

# Deadline Assignment in a Distributed Soft Real-Time System\*

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## Abstract

*In a distributed environment, tasks often have processing demands on multiple different sites. A distributed task is usually divided up into several subtasks, each one to be executed at some site in order. In a real-time system, an overall deadline is usually specified by an application designer indicating when a distributed task is to be finished. However, the problem of how a global deadline is automatically translated to the deadline of each individual subtask has not been well studied. This paper examines (through simulations) four strategies for subtask deadline assignment in a distributed soft real-time environment.*

**Keywords:** *soft real-time, distributed systems, deadline assignment, scheduling.*

## 1 Introduction

Consider a radar surveillance system whose task is to track flying objects, decide whether an object is friendly or hostile, and in the latter case, come up with a combat strategy. This system requires the cooperation of several different components: a radar sensor component gathering radar images, a vision system extracting the features of objects, a database component matching those features with those of known objects, an expert system selecting the best defense plan, and so on. Each component may run on a separate device or computer, using its own scheduling policy. For instance, the database lookup may be done on a back-end database server that uses an earliest (local) deadline first scheduler.

In this example, several components of the system are involved between the first sighting of an object and a defensive action like launching a missile. The system specification indicates how much time the system as a whole is allowed to respond to the threat of an intruder. In other words, a deadline of the complete task (from sighting to action) is specified. However, the system is faced with the problem of assigning deadlines or priorities to each of the subtasks. For example, the subtask that is doing

a database lookup for a particular object will be running on the database server, competing against other database tasks. What local deadline is to be assigned to the lookup subtask in this case? Answering this question is the main goal of this paper.

Our focus is on *soft real-time* systems. In such systems, it is very difficult to guarantee that all deadlines will be met, and hence one tries to *minimize* the number of deadlines that are missed. Guaranteeing all deadlines may be hard because it is impossible to impractical to place an upper bound on the load, or tasks are so complex that it is hard to predict exactly how long they will run or what resources they may need.

In this paper we study the *subtask deadline assignment problem*, or SDA for short. A given task is to be executed and completed by a specified deadline. The task executes several subtasks, each at possibly different system components. As each subtask is submitted to its component, a local deadline must be assigned to it. At each component, there may also be local tasks that just run at that component and that compete for resources with the subtasks assigned there.

To study the SDA problem, we make three assumptions:

- The subtask deadlines are to be assigned *on-line*, as opposed to a-priori when the global task is defined or first submitted. On-line assignment is superior in soft real-time systems, where the types of subtasks or their durations may be unknown in advance. We assume a subtask receives its deadline just before it is submitted for execution at its corresponding component.

- The scheduler at each component is independent of the others. There is no global scheduler that instructs each component scheduler what to do. Each scheduler makes decisions based solely on the subtasks (and their deadlines) that have been presented to it for execution, without consulting other schedulers. We believe that large systems are built out of preexisting components. Each component will have its own scheduling policy and will be unable or unwilling to coordinate or subordinate its scheduling decisions with (or to) others.

- Each system component is unique. If a subtask must be executed at a particular component, it must run there. There is no load balancing, i.e., an overloaded component cannot ship subtasks to other components.

To illustrate how the choice of a SDA strategy affects a real-time system, let us consider the following example.

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Suppose we have a real-time task  $T$  that consists of two subtasks  $T_1$  and  $T_2$  to be executed in series at components  $C_1$  and  $C_2$  respectively. Before a subtask is submitted for execution, a deadline has to be assigned to it so that the component real-time scheduler knows about the relative priority of the subtask compared to other tasks. Since  $T_2$  is the last subtask of  $T$ , its deadline should just be the (ultimate) deadline of  $T$ . If  $T_1$  also adopts the same ultimate deadline, there will be a problem when the system load is high: In a tight situation, when tasks are being finished close to their deadlines, this scheme would leave little or no slack for the execution of  $T_2$ . Task  $T$  would thus have a high probability of missing its deadline. This discussion suggests that an earlier deadline should be assigned to  $T_1$  instead. The question is: how early? If the deadline is not early enough, we have the same problem; on the other hand, if the deadline is too early, then the  $C_1$  scheduler will be fooled regarding the urgency of subtask  $T_1$ . Other "more urgent" tasks will have to give way to this "false urgent" subtask and possibly miss their deadlines.

We believe that the SDA problem is a central one in distributed soft real-time systems. Notice that it even encompasses the communication subsystem. That is, sending messages can be viewed as another type of subtask. For instance, let us return to our two task example:  $T = T_1, T_2$ . Say that after  $T_1$  completes, it is necessary to send a message from  $C_1$  to  $C_2$  containing the inputs for  $T_2$ . Then after  $T_2$  finishes it is necessary to ship the final result to some other site. The two transmissions can be seen as two additional subtasks,  $T_a, T_b$ , so that the global task is really  $T = T_1, T_a, T_2, T_b$ . The communications subsystem needs to be given a deadline when  $T_a$  (and  $T_b$ ) is submitted, so again we see a need for SDA. Also note that the SDA problem may arise *within* a single site that contains multiple subsystems such as the CPU, the disk, and memory. For example, even within a single database system, sub-deadlines may have to be used when requesting a disk block read, a buffer page allocation, or a processor for computation.

As we proceed, we will address the following questions:

- (1) What are the options in choosing a SDA strategy?
- (2) How does a given SDA strategy affect a task's chances of meeting its deadline?
- (3) What are the underlying reasons for the observed effects of a SDA strategy?
- (4) Given a set of system parameters (e.g. load, slack of tasks), and performance goals (e.g. to minimize the number of tardy tasks, to treat tasks fairly), how would one choose a SDA strategy?
- (5) For those strategies that use a prediction of task execution times, how accurate must the prediction be to maintain a low level of missed deadlines?

