STM Concurrency Control for Multicore Embedded Real-Time Software: Time Bounds and Tradeoffs

ABSTRACT

We consider software transactional memory (STM) concurrency control in multicore embedded real-time software. We investigate real-time contention managers (CMs) for resolving transactional conflicts, including those based on dynamic and fixed priorities, and establish upper bounds on transactional retries and task response times. We identify the conditions under which STM (with the proposed CMs) is superior to lock-based and lock-free synchronization.

1. INTRODUCTION

Embedded systems sense physical processes and control their behavior, typically through feedback loops. Since physical processes are concurrent, computations that control them must also be concurrent, enabling them to process multiple streams of sensor input and control multiple actuators, all concurrently. Often, such computations need to concurrently read/write shared data objects. Typically, they must also process sensor input and react in a timely manner.

The de facto standard for programming concurrency is the threads abstraction, and the de facto synchronization abstraction is locks. Lock-based concurrency control has significant programmability, scalability, and compositionality challenges [11]. Transactional memory (TM) is an alternative synchronization model for shared in-memory data objects that promises to alleviate these difficulties. With TM, programmers write concurrent code using threads, but organize code that read/write shared objects as transactions, which appear to execute atomically. Two transactions conflict if they access the same object and one access is a write. When that happens, a contention manager (or CM) [9] resolves the conflict by aborting one and allowing the other to proceed to commit, yielding (the illusion of) atomicity. Aborted transactions are re-started, often immediately. In addition to a simple programming model, TM provides performance comparable or superior to highly concurrent fine-grained locking and lock-free approaches [14], and is composable [10]. Multiprocessor TM has been proposed in hardware, called HTM (e.g., [13]), and in software, called STM (e.g., [17]), with the usual tradeoffs: HTM provides strong atomicity [13], has lesser overhead, but needs transactional support in hardware; STM is available on any hardware.

Given STM's programmability, scalability, and compositionality advantages, we consider it for concurrency control in multicore embedded real-time software. Doing so will require bounding transactional retries, as real-time threads, which subsume transactions, must satisfy time constraints. Retry bounds in STM are dependent on the CM policy at hand (analogous to the way thread response time bounds are scheduler-dependent). Thus, real-time CM is logical.

Designing a real-time CM is straightforward. Transactional contention can be resolved using dynamic or fixed priorities of parent threads, resulting in Earliest-Deadline-First (EDF) CM or Rate Monotonic Assignment (RMA)-based CM, respectively. But what upper bounds exist for transactional retries and thread response times under such CMs and respective multicore real-time schedulers, global EDF (G-EDF) and global RMA (G-RMA)? How does real-time STM compare against locking and lock-free protocols? i.e., are there upper or lower bounds for transaction lengths below or above which is STM superior to locking/lock-free?

We answer these questions. We consider EDF and RMA CMs, and establish their retry and response time upper bounds, and the conditions under which they outperform locking and lock-free protocols. Our work reveals a key result: for most cases, for G-EDF/EDF CM and G-RMA/RMA CM to be better or as good as lock-free, the atomic section length under STM must not exceed half of the lock-free retry loop-length. However, in some cases, for G-EDF/EDF CM, the atomic section length can reach the lock-free retry loop-length, and for G-RMA/RMA CM, it can even be larger than the lock-free retry loop-length. This means that, STM is more advantageous with G-RMA than with G-EDF. These results, among others, for the first time, provide a fundamental understanding of when to use, and not use, STM concurrency control in multicore embedded real-time software, and constitute the paper's contribution.

We overview past and related efforts in Section 2. Section 3 outlines the work's preliminaries. Sections 4 and **??** establish response time bounds under G-EDF/EDF CM and G-RMA/RMA CM, respectively. We consider the FMLP [4] and OMLP [5] protocols as the best locking competitors to STM, given their superiority, and bound their blocking times in Section **??**. We compare STM against locking and lock-free approaches in Section **??**. We conclude in Section 5.

2. RELATED WORK

Transactional-like concurrency control without using locks, for real-time systems, has been previously studied in the context of non-blocking data structures (e.g., [1]). Despite their numerous advantages over locks (e.g., deadlock-freedom), their programmability has remained a challenge. Past studies show that they are best suited for simple data structures where their retry cost is competitive to the cost of lock-based synchronization [6]. In contrast, STM is semantically simpler [11], and is often the only viable lock-free solution for complex data structures (e.g., red/black tree) [8] and nested critical sections [14]. (The relationship between lock-free and STM is similar to that between programmer-controlled memory management and garbage collection.)

