Scheduling Real-Time Applications in an Open Environment

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Abstract

This paper extends the two-level hierarchical scheme in [1] for scheduling independently developed real-time applications with non-real-time applications in an open environment. The environment allows the schedulability of each real-time application to be validated independently of other applications in the system. The extended scheme removes the following two restrictions of the scheme in [1]: (1) real-time applications that are scheduled preemptively must consist solely of periodic tasks and (2) applications must not share global resources (i.e., resources used by more than one application). Consequently, the extended scheme can accommodate a much broader spectrum of real-time applications.

1 Introduction

Recent advances in real-time systems technology have given us many good schemes for scheduling hard real-time applications. Examples are [2–6]. A weakness shared by most existing schemes is that schedulability of each application can be determined only by analyzing all applications in the system together, i.e., by a global schedulability analysis. While the necessity of global schedulability analysis imposes no serious problem when the system is closed, it does so when the system is open. Here, by *closed system*, we mean one in which detailed timing attributes of all real-time applications on each processor are known. Oftentimes, the applications are developed together, and the schedulability of every combination of applications that can run at the same time is determined *a priori*. In contrast, in an *open system*,[1] applications may be developed and validated independently. During run-time, the user may request the start of a real-time application whose schedulability has not been analyzed together with currently executing applications. The system must determine whether to accept the request and admit the new application. It usually admits a new real-time application only when the application and all the existing real-time applications are schedulable. A global schedulability analysis as an acceptance test is sometimes not feasible because many characteristics of real-time applications in the system are unknown. Even when it is feasible, such an acceptance test can be time consuming when the applications are multi-threaded and complex.

We proposed in [1] a two-level hierarchical scheme for scheduling an open system of multi-threaded, real-time applications together with non-real-time applications on a single processor. It allows different applications to be scheduled according to different scheduling algorithms. A real-time application in the open system can be scheduled according to either a time-driven algorithm or a priority-driven algorithm. If the application uses a priority-driven scheduling algorithm, the algorithm can be preemptive or nonpreemptive, fixed-priority or dynamic priority. More importantly, the two-level scheme allows the schedulability of each application to be validated in isolation from other applications. Because it does not rely on fixed allocation of processor time or fine-grain time slicing, it is suited for applications with varying time demands and stringent timing requirements.

A serious limitation of the two-level scheme in [1] is that it can handle only predictable real-time applications. *Predictable applications* include all applications that are scheduled nonpreemptively or in a time-driven manner, as well as preemptively scheduled applications in which the release times of all jobs are known *a priori*. (We will return shortly to explain why such real-time applications are said to be predictable.) In this paper, we present an extension to the two-level scheme that removes this limitation. Specifically, the extended two-level scheme can accommodate real-time applications containing the following kinds of tasks while the original scheme cannot.

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[1] The term open system has a much broader meaning than the sense in which it is used here. We are concerned with only timing aspect and ignore the functional aspects.

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- Tasks may have nonpreemptable sections.[2]
- Tasks may be aperiodic or sporadic and are scheduled according to a preemptive, priority-driven algorithm. (A real-time application containing such tasks is said to be *nonpredictable*.)
- Tasks may request for local resources (i.e., the resources shared only by tasks in the application) and global resources (i.e., the resources shared by tasks of different applications).

Following this introduction, Section 2 describes related work. To make this paper self-contained, Section 3 gives an overview of the open system architecture and the sufficient condition for predictable applications that are described in [1]. Sections 4 presents a sufficient schedulability condition for all types of real-time applications in the open system when there is global resource contention. Section 5 describes the extended two-level scheduling scheme used in the open system to schedule different types of real-time applications. Because it is designed so that the condition in Section 4 is satisfied, the schedulability of each application can be determined independently from others in the system. Section 6 is a summary and presents future work.

2 Related Work

Again, this paper presents an extension of the results in [1]. The acceptance test and the scheduler operations described in the subsequent sections take into account the effects of nonpreemptability and release time jitters. In contrast, the two-level scheme in [1] does not allow applications to have nonpreemptable sections and allows applications with release time jitters only when they are scheduled nonpreemptively.

Our two-level scheduling scheme resembles the proportional share resource allocation scheme proposed by Stoica, *et al* [7]. Their scheme provides fair sharing of a processor among multiple processes running on the processor, but does not guarantee their timely completion. In contrast, our scheme guarantees that the deadlines of multi-threaded, hard real-time applications on a processor are always met, but provides fair sharing of the processor only to non-real-time applications. In particular, our scheme allows different applications to be scheduled according to different scheduling algorithms and the schedulability of each real-time application to be validated independently of other applications. This difference in the design objectives of the two schemes leads to different structures of the scheduler, as well as different acceptance tests.

The constant utilization server algorithm [1] used in our scheme is essentially the same as the total bandwidth server algorithm developed by Spuri and Buttazo [6]. (In turn, the total bandwidth server algorithm is similar to the fair queueing and virtual clock algorithms proposed for scheduling network traffic through ATM switches [8, 9]; The only difference is that the former is preemptive.) According to both the total bandwidth server and constant utilization server algorithms, each server is characterized by its size. When the budget of a server of size σ is replenished to e time units at time t, the new server deadline is set to $\max\{t, d\} + e/\sigma$, where d is the current server deadline. A server is ready for execution only when it has budget, and it consumes its budget at the rate of one per unit time when it executes. According to the total bandwidth server algorithm, the server budget is replenished immediately after the budget becomes zero if the ready queue of the server is not empty. According to the constant utilization server algorithm, the budget is replenished no earlier than the current server deadline. Consequently, a constant utilization server cannot make use of any background time, while a total bandwidth server can. We use constant utilization servers to execute hard real-time applications in the open system whenever it is possible to do so and there is no advantage to complete jobs in the applications early. Thus, we leave the processor time not required by such applications to non-real-time and soft real-time applications. We use a total bandwidth server to execute all the non-real-time applications and soft real-time applications so that the system is more responsive for them.