The rest of this paper is organized as follows. In Section 2, we mention some related work. Section 3 describes the logical base model for our study. Different SDA strategies are introduced in Section 4. A brief description of our simulation experiments is contained in Section 5. In Section 6 we display and analyze the results of our experiments, while Section 7 discusses other variations of our base model. In Section 8 we present conclusions.

## 2 Related Work

A lot of research has been done on real-time scheduling in various environments, be it I/O scheduling, processor scheduling, or transaction scheduling [3, 1, 2, 9]. However, most of this work either:

- Focuses on the characteristics of a specific system component and evaluates the performance of various scheduling policies when applied to that component. For example, there have been studies on real-time database systems [6], or communication systems [8, 13]. These studies make the tacit assumption that the deadlines of tasks when they arrive at the component are known. They do not concern themselves on whether these tasks are really subtasks of a global task that involves multiple components.

- Assumes a global scheduling strategy that controls in some way all component schedulers. For example, in [12], schedulers interact with each other to decide the best place to execute a subtask. As we have stated, here we look instead at an environment where local schedulers are autonomous and subtasks cannot move.

There are however at least two studies that are closely related to our approach and the SDA problem. Bettati and Liu [4, 5] discussed the problem of scheduling subtasks in a *hard* real-time distributed environment. Their work focuses on those systems for which global tasks can be characterized as "flow shops." In their model, global tasks consist of the same set of subtasks to be executed on nodes in the same order. The goal is to devise efficient *off-line* algorithms (assuming all the information about global tasks is known ahead) for computing a schedule of the subtasks such that all deadlines are met (if such a schedule exists).

Another interesting paper [11] by Pang, Livny, and Carey investigates the problem of "bias" against longer transactions under "earliest-deadline-based" scheduling policies in *real-time database systems*. The study shows that long transactions miss more deadlines compared to short ones. This is not because of tighter timing constraints (the phenomenon occurs even when long transactions have larger amount of slack), but because of their bigger size, which causes them to have "further-in-the-future" deadlines. Long transactions thus compete unfavorably with short transactions in accessing system resources.

Their approach to the problem is to assign *virtual deadlines* to all transactions. A transaction with an earlier virtual deadline is served before one with a later virtual deadline. The virtual deadline of a transaction is adjusted dynamically as the transaction progresses, and is computed as a function related to the size of the transaction. By monitoring the system and gathering runtime statistics, a parameter in computing virtual deadlines is carefully adjusted in such a way that the linear correlation between miss ratio and transaction size is minimized.

Our work is similar to [11] in that we both try to assign earlier deadlines to tasks. However, in their case there is a single scheduler for a single database system. For our problem, there are multiple "resources" handled by independent schedulers. Furthermore, distributed tasks have natural breaks (subtasks) that make the assignment of deadline more natural.

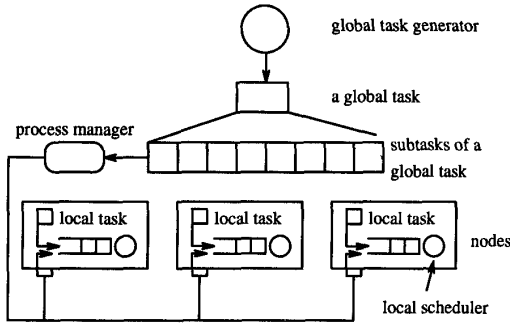


Figure 1: Model.

### 3 Base Model

To study the SDA problem we postulate a simple model of the system and tasks. A distributed real-time system consists of several *nodes* representing system components (see Figure 1). Each node manages one or more resources, for example, a database, a cycle server, or a communication channel. At each node, there is a real-time scheduler prioritizing tasks according to some real-time queueing discipline, e.g., earliest deadline first. We consider two categories of tasks: *local* and *global*. A task that visits only one node and is submitted to a scheduler only once is termed a local task. On the other hand, a global task is a *set* of several related *subtasks* (or *stages*) to be executed in series.<sup>1</sup> The deadline of a global task is the time by which the last subtask must complete. Each subtask is associated with an *execution node* to which it is submitted for execution.

We further assume that a global task is controlled and monitored by a process manager. The manager runs at any node, and may be different for each global task. When a global task is generated, its process manager will submit the first subtask to the corresponding execution node. When a subtask,  $X$ , finishes, its manager is notified and immediately submits the next subtask (if there is any) of  $X$ 's global task. We assume that the process manager of a global task does not consume any resources.

Associated with each task  $X$  (whether it is local, global, or a subtask) are five attributes denoted by the following functions:

- $ar(X)$  = arrival (or submission) time of  $X$ ,
- $sl(X)$  = slack of  $X$ ,
- $dl(X)$  = deadline of  $X$ ,
- $ez(X)$  = *real* execution time of  $X$ ,
- $pez(X)$  = *predicted* execution time of  $X$ .

The first four attributes are related by the following equation:

$$dl(X) = ar(X) + ez(X) + sl(X).$$

<sup>1</sup>Subtasks could also be executed in parallel, but this is not considered here due to space limitations.

When a global task  $X$  is first processed by its manager, we assume its deadline  $dl(X)$  is known. Since its arrival time is also known, the slack can be computed using the above equation. The execution time  $ez(X)$  is *not* known in advance; we only define it here to help us in the discussion.

In some scenarios, an estimate of the execution time,  $pez(X)$ , may be available and can be used by the manager for making subtask deadline assignments. Furthermore, in some cases, the manager may know an estimate or prediction on the number of subtasks involved in  $X$ , plus an estimate of their duration. Most of the subtask deadline assignment policies to be discussed in the next section will utilize this information.

We also define flexibility (denoted by  $fl(\cdot)$ ) of a task  $X$  to be the ratio of the amount of  $X$ 's slack to the execution time of  $X$ . That is,

$$fl(X) = sl(X)/ez(X).$$

Intuitively, the more flexible a task is (higher  $fl(\cdot)$ ), the less stringent is its timing constraint.