STM concurrency control for real-time systems has been previously studied in $[2, 7, 8, 12, 15, 16]$.

[12] proposes a restricted version of STM for uniprocessors. Uniprocessors do not need contention management.

[7] bounds response times in distributed multiprocessor systems with STM synchronization. They consider Pfair scheduling, limit to small atomic regions with fixed size, and limit transaction execution to span at most two quanta. In contrast, we allow atomic regions with arbitrary duration.

[15] presents real-time scheduling of transactions and serializes transactions based on deadlines. However, the work does not bound retries and response times, nor establishes tradeoffs against locking and lock-free approaches. In contrast, we establish such bounds and tradeoffs.

[16] proposes real-time HTM, unlike real-time STM that we consider. The work does not describe how transactional conflicts are resolved. In contrast, we show how task response times can be met using different conflict resolution policies. Besides, the retry bound developed in [16] assumes that the worst case conflict between atomic sections of different tasks occurs when the sections are released at the same time. However, we show that this is not the worst case. We develop retry and response time upper bounds based on much worse conditions.

The past work that is closest to ours is [8], which upper bounds retries and response times for EDF CM with G-EDF, and identify the tradeoffs against locking and lock-free protocols. Similar to [16], [8] also assumes that the worst case conflict between atomic sections occurs when the sections are released simultaneously. In addition, we consider RMA CM, besides EDF CM.

The ideas in [8] are extended in [2], which presents three real time CM designs. But no retry bounds nor schedulability analysis techniques are presented for those CMs.

3. PRELIMINARIES

We consider a multiprocessor system with m identical processors and n sporadic tasks $T_1, T_2, \ldots, T_n$. The k^{th} instance (or job) of a task T_i is denoted T_i^k. Each task T_i is specified by its worst case execution time (WCET) c_i, its minimum period $t(T_i)$ between any two consecutive instances, and its relative deadline $D(T_i)$, where $D(T_i) = t(T_i)$. Job T_i^j is released at time $r(T_i^j)$ and must finish no later than its absolute deadline $d(T_i^j) = r(T_i^j) + D(T_i)$. Under a fixed priority scheduler such as G-RMA, $p(T_i)$ determines T_i's (fixed) priority. Under a dynamic priority scheduler such as G-EDF, a job's priority is determined by its absolute deadline. A task T_j may interfere with task T_i for a number of times during a duration L, and this number is denoted as $G_{ij}(L)$. T_j's workload that interferes with T_i during L is denoted $W_{ij}(L)$.

Shared objects. A task may need to access (i.e., read, write) shared, in-memory objects while it is executing any of its atomic sections, which are synchronized using STM. The set of atomic sections of task T_i is denoted s_i. s_i^k is the k^{th} atomic section of T_i. Each object, θ, can be accessed by multiple tasks. The set of objects accessed by T_i is θ_i. The set of atomic sections used by T_i to access θ is $s_i(\theta)$, and the sum of the lengths of those atomic sections is $len(s_i(\theta))$.

$s_i^k(\theta)$ is the k^{th} atomic section of T_i that accesses θ. $s_i^k(\theta)$ executes for a duration $len(s_i^k(\theta))$, which is the whole length of the atomic section (and not just the part that accesses θ). Thus, for two objects θ_1 and θ_2 that are accessed within the same atomic section of T_i, $len(s_i^k(\theta 1)) = len(s_i^k(\theta 2))$. If θ is shared by multiple tasks, then $s(\theta)$ is the set of atomic sections of all tasks accessing θ, and the set of tasks sharing θ with T_i is denoted $\gamma(\theta)$. Atomic sections are non-nested.

The maximum-length atomic section in T_i that accesses θ is denoted $s_{i_{max}}(\theta)$, while the maximum one among all tasks is $s_{max}(\theta)$, and the maximum one among tasks with priorities lower than or equal to that of T_i is $s_{max}^i(\theta)$.

STM retry cost. If two or more atomic sections conflict, the CM will commit one section and abort and retry the others, increasing the time to execute the aborted sections. The increased time that an atomic section $s_i^p(\theta)$ will take to execute due to interference with another section $s_j^k(\theta)$, is denoted $W_i^p(s_j^k(\theta))$.

