Operating System Support for Coexistence of Real-Time and Conventional Scheduling

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Abstract

The advent of multimedia calls for new scheduling paradigms to handle the combination of time-critical and conventional applications present on many multimedia systems. The scheduler of the Mach 3.0 Microkernel has been rewritten to allow a wide spectrum of scheduling policies, from real-time through time-sharing to background, to be selected simultaneously for different tasks executing on the same processor. Scheduling policies can be set for a task or for individual threads within the task. The set of scheduling policies allowed on a processor or set of processors may be dynamically altered. Scheduling parameters can be set individually for each thread, task, or scheduling policy enabled on a processor. Each scheduling policy may have its own format for parameters; they are not limited to integer priorities. New scheduling policies may be configured into a kernel and may be ordered in any way desired. The resulting system provides enough flexibility for experimentation with new scheduling regimes, yet is efficient enough to allow a reasonable number of scheduling policies to coexist. When configured with both real-time and timesharing schedulers, the system smoothly supports both conventional and time-critical applications.

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1. Introduction

General-purpose and real-time computation have existed in two separate worlds. General-purpose operating systems share processors, large address spaces, and file systems between different users, but do not guarantee performance. Systems that can meet the strict timing requirements of real-time applications have often been written for limited hardware and are customized for one specific purpose.

However, the introduction of multimedia into business applications on personal computers has brought the two worlds together. Users expect smooth video display to coexist with fast spreadsheet calculation. This requires an operating system that can support both real-time and conventional applications, without compromising either one. Ideally, the resulting system should allow both general and real-time applications to make full use of the hardware and operating system.

Recent research on real-time scheduling has provided a firmer theoretical and practical basis for designing real-time operating systems. A considerable contribution to this area has come from the Advanced Real Time Systems group (ARTS) at Carnegie Mellon University [8]. Members of the group have explored the rate-monotonic and earliest-deadline-first scheduling algorithms for real-time jobs. Building a real-time application using these scheduling paradigms requires analyzing the computation times of the threads in the application. The classical time line schedule, in contrast, requires determining exactly which activities are executing at each point in time.

These scheduling solutions have been incorporated in RT-Mach [9], a version of the Mach kernel incorporating real-time features. It provides selectable scheduling policies suitable for real-time applications, taken from the Integrated Time-Driven Scheduler [7] written for the ARTS system. The interface between the scheduling policy modules and the rest of the kernel is written so that new scheduling policies can easily be added to the kernel.

At first, scheduling requirements for time-critical applications and conventional jobs appear completely incompatible. The primary objective of a real time scheduler is to meet the timing requirements of the application, not to fairly distribute the time among different applications. A low-priority job may be delayed indefinitely by high-priority jobs; this is acceptable and expected. However, if the conventional jobs are given the lowest priority, lower than any of the time-critical tasks, real-time applications will automatically be given preference, and both types of applications can run simultaneously. The time not used by the real-time applications is split fairly among the conventional applications by the timesharing scheduler.

The RT-Mach kernel itself falls short of meeting these requirements. Each processor is restricted to running exactly one scheduling policy at any time. Conventional applications must therefore be shut down when a real-time application is to be run. Since some conventional applications use fixed priority and time sharing scheduling simultaneously, even these cannot be handled. The only provision for running applications using more than one scheduling policy is to write a customized policy module that combines the policies and imposes an ordering on them. Such a customized solution clearly cannot be extended beyond a very small set of policies.

2. New Mach Scheduling Paradigm

The new Mach scheduling paradigm incorporates the real-time scheduling algorithms from RT-Mach, but places them within a framework which allows them to coexist with timesharing scheduling for conventional applications. The scheduling paradigm imposes an ordering on the applications' threads, depending on the scheduling policies to which they are assigned. The conventional *priority* value used to schedule threads has been changed to a two-component value: (*policy*, *ordering*). Threads are ordered first by their scheduling policy: time-critical threads have priority over all non-time-critical threads. Within each scheduling policy, an ordering is also imposed. Time-critical threads may be ordered by their deadlines; non-time-critical threads are ordered by an arbitrary priority value.