An additional attribute for a subtask is its *stage*, which is defined by:

$$stage(X) = i \text{ if } X \text{ is the } i\text{th subtask of its global task.}$$

We say that a subtask  $X$  is an *earlier-stage* compared to another subtask  $Y$  if they are of the same global task and  $stage(X) < stage(Y)$ .

Finally, there is the issue of tardy tasks, or overload management policy. Say a task  $X$  has already missed its deadline, but has not completed execution. One option is to abort  $X$  as soon as it misses its deadline, under the assumption that whatever it was doing is now useless. A second option is to continue to process  $X$ , under the assumption "better late than never." Due to space limitations, in this paper, we focus on the no abortion case (no specific action is taken when a deadline expires). However, as is briefly mentioned in Section 7, the results for the abortion case do not significantly change the relative performance of the SDA strategies.

### 4 SDA strategies

In this section, we propose four SDA strategies and give their formal definition. We consider a global task  $T$  that consists of  $m$  subtasks  $T_1, \dots, T_m$  to be executed in series. An SDA strategy is one that determines the values of  $dl(T_i)$  ( $1 \leq i \leq m$ ) at the time when  $T_i$  is submitted.

We demonstrate the various SDA strategies by an example shown in Figure 2. In the example, the global task  $T$  has 4 subtasks  $T_i, T_{i+1}, T_{i+2}, T_{i+3}$  remaining. (subtasks  $T_1, \dots, T_{i-1}$  have completed). These subtasks have execution times of 3, 1, 1, and 1 units respectively. Moreover,  $T_i$  arrives at time 0 (i.e.,  $T_{i-1}$  finished at time 0) and the ultimate deadline of  $T$  is time 12. The amount of slack remaining for  $T$  is 6 units.

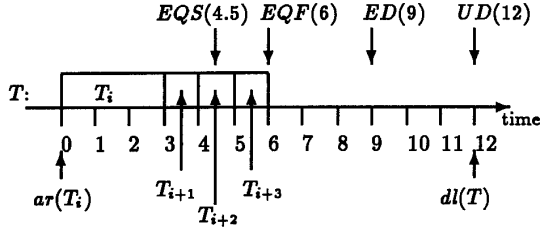


Figure 2: Example on the various SDA strategies. Key:  $X(y) \leftrightarrow dl(T_i) = y$  under SDA strategy  $X$ .

Without any knowledge on the execution times of the subtasks, the only available measure of their timing requirement is the deadline of their global task  $T$ . A simple SDA strategy would be to set the deadline of a subtask to be equal to the deadline of its global task (12 in Figure 2). We call this strategy *Ultimate Deadline (UD)*.

(1) **Ultimate Deadline (UD):**

$$dl(T_i) = dl(T).$$

A problem with *UD* is that the time for the execution of a later-stage subtask (e.g.  $T_{i+1}$  in Figure 2) is considered slack to an earlier stage ( $T_i$ ). This gives the schedulers incorrect information about how much time a subtask can be delayed in its execution without causing a missed deadline.

If an estimate of the subtask execution time is available, we can compute the effective deadline of a subtask. The effective deadline of a subtask  $T_i$  is equal to the deadline of its global task  $T$  (time 12 in the example) minus the total expected execution time of the subtasks of  $T$  following  $T_i$  (3 units)<sup>2</sup>. Formally, we have,

(2) **Effective Deadline (ED):**

$$dl(T_i) = dl(T) - \sum_{j=i+1}^m pex(T_j).$$

A problem common to both *UD* and *ED* is that all the remaining slack of  $T$  (6 units in the example) is allocated to the currently active subtask ( $T_i$ ). This subtask thus has a low priority compared to other tasks of the system. A big portion of this slack may be consumed while the subtask is waiting for its turn in the scheduler queue. Subtasks that represent early stages of global tasks thus consume most of the slack of their global tasks. This leaves little slack for the subtasks to follow. Global tasks may therefore have a low probability of meeting their deadlines.

The problem of “little slack for final-stage subtasks” gets worse when there are many local tasks in the system. This is because local tasks have only one, probably short stage.<sup>3</sup>

<sup>2</sup>We assume the estimates are perfect in our example.

<sup>3</sup>The experimental result shown in this paper assumes a local task and a subtask have similar processing demand on average (see Section 5 and table 1 for more details). Experiments with different resource requirement for local tasks and subtasks have also been conducted, but the result is not included due to space limitation.

If local tasks have similar flexibility ( $sl(\cdot)/ex(\cdot)$ ) as compared to global tasks, then on average they have smaller total amount of slack than global ones do. When competing for system resources, early-stage subtasks of global tasks will be discriminated against (i.e., scheduled later than other tasks), because of their much larger slack. The scheduler is therefore biased in favor of local tasks at the expense of global ones.

To avoid discrimination and to allow enough slack for final-stage subtasks, each subtask should have its fair share of its global task’s slack. One way of doing it is to divide the total remaining slack (6 units in Figure 2) equally among the *remainings* subtasks (4 of them). This gives us the *Equal Slack (EQS)* strategy:

(3) **Equal Slack (EQS):**

$$dl(T_i) = ar(T_i) + pex(T_i) + [dl(T) - ar(T_i) - \sum_{j=i}^m pex(T_j)] / (m - i + 1).$$

The term in brackets represents the remaining slack. In our example, *EQS* would assign  $dl(T_i)$  as  $0 + 3 + 6/4$  or 4.5. This is shown at the top of Figure 2.

A fourth strategy is to divide the total remaining slack among the subtasks in proportion to their execution times. In this way, subtasks of the same global task do not have equal slack, but equal flexibility. We call this strategy *Equal Flexibility (EQF)*.

