-Sparc[29] have GPU resource management with not modify the kernel and device drivers. However, these work use sycnhronizations

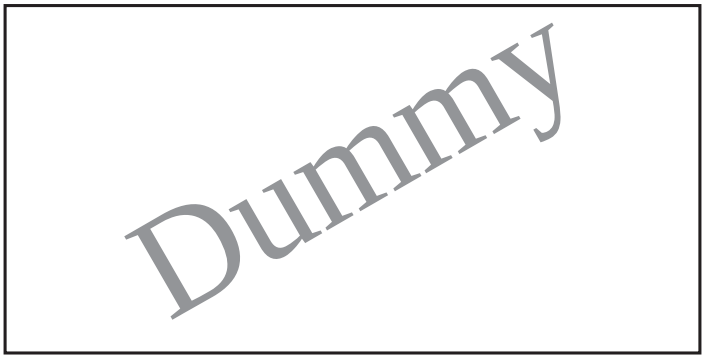


Fig. 11. Utilization of four tasks on the Gdev resource resevation. All tasks are fairy given resources which is 25%

that are depended 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 modificated the kernel and device drivers.

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 resouce coordination is 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. Linux-RTXG present 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 is not need to modify the kernel and device drivers, presented by intercept interrupt top-half ISRs.

TODO:評価結果について: TODO:overhead: 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 の性能を検証し多少の性能低下で収まることを確認した。TODO:qos management

TODO:結果について終わり

The Basic frame of scheduling framework is already completion for realized real-time GPU. In the future work, Be addressed to improvement GPU execution (preemptive, p2p migration) is essensial matter in order to more real-time framework.

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TABLE 2
Linux-RTXG vs prior work

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

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