As in a conventional scheduler, the next thread to run is determined by the priorities of all the currently runnable threads. Since the thread's scheduling policy is the first component of its priority value, any thread in a higher scheduling policy (for example, real-time) is automatically of higher priority than any thread in a lower scheduling policy (for example, time-sharing). Interaction between threads in different scheduling policies is resolved by obeying the ordering of the policies. In contrast to the Real-Time Mach system, it is unnecessary for any one scheduling policy to know about the other possible policies that have been configured in order to provide the correct ordering.

The two-component priority value also allows the scheduler interfaces that set thread priorities to be generalized for multiple scheduling policies. Again, the *priority* value passed to the interface includes both *scheduling policy* and relative *ordering* within that policy. The format of the *ordering* component has been made flexible, to allow any scheduling policy to be supported by these uniform interfaces.

2.1. Available Scheduling Policies

The Mach kernel is normally configured with the following scheduling policies:

- Earliest Deadline First

  The thread with the earliest deadline (in actual time) is scheduled to run first. This policy provides for real-time systems where threads are dynamically added and removed.

- Rate Monotonic

  This handles a group of periodic real-time threads whose processor usage can be analyzed in advance. Threads are run in order of their periods, shortest period first. Non-periodic threads are run after all periodic threads, in no particular order.

- Fixed Priority

  Each thread has a *priority*, ranging from 0 (highest) to 31 (lowest). The runnable thread with the highest priority value is chosen to run first.

- Time Sharing

  Each thread is assigned a *priority* from 0 (highest) to 31 (lowest). In addition, a priority increment value is assigned, depending on the amount of processor time used. The increment depends on a running exponential average of the processor time used during the last second, adjusted for the total load on the processor.

- Background

  Background threads are run only if no other threads are eligible to run.

2.2. External Interfaces

The interfaces to the priority mechanism have been generalized to support selectable scheduling policies, based on older Mach interfaces which only supported timesharing scheduling. Priorities appear in four places in the Mach kernel:

- Each thread has a *base priority* value. For most scheduling policies, this is the actual priority value; for timesharing, an increment based on CPU usage is added to form the current priority.
- Each thread also has a *maximum priority* or *priority limit*. An unprivileged user cannot set the thread's priority higher than its maximum priority.
- A task has a *default priority*, used to initialize the *base priority* of newly created threads. One can also change the priority of all of the threads in a task by changing the task's priority.
- A processor set has a *priority limit* used to control the priorities of all of the threads running on that processor or group of processors.

Following the scheduling paradigm, all of these priorities are now two-component values: *policy, parameters*. Each policy has its own notion of *parameters* for base priority and priority limit. For the timesharing and fixed-priority policies, these are still numeric values, with lower values denoting higher priorities. For the real-time policies, the *parameter* is a time (the thread's period or deadline). A corresponding limit value is a lower limit on the period of periodic threads.

The task's default priority has become a default *scheduling policy* for newly created threads within the task. In addition to supplying the base priorities for all new threads, this allows a user to easily specify that all the threads within a particular task run under the same policy (for example, they are all real-time threads scheduled under the rate-monotonic policy).

The processor set's data has been expanded to hold limit values for each scheduling policy currently enabled. Scheduling policies may be freely enabled or disabled on each processor set, by users with appropriate privilege. On a multiprocessor, a user may force all time-sharing threads to run on a small number of processors by grouping them into a processor set and enabling timesharing only on this processor set.

The Mach kernel interfaces for the flexible scheduling policy support are:

```
kern_return_t processor_set_policy_add(
        processor_set_t         pset,
        int                     policy,
        policy_param_t          limit,
        unsigned int            count)
```

Adds the new scheduling policy *policy* to the processor set *pset*, with the scheduling parameter maximum values set by *limit*.

```
kern_return_t processor_set_policy_remove(
        processor_set_t         pset,
        int                     policy)
```

Removes the scheduling policy *policy* from the processor set *pset*. Threads running *policy* have their policy reset to timesharing, or to background if timesharing is not available on the processor set.