(4) **Equal Flexibility (EQF):**

$$dl(T_i) = ar(T_i) + pex(T_i) + [(dl(T) - ar(T_i) - \sum_{j=i}^m pex(T_j))] * [pex(T_i) / \sum_{j=i}^m pex(T_j)].$$

For our example, under *EQF*,  $dl(T_i)$  is  $0 + 3 + 6 * (3/6)$  or 6.

## 5 Simulation Model

In order to study and contrast system behavior under these SDA strategies, we developed a simulation model and performed extensive experiments. In this section we describe the model; our results are presented in Section 6.

In practice, the soft real-time systems we are trying to study can be very complex. For instance, each node may have a different scheduler type, and different execution characteristics. For example, the communications subsystem may schedule outgoing messages using a simple earliest deadline first strategy, and its subtasks may take on the order of microseconds to execute. A database server node, on the other hand, may take into account lock contention in its scheduling decisions and subtasks may take on the order of seconds. Similarly, global tasks can be extremely varied, ranging from ones with a few short subtasks, to ones lasting days and spanning many nodes.

If we model all this diversity and complexity, our results on SDA would be obscured by many irrelevant parameters.

Instead, we use a very simple model that captures the essential features that impact SDA. To pick a particular example, in a given experiment we assume that all global tasks have a fixed number of subtasks,  $m$ . Clearly this is not “realistic;” as we have stated, tasks will have a variety of subtasks. If we were trying to predict performance of a particular distributed application, this assumption would not be acceptable. But if we are trying to understand how the number of subtasks affects the choice of SDA algorithm, this is the best assumption. By running different experiments with different values of  $m$ , we may be able to see that for short global transactions maybe algorithm  $X$  is better than  $Y$ . For long tasks, the reverse may be true. The same argument can be made for all the modeling assumptions we are about to make. Our point is that only by selecting a small number of simple, key parameters will we be able to understand the fundamental interactions.

Our simulator is written in the simulation language DeNet[10]. Each simulation experiment (generating one data point) consists of two simulation runs each lasts one million time units (at least 100,000 tasks are generated per run, many more for high load experiments). The 95% confidence interval is  $\pm 0.35$  percentage point, or 0.0035 (much smaller for high load experiments) for the missed deadlines figures shown in later sections.

The structure of our simulation model follows the conceptual model described in Section 3 with the following characteristics.

**Nodes** There are  $k$  (homogeneous) nodes in the system. Each node services their tasks according to some real-time scheduling algorithm with *no preemption*. In this paper, we use *earliest-deadline-first*<sup>4</sup> as the scheduling algorithm for most of our experiments, mainly due to its popularity. We will also discuss briefly the case when *minimum-laxity-first*<sup>5</sup> is used as the scheduler algorithm in Section 7.

**Local Tasks** Local tasks are being generated at each node according to a Poisson distribution with mean interarrival time  $1/\lambda_{local}$  time units. Since there are  $k$  nodes, the total average arrival rate is  $k\lambda_{local}$  per unit time. Execution times of local tasks are exponentially distributed with mean  $1/\mu_{local}$  time units. The rate of work due to local tasks is thus  $k\lambda_{local}/\mu_{local}$ . In this paper, we set  $\mu_{local} = 1$ , other time measures are thus relativized to the average execution time of a local task. Slack of local tasks is uniformly distributed in the range  $[S_{min}, S_{max}]$ .

**Global Tasks** Similar to local tasks, global tasks are being generated as a *single stream* of Poisson process with mean interarrival time  $1/\lambda_{global}$ . In order to simplify our discussion, we hold a simple view of the world that global tasks are homogeneous. In particular, we assume that all global tasks consist of  $m$  subtasks and the execution times of the subtasks all follow the same exponential distribution with mean equal to  $1/\mu_{subtask}$  time units. The total execution times of global tasks thus follow an  $m$ -stage Erlang distribution with mean  $m/\mu_{subtask}$ . The rate of work due to global tasks is therefore  $m\lambda_{global}/\mu_{subtask}$ . We assume

<sup>4</sup>Tasks in a scheduler queue are ordered in increasing deadlines; The task with the earliest deadline is served first.

<sup>5</sup>Tasks in a scheduler queue are ordered in increasing slack; The task with the least slack is served first.

that nodes are equally likely to be chosen as the execution node of a subtask.

We define the term *rel-flex* to be the relative flexibility of global tasks with respect to local tasks<sup>6</sup>. So if the distribution of slacks of global tasks is uniform in the range  $[a, b]$ , we can determine  $a$  and  $b$  by the following equations<sup>7</sup>:

$$\left(\frac{a}{m/\mu_{subtask}}\right) / \left(\frac{S_{min}}{1/\mu_{local}}\right) = rel\_flex,$$

$$\left(\frac{b}{m/\mu_{subtask}}\right) / \left(\frac{S_{max}}{1/\mu_{local}}\right) = rel\_flex.$$

Or,

$$a = m \cdot rel\_flex \cdot S_{min} \cdot (\mu_{local}/\mu_{subtask}),$$

$$b = m \cdot rel\_flex \cdot S_{max} \cdot (\mu_{local}/\mu_{subtask}).$$

A *rel-flex* of 1 means that global tasks and local tasks have the same flexibility distribution. A greater (smaller) than 1 *rel-flex* means in general, global tasks are more (less) flexible than local ones.

**System Load** We define the *normalized load* (or *load* for short) to be the ratio of the rate of work generated to the total processing capacity of the system. That is,

$$load = \left(\frac{m \cdot \lambda_{global}}{\mu_{subtask}} + \frac{k \cdot \lambda_{local}}{\mu_{local}}\right) / k.$$

For a stable system, we have  $0 \leq load < 1$ .

