Achieving Predictable Timing and Fairness Through Cooperative Polling

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Yet another new scheduler?!

- Scheduling Challenges in a General Purpose OS
- Earlier Attempts to Address the Issues
- The Vanilla $O(1)$ Scheduler

Outline

1. Yet another new scheduler?!
   - Scheduling Challenges in a General Purpose OS
   - Earlier Attempts to Address the Issues
   - The Vanilla $O(1)$ Scheduler

2. Our Design Objectives

3. Our Approach
   - The Design of Our Scheduler
   - The Algorithms
   - The Implementation

4. Evaluation
   - Fairshare Evaluation
   - Cooperative Polling (+ policing) Evaluation
   - Pure Fairshare Vs Cooperative Polling
   - Experiments with High Definition Video

5. Summary
Multimedia capable (soft) realtime applications are increasingly becoming common.

Many of these applications are *adaptive*:
- They consume as much CPU resources as are available.
- Adaptive tasks keeps the system overloaded at all times (when adaptation is active).

They are *peculiar*:
- They are *time-sensitive*:
  - Have specific deadlines for doing certain jobs.
- They are often *both* IO intensive with considerable CPU requirements.

Other kinds of mixed workloads (e.g., security enabled web-servers, databases) are also common.
Challenges for a task scheduler therefore are as follows:

- Provide a good balance of overall throughput and timeliness.
- Uphold work conservation
  - Maximum utilization of available CPU resources.
- Allow graceful & coordinated adaptation.
- Avoid starvation.
- Use an effective strategy for load balancing in SMP environments.

We do not address the last issue in this work.
Earlier Attempts to Address the Issues

The space of multimedia scheduling for general purpose OS is well explored:

Related Works

- SMART: Jason Nieh and Monica S. Lam. The design, implementation and evaluation of SMART: a scheduler for multimedia applications. SOSP 1997.
Earlier Attempts to Address the Issues

The drawbacks

- Use of complicated schedulability analysis and/or kernel-userspace interaction mechanism.
- Use of some notion of priorities that can lead to starvation.
- Dependence on CPU reservations (or assumption of underloaded system) for providing better timing.
  - Throw away work conservation.
The Vanilla $O(1)$ Scheduler

**The $O(1)$ Scheduler Overview**

- Uses multi-level feedback queue scheduling algorithm.
- Uses static (nice levels) and dynamic priorities.
  - Affected by starvation and live locks.
- Is not particularly effective for mixed IO and CPU bound workloads.
- Has rather large timeslices for high priority IO bound jobs (800 ms).
- Uninformed preemptions leads to poor adaptations.
  - No mechanism to achieve coordinated adaptation for adaptive workloads.

We do not discuss the new 2.6.23 CFS scheduler in this work.
The Vanilla \( O(1) \) Scheduler

The \( O(1) \) Scheduler Performance

Six VLC players playing one video each on Vanilla 2.6.20 Kernel

![Graph showing frame rate over video position](image-url)
The Vanilla $O(1)$ Scheduler

The $O(1)$ Scheduler Performance

Six VLC players playing one video each on Vanilla 2.6.20 Kernel

Frame Jitter
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5. Summary
Our Scheduler Design Objectives

Our scheduler tries to satisfy the following objectives:

- Have overall long term fairness in the system.
- Have predictable timeliness (within the bounds of fairness) even in overload.
- Allow time sensitive applications to cooperate.
  - Cooperation helps to achieve coordinated adaptation.
  - Cooperation provides better timeliness.
- Uncooperative, misbehaving cooperative tasks should be policed.
- Achieve a good balance of throughput and responsiveness.
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5. Summary
The Design of Our Scheduler

Design Highlights

- Fairshare scheduler based on virtual time to schedule all tasks.
  - Ensures long term fairness.
  - *Borrowing* prevents accumulation of virtual time.
- All time sensitive tasks form a cooperation group.
  - A common virtual time for the whole group.
  - No fairsharing or allocation enforcement within the group.
  - Tasks in the cooperation group cooperate with one another through kernel using `coop_poll` primitive.
  - Tasks within cooperation group are scheduled based on their deadlines and best effort priorities.
- Preferential treatment and policing of cooperative tasks by fairshare scheduler.
The Design of Our Scheduler

The coop_poll() Primitive

- `coop_poll(IN, OUT)`
  - **IN**: Most important deadline and best effort priority event of the current task.
  - **OUT**:
    - Most important deadline of all the external time sensitive tasks *or* the fairshare policing deadline, whichever is earlier.
    - Best effort event of all the external time sensitive tasks.

- **Kernel Responsibility**:
  - Resume the task when:
    - IN parameter deadline has expired (preferential treatment) or
    - IN parameter best effort is most important.

- **Task Responsibility**:
  - Treat the OUT events as it’s own
  - yield back to kernel using `coop_poll` when they fire.
The Design of Our Scheduler

Scheduling Overview

Step 1: Cooperative tasks inform the kernel their most important event parameters.