The background policy cannot be removed. This guarantees that a processor set will have at least one available scheduling policy.

```
kern_return_t processor_set_policy_limit(
        processor_set_t         pset,
        int                     policy,
        policy_param_t          limit,
        unsigned int            count,
        boolean_t               change_threads)
```

Changes the parameter limit values for *policy* on processor set *pset* to the new *limit* values. These limit values will affect new threads that are created as assigned to processor set *pset*, or assigned to it.

If *change_threads* is TRUE, any thread assigned to *pset*, and running *policy*, whose scheduling parameters violate the new *limit* values, will have its scheduling parameters reduced to *limit*. Otherwise, existing threads will be unaffected. This allows a privileged user to set up several high-priority threads, then change the limit values, preventing any new threads from being assigned as high a priority as the existing threads.

```
kern_return_t thread_set_policy(
        thread_t                thread,
        processor_set_t         pset,
        int                     policy,
        policy_param_t          param,
        unsigned int            count)
```

Sets *thread* to run the scheduling policy *policy*, with its scheduling parameters (priority, period, deadline, etc.) set to *param*. If no scheduling parameters are supplied (*count* is zero), the default values for the policy will be used.

The thread's processor set, *pset*, must be supplied as a privilege key to allow the policy to be selected; if *pset* is not the processor set to which the thread is currently assigned, the call will fail.

The supplied scheduling parameters must be less than or equal to the limit values for *pset* for this policy; otherwise the call will fail.

```
kern_return_t thread_set_policy_param(
        thread_t                thread,
        boolean_t               set_limit,
        policy_param_t          param,
        unsigned int            count)
```

Sets new scheduling parameter values for *thread*'s current scheduling policy. If *set_limit* is true, this call also sets the thread's parameter limit value. The parameters must be valid for the current scheduling policy, and less than or equal to the limit values for the thread's current processor set for this policy, **and** less than or equal to the *thread's* limit values. This allows a privileged user to set a maximum priority (or minimum period) for a thread, and let an unprivileged user vary the thread's priority up to the maximum priority, but no higher.

```
kern_return_t thread_set_policy_limit
        thread_t                thread,
        processor_set_t         pset,
        policy_param_t          limit,
        unsigned int            count)
```

Sets new scheduling parameter limit values for *thread*'s current scheduling policy. The thread's current processor set, *pset*, must be supplied as a privilege key; if this is not the processor set to which the thread is currently assigned, the call will fail.

```
kern_return_t task_set_default_policy(
        task_t                  task,
        processor_set_t         pset,
        int                     policy,
        policy_param_t          param,
        unsigned int            count,
        boolean_t               change_threads)
```

Sets the default scheduling policy for *task* to be *policy*, and the default scheduling parameters for that policy to be *param*. The default policy and parameters are assigned to new threads created within the task.

If *change_threads* is true, all existing threads within the task are changed to run *policy* with the new scheduling parameters. If any thread cannot be made to run *policy* with these parameters, the call will return *KERN_FAILURE*. This may happen if a thread is assigned to a processor set that does not run *policy*, or if the scheduling parameters exceed the limit values for a thread or its assigned processor set. If the call returns *KERN_FAILURE*, as many threads as possible will be running the new policy, but there will be no indication of which threads are not.

The task's processor set, *pset*, must be supplied as a privilege key to allow the policy to be selected; if *pset* is not the processor set to which the task is currently assigned, the call will fail.

3. Internal Reorganization

To allow new scheduling policies to be easily added to the Mach kernel, the routines that manage the queue of runnable threads have been split into two distinct modules, connected by a well-defined interface. The *run_queue* module supplies the abstraction of a queue of runnable threads to the rest of the scheduler. Routines are provided to add a thread to the run queue, to choose the highest priority thread from the run queue and remove it, and to remove a thread from the run queues to adjust its priority or terminate it. Each of these routines calls a corresponding routine in the thread's *scheduling policy* to implement the actual run queue structure.