The total time that a task T_i's atomic sections have to retry is denoted $RC(T_i)$. When this retry cost is calculated over the task period $t(T_i)$ or an interval L, it is denoted, respectively, as $RC(t(T_i))$ and $RC(L(T_i))$.

4. G-EDF/EDF CM RESPONSE TIME

Since only one atomic section among many that share the same object can commit at any time under STM, those atomic sections execute in sequential order. A task T_i's atomic sections are interfered by other tasks that share the same objects with T_i. An atomic section of T_i, $s_i^k(\theta)$, is aborted and retried by a conflicting atomic section of T_j, $s_j^l(\theta)$, if $d(T_j) \leq d(T_i)$, by the EDF CM. We will use *ECM* to refer to a multiprocessor system scheduled by G-EDF and resolves STM conflicts using the EDF CM.

The maximum number of times a task T_j interferes with T_i is given in [3] and is shown in Figure 1. Here, the deadline of an instance of T_j coincides with that of T_i, and T_j^1 is delayed by its maximum jitter J_j, which causes all or part of T_j's execution to overlap within T_i's period $t(T_i)$.

T_j's maximum workload that interferes with T_i in $t(T_i)$ is:

$$\begin{aligned} W_{ij}^{*}\left(t\left(T_i\right)\right) &= \left\lfloor \frac{t\left(T_i\right)}{t\left(T_j\right)} \right\rfloor .c_j + min\left(c_j, t\left(T_i\right) - \left\lfloor \frac{t\left(T_i\right)}{t\left(T_j\right)} \right\rfloor .t\left(T_j\right)\right) \\ &\leq \left\lceil \frac{t\left(T_i\right)}{t\left(T_j\right)} \right\rceil .c_j \end{aligned} \quad (1)$$

For an interval $L < t(T_i)$, the worst case pattern of interference is shown in Figure 2, and the workload of T_j is:

$$\hat{W}_{ij}\left(L\right) = \left(\left\lceil \frac{L - c_j}{t\left(T_j\right)} \right\rceil + 1\right).c_j \quad (2)$$

Thus, the overall workload, over an interval R is:

$$W_{ij}\left(R\right) = min\left(\hat{W}_{ij}\left(R\right), W_{ij}^{*}\left(t\left(T_i\right)\right)\right) \quad (3)$$

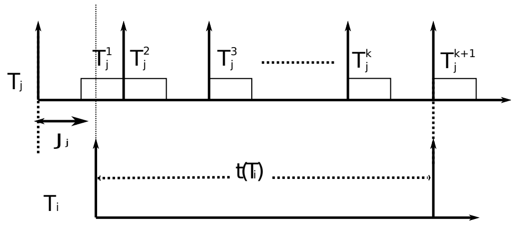


Figure 1: Maximum interference between two tasks under G-EDF

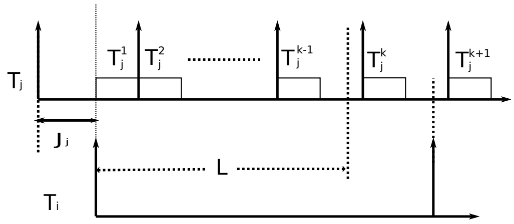


Figure 2: Maximum interference during part L of $t(T_i)$

4.1 Retry Cost of Atomic Sections

CLAIM 1. *Under ECM, a task T_i's maximum retry cost during $t(T_i)$ is upper bounded by:*

$$RC(T_i) \leq \sum_{\theta \in \theta_i} \Big(\Big(\sum_{T_j \in \gamma(\theta)} \Big(\left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\big(s_j^l(\theta) + s_{max}(\theta)\big) \Big) \Big) - s_{max}(\theta) + s_{i_{max}}(\theta) \Big) \quad (4)$$

PROOF. Given two tasks T_i and T_j, where T_i has a longer absolute deadline than T_j. When a shared object conflict occurs, the EDF CM will commit T_j and abort and retry T_i. Thus, an atomic section of T_i, $s_i^k(\theta)$, will experience its maximum delay when it is at its end of the atomic section, and the conflicting atomic section of T_j, $s_j^l(\theta)$, starts. The CM will retry $s_i^k(\theta)$.

Validation (i.e., conflict detection) in STM is usually done in two ways [13]: a) eager (pessimistic), in which conflicts are detected at access time, b) lazy (optimistic), in which conflicts are detected at commit time. Despite the validation time incurred (either eager or lazy), $s_i^k(\theta)$ will retry for the same time duration, which is $len(s_j^l(\theta) + s_i^k(\theta))$. Then, $s_i^k(\theta)$ can commit successfully unless interferred by another conflicting atomic section, as shown in Figure 3.