We also define *frac.local* to be the fraction of *load* that is contributed by local tasks. That is,

$$frac\_local = \frac{k \cdot \frac{\lambda_{local}}{\mu_{local}}}{m \cdot \frac{\lambda_{global}}{\mu_{subtask}} + k \cdot \frac{\lambda_{local}}{\mu_{local}}}.$$

If the system does not have any local tasks, *frac.local* = 0; a *frac.local* of 1 means no global tasks. As another example, if subtasks and local tasks have similar execution time, then a *frac.local* of 1/2 means that there are the same *number* of local tasks and global *subtasks*. However, since it takes  $m$  subtasks to make a global task, when *frac.local* is 1/2, there are  $m$  times more *local tasks* generated than *global tasks*.

Table 1 shows the parameter setting of our baseline experiment. In particular, we assume that the prediction on execution time is perfect, i.e.,  $pez(.) = ex(.)$  (In Section 7 we return to this issue and discuss the impact of error in the predictions.) To study the effect of these parameters on system performance, we will vary the parameters from their base settings. This is discussed in the following section.

<sup>6</sup>Recall that the flexibility of a task is defined to be the ratio of its slack over its execution time.

<sup>7</sup>Recall that the slack distribution of local tasks is uniform in the range  $[S_{min}, S_{max}]$ .

Overload Management Policy	No Abortion
Local Scheduling Algorithm	Earliest Deadline First
$\#subtask$	1.0
$\#local$	1.0
$k$ (# of nodes)	6
$m$ (# of subtasks of a global task)	4
$load$	0.5
$frac\_local$	0.75
$[S_{min}, S_{max}]$	[0.25, 2.5]
$rel\_flex$	1.0
$pez(X)/ex(X)$	1.0

Table 1: Baseline setting

## 6 Analysis

In this section, we summarize the results of our simulation experiments. As performance measure we use the percentage of missed deadlines (or miss ratio).<sup>8</sup> In particular, we look at the probability of a task missing its deadline conditional on its task class (i.e. global or local). We adopt the notation  $MD_A^B$  where  $MD$  stands for fraction of missed deadlines, and  $A \in \{\text{local, global}\}$ ,  $B \in \{UD, ED, EQS, EQF\}$  are optional modifiers describing the task class and SDA strategy used. For example,  $MD_{global}^{UD}$  denotes the probability that a global task misses its deadline under the  $UD$  strategy.

### 6.1 Baseline Experiment

As a starting point, let us look at how the various strategies do relative to each other in our baseline experiment. Figures 3(a) and 3(b) show  $MD_{local}$  and  $MD_{global}$  of the various SDA strategies as  $load$  varies from 0.1 to 0.5<sup>9</sup>.

Comparing Figures 3(a) and 3(b), we see that even though global tasks and local tasks have the same average flexibility ( $rel\_flex = 1$  for the baseline setting), there is a significant difference in their ability to meet deadlines. For example, at  $load = 0.5$ ,  $MD_{global}^{UD} = 40\%$  (point A), while  $MD_{local}^{UD} = 24\%$  (point B). However, for local tasks (Figure 3(a)) and for light loads, there is little difference.

We should point out that traditionally soft real-time systems are studied under high load situations. Most of the time, the system will hopefully operate under low load; no deadlines will be missed regardless of what scheduling policy is used. However, once in a while the system will be overloaded, and it is precisely at those times when we need a scheduling policy that can miss the fewest deadlines. For this reason, the big differences in missed deadlines under high load in Figure 3(b) are important.

In order to understand these differences, let us consider the types of resource competition among tasks. Since there are 2 task classes, there are 3 types of contention: local-local, local-global and global-global. A local scheduler

<sup>8</sup> A secondary measure could be tardiness, i.e., by how much time do tasks miss their deadlines. However, due to space limitations, we do not consider this measure.

<sup>9</sup> We use dotted lines for  $MD_{local}$  and solid lines for  $MD_{global}$ . We also associate symbols like  $\diamond$  and  $+$  to different SDA strategies.

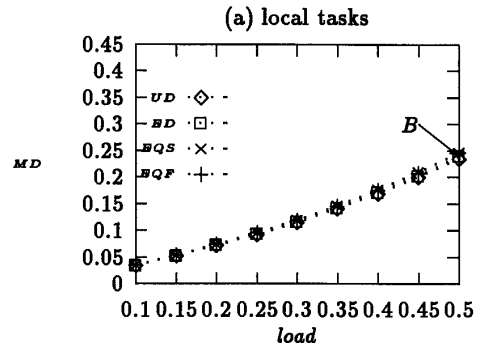


Figure 3: (a) Performance of various SDA strategies in the baseline experiment (local tasks).

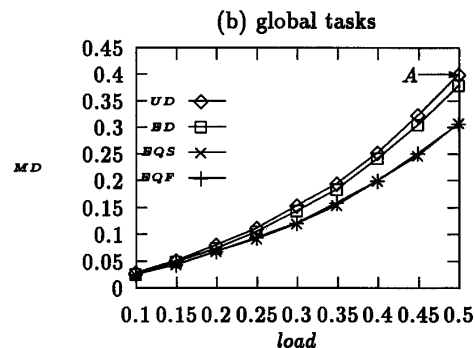


Figure 3: (b) Performance of various SDA strategies in the baseline experiment (global tasks).

resolves contention by comparing the deadlines of tasks. Since a SDA strategy only affects subtask deadlines, it only impacts local-global and global-global contention. The reason why local tasks are not affected by the SDA strategy (Figure 3(a)) is that in our baseline experiment, 75% of the load is contributed by local tasks. Thus, much of the contention faced by local tasks is local-local, and unaffected by the SDA strategy. On the other hand, global tasks face local-global and global-global contention, so the choice of a SDA strategy affects them significantly (Figure 3(b)).