3.1. Run Queue Module

Each processor set has a *run queue header* that holds pointers to the run queues for each policy enabled on that processor set. There is a common lock for all of the run queues, a count of the total number of runnable threads, and a bit map of the run queues that contain runnable threads.

The *thread_setrun* routine adds a runnable thread to the run queues. It calls the enqueuing routine for the thread's scheduling policy to add the thread to its policy's run queue, and sets the bit in the bit map to indicate that this policy has runnable threads.

The *rem_runq* routine removes a runnable thread from the run queues. It calls the remove-from-queue routine to remove the thread from its policy's run queue, and clears the bit in the bitmap if the policy's run queue is now empty.

The processor searches for a new thread to run by calling *thread_select*. This routine scans the bit map for the highest priority scheduling policy that contains runnable threads. It then calls the dequeueing routine for that run queue's scheduling policy, which removes and returns the highest priority thread for that policy. The scan of the bit map makes finding the highest-priority scheduling policy very fast. As in *rem_runq*, the policy's bit in the bitmap is cleared if the policy's run queue has no more runnable threads.

At clock interrupts, routine *csw_needed* is called to check the run queues to determine whether the current thread should be preempted by a higher priority thread. Again, this is done by scanning the bit map of policies with runnable threads. However, the search stops at the policy belonging to the current thread. Clearly, the current thread cannot be preempted by a thread in a lower scheduling class; similarly, it will always be preempted by a thread in a higher scheduling class. If the first non-empty run queue is the current thread's run queue, a policy-specific routine is called to compare the current thread's priority (ordering) with the highest-priority thread on that run queue. If the routine indicates that the thread on the run queue has higher priority, the current thread will be preempted.

3.2. Scheduling Policies

The run queue module and the Mach external interfaces call the individual scheduling policies through a well-defined interface. The scheduling policy is structured as an object. A policy that is active on a processor set has its own set of run queues and other local data structures that belong to that instance of the policy. The policy holds a pointer to the set of interface routines that are called for all operations on run queues, tasks, and threads that run the policy.

The local run queue structure contains a common header that holds a count of the number of runnable threads on the queue and a pointer to the function vector for the scheduling policy. Following the header is a policy-specific structure that includes the priority limit value for the instance of the policy, and the list of runnable threads. Placing the thread list in the policy-specific portion allows it to be tailored to the policy. For example, the timesharing and fixed-priority policies use an array of 32 queues, one per priority level. In contrast, the real-time policies use a single ready queue, on which threads are queued in order of deadline time or period.

The operations are listed here, along with the kernel routines that call them:

Run queue manipulation:

```
thread_t        (*thread_dequeue)(
        run_queue_t     runq)
```

Called by *thread_select* to remove the highest priority thread from *runq*, and return it. The run queue is known to be non-empty.

```
boolean_t       (*thread_enqueue)(
        run_queue_t     runq,
        thread_t        thread,
        boolean_t       may_preempt)
```

Called by *thread_setrun* to enqueue *thread* on *runq*, in order by priority. The queuing policy is invisible outside the policy module itself.

If *may_preempt* is **TRUE**, the routine returns whether *thread* is of higher priority (according to the policy) than the currently executing thread. Otherwise the routine returns **FALSE**.

```
void            (*thread_remqueue)(
        run_queue_t     runq,
        thread_t        thread)
```

Removes *thread* from *runq*. The thread is known to be on the run queue.

Called by *rem_runq* (from *thread_hold and thread_dowait*) to suspend a thread that is on the run queues. Also called by routines that change the thread's policy or scheduling parameters. If the thread is runnable, these routines remove it from its current run queue, alter its policy or parameters, and replace it on the (possibly new) run queue at its new position.