In Figure 3(a), $s_j^l(\theta)$ validates at its beginning, due to early validation, and a conflict is detected. So T_i retries multiple times (because at the start of each retry, T_i validates) during the execution of $s_j^l(\theta)$. When T_j finishes its atomic section, T_i executes its atomic section.

In Figure 3(b), T_i validates at its end (due to lazy validation), and detects a conflict with T_j. Thus, it retries, and because its atomic section length is shorter than that of T_j, it validates again within the execution interval of $s_j^l(\theta)$. However, the EDF CM retries it again. This process continues until T_j finishes its atomic section. If T_i's atomic section length is longer than that of T_j's, T_i would have incurred the same retry time, because T_j will validate when T_i is retrying, and T_i will retry again, as shown in Figure 3(c). Thus, the retry cost of $s_i^k(\theta)$ is $len(s_i^k(\theta) + s_j^l(\theta))$.

If multiple tasks interfere with T_i or interfere with each other and T_i (see the two interference examples in Figure 4), then, in each case, each atomic section of the shorter deadline tasks contributes to the delay of $s_i^p(\theta)$ by its total length, plus a retry to some atomic section in the longer deadline tasks. For example, $s_j^l(\theta)$ contributes by $len(s_j^l(\theta) + s_i^p(\theta))$ in both figures 4(a) and 4(b). In Figure 4(b), $s_k^y(\theta)$ causes a retry to $s_j^l(\theta)$, and $s_h^w(\theta)$ causes a retry to $s_k^y(\theta)$.

Since we do not know in advance which atomic section will be retried due to another, we can safely assume that, each atomic section (that share the same object with T_i) in a shorter deadline task contributes by its total length, in addition to the maximum length between all atomic sections that share the same object, $len(s_{max}(\theta))$. Thus,

$$W_i^p\left(s_j^k(\theta)\right) \leq len\left(s_j^k(\theta) + s_{max}(\theta)\right) \quad (5)$$

Thus, the total contribution of all atomic sections of all other tasks that share objects with a task T_i to the retry cost of T_i during T_i's period $t(T_i)$ is:

$$RC(T_i) \leq \sum_{\theta \in \theta_i} \sum_{T_j \in \gamma(\theta)} \Big(\left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\big(s_j^l(\theta) + s_{max}(\theta)\big) \Big) \quad (6)$$

Here, $\left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\left(s_j^l(\theta) + s_{max}(\theta)\right)$ is the contribution of all instances of T_j during $t(T_i)$. This contribution is added to all tasks. The last atomic section to execute is $s_i^p(\theta)$ (T_i's atomic section that was delayed by conflicting atomic sections of other tasks). One of the other atomic sections (e.g., $s_m^n(\theta)$) should have a contribution $len(s_m^n(\theta) + s_{i_{max}}(\theta))$, instead of $len(s_m^n(\theta) + s_{max}(\theta))$. That is why one $s_{max}(\theta)$ should be subtracted, and $s_{i_{max}}(\theta)$ should be added (i.e., $s_{i_{max}}(\theta) - s_{max}(\theta)$). Claim follows. □

CLAIM 2. *Claim 1's retry bound can be minimized as:*

$$RC(T_i) \leq \sum_{\theta \in \theta_i} min(\Phi_1, \Phi_2) \quad (7)$$

where Φ_1 is calculated by (4) for one object θ (not the sum of $\theta \in \theta_i$), and

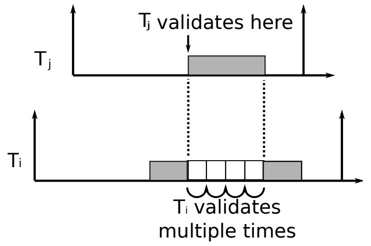
$$\Phi_2 = \Big(\sum_{T_j \in \gamma(\theta)} \Big(\left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\big(s_j^l(\theta) + s_{max}^*(\theta)\big) \Big) \Big) - \bar{s}_{max}(\theta) + s_{i_{max}}(\theta) \quad (8)$$

PROOF. (4) can be modified by noting that a task T_i's atomic section may conflict with those of other tasks, but not with T_i. This is because, tasks are assumed to arrive sporadically, and each instance finishes before the next begins. Thus, (4) becomes:

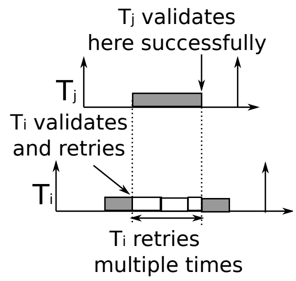
$$RC(T_i) \leq \sum_{\forall \theta \in \theta_i} \Big(\Big(\sum_{T_j \in \gamma(\theta)} \Big(\left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\big(s_j^l(\theta) + s_{max}^*(\theta)\big) \Big) \Big) - \bar{s}_{max}(\theta) + s_{i_{max}}(\theta) \Big) \quad (9)$$

where, $s_{max}^*(\theta) \in s(\theta)$ and $s_{max}^*(\theta) \notin s_j(\theta)$, because T_j will not cause a retry to one of its instances.

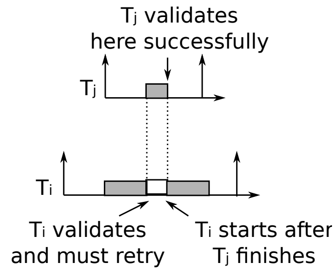
To obtain $\bar{s}_{max}(\theta)$, the maximum-length atomic section of each task that accesses θ is grouped into an array, in



(a) Early validation

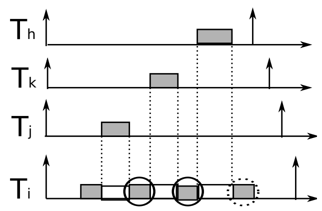


(b) Lazy validation with $s_i^k(\theta) \leq s_j^l(\theta)$

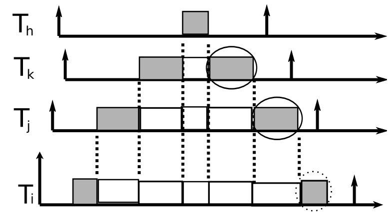


(c) Lazy validation with $s_i^k(\theta) > s_j^l(\theta)$

Figure 3: Retry of $s_i^k(\theta)$ due to $s_j^l(\theta)$



(a) Other atomic sections interfere only with $s_i^p(\theta)$



(b) All atomic sections interfere with each other and $s_i^p(\theta)$

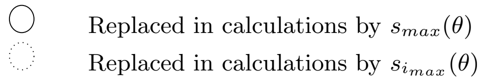


Figure 4: Retry of $s_i^p(\theta)$ due to other atomic sections

non-increasing order of their lengths. $s_{max}(\theta)$ will be the first element of this array, and $\bar{s}_{max}(\theta)$ will be the next element, as illustrated in Figure 5, where the maximum atomic section of each task that accesses θ is associated with its corresponding task. In (9), all tasks but T_j will choose $s_{j_{max}}(\theta)$ as the value of $s^*_{max}(\theta)$, as it is the maximum-length atomic section not associated with the interfering task. But when T_j is the one whose contribution is studied, it will choose $s_{k_{max}}(\theta)$, as it is the maximum one not associated with T_j. This way, it can be seen that the maximum value always lies between the two values $s_{jmax}(\theta)$ and $s_{kmax}(\theta)$. Of course, these two values can be equal, or the maximum value can be associated with T_i itself, and not with any one of the interfering tasks. In the latter case, the chosen value will always be the one associated with T_i, and yet, it will lie between the two largest values.

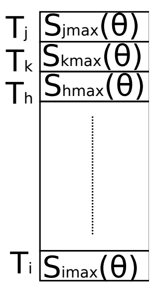


Figure 5: Values associated with $s^*_{max}(\theta)$

This means that the subtracted $s_{max}(\theta)$ in (4) must be replaced with one of these two values ($s_{max}(\theta)$ or $\bar{s}_{max}(\theta)$). However, since we do not know which task will interfere with T_i, the minimum is chosen, as we are determining the worst case retry cost (as this value is going to be subtracted), and this minimum is the second maximum.