Through extensive simulation experiments (not shown here), we observe (and this is confirmed in Figure 3) that the performance of  $ED$  lies between that of  $UD$  and  $EQF$ . We also observe that  $EQS$ 's performance is very close to that of  $EQF$  over a wide range of parameter settings. In cases when they differ,  $EQF$  usually is superior. Thus, in order to simplify our presentation, we will exclusively focus on  $UD$  and  $EQF$  in the rest of this paper.

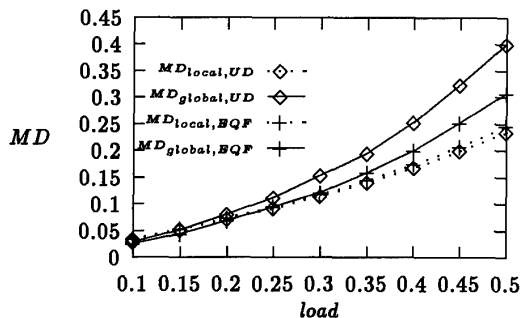


Figure 4: Comparing *UD* and *EQF* in baseline experiment.

## 6.2 *UD* Vs *EQF*: Their different treatment of global tasks

To further compare *UD* and *EQF*, we overlap Figures 3(a) with 3(b), and remove the curves for *ED* and *EQS*. The result is plotted in Figure 4. From this figure, we make the following three observations:

(I) Under *UD* and high loads, global tasks miss many more deadlines than local tasks.

(II) Strategy *EQF* significantly improves the performance of global tasks (high load), but still local tasks have a better chance of meeting their deadlines.

(III) Comparing the local tasks under the two strategies (dotted lines). *UD* gives a lower local task missed deadlines figure than *EQF* does. The difference, however, is very small.

Observation (I) is not surprising. In Section 4 we had hypothesized that *UD* would assign too much slack to early subtasks, resulting in a scheduling discrimination when they competed against local tasks. However, observation (II) is surprising because by assigning global tasks flexibility that was comparable to that of local tasks, we expected a “fair playing field.” Unfortunately, in spite of our efforts, global tasks somehow are still hurt.

Before studying the causes of observation (II), let us confirm the hypothesis behind observation (I). Let us call this hypothesis the *discrimination hypothesis*: by giving early subtasks of global tasks too much slack, *UD* makes global tasks “second class citizens” as they compete with local tasks. To confirm the hypothesis, in Figure 5 we vary the relative proportion of the two task classes, i.e., we vary *frac.local* from 0.1 to 0.95<sup>10</sup>.

In the figure we see that as *frac.local* increases (fewer global tasks), indeed  $MD_{global}^{UD}$  increases. This is because

<sup>10</sup>Recall that *frac.local* is the fraction of load contributed by local tasks (see definition on page 5).

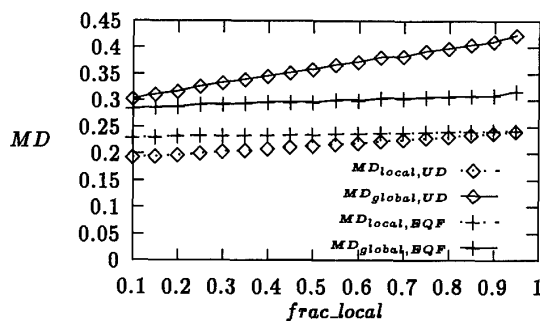


Figure 5: Effect of varying the fraction of local tasks.

global tasks face more and more conflicts with local tasks, and are discriminated against more and more. Notice that  $MD_{local}^{UD}$  also increases (although to a smaller extent): this is because local tasks are also facing more and more conflicts with “first class” tasks. On the other hand, observe that the  $MD_{local}^{EQF}$  and  $MD_{global}^{EQF}$  values hardly change as *frac.local* varies. This is because *EQF* does not discriminate against global tasks.

As another observation on Figure 5, notice that when *frac.local* is close to zero (almost all tasks are global), *UD* and *EQF* miss similar number of global task deadlines. Strategy *UD* is still assigning too much slack to global tasks, but since everybody is a “second class citizen,” it does not really matter. Hence, in an application where most tasks are global, *UD* may be an adequate (and simpler) strategy.

Observation (III), namely,  $MD_{local}^{UD} < MD_{local}^{EQF}$ , can be explained by the fact that *EQF* assigns earlier deadlines to subtasks than *UD* does. The subtasks can therefore compete better with local tasks. Local tasks thus miss more deadlines under *EQF* than under *UD*. In Figure 5, the gap between  $MD_{local}^{UD}$  and  $MD_{local}^{EQF}$  widens as the fraction of local work decreases, for more subtasks enter the arena fighting for resource with local tasks.

## 6.3 Why $MD_{global}^{EQF} \neq MD_{local}^{EQF}$ ?

If there is no discrimination under *EQF*, then why are global tasks still performing poorly (observation (II))? The reason is that global tasks consist of a *series* of subtasks and there are two phenomena affecting the series. One phenomenon is beneficial to global tasks: if one subtask finishes early, its leftover slack is inherited by the subtasks that follow. Thus, later subtasks will tend to have even more slack. The second phenomenon is detrimental to tight tasks. If a global task has little slack to begin with, it may miss an early sub-deadline, robbing slack from the

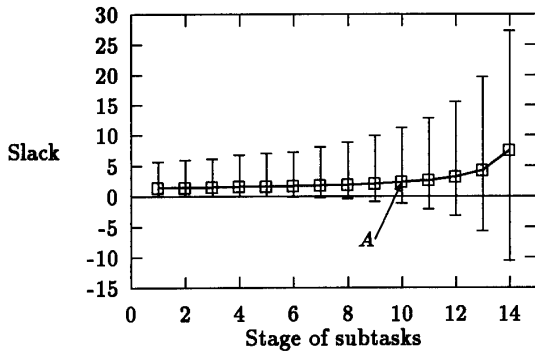


Figure 6: Average and the mid-95 percentile range of slack of subtasks versus stage of subtasks.

following subtasks, and making things even worse for them. Essentially, “the poor get poorer while the rich get richer.”