Thread priority update and context switch checks:

```
boolean_t       (*csw_needed)(
                run_queue_t     runq,
                thread_t        thread)
```

Called by *csw_needed* from clock-interrupt code to determine whether *thread* (the currently running thread) should be preempted by the highest-priority thread in *runq*. Returns **TRUE** if this is so. *Thread* is known to run *runq*'s scheduling policy.

```
void            (*clock_sched)(
        thread_t        thread,
        boolean_t       end_of_quantum);
```

Called by the system clock interrupt to perform random scheduling decisions on *thread*. *End_of_quantum* is **TRUE** if the clock interrupt marks the end of the current quantum. *Thread* is the currently running thread.

This is used by the timesharing policy to update *thread*'s CPU usage and current priority. For other policies, this checks whether there is any other reason to preempt *thread*.

```
void            (*update_priority)(
        thread_t        thread)
```

Called by *thread_setrun* to perform random scheduling decisions on *thread*. This differs from *clock_sched* in that the thread is just being made runnable.

This is used by the timesharing policy to update *thread*'s CPU usage and current priority when *thread* has not run for a period of time.

Processor set priority limits:

```
kern_return_t   (*runq_set_limit)(
        run_queue_t     runq,
        policy_param_t  limit,
        natural_t       count)
```

Sets *limit[count]* as the limit values for the scheduling policy on a processor set. *Runq* is the run queue for the policy on the processor set.

```
kern_return_t   (*runq_get_limit)(
        run_queue_t     runq,
        policy_param_t  limit,
        natural_t       *count)
```

Returns the the limit values for the scheduling policy on a processor set in *limit[count]*. *Runq* is the run queue for the policy on the processor set.

Thread priority values and limits:

```
kern_return_t   (*thread_set_limit)(
        thread_t        thread,
        policy_param_t  limit,
        natural_t       count)
```

Sets *limit[count]* as *thread*'s limit values for the scheduling policy.

```
kern_return_t   (*thread_set_param)(
        thread_t        thread,
        policy_param_t  param,
        natural_t       param_count,
        boolean_t       new_policy,
        boolean_t       check_limits)
```

Sets *param[count]* as the scheduling policy parameters for *thread*. If *param* is **NULL**, *thread*'s current parameters are not changed if *new_policy* is **FALSE** (thread is running the policy); otherwise, the thread's parameters are set to the policy-specific default values.

The policy parameters (supplied, current, or default) are checked against the limit values for the policy. Parameters that are invalid for the policy or that exceed the limit values result in an error if *check_limits* is **TRUE**; in this case, the thread's policy parameters are not changed. Otherwise, the policy parameters are silently set to the limit values.

If *new_policy* is **TRUE**, *thread*'s limit values are used for the check. Otherwise, the limit values are taken from the processor set to which *thread* is assigned.

```
kern_return_t   (*thread_get_param)(
        thread_t        thread,
        policy_param_t  param,
        natural_t       *count)
```

Returns *thread*'s policy parameters and limit values for the scheduling policy in *param[count]*.

Task priority values:

```
kern_return_t   (*task_set_param)(
        task_t          task,
        policy_param_t  param,
        natural_t       count)
```

Sets *param[count]* as the default policy parameters for *task*.

```
kern_return_t   (*task_get_param)(
        task_t          task,
        policy_param_t  param,
        natural_t       *count)
```

Returns *task*'s default policy parameters for the scheduling policy in *param[count]*.

4. Evaluation

The scheduling policy framework has been used to implement fixed, high priorities for server threads in the single server Unix emulation under Mach [2]. User threads run under the time-sharing scheduling policy. Server threads use the fixed priority policy, but may temporarily run as background threads while waiting for synchronization variables [1]. Although the indirect procedure calls to the scheduler policy modules are in the critical context switch and system clock interrupt paths, measurements on compilation benchmarks show that they have *no* effect on system performance. Part of this result is due to a reorganization of the scheduler code that was done concurrently with the other work, reducing the aggregate path lengths in spite of the extra functionality.