3 Open System Architecture

Figure 1 shows the open system architecture supported by our two-level hierarchical scheduling scheme. The system has a single processor whose speed is one. The workload on the processor consists of real-time applications and non-real-time applications. To develop a real-time application A_k that is to run in the open system, its developer first chooses an algorithm Σ_k to schedule jobs in A_k. The schedulability of the application is then analyzed based on the assumption that the application executes alone on a processor of speed σ_k. Specifically, if the execution time of a job in the open system is e, the execution time used for the purpose of schedulability analysis is e/σ_k. The minimum speed σ_k at which A_k is schedulable is called its *required capacity*.

[2] When a job is in one of its nonpreemptable sections, it effectively executes at the highest priority and cannot be preempted by any jobs in the system. We also speak of applications that are scheduled nonpreemptively. A job in such an application is never preempted by other jobs in the application, but may be preempted by jobs in other applications.

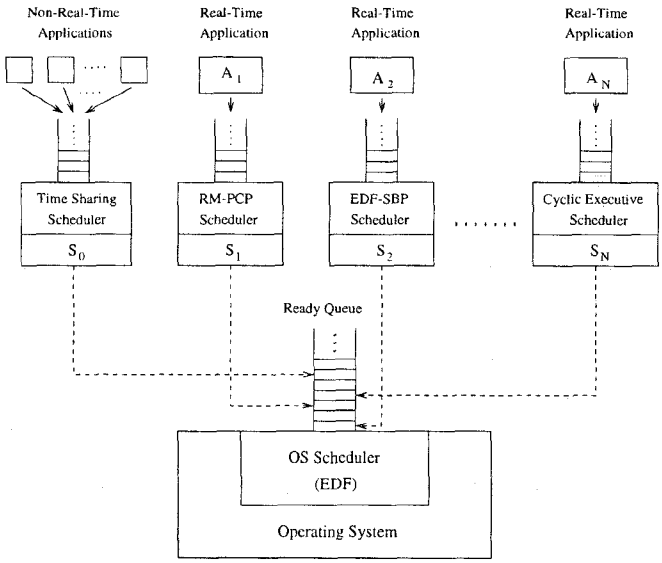


Figure 1: An Open System Architecture

We assume that $\sigma_k < 1$ for every real-time application A_k in the system, i.e., every real-time application A_k is schedulable if it executes alone on a slower processor of speed σ_k less than one. We say that the *real-time application A_k is schedulable in the open system* if all jobs in A_k meet their deadlines when A_k runs in the open system together with other applications and the order in which jobs in A_k are executed is determined by algorithm Σ_k.

3.1 Scheduling Hierarchy

Applications in the open system are scheduled and executed according to our two-level hierarchical scheme. Specifically, all non-real-time applications are executed by a total bandwidth server, which is called S_0 in Figure 1. Each real-time application A_k is executed by a server S_k, for $k \geq 1$, which is either a constant utilization server or a total bandwidth server, depending on the characteristics of the real-time applications. Each server has a ready queue containing ready jobs of the application(s) executed by the server. Each server has a scheduler associated with it, which we call *server scheduler*. The server scheduler of the server S_0 uses a time-sharing algorithm to schedule ready jobs of all non-real-time applications. The server scheduler of server S_k for each real-time application A_k uses the scheduling algorithm Σ_k chosen for the application. Similarly, contentions for local resources among jobs in an application are resolved according to the resource access control protocol used by the application. To illustrate this, Figure 1 shows that three well-known algorithms [10, 11] are used for real-time applications.

The scheduler provided by the operating system at the lower level is called the *OS scheduler*. The OS scheduler maintains all the servers in the system. It replenishes the server budget and sets the server deadline for every server according to the characteristics of the application(s) the server executes; Section 5 will discuss how this is done. A server is ready when its budget is nonzero and its ready queue is not empty. The OS scheduler schedules all the ready servers according to the EDF algorithm. Whenever a server is scheduled, it executes the job at the head of its ready queue.

Global resource contentions among applications are handled by the nonpreemptable critical section (NPS) protocol [12]. According to this protocol, whenever a job of an application A_k requests a global resource, the request is always granted. When a job in A_k holds a global resource, it becomes nonpreemptable, and so does the server S_k, until the job releases all global resources it holds. This protocol is simple to implement and can be used for non-real-time applications as well as real-time applications. For our scheme to work correctly, the operating system (i.e., OS scheduler) must ensure that no application ever stays in a nonpreemptable section for longer than a maximum allowable time. We assume that this protection is provided and will ignore this point in our subsequent discussion.

Figure 2 shows the operations of the OS scheduler. When the system starts, the OS scheduler creates the server S_0 for non-real-time applications. The open system always admits non-real-time applications. It admits and starts a new real-time application A_k only when A_k passes an acceptance test. The new application A_k requests admission by providing the OS scheduler the information needed to conduct the acceptance test. If the application A_k passes the test, the open system admits the application and creates either a constant utilization server or a total bandwidth server S_k to execute A_k. (We will describe in Section 5 the information provided by the requesting application and the algorithm used by the OS scheduler to do the acceptance test.) When an application A_k terminates, the OS scheduler destroys the server S_k.

When a job of a real-time application A_k is released, the OS scheduler invokes the server scheduler of the server S_k to insert the newly released job in the proper location in the server's ready queue according to the scheduling algorithm Σ_k. We assume that the time taken for inserting each newly released job into the ready queue is accounted for when determining the schedulability of A_k and therefore need not be considered separately during acceptance test.