Step 2: The kernel inserts this information in its own event queue containing event info. for all coop-tasks.

Step 3: The kernel chooses the next task to run by inspecting the head of the virtual time queue. The task with smallest virtual time gets chosen.

Step 4: If a cooperative task is selected from the virtual time queue, the kernel selects the task that is at the top of the coop event queue. It calculates the task's timeslice based on the nearest deadline of other coop tasks.

Step 5: Kernel informs the task of the next most important event of the other coop tasks.
The Algorithms

The Main Kernel Scheduler

Algorithm: `schedule()`

Global `TimeVal` `sched_granularity`;
Global `TimeVal` `sched_min_timeslice`;
schedule() {
    prevTask = currentTask;
    if (fsTimerActive == FALSE) {
        safely_charge_running_times(prevTask);
        nextTask = choose_next_task();
        nextTask.timeslice_start = now;
        TimeVal timeslice = calculate_timeslice();
        schedule_timer(timeslice);
        nextTask.sched_deadline = now + timeslice;
    } else {
        nextTask = prevTask;
    }
    if (nextTask != prevTask) {
        context_switch(prevTask, nextTask);
    }
}
The Algorithms

Choosing the Next Task

Algorithm: choose_next_task()

choose_next_task() {
    nextTask = q_head(Wfq);
    if (nextTask.sched_dom == COOP_DOM) {
        nextTask = choose_next_coop_task();
    }
    return nextTask;
}
Choosing the Next Time Sensitive Task

Algorithm: `choose_next_coop_task()`

```c
choose_next_coop_task() {
    if (head_expired(CoopDomain.dead_ev)) {
        nextDeadEv = q_head(CoopDomain.dead_ev);
        return task(nextDeadEv);
    } else if (q_not_empty(CoopDomain.be_ev)) {
        nextBeEvent = q_head(CoopDomain.be_ev);
        return task(nextBeEvent);
    } else {
        return ERR;
    }
}
```
The Algorithms

Calculating Timeslice

**Algorithm: cal_Tslice()**

cal_Tslice(nextTask, &Tslice) {
    fsPrd = find_fs_prd();
    coopPrd = earliestCoopDead - now;
    if (coopPrd < 0) coopPrd = 0;
    nextDeadTask = find_earliest_deadline_task();
    if (nextTask.virtual_time + coopPrd <
        nextDeadTask.virtual_time) {
        timeDelta = nextDeadTask.virtual_time
                  - (nextTask.virtual_time
                    + coopPrd);
        coopPrd = coopPrd + timeDelta;
    }
    Tslice = max(min(fsPrd, coopPrd), minTslice);  
}
Implementation Overview

- Implementation on 2.6.20 kernel + highres timers
  - High resolution timers for timeslice enforcement.
  - Use of fine grained time accounting in the kernel.
- Binary heaps for our runqueue.
  - Tasks sorted based on their virtual time.
  - Also two heaps for sorting the time sensitive tasks based on deadlines and best effort priorities.
  - Heaps implemented with existing kernel runqueue - no separate locking mechanism needed.
- A new system call coop_poll().
- We override the vanilla kernel scheduling decision with ours.
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Evaluation Strategy

- Use a broad spectrum of load conditions: underloaded to fully overloaded.
- Vary the # of Qstream applications for varying the load.
  - 6 players => CPU just saturated. 12 players => complete saturation.
  - Qstream is a mixed CPU and IO intensive workload.
  - The challenge => achieve coordinated adaptations with graceful degradation.
- Qstream server run on a different machine.
  - Server load has no impact on the client performance.
- Enough memory & network bandwidth to handle 12 players - no memory pressure.
- Stray applets and services on client disabled.
Evaluation of Fairshare Scheduling

Salient Points of the Experiment

- Qstream applications run as best effort task under the fairshare scheduler.
- No cooperation between applications.
- Frame display disabled.
  - Xserver has coarse grained event dispatch mechanism - perturbs our results.
  - Effects of Xserver eliminated.
Yet another new scheduler?! Our Design Objectives

Our Approach

Evaluation

Summary

Fairshare Evaluation

Results

Dispatcher Latency
Throughput vs Monolithic (single player case)

- **Throughput** vs. **Monolithic** (single player case)
- **Relative Throughputs**
- **# of Videos**
- **FPS throughput as % of single player throughput.**

- **Timeslice: 1 ms**
- **Timeslice: 10 ms**
- **Timeslice: 15 ms**
- **Timeslice: 20 ms**
- **Timeslice: 5 ms**

---

**Results**

- Fairshare Evaluation
- Evaluation
- Summary
Fairshare Evaluation

Results

Context Switch Rate

- Global kernel context switches per second.
- Timeslice: 1 ms
- Timeslice: 10 ms
- Timeslice: 15 ms
- Timeslice: 20 ms
- Timeslice: 5 ms