To observe these phenomena, we ran an experiment with the same parameter values as our baseline experiment except that the number of subtasks of a global task ( $m$ ) is now 14 instead of 4. In Figure 6, we plot the average slack of a subtask versus the stage of the subtask (the ‘□’ line). For example, point *A* shows that the average slack of a 10th stage subtask is 2.3 units in our experiment. Also shown in the figure is the range of the slack data points with the largest 2.5 percentiles and the smallest 2.5 percentiles removed. The graph thus shows, for example, that the “middle” 95% of all 13th-stage subtasks have slacks in the range [-5.7, 19.7].

We can see that the average slack of a subtask increases as it advances. This is due to the beneficial phenomenon. However, the variability in slack increases, due to the detrimental phenomenon. Even though there is more slack on the average, there is a group of tasks that are suffering (the “poor”) and are more likely to miss their ultimate deadlines. This is suggested by the fact that part of the 95% range bars lie below the x-axis. (As an analogy, even if the standard of living is increasing, more people may be under the poverty line.)

Depending on the system parameters, the beneficial and detrimental phenomena may have more or less force. In Figure 4, as the load increases, there are more global tasks that are “poor” to begin with (do not have much slack to spare). Thus, the detrimental effect causes more global tasks to miss their deadlines. As the load decreases, however, there are fewer poor tasks, and global tasks miss roughly the same number of deadlines as local tasks. As the load decreases further, the beneficial effect may actually cause global tasks to do *better* than local tasks. This effect can barely be seen in Figure 4, but will be seen clearly later in other graphs.

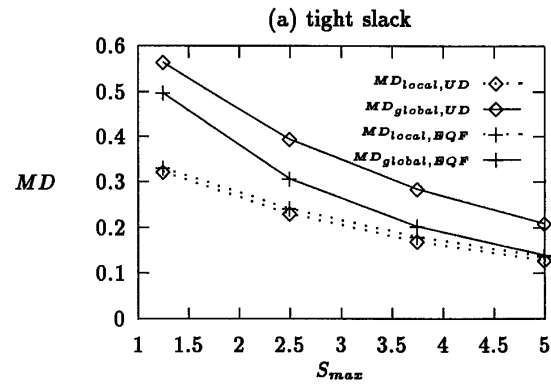


Figure 7: (a) Effect of varying  $S_{max}$  (tight slack).

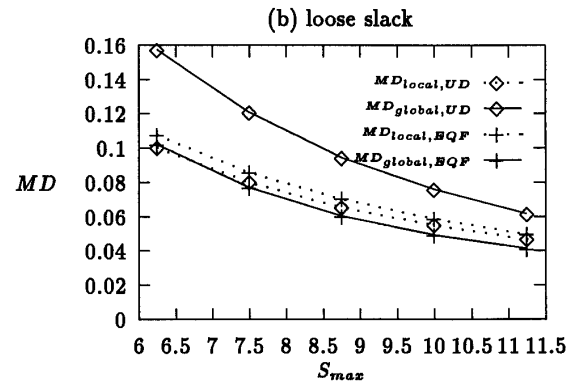


Figure 7: (b) Effect of varying  $S_{max}$  (loose slack).

#### 6.4 The effect of slack and the number of subtasks of a global task ( $m$ )

To evaluate the gains of *EQF* over *UD*, we varied over wide ranges all of our model parameters (Table 1). Here we report on two of the more interesting experiments, involving the slack and the number of subtasks of a global task ( $m$ ).

Figure 7 shows the result of varying  $S_{max}$  from 1.25 to 11.25 for the baseline setting. To improve legibility, we divide the graph into two parts: 7(a) and 7(b), showing tight and loose slack conditions respectively. Note that these subfigures use a different *MD* scale.

As expected, Figure 7 shows that as slack ( $S_{max}$ ) increases, tasks of all types enjoy a lower miss ratio. As in Figure 4,  $MD_{local}$  is not affected by the SDA policy (75% of the load is local tasks, and their local-local conflicts are not affected by SDA).



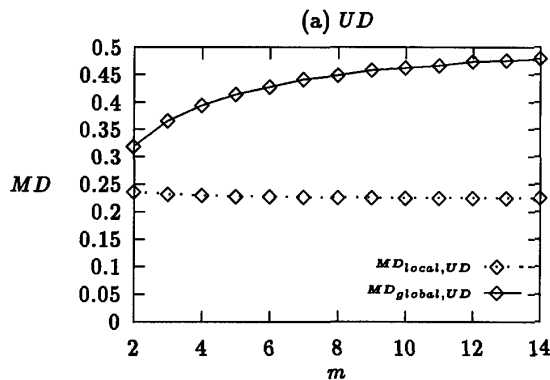


Figure 8: (a) Effect of varying  $m$  ( $UD$ ).

The choice of a SDA strategy, however, strongly affects global tasks (solid lines). When slack is large (Figure 7(b)),  $UD$  consistently misses about 50% more global task deadlines than  $EQF$  does. As slack tightens (Figure 7(a)), global tasks miss more deadlines, and the gap between  $EQF$  and  $UD$  narrows, eventually closing when there is effectively too little slack and most of the deadlines are missed.

Comparing the  $MD_{local}^{EQF}$  and  $MD_{global}^{EQF}$  curves, we observe the same effect of Section 6.3. With tight slack, there are more “poor” tasks that end up missing their deadlines because of the detrimental effect of serial subtasks. However, with more slack, the beneficial effect is stronger and we see that global tasks actually miss fewer deadlines as compared to local tasks. The crossover point occurs when  $S_{max} \simeq 5$  units.