Results from the Real-Time Mach group show that switching from timesharing to real-time scheduling policies does, in fact, lead to correct behavior for a time-constrained application. Tokuda [9] evaluates the visual performance of a program that simulates the rotation of a molecule by using individual threads to move each atom to its new position. Using time-sharing scheduling, the atoms drift apart and the molecule loses its shape; under the rate-monotonic scheduling policy, the atoms in the molecule correctly move in synchrony. Similar test programs running under the Mach kernel with this scheduling policy framework, and using rate monotonic scheduling, show identical behavior.

A truer test of the scheduling framework is to run real-time and time-sharing threads simultaneously. When both the test programs and a time-sharing application are running, the test program still shows its desired synchronous behavior, up to the point where the kernel starts paging to disk. Above this point, of course, there is no guaranteed behavior, since the real-time application is not wired into memory.

The scheduler framework allows the easy addition of new scheduling policies, such as Mercer's processor capacity reservation scheme [3]. To install a new policy, only the routines that queue threads according to the policy's priority scheme need to be written. The surrounding framework manages the interactions between threads running different policies, and distributes threads to CPUs in a multiprocessor system. The background policy, for example, was added to the system with about an hour's work.

5. Related Work

Other operating systems have incorporated both real-time and conventional processing. The CP-V operating system for the SDS Sigma 7 [5] supported both conventional (batch) and real-time processes via a common run queue structure. Each process was assigned a base priority, with higher (numeric) values giving lower priority. Conventional processes had positive priority values; the priorities were varied according to the process' CPU usage, as in the Mach timesharing scheduling policy. Real-time processes had negative priorities that were not varied. A negative priority also prevented a process' memory from being swapped to disk.

SunSoft's Solaris 2.1 operating system [6] similarly allows processes to be designated as "real-time." Real-time processes, as in CP-V, are given fixed priority, and preempt timesharing threads. They are also exempt from the usage and load-dependent priority adjustments for timesharing threads.

The actual real-time scheduling policies provided by these two systems include only fixed-priority, round-robin scheduling. The application designer must carefully calculate the sequence of execution for the set of real-time processes, and vary priorities at appropriate points during the application in order to ensure timely response. The rate-monotonic and earliest-deadline-first policies included in the Mach kernel, in contrast, automatically vary process priorities to guarantee completion; the designer merely has to analyze the application's total computational load, not the exact mix of processes executing at each point.

The Mach/RT project [4], like RT-Mach, extends the Mach microkernel to incorporate real-time scheduling policies. Scheduling policies are separated into individual modules that may be configured into a kernel; the description places more emphasis on the configurable scheduler interface than on the scheduling policies themselves. As in RT-Mach, only one scheduling policy may be in effect on a processor at any one time. The only way to share a machine between conventional and time-critical tasks is to write a customized scheduling policy. In contrast, the rewritten Mach scheduler automatically dispatches both classes of threads in the correct order.

The closest commercial scheduler equivalent to Mach's multiple-scheduler framework is IBM's OS/2 scheduler. Threads may be assigned to one of four ordered scheduling classes: real-time, fixed priority, timesharing, and background. Each scheduling class has 32 priority levels. However, the implementation does not provide for adding more scheduling classes: threads are queued onto one of 128 queues, and the scheduler looks through all of those queues to find the next runnable thread. Adding a true rate-monotonic scheduler requires not only that more run queues be added, but that each thread's rate, measured in microseconds, be reduced to one of the small set of added queues. This may result in priority inversion among the threads assigned to the same run queue.

6. Conclusion

This paper has presented a scheduling paradigm that handles the needs of multimedia systems running both real-time and conventional applications. This scheduler framework has been implemented in a version of the Mach 3.0 microkernel. It expands on previous work in real-time scheduling to support modern real-time scheduling algorithms, allow experimentation with new scheduling policies, and enable timesharing and background jobs to coexist with real-time applications.

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