Initiation:

- Create a total bandwidth server S_0 with size U_0 for non-real-time applications.
- Set the total server size U_t of all servers in the system to U_0.

Acceptance test and admission of A_k:

Do according to the algorithm described in Figure 5.

Maintenance of each server S_k:

Replenish the budget and set the deadline of server S_k depending on the characteristics of the application A_k and all applications executing in the open system (see Section 6).

Interaction with server scheduler of each server S_k:

- When a job J in the application A_k is released, invoke the server scheduler of S_k to insert J in S_k's ready queue.
- If the application A_k uses a preemptive scheduling algorithm, before replenishing the budget of S_k, invoke the server scheduler of S_k to update the occurrence time t_k of the next event of A_k.
- When a job J in the application A_k enters its nonpreemptable section, mark the server S_k nonpreemptable until the job J in A_k leaves its nonpreemptable section.
- When a job J in the application A_k requests for a global resource, grant J the resource and mark the server S_k nonpreemptable until the job J in A_k no longer holds any global resource.

Scheduling of all servers:

Schedule all servers on the EDF basis, except when a server S_k is marked nonpreemptable; in which case, S_k has the highest priority among all servers in the system.

Termination of a real-time application A_k:

- Destroy the server S_k.
- Decrease U_t by U_k.

Figure 2: Operations of the OS scheduler

We assume that the (maximum) execution time and relative deadline of each job in every real-time application become known when the job is released. The summary section will discuss the case when a job may actually execute for a shorter amount of time than its execution time.

3.2 Scheduling Independent Predictable Applications

As mentioned in Section 1, we divide real-time applications into two broad categories: predictable and nonpredictable. A real-time application is said to be *nonpredictable* if it contains aperiodic/sporadic tasks or periodic tasks with release time jitters and is scheduled according to a preemptive, priority-driven algorithm. From Figure 2, we see (and will shortly provide the rationale for) that at each server budget replenishment time, the server scheduler of a preemptively scheduled real-time application computes the occurrence time of the next event (e.g., the release and completion of a job) of the application which may trigger a scheduling decision. The server scheduler of a nonpredictable application cannot predict this occurrence time precisely. Other types of applications are predictable. Specifically, a preemptively scheduled application is predictable if the release times and resource request times of all jobs are fixed and known. All time-driven applications are predictable because the next scheduling decision time is known. It is not necessary for the server scheduler of a nonpreemptively scheduled application to predict the next event occurrence time. For convenience, we say that all nonpreemptively scheduled applications are predictable.

Our earlier paper [1] focuses on how the OS scheduler should maintain (i.e., replenish server budget and set server deadline) the server for each predictable application so that the application is schedulable in the open system. It is simple to maintain its server S_k if the application A_k is scheduled nonpreemptively. The server S_k is a constant utilization server of size σ_k, the required capacity of A_k. At each replenishment time t, the OS scheduler sets the server budget to the execution time e of the job J at the head of S_k's ready queue and the server deadline to $t + e/\sigma_k$. We have shown in [1] that the server emulates a slower processor of speed σ_k. For every job J in A_k, the replenishment time at which the server S_k is given budget to execute J is same as the decision time when J would be scheduled if A_k were to execute alone on a processor with speed σ_k. Moreover, if the server is schedulable, the job completes no later than the time at which it would complete if A_k were to execute alone on the slow processor. (By the *server being schedulable*, we mean that after each replenishment, the server budget is always exhausted at or before the server deadline.) Because the OS scheduler accepts the application A_k only when the constant utilization server S_k of size σ_k for A_k is schedulable, the application A_k is schedulable in the open system.

Unfortunately, this simple maintenance rule cannot be used for servers of preemptively scheduled applica-

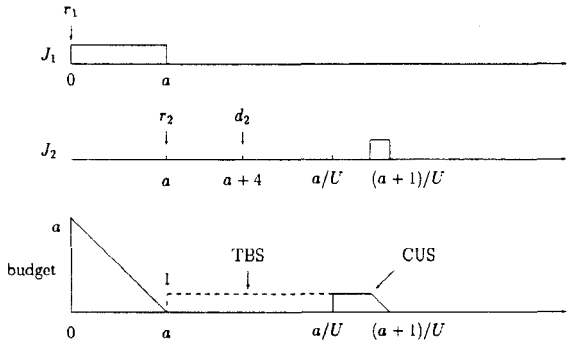


Figure 3: An Example Illustrating the Effect of Improper Server Maintenance

tions. The example in Figure 3 explains why. The application has two jobs and uses the preemptive EDF algorithm to schedule them. The jobs are $J_1(0, a, 10a+4)$ and $J_2(a, 1, a+4)$, where a is an arbitrary positive number. (Three numbers in parenthesis next to the job name represent the release time, execution time and deadline of the job, respectively.) If this application were to execute alone on a slow processor with speed 0.25, both jobs could complete in time. On the other hand, if we were to use a constant utilization server or a total bandwidth server of some size, say U, to execute the two jobs and maintain the server in the way described above, the budget of the server and the schedule of the jobs can be as shown in Figure 3. For J_2 to complete by its deadline in the open system, the worse case completion time $(a+1)/U$ of J_2 according to this schedule must be earlier than its deadline $a+4$. For arbitrary $a > 0$, this inequality holds only when U is equal to one, i.e., the application executes alone in the open system. This, clearly, is not what we want. We note from the figure that at time 0, the server budget is set to a, the execution time of J_1. By over-replenishing the server budget, the OS scheduler allows J_1 to borrow the budget that should be saved and used later at time a to execute J_2. Thus it allows a form of priority inversion to occur.

In [1], we proved the following sufficient condition under which a real-time application A_k is schedulable in the open system if no application in the open system has nonpreemptable sections or uses global resources. (Hereafter, we will simply say that there is no nonpreemptable section, since this fact implies that no application uses global resources.)

