SysRT: A Modular Multiprocessor RTOS Simulator for Early Design Space Exploration

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Abstract—Modern embedded systems increasingly accommodate several applications running concurrently on a multiprocessor platform managed by a real-time operating system (RTOS). The increasing design complexity of such systems calls for good design tools to evaluate real-time performance during the very early stages of design. To this end, fast system-level simulators that allow for efficient hardware/software co-simulation are essential. In this paper, we present SysRT, a generic and high-level RTOS simulator that is highly suited for early design space exploration (DSE). The simulator contains different types of application models and a modular RTOS kernel model, all developed in SystemC. Efficient and precise modeling of preemptive scheduling is achieved via an event-driven simulation approach, allowing simulations to be performed much faster than cycle-accurate simulations. At the same time, the kernel model is developed to be generic and modular to support for easy plug-in of new schedulers as well as new resource sharing protocols. Comparing SysRT with state-of-art simulators, it achieves faster simulation speeds with an identically small simulation error. We demonstrate the flexibility of SysRT and its benefits for early DSE using experiments with a mixed workload executing on multiprocessor platforms with different numbers of cores.

I. INTRODUCTION

In the past years, the design of systems-on-chip (SoCs) has become increasingly complex. Hardware architectures are migrating from simple single-core based systems to more complex multi-core architectures. In the embedded systems domain, together with the increasing hardware complexity, the software complexity has also been growing dramatically. Modern embedded systems increasingly execute several applications of different types concurrently on the underlying computing platform. These applications can have different execution requirements. For example, control applications typically are hard real-time applications and thus have stringent timing constraints, while best-effort applications prefer a short task response time. These systems are usually managed by a Real-Time Operating System (RTOS).

Raising the level of abstraction is generally considered as a solution to address the design complexity, thus reducing time-to-market. To provide a simulation environment and to help in the design space exploration (DSE) at the early stages of design, various system-level design languages (SLDL) and methodologies have been proposed, such as SystemC [1] and SpecC [2]. Originally, SLDLs primarily focused on hardware modeling and did not properly address the modeling of software aspects. Later efforts introduced methods to model timing behavior of software in SLDLs. But most solutions still lack direct support for simulating the real-time behavior of concurrent applications, such as preemption or scheduling within the RTOS. To verify that the timing requirements posed by applications are met during the early stages of design, a fast system-level simulator, capturing both the modeling of software and hardware, is needed.

In this paper, we present SysRT [3], a generic and modular high-level RTOS simulator that is highly suited for early DSE to study RTOS design alternatives. The SystemC-based SysRT simulator improves on current state-of-art RTOS simulators by providing the unique combination of being, at the same time, highly accurate, efficient and easy to extend to facilitate early DSE. SysRT contains different types of application models, an RTOS kernel model and an abstract architecture model. Efficient and precise modeling of preemptive scheduling is achieved via an event-driven simulation approach, which utilizes scheduling events associated with task states and interrupts. At the same time, the kernel model is developed to be generic and modular to support for easy plug-in of new schedulers as well as new resource sharing protocols. We have compared the accuracy and simulation performance of SysRT with state-of-art RTOS simulators, of which the results show that our simulator is faster while still producing the most accurate results.

The rest of the paper is organized as follows. Section II gives an overview of the related work. The overall RTOS simulation framework is described in Section III. Section IV describes the application models. In Section V, the kernel model is detailed, and Section VI presents a range of experimental results. Section VII concludes the paper.

II. RELATED WORK

The modeling and simulation of RTOS with SLDL have received widespread attention from many researchers, [4], [5], [6]. In [7], the modeling capability of SystemC has been extended by RTOS services to provide more realistic software modeling features. However, to realize features such as preemption and scheduling, a scheduler model is invoked every simulation quantum, similar to the way a real OS scheduler behaves. This quantum-granularity based simulation approach therefore introduces large overheads, resulting in low simulation speeds. Later efforts such as [8], [9] focused on improving the accuracy of high-level simulation via while
maintaining high performance. However, these works still trade-off speed for accuracy.

In [10], a host-compiled multi-core system simulator is presented for early real-time performance evaluation. They present an integrated approach for automatic timing granularity adjustment to optimally navigate simulation speed versus accuracy. This approach switches between prediction mode and fallback mode. In prediction mode, a prediction of the next scheduling points is performed based on the simulation parameters and states of periodic tasks. Schirner et al. [11] introduce preemptive scheduling in abstract RTOS models using Result Oriented Modeling (ROM). To speed up simulation, ROM optimistically predicts the finish time of a process already at the start time by a “run to finish” assumption. ROM records any possible preemption that may alter the predicted outcome. While time passes, it validates the prediction and takes corrective measures to ensure accuracy. However, predictions of preemption points are difficult if the simulation uses more complex task models like Directed Acyclic Graphs (DAGs) and resource sharing models as supported by SysRT.

SysRT provides a framework of RTOS services in SystemC that allows developers and researchers to easily explore and validate embedded RTOS design alternatives. Compared with quantum-granularity based simulators and prediction-based simulators, SysRT has two main advantages: (i) it has been developed to be generic and modular to support for easy plug-in of new schedulers as well as new resource sharing protocols. Thus, it is more flexible to simulate various real-time scheduling algorithms; (ii) it typically achieves higher simulation speeds via an event-driven simulation approach while obtaining identical accuracy results.

III. Modeling Framework

SysRT consists of three layers, as shown in Fig. 1