Let $p_j = \left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil$, g_j be the number of times T_j accesses θ, and $Const_j = \left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \times \sum_{\forall s_j^l(\theta)} len(s_j^l(\theta))$. If θ_1's maximum-length atomic section is associated with T_i (i.e., $s_{max}(\theta_1) = s_{i_{max}}(\theta_1)$), all other tasks will choose it, and Φ_1 (the result of (4) for θ_1) will be $\sum_{\forall T_j \in \gamma(\theta_1)} (Const_j + p_j g_j s_{i_{max}}(\theta_1)) - s_{i_{max}}(\theta_1) + s_{i_{max}}(\theta_1)$, whereas Φ_2 (the result of (9) for θ_1) will be $\sum_{\forall T_j \in \gamma(\theta_1)} (Const_j + p_j g_j s_{i_{max}}(\theta_1)) - s_{k_{max}}(\theta_1) + s_{i_{max}}(\theta_1)$. Since $s_{k_{max}}(\theta_1) \leq s_{i_{max}}(\theta_1)$, $\Phi_1 \leq \Phi_2$.

Let the maximum-length atomic section for θ_2 be $s_{d_{max}}(\theta_2)$ ($s_{max}(\theta_2) = s_{d_{max}}(\theta_2)$), and be associated with another task T_d, and not with T_i. Let $s_{k_{max}}(\theta_2) = \bar{s}_{max}(\theta_2)$, which will be the second minimum. Let T_d has g_d atomic sections that share θ_2 with T_i. Then, Φ_1 for θ_2 will result in $\sum_{\forall T_j \in \gamma(\theta_2)} (Const_j + p_j g_j s_{d_{max}}(\theta_2)) - s_{d_{max}}(\theta_2) + s_{i_{max}}(\theta_2)$, and Φ_2 will be $\sum_{\forall T_j \in \gamma(\theta_2) \wedge T_j \neq T_d} (Const_j + p_j g_j s_{d_{max}}(\theta_2)) + Const_d + p_d g_d s_{k_{max}}(\theta_2) - s_{k_{max}}(\theta_2) + s_{i_{max}}(\theta_2)$. So, $\Phi_1 - \Phi_2 = (p_d g_d - 1)(s_{d_{max}}(\theta_2) - s_{k_{max}}(\theta_2))$. Since T_d has at least one job that shares θ_2 with T_i (otherwise, T_d would not be included in $\gamma(\theta_2)$), $p_d g_d - 1 \geq 0$. Since $s_{d_{max}}(\theta_2) \geq s_{k_{max}}(\theta_2)$, $\Phi_1 \geq \Phi_2$.

Thus, given an object θ, Φ_1 may be greater, smaller, or equal to Φ_2. The minimum of Φ_1 and Φ_2 therefore yields the worst-case contribution for θ in $RC(T_i)$. Claim follows. □

4.2 Upper Bound on Response Time

To obtain an upper bound on the response time of a task T_i, the term $RC(T_i)$ must be added to the workload of other tasks during the non-atomic execution of T_i. But this requires modification of the WCET of each task as follows. The WCET, c_j, of each interfering task T_j should be inflated to accommodate for the interference of tasks other than T_k, $k \neq j, i$. Meanwhile, atomic regions that access shared objects between T_j and T_i should not be considered in the inflation cost, because they have already been calculated in T_i's retry cost. Thus, T_j's inflated WCET becomes:

$$c_{ji} = c_j - \left(\sum_{\theta \in (\theta_j \wedge \theta_i)} len\left(s_j(\theta)\right) \right) + RC(T_{ji}) \tag{10}$$

where, c_{ji} is the new WCET of T_j relative to T_i; the sum of lengths of all atomic sections in T_j that access object θ is $\sum_{\theta \in (\theta_j \wedge \theta_i)} len(s_j(\theta))$; and $RC(T_{ji})$ is the $RC(T_j)$ without including the shared objects between T_i and T_j. The calculated WCET is relative to task T_i, as it changes from task to task. The upper bound on the response time of T_i, denoted R_i^{up}, can be calculated iteratively, using a modification of Theorem 6 in [3], as follows:

$$R_i^{up} = c_i + RC(T_i) + \left\lfloor \frac{1}{m} \sum_{j \neq i} W_{ij}(R_i^{up}) \right\rfloor \tag{11}$$

where R_i^{up}'s initial value is $c_i + RC(T_i)$.