Theorem 1: *A real-time application A_k that has required capacity $\sigma_k < 1$ when scheduled according to some scheduling algorithm Σ_k is schedulable in the open system in which no application has nonpreemptable sections and A_k is executed by a constant utilization server S_k whose scheduler uses Σ_k, provided that all the following conditions are true.*

1. *At each replenishment time, the replenished budget given to S_k never exceeds the remaining execution time of the job at the head of S_k's ready queue.*
2. *During the interval (t, d) following any replenishment time t to the corresponding deadline d of the server, there would be no context switch among the jobs in the application A_k if A_k were to execute alone on the slow processor with speed σ_k.*
3. *The server S_k has server size σ_k.*
4. *The total size of all servers including S_k is equal to or less than one.*

For a predictable real-time application, it is possible for the OS scheduler to do acceptance test and replenish the budget of its server in such a way that conditions of Theorem 1 are true, and the scheme for predictable applications that we described in [1] indeed works this way. For example, the size of the server for the application in Figure 3 should be 0.25. At time 0, the OS scheduler invokes the server scheduler to calculate the release time of J_2. Since the release time a of J_2 is known, the OS scheduler can set the server budget to $a/4$ so that the server deadline is a and condition 2 is satisfied. The form of priority inversion mentioned above cannot occur, and both jobs can complete in time.

However, for a nonpredictable real-time application, it is not always possible to meet the condition 2 of Theorem 1, since the release times of jobs are not known *a priori*. Still, it is possible to maintain the server of a nonpredictable application A_k so that A_k is schedulable in the open system if we are willing to pay some penalty in processor utilization.

4 Schedulability Condition of Real-Time Applications in Open System

We now proceed to derive a sufficient schedulability condition for both predictable and nonpredictable applications in open systems. This general schedulability condition gives the increase in the server size needed to compensate for the inability of the server scheduler to predict accurately future scheduling decision times of a nonpredictable application as well as the reduction in the total processor utilization usable by servers in the presence of blocking. The schedulability condition is in fact two conditions: a sufficient condition under which all the servers are schedulable and a sufficient condition

for any real-time application to be schedulable in the open system given that its server is schedulable.

Again, we say that a server is *schedulable* if every time after the server budget and deadline are set, its budget is always exhausted at or before its deadline. The following theorem gives a sufficient condition for a system consisting of constant utilization servers and total bandwidth servers to be schedulable according to the EDF algorithm. Its proof is in the Appendix. Theorem 1 in [1] is for the special case when no job has nonpreemptable sections.

Theorem 2: *A system of constant utilization servers and total bandwidth servers are schedulable according to the EDF algorithm if the total size U_t of all servers is such that $U_t \leq 1 - \max_i\{B_i/\delta_i\}$ at all times, where B_i is the execution time of the longest nonpreemptable section in jobs executed by servers other than server S_i and δ_i is the shortest relative deadline of all jobs executed by server S_i.*

The general schedulability condition is given by Theorem 5. The proof the theorem replies on the following lemmas.

Lemma 3: *If n independent periodic and/or sporadic tasks $T_1, T_2, \cdots, T_n$ is schedulable on a processor with speed σ according to some preemptive scheduling algorithm, it is also schedulable on a processor with speed $\alpha\sigma$ for some $\alpha > 1$ according to the same scheduling algorithm when the relative deadline D_i of every task T_i is shortened to D_i/α.*

Proof: Since the task T_i is schedulable, the maximum time demand t_d of any job J in T_i (i.e., the sum of the maximum execution time of J, the total maximum execution time of all jobs with equal or higher priorities than J that can possibly be released in the interval between the release time and deadline of J, and any blocking time suffered by J) must be less than or equal to D_i. If the system executes on a fast processor with speed $\alpha\sigma$ for some $\alpha > 1$ according to the same scheduling algorithm, the maximum time demand of the job J is $t_d/\alpha \leq D_i/\alpha$. Therefore, the task with the shortened relative deadline is schedulable on the fast processor. □

Lemma 4: *In an open system in which no application has nonpreemptable sections, a real-time application A_k whose required capacity is σ_k and whose scheduling algorithm is Σ_k is schedulable when it is executed by a constant utilization server S_k whose server scheduler uses Σ_k, provided that all the following conditions are true.*

1. *At each replenishment time, the OS scheduler never gives the server S_k more budget than the remaining execution time of the job at the head of S_k's ready queue at the time.*
2. *During the interval $(t, d - q)$ from any replenishment time t of the server S_k to q time units before the corresponding deadline d of the server, for some nonnegative constant q which is such that $t < d - q$, there would be no context switch among the jobs in the application A_k if A_k were to execute alone on the slow processor with speed σ_k.*
3. *The server S_k has size $U_k = \delta_k\sigma_k/(\delta_k - q)$, where δ_k is the shortest relative deadline of all jobs in A_k if Σ_k is a priority-driven algorithm, or the shortest length of time between consecutive scheduling decision times if Σ_k is a time-driven algorithm.*
4. *The total size of all servers including S_k is equal to or less than one.*

Proof: If a job with the highest priority in A_k is released (or unblocked) after the budget of the server S_k is exhausted but before the current server deadline d, the job will not be ready for execution in the open system until d. In effect, the ready time of the job is delayed until d. When condition 2 is true, the ready time of any job in A_k can be delayed for no more than q time units. This is equivalent to shortening the relative deadline of the job by at most q time units, or a factor of at most $\delta_k/(\delta_k - q)$. According to Lemma 3, the application A_k by itself would be schedulable on a processor with speed U_k given by condition 3 even if the relative deadline of every job in A_k is shortened by up to q time units. All four conditions of Theorem 1 are satisfied if the size of server S_k is U_k and the ready time of every job released in the interval between any replenishment time and the corresponding server deadline is delayed until that server deadline. Therefore, A_k is schedulable in the open system. □

When some application in the open system has nonpreemptable sections, the execution of a job in one application can be blocked by the nonpreemptable sections in other applications. Theorem 5 takes into account the adverse effect of blocking, as well as nonpredictability.