Keeping all other baseline parameters fixed, Figures 8(a) and 8(b) show the results of varying the number of subtasks,  $m$ , from 2 to 14 for  $UD$  and  $EQF$  respectively. From Figure 8(a), we see that  $MD_{global}^{UD}$  increases as  $m$  increases while  $MD_{local}^{UD}$  decreases. This shows that the discrimination problem is intensified by the length (number of subtasks) of global tasks. As a global task grows,  $UD$  incorrectly assigns more and more slack to early subtasks.

For  $EQF$  (Figure 8(b)), increasing  $m$  increases both the beneficial and the detrimental phenomena. For our parameter settings, the effects cancel each other and the result is a rather flat curve of  $MD_{global}^{EQF}$ .

To sum up,  $EQF$  always performs better than, or at least as well as,  $UD$ . The  $EQF$  gains are more significant when there is “moderate” slack and load. That is, if slack is too tight or the load too high, no matter what SDA policy we use, many deadlines will be missed. If slack is too loose or load too light, then all tasks will make their deadlines, no matter how we schedule. But in the intermediate range a smart SDA policy can make a difference and this is where  $EQF$  wins big. The  $EQF$  strategy is also superior when

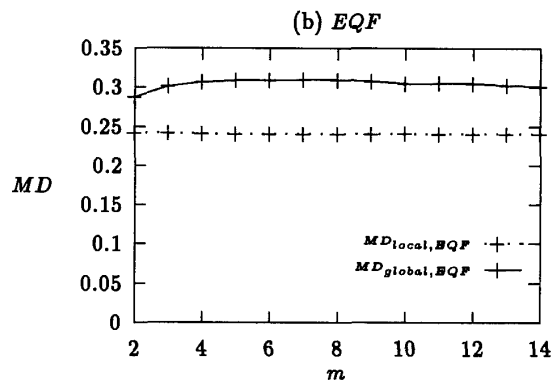


Figure 8: (b) Effect of varying  $m$  ( $EQF$ ).

global tasks have many subtasks.

## 7 Other System Properties

In our simulation model, several assumptions are made, such as tardy tasks are not aborted, the local scheduling algorithm is earliest deadline first, and perfect execution time information is available. Extensive simulation has been done with these assumptions relaxed. In this section we give a brief account on our findings. Readers are referred to [7] for more details.

In order to study the  $EQF$ 's performance sensitivity to estimate errors, we introduce “random noise” to the estimates. Surprisingly, the performance of  $EQF$  is not very sensitive to errors in the execution time estimate under our baseline setting. Even if estimates are off by up to a factor of two,  $EQF$  continues to perform well compared to  $UD$ , which is unaffected by these errors. Further experimentation shows that this sensitivity is increased by a small amount in a high load, tight slack environment, and when *minimum-laziness-first* is used as the local scheduling algorithm.

Another assumption we made in the base model is that all tardy tasks are valuable and no particular action is taken when a task misses its deadline. (See Section 3.) Although not reported here in detail, we modified our simulator to abort tardy tasks. The results show that aborting tardy tasks does not significantly change our conclusions regarding the  $UD$  and  $EQF$  policies. However, abortion does help  $UD$  (in reducing the number of local and global task missed deadlines) more than it helps  $EQF$ . The reason is, for  $EQF$ , early-stage subtasks have less slack than later-stage subtasks (due to slack accumulation, see Figure 6). Early-stage subtasks are thus served more promptly than later-stage subtasks. A global task therefore spends relatively more time in its later stages (due to longer wait in the scheduler queues). The converse is true for  $UD$ , i.e.,

a global task spends more time in its early stages. Consequently, under *EQF*, abortion of global tasks usually happens at a later stage as compared to *UD*. The effective reduction of workload due to abortion is thus more significant in *UD* than in *EQF*.

Finally, we repeat the set of experiments presented in Section 6 with the earliest-deadline-first schedulers replaced by minimum-laxity-first schedulers. The results of such experiments show similar trends and relative performance between *UD* and *EQF*.

## 8 Conclusions

This paper considered the problem of subtask deadline assignment in a distributed soft real-time environment. By means of extensive simulations, we compared the performance of several SDA strategies.

The main advantage of the *UD* (Ultimate Deadline) strategy is that only the final deadline of a global task is required for scheduling. However, our study showed that with *UD* global tasks miss significantly more deadlines than local tasks. An exception occurs when the system is in a low stress situation or when most tasks are global. With an estimate on subtask execution times, *EQF* (Equal Flexibility), on the other hand, ensures that substantially fewer global tasks miss their deadlines. This is a result of distributing the slack of a global task more "fairly" among its subtasks.

We also considered other policies that give intermediate performance but require less information than *EQF* does. *EQS* (Equal Slack), for example, is useful when only the number of subtasks and the total remaining execution time (instead of individual subtask execution time) are known. *ED* (Effective Deadline), as another example, does not need to know the number of pending subtasks.

Our performance study revealed that even though *EQF* significantly reduces the difference between the miss ratios of local and global tasks, global tasks still miss (in many cases) more deadlines than local ones. As we pointed out, this phenomenon is due to the "multiple stages" of global tasks which induces variation in the slack distribution. An interesting modification to *EQF* would control the extent of slack variability, perhaps by giving subtasks of tight global tasks less slack than *EQF* would give. We intend to study this option in future research.

Finally, we would like to remark that the SDA problem is an important one in the design of open systems. An open system is usually built with existing standard components, often developed by different vendors. It is thus hard (or impossible) to orchestrate the independent schedulers, that are built into each individual component, to carry out a global scheduling policy. A good way of automatically assigning deadlines to subtasks which truly reflects the urgency of each unit of work is thus vital in an open system environment.

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