$W_{ij}(R_i^{up})$ is calculated by (3), and $W_{ij}^*(t(T_i))$ is calculated by (1), with c_j replaced by c_{ji}, and changing $\hat{W}_{ij}(L)$ as:

$$\hat{W}_{ij}(L(T_i)) = max \begin{cases} \left(\left\lceil \frac{L - c_{ji} - \sum_{\theta \in (\theta_j \wedge \theta_i)} len(s_j(\theta))}{t(T_j)} \right\rceil + 1 \right) .c_{ji} \\ \left\lceil \frac{L - c_j}{t(T_j)} \right\rceil .c_{ji} + c_j - \sum_{\theta \in (\theta_j \wedge \theta_i)} len(s_j(\theta)) \end{cases} \tag{12}$$

(12) compares between two terms, as we have two cases:

Case 1. The carried-in job (i.e., a job whose release is before $r(T_i)$ and its deadline is after $r(T_i)$ but before $d(T_i)$, as defined in [3]) of T_j contributes by c_{ji}. Thus, other instances of T_j will begin after this modified WCET, but the sum of the shared objects' atomic section lengths is removed from c_{ji}, causing other instances to start earlier. Thus, the term $\sum_{\theta \in (\theta_i \wedge \theta_j)} len(s_j(\theta))$ is added to c_{ji} to obtain the correct start time.

Case 2. T_j's carried-in job contributes its c_j. Thus, other instances begin after this c_j of the carried-in job (as shown in Figure 2), but the sum of the shared atomic section lengths between T_i and T_j should be subtracted from this carried-in instance, as they are already included in the retry cost.

It should be noted that subtraction of the sum of the shared objects' atomic section lengths is done in the first case to obtain the correct start time of other instances, while in the second case, this is done to get the correct contribution of the carried-in instance. The maximum is chosen from the two terms in (12), because they differ in the contribution of their carried-in jobs, and the number of instances after that.

4.2.1 Tighter Upper Bound

To tighten T_i's response time upper bound, the response time can be calculated recursively over duration R_i^{up}, and not directly over $t(T_i)$, as done in (11). Thus, $RC(T_i)$ will change according to T_i's recursive response time (i.e., R_i^{up}). So, (7) must be changed to include the modified number of interfering instances, in the same way this term is calculated in (3). Also, when calculating this term for the entire $t(T_i)$, a situation like that shown in Figure 6 can happen.

Atomic sections of T_j^1 that are contained in the interval δ are the only ones that can contribute to $RC(T_i)$. Of course,

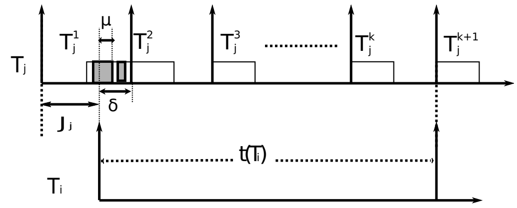


Figure 6: Atomic sections of job T_j^1 contributing to period $t(T_i)$

they can be lower, but cannot be greater, because T_j^1 has been delayed by its maximum jitter. Hence, no more atomic sections can interfere during the duration $[d(T_j^1) - \delta, d(T_j^1)]$. Even though only one of T_j^1's atomic sections contributes by length μ to T_i, the effect of this μ will still be the retry of one of the other atomic sections.

For simplicity, we use the following notations:

- $\lambda_1(j, \theta) = \sum_{\forall s_j^l(\theta) \in [d(T_j^1) - \delta, d(T_j^1)]^*} len\left(s_j^{l^*}(\theta) + s_{max}(\theta)\right)$
- $\chi_1(i, j, \theta) = \left\lfloor \frac{t(T_i)}{t(T_j)} \right\rfloor \sum_{\forall s_j^l(\theta)} len\left(s_j^l(\theta) + s_{max}(\theta)\right)$
- $\lambda_2(j, \theta) = \sum_{\forall s_j^l(\theta) \in [d(T_j^1) - \delta, d(T_j^1)]^*} len\left(s_j^{l^*}(\theta) + s_{max}^*(\theta)\right)$
- $\chi_2(i, j, \theta) = \left\lceil \frac{t(T_i)}{t(T_j)} \right\rceil \sum_{\forall s_j^l(\theta)} len\left(s_j^l(\theta) + s_{max}^*(\theta)\right)$

Here, $s_j^{l^*}(\theta)$ is the part of $s_j^l(\theta)$ that is included in interval δ. The term $\left[d\left(T_j^1\right) - \delta, d\left(T_j^1\right)\right]^*$ contains $s_j^l(\theta)$, whether it is partially or totally included in it. If it is partially included, $s_j^l(\theta)$ will contribute by its included length μ.