Theorem 5: *A real-time application A_k whose required capacity is $\sigma_k < 1$ is schedulable in the open system when it is executed by a server S_k of size U_k provided that all the following conditions are true.*

1. *The server S_k is a total bandwidth server if A_k is scheduled by some preemptive algorithm, and is a constant utilization server if A_k is nonpreemptively scheduled (or is time-driven).*

2. *(a) If A_k is a nonpreemptive application, U_k is equal to σ_k. At each replenishment time of the server, the budget is set to the execution time of the job at the head of its ready queue.*

   (b) If the application A_k is a predictable preemptive real-time application, conditions 1, 2 and 3 of Theorem 1 are true.

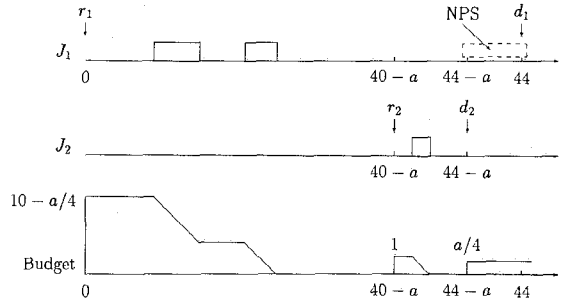
   (c) If A_k is nonpredictable, conditions 1, 2 and 3 of Lemma 4 are true.

3. *The total size of all servers in the open system is no more than $1 - \max_{j \geq 1}\{B_j/\delta_j\}$, where B_j is the maximum duration of nonpreemptable sections of all applications other than application A_j and δ_j is the shortest relative deadline of all jobs in A_j.*

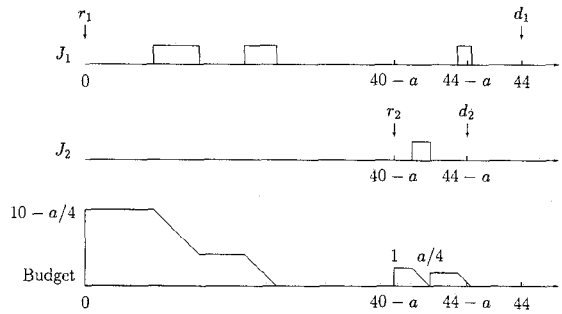
Proof: We first examine the case when the application A_k is scheduled by some nonpreemptive algorithm. Condition 2(a) ensures that once its server S_k becomes ready to execute the job at the head of its ready queue, it is always ready until the job completes. Therefore, each job in A_k can be delayed at most once due to nonpreemptable sections of jobs in other applications for no more than B_k time units. Every job in A_k can complete by its deadline if the server S_k is schedulable. According to Theorem 2, S_k is schedulable if condition 3 is satisfied.

Since the server S_k of each application A_k that is scheduled by a preemptive algorithm is a total bandwidth server, the server is always ready to execute when its ready queue is not empty. Therefore, a job can be blocked only once and for no longer than B_k time units. The relative deadline of any job in A_k is at least δ_k time units. It follows from Theorem 2 and Lemma 4 that A_k is schedulable if condition 3 is true. □

Condition 1 of Theorem 5 says that it suffices if the server of an application A_k scheduled according to a preemptive, priority-driven algorithm is a total bandwidth server. In fact, this condition is also necessary when some applications contain nonpreemptable sections. The reason is that a job in A_k can potentially be blocked by a nonpreemptable section of another application each time the job is preempted if the server S_k is a constant utilization server. Consequently, the schedulability of the application A_k in the open system cannot be guaranteed. In contrast, if its server S_k is a total bandwidth server, any job of the application A_k can be blocked at most once. The example in Figure 4 illustrates this fact. The application A_k in the example uses the EDF algorithm to schedule its two jobs, $J_1(0, 10, 44)$ and $J_2(40-a, 1, 44-a)$, where $0 < a < 40$. The required capacity of the application is 0.25. Now suppose that the release time of the jobs in A_k are known (i.e., A_k is predictable), the application A_k is executed by a constant utilization server S_k with server size 0.25 in the open system, and the server budget is replenished in such a way that all four conditions of Theorem 1 are satisfied. In particular, to meet condition 2 in Theorem 1, at time 0 the OS scheduler gives the server S_k $10 - a/4$ units of budget and sets the deadline of the server to $40 - a$. It subsequently gives the server 1 unit and $a/4$ unit of budget at time $40 - a$ and $44 - a$, respectively. Figure 4(a) shows a possible schedule of A_k. Everything goes well until job J_2 completes and server S_k is no longer ready to execute. Before the server becomes ready again at $44 - a$, the processor executes a job J in another application whose server has a deadline later than 44, and the job J enters its nonpreemptable section before $44 - a$. The server S_k cannot execute the remaining piece of job J_1 until the job J leaves its nonpreemptable section. If the length of the nonpreemptable section is longer than a, J_1 misses its deadline at 44. Since a can be arbitrarily small, we cannot guarantee the schedulability of the application A_k. If the application A_k is executed by a total bandwidth server with server size 0.25, however, it is schedulable, as shown in Figure 4(b). When the job J_2 completes, the budget of the server S_k is replenished immediately and the deadline is set to 44. The server remains ready to execute at this time, and J cannot enter its nonpreemptable section.