Context Switches
Yet another new scheduler?! Our Design Objectives

Our Approach

Evaluation

Summary

Cooperative Polling (policing) Evaluation

Evaluation of Cooperative Polling Algorithm with Policing

Salient Points of the Experiment

- Qstream applications cooperate with each other through kernel using `coop_poll()` system call.
- It's a homogeneous environment - all of the applications are well behaved.
- Frame display disabled.
  - Effects of Xserver eliminated.
Cooperative Polling (+ policing) Evaluation

Results

Dispatcher Latency

Average Tardiness (ms) vs. # of Videos

- Timeslice: 1 ms
- Timeslice: 5 ms
- Timeslice: 10 ms
- Timeslice: 15 ms
- Timeslice: 20 ms
Cooperative Polling (+ policing) Evaluation

Results

Throughput vs Monolithic (single player case)

![Graph showing throughput comparison]

- FPS throughput as % of single player throughput.
- # of Videos
- Relative Throughputs
- Timeslice: 1 ms
- Timeslice: 10 ms
- Timeslice: 15 ms
- Timeslice: 20 ms
- Timeslice: 5 ms
Cooperative Polling (+ policing) Evaluation

Results

Context Switch Rate

![Context Switch Rate Chart]

- Global kernel context switches per second.
- # of Videos
- Context Switches

- Timeslice: 1 ms
- Timeslice: 10 ms
- Timeslice: 15 ms
- Timeslice: 20 ms
- Timeslice: 5 ms

Anirban (Ani) Sinha

M.Sc Thesis Presentation
Cooperative Polling (+ policing) Evaluation

Results

Frame Rates

Frame Rate for 12 videos with Xserver run as best effort task.
## Pure Fairshare Vs Cooperative Polling

**Cooperative Scheduling is Better Than Pure Fairsharing**

### Results with 10 players

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Fairshare Scheduler (1 ms period)</th>
<th>Coop Scheduler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispatcher Latency</td>
<td>4.3 ms</td>
<td>0.9 ms</td>
</tr>
<tr>
<td>Context Switches</td>
<td>9430 /sec</td>
<td>4766 /sec</td>
</tr>
<tr>
<td>Throughput as % of single player</td>
<td>87%</td>
<td>95%</td>
</tr>
</tbody>
</table>
Experiments with High Definition Video

Performance Evaluation with High Definition Video

Salient Points of the Experiment

- A single Qstream player playing a 1080p high definition video, 679.2 kbyte/s bit-rate and 25 FPS.
  - The single video alone can take 70% of CPU.

- A best effort video encoding job run in parallel to completely saturate the CPU.

- Represents a common scenario where users watching a high definition video perform some video/audio encoding work in parallel.

- Xserver run as a best effort task in our fairshare scheduler.
  - Scheduled according to vanilla heuristics on the vanilla kernel.
Experiments with High Definition Video

Results

Dispatcher Latency as a function of global scheduling period

![Graph showing the relationship between scheduling granularity (timeslice) and average tardiness and dispatcher latency.](image-url)
Experiments with High Definition Video

Results

**FPS throughput as a function of scheduling period**

![Graph showing FPS throughput as a function of scheduling period.](attachment:image.png)

- Average FPS
- Scheduling granularity (timeslice) ms

**Graph Details:**
- X-axis: Scheduling granularity (timeslice) in milliseconds
- Y-axis: FPS Throughput
- Line graph showing constant throughput across different scheduling periods.
Results

Context switch rate as a function of scheduling period

- **X-axis:** Scheduling granularity (timeslice) ms
- **Y-axis:** Global kernel context switches per second

The graph illustrates how the context switch rate decreases as the scheduling granularity increases. This suggests that finer scheduling periods result in fewer context switches, potentially improving system efficiency.
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Summary

- Fairshare scheduling alone provides a baseline performance proportional to global period.
- The cost of smaller period and finer grained scheduling is high context switch overhead.
- Cooperative polling can provide improved timeliness with reduced context switch overheads.
  - Informed context switches are less expensive.
  - Helps to achieve coordinated adaptation.
- Policing through fairsharing ensures long term fairness in the system with no starvation.
Project Resources

<table>
<thead>
<tr>
<th>Everything is Open Source!</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project URL:</strong> <a href="http://dsg.cs.ubc.ca/coopfsched">http://dsg.cs.ubc.ca/coopfsched</a></td>
</tr>
<tr>
<td>Contains project updates, publications and code repository checkout URLs.</td>
</tr>
<tr>
<td><strong>Qstream source:</strong> <a href="http://Qstream.org">http://Qstream.org</a></td>
</tr>
<tr>
<td>Has all the benchmark scripts.</td>
</tr>
</tbody>
</table>
Acknowledgements

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Questions