Now, (7) can be modified as:

$$RC\left(t\left(T_i\right)\right) \leq \sum_{\theta \in \theta_i} min \begin{cases} \begin{cases} \left(\left(\sum_{T_j \in \gamma(\theta)} \lambda_1(j, \theta) + \chi_1(i, j, \theta) \right) \right. \\ \left. -s_{max}(\theta) + s_{i_{max}}(\theta) \right) \end{cases} \\ \begin{cases} \left(\left(\sum_{T_j \in \gamma(\theta)} \lambda_2(j, \theta) + \chi_2(i, j, \theta) \right) \right. \\ \left. -\bar{s}_{max}(\theta) + s_{i_{max}}(\theta) \right) \end{cases} \end{cases} \tag{13}$$

We can compute $RC(T_i)$ during a duration of length L, which does not extend to the last instance of T_j. Let:

- $\upsilon(L, j) = \left\lceil \frac{L - c_j}{t(T_j)} \right\rceil + 1$
- $\lambda_3(j, \theta) = \sum_{\forall s_j^l(\theta)} len\left(s_j^l(\theta) + s_{max}(\theta)\right)$
- $\lambda_4(j, \theta) = \sum_{\forall s_j^l(\theta)} len\left(s_j^l(\theta) + s_{max}^*(\theta)\right)$

Now, (7) becomes:

$$RC\left(L\left(T_i\right)\right) \leq \sum_{\theta \in \theta_i} min \begin{cases} \begin{cases} \left(\sum_{T_j \in \gamma(\theta)} \left(\upsilon(L, j)\, \lambda_3(j, \theta)\right) \right) \\ -s_{max}(\theta) + s_{i_{max}}(\theta) \end{cases} \\ \begin{cases} \left(\sum_{T_j \in \gamma(\theta)} \left(\upsilon(L, j)\, \lambda_4(j, \theta)\right) \right) \\ -\bar{s}_{max}(\theta) + s_{i_{max}}(\theta) \end{cases} \end{cases} \tag{14}$$

Thus, an upper bound on $RC(T_i)$ is given by:

$$RC(R_i^{up}) \leq min \begin{cases} RC(R_i^{up}(T_i)) \\ RC(t(T_i)) \end{cases} \tag{15}$$

The final upper bound on T_i's response time can be calculated as in (11) by replacing $RC(T_i)$ with $RC(R_i^{up})$.

5. CONCLUSIONS

Under both ECM and RCM, a task incurs $2.s_{max}$ retry cost for each of its atomic section due to a conflict with another task's atomic section. Retries under RCM and lock-free are affected by a larger number of conflicting task instances than under ECM. While task retries under ECM and lock-free are affected by all other tasks, retries under RCM are affected only by higher priority tasks.

STM and lock-free have similar parameters that affect their retry costs—i.e., the number of conflicting jobs and how many times they access shared objects with a task T_i, while FMLP and OMLP are affected by the total number of tasks and the number of requests made by T_i. This is because, requests in FMLP and OMLP are arranged in a queue, and the order of the requests in the queue does not change (except for the case of OMLP's priority queue). Thus, STM and lock-free can be compared in terms of parameters affecting their retry costs, while STM and locking protocols can only be compared asymptotically.

The s_{max}/r_{max} ratio determines whether STM is better or as good as lock-free. For ECM, this ratio cannot exceed 1, and it can be 1/2 for higher number of conflicting tasks. For RCM, for the common case, s_{max} must be 1/2 of r_{max}, and in some cases, s_{max} can be larger than r_{max} by many orders of magnitude. For locking protocols, a comparative schedulability of STM to that of FMLP and OMLP depends on the number of tasks and processors.

Thus, no synchronization method fits all applications from a timing standpoint; our results shed light on which method to select under what application conditions. From a programmability standpoint, however, STM is semantically as simple as coarse-grain locks.

Our work has only further scratched the surface of real-time STM. The questions that we ask (see Section 1) are fundamentally analytical in nature, and hence, our results are analytical. However, significant insights can be gained by experimental work on a broad range of embedded software, which is outside our work's scope. For example, what are the typical range of values for the different parameters that affect the retry cost (and hence the response time)? How tight is our retry and response time bounds in practice? Can real-time CMs be designed for other multiprocessor real-time schedulers (e.g., partitioned, semi-partitioned), and those that dynamically improve application timeliness behavior? These are important directions for further work.

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