(a). Fast Processor (executed by a constant utilization server)



(b). Fast Processor (executed by a total bandwidth server)

Figure 4: Schedules of Application A_k

5 Two-Level Hierarchical Scheduling Algorithms

We are now ready to describe the algorithms used for the acceptance test and admission of new applications and maintenance of servers of existing applications. Their correctness follows directly from Theorem 5. In our discussion, an *event* of a real-time application A_k refers to one of the following:

- a job in A_k is released or completes;
- a job in A_k requests for or releases a local or a global resource; and
- a job in A_k enters or leaves a nonpreemptable section.

At any time t, the next event of A_k is the one that would have the earliest possible occurrence time at or after t if the application A_k were to execute alone on a slow processor with speed σ_k.

5.1 Acceptance Test and Admission of New Applications

Again, the open system subjects each new real-time application A_k to an acceptance test, which is described in Figure 5. If A_k passes the acceptance test, the system accepts A_k and creates a server S_k to execute A_k. Specifically, Figure 5 lists the types of information a new application A_k provides to the OS scheduler in its request for admission. In addition to its required capacity σ_k and scheduling algorithm Σ_k, the new application also provides the maximum length L_k of its nonpreemptable sections if its jobs have any, as well as the shortest relative deadline δ_k of all its jobs if the application is priority-driven, or the shortest length of intervals between consecutive scheduling decision times if the application is time-driven. We have already mentioned these parameters in the earlier sections. Another parameter provided by the application is its jitter factor Δ_k. Δ_k is the maximum, over all periodic tasks in A_k, the ratio of the relative deadline D_i of each periodic task T_i and the difference between the relative deadline and release time jitter $\Delta\phi_i$ of the task, that is,

$$\Delta_k = \max_{T_i \in A_k} \{\frac{D_i}{D_i - \Delta\phi_i}\}$$

Figure 6 summaries how the OS scheduler chooses the server type and calculates the server size for the new application in Step 1 of the acceptance test. According to Theorem 5, the server size is σ_k if A_k is predictable.

When a new application A_k requests admittance, it provides in its admission request the following information:

- the scheduling algorithm Σ_k;
- the required capacity σ_k;
- the jitter factor Δ_k;
- the existence of aperiodic/sporadic tasks, if any;
- the maximum length L_k of all nonpreemptable sections; and
- the shortest relative deadline δ_k of all jobs if A_k is a priority-driven application, or the shortest length δ_k between consecutive scheduling decision times if A_k is a time-driven application.

1. Find the type and the size U_k of the server S_k in the way described by in Figure 6.
2. If $U_t + U_k + \max_{1 \le j \le N}\{B_j/\delta_j\} > 1$, where $B_j = \max_{i \ne j}\{L_i\}$ and N is total number of applications in the system including A_k, reject A_k. Else, admit A_k, and
   - if A_k is the first application that has nonpreemptable sections, change the server type of all servers that execute preemptive applications to total bandwidth server;
   - increase U_t by U_k;
   - create a server S_k of the specified type with size U_k for A_k; and
   - set server budget and server deadline d to zero.

Figure 5: Acceptance Test and Admission of Application A_k

If the application A_k is nonpredictable, it is impossible for the server scheduler to calculate accurately the occurrence time of the next event of A_k. In this case, the server scheduler uses an estimated next event occurrence time t_k, which we will show shortly, is never more than q units later than the actual next event occurrence time. The parameter q first appeared in Lemma 4 and is called the *scheduling quantum* in Figure 6. Conditions stated in Theorem 5 are satisfied if the server size U_k of S_k is equal to $\delta_k\sigma_k/(\delta_k - q)$. In a special case, when the nonpredictable application A_k does not contain aperiodic/sporadic tasks, the actual next event occurrence time is never more than $\min\{q, \max_{T_i \in A_k}\{\Delta\phi_i\}\}$ time units sooner than t_k. This is the reason that the size U_k of the server for such an application is the minimum of $\Delta_k\sigma_k$ and $\delta_k\sigma_k/(\delta_k - q)$.

Server Type of S_k:

If some application (including A_k) in the system has non-preemptable sections or uses global resources, and if A_k is scheduled by some preemptive algorithm, S_k is a total bandwidth server. Otherwise, S_k is a constant utilization server.

Server Size U_k of S_k:

- If A_k is predictable, $U_k = \sigma_k$.
- If A_k is nonpredictable,
  - if A_k contains no aperiodic/sporadic tasks, $U_k = \min\{\Delta_k, \delta_k/(\delta_k - q)\}\ \sigma_k$,
  - else, $U_k = \delta_k \sigma_k/(\delta_k - q)$.

where q is the scheduling quantum.

Figure 6: Server Type and Server Size of S_k

After determining the type and size U_k of the server S_k for the new application A_k, the OS scheduler accepts A_k if $U_t + U_k + \beta \leq 1$, where $\beta = \max_{1 \leq j \leq N}\{B_j/\delta_j\}$. The term β takes into account the effect of maximum blocking time that jobs of A_k may experience due to nonpreemptivity of other applications. As described in Section 4, if some application in the system has nonpreemptable sections, the servers of all preemptive applications must be total bandwidth servers. As long as no application in the system has nonpreemptable sections, the OS scheduler continues to use constant utilization servers for all hard real-time applications in order to be more responsive for non-real-time and soft real-time applications. When the OS scheduler admits the first application that has nonpreemptable sections, it changes the servers of all the existing preemptive applications in the system to total bandwidth servers, as stated in Figure 5. Only the next replenishment time of each involved server is changed. This change can be done by the OS scheduler immediately and with a negligible amount of overhead.

5.2 Server Scheduler of Nonpredictable Application

Figure 7 describes the actions taken by the OS scheduler to maintain the total bandwidth server S_k for a nonpredictable application A_k. (Descriptions for servers of predictable applications can be found in [1].) The algorithm governing the server budget replenishment is slightly different from the total bandwidth server algorithm in [6]. Specifically, when a job completes at time t before the current server deadline d, the budget of the server S_k is not replenished immediately if a job in A_k with a higher priority than the job J at the head of S_k's ready queue will be released at time d. This is so that the job J cannot use the budget reserved for the higher priority job released at time d, thus the form of priority inversion described in Section 3 is avoided. Since the precise release times of jobs in a nonpredictable application are unknown, the server scheduler of S_k is unable to compute an accurate occurrence time of the next event of A_k. The algorithm described in Figure 8 gives an estimate. For the purpose of computing this estimate, the server scheduler maintains for each task T_j in A_k the latest release time $r_{-1}(j)$, i.e., the latest release time of all jobs in T_j prior to time t of the computation. The error in the estimate t_k is the error in the estimate of release time t' of the job that will be released first at or after time t among all jobs in A_k. The actual release time of this job is never sooner than q time units before the estimate t', and hence, the actual occurrence time of the next event in A_k is never sooner than q units before the estimate t_k. From Figures 7 and 8, we can see that the effect of using the estimate t_k is that the OS scheduler may give the server S_k up to qU_k units more budget than the budget computed based on the accurate next event occurrence time of A_k. The adverse effect of this over-budgeting is compensated for by letting the server S_k have the larger size stated in Figure 6.

We call q the *scheduling quantum*, and its value is chosen by the open system designer. Its value has no effect for a predictable application. In the other extreme, when even the ranges of the release times of some jobs in a preemptively scheduled application A_k are unknown, the estimate t_k of the next event occurrence time is q units from the current replenishment time. Consequently, the amount of budget of the server S_k replenished each time is qU_k units and the deadlines of the server are q units apart. In other words, the OS scheduler maintains S_k like the server S_0 for non-real-time applications. When we know the minimum and maximum inter-arrival times of each task in the application, we can get a better estimate but doing so incurs additional scheduling overhead, which is the time required to do the *for* loop in Figure 8 and has complexity $O(n)$, where n is the number of tasks in application A_k. In general, the smaller the value of q, the more frequent the server budget of S_k is replenished, and the higher the scheduling overhead. But smaller value of q also means a smaller server size U_k of S_k, thus consuming less processor utilization on behalf of A_k.

Maintenance of total bandwidth server S_k whose deadline is d:

1. When a new job J_i of A_k arrives at t,
   - invoke the server scheduler of S_k to insert J_i in S_k's ready queue;
   - update the latest release time $r_{-1}(j)$ of the task T_j to which J_i belongs;
   - set J_i's remaining execution time e_i' to e_i;
   - if J_i is the only job in the ready queue,
     (a) invoke the server scheduler of S_k to estimate the occurrence time t_k of the next event of A_k as described in Figure 8,
     (b) set the server budget to $(t_k - \max\{t, d\})U_k$, and server deadline d to t_k, and
     (c) decrease the remaining execution time e_i' of J_i by $(t_k - \max\{t, d\})U_k$.
2. When a job in A_k completes at time t,
   - if S_k's ready queue is not empty and job J_i is at the head of the ready queue,
     (a) if $t < d$ and if a job in A_k with a higher priority than that of J_i is released at time d, do nothing. Otherwise,
     - invoke the server scheduler of S_k to estimate the occurrence time t_k of the next event of A_k after time d as described in Figure 8,
     - set the server budget to $(t_k - d)U_k$, and server deadline d to t_k, and
     - decrease the remaining execution time e_i' of J_i by $(t_k - d)U_k$.
3. After a job J_i in A_k requests for or releases a local resource, invoke the server scheduler of S_k to change the priorities of some jobs in its ready queue if necessary and move the job with the highest priority to the head of its ready queue.

Figure 7: Maintenance of Total Bandwidth Server S_k for a Preemptive Application A_k

Input:

n:	the number of tasks in A_k
$p^m[1 \ldots n]$:	the minimum inter-arrival time of each task in A_k
$p^M[1 \ldots n]$:	the maximum inter-arrival time of each task in A_k
$r_{-1}[1 \ldots n]$:	the latest release time of each task in A_k
q:	the length of scheduling quantum in the open system.

Calculation of the Next Event Time t_k at time t:

$t' \leftarrow \infty$;
for $(i = 1; i \leq n; i++)$ {
  $r_e \leftarrow \max\{t, r_{-1}[i] + p^m[i]\}$;
  $r_l \leftarrow r_{-1}[i] + p^M[i]$;
  $t' \leftarrow \min\{t', \min\{r_e + q, r_l\}\}$;
}
if the ready queue of S_k is empty at time t
  $t_k \leftarrow t'$;
else {
  $J_i \leftarrow$ the job at the head of the ready queue of S_k at time t;
  $e_i'' \leftarrow$ the amount of time J_i must attain to reach the point when J_i either completes, or requests or releases a resource, or enters or leaves a nonpreemptable section, whichever occurs the earliest;
  $t_k \leftarrow \min\{t', t + e_i''/U_k\}$;
}

Figure 8: Calculation of the Next Event Occurrence Time by the Scheduler of the Server S_k of a Nonpredictable Application A_k

6 Summary

The two-level hierarchical scheduling scheme described in this paper extends the scheme proposed in [1]. The extended scheme can deal with the real-time applications that have nonpreemptable sections, use global resources, have release time jitters while the original scheme cannot. With this extension, the open system architecture and the two-level hierarchical scheduling scheme can provide an isolated virtual machine that guarantees the schedulability of an arbitrary real-time application once this application is admitted into the open system.

Throughout our discussion here, we have assumed that the maximum execution time of every job is known when the job is released and the job actually executes for that amount of time. In reality, a job may execute for a shorter amount of time. The system can easily reclaim the time allocated to any job executed by server S_k but unused by the job by taking back the remaining budget, thus allowing applications executed by total bandwidth

servers to make use of the budget.

We are currently building a proof-of-concept prototype run-time environment and application system interfaces based on the two-level hierarchical scheme within the framework of Windows NT operating system. Specifically, we will replace the existing NT kernel scheduler by our two-level scheduler and introduce a *server* object to indirectly manage the ready *threads* (the basic scheduling entities) in the NT kernel. We will also provide a set of Real-Time Application Programming Interface (RTAPI) for the real-time applications. These applications can use RTAPI to specify their real-time attributes, for example, to register the periodic tasks in the applications.

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Appendix

This appendix presents the proof of Theorem 2, which needs the following lemma. Theorem 1 in [1] and the classical schedulability condition of periodic tasks [2] also follow directly from this lemma.

The lemma gives a sufficient schedulability condition for independent sporadic jobs. The jobs are preemptable but may contain nonpreemptable sections. We characterize each sporadic job J_i by its release time r_i, execution time e_i, deadline d_i, and the execution time L_i of its longest nonpreemptable section. The ratio $e_i/(d_i - r_i)$ is the *density* of the job J_i, and the interval $(r_i, d_i]$ is its *active interval*. J_i is said to be an *active job* at any time instant t in $(r_i, d_i]$, but is not active outside this interval. Let B_i be the maximum blocking time the job J_i can suffer due to the nonpreemptivity of other jobs, i.e., $B_i = \max_{j \neq i}\{L_j\}$. The lemma below tells us when such sporadic jobs are schedulable on the EDF basis.

Lemma A: *A system of independent, preemptable sporadic jobs that have nonpreemptive sections is schedulable according to the EDF algorithm if at all times, the total density of all active jobs is less than or equal to* $1 - \max_i\{B_i/(d_i - r_i)\}$.

Proof: We prove the lemma by contradiction. To do so, we suppose that a job misses its deadline at time t, and there is no missed deadline prior to t. Let t_0 be the latest time before t at which either the system idles or some job with a deadline after t executes. Suppose that during the interval $(t_0, t]$, the system executes n jobs, $J_1, J_2, \cdots, J_n$, ordered in increasing order of their

deadlines. Job J_n is the one that misses its deadline. Without loss of generality, we assume that immediately prior to time t_0, the system executes some job that is in its nonpreemptable section. Let t_{-1} be the start of this nonpreemptable section. $t_{-1} \leq t_0$.

We say that an *event* occurs when (1) a job is released or completes, or (2) a job misses its deadline, or (3) a job enters or leaves its nonpreemptable section. Suppose that during the interval $(t_{-1}, t]$, there are m events, ordered in ascending order of their occurrences. Let t_i denote the time instant when the i-th event occurs, where $i = 1, 2, \cdots, m$. We must have $t_1 = t_{-1}$ and $t_m = t$. The entire interval $(t_{-1}, t]$ is partitioned into $m-1$ disjoint subintervals, $(t_1, t_2], (t_2, t_3], \cdots, (t_{m-1}, t_m]$. By definition of events, in each subinterval, active jobs in the system remain unchanged, and so does the total density of all the active jobs. Let Λ_i denote the subset containing all the jobs that are active during the interval $(t_i, t_{i+1}]$ for $1 \leq i \leq m-1$ and u_i denote the total density of the jobs in Λ_i.

We note that

$$\begin{aligned}
\sum_{i=1}^{n} e_i &= \sum_{i=1}^{n} \frac{e_i}{d_i - r_i}(d_i - r_i) \\
&\leq \sum_{j=1}^{m-1} (t_{j+1} - t_j) \sum_{J_k \in \Lambda_j} \frac{e_k}{d_k - r_k} \\
&= \sum_{j=1}^{m-1} u_j (t_{j+1} - t_j)
\end{aligned}$$

Since $u_j \leq 1 - \max_i\{B_i/(d_i - r_i)\}$ for all $j = 1, 2, \cdots, m-1$, we have

$$\begin{aligned}
\sum_{i=1}^{n} e_i &\leq \sum_{j=1}^{m-1} (t_{j+1} - t_j)(1 - \max_i\{\frac{B_i}{d_i - r_i}\}) \\
&= (t - t_{-1})(1 - \max_i\{\frac{B_i}{d_i - r_i}\}) \\
&\leq (t - t_{-1})(1 - \frac{B_n}{t - r_n})
\end{aligned}$$

At time t_{-1}, a job J with deadline later than t executes and enters its nonpreemptable section. J_n must be released after t_{-1}, that is, $r_n > t_{-1}$. Moreover, the job J remains in the nonpreemptable section at time t_0. We must have $B_n \geq t_0 - t_{-1} \geq 0$. Substituting these lower bounds into the right hand side of the expression above, we have

$$\begin{aligned}
\sum_{i=1}^{n} e_i &\leq (t - t_{-1})(1 - \frac{B_n}{t - t_{-1}}) \\
&= t - t_{-1} - B_n \\
&\leq t - t_0
\end{aligned}$$

However job J_n misses its deadline at time t, therefore, $\sum_{i=1}^{n} e_i > t - t_0$, which is clearly a contradiction. □

Proof of Theorem 2: To see why Theorem 2 follows from Lemma A, we note that each constant utilization server can be thought of as a stream of sporadic jobs, only one of which is active at any time, and the density of these sporadic jobs are all equal to the size of the server by definition. A total bandwidth server can be thought of as a constant utilization server that is allowed to execute in time intervals when no job with an earlier deadline than the server is ready to execute. Moreover, it does not consume more processor time before each server deadline than the constant utilization server. Therefore, from the point of view of schedulability, it can be thought of as a constant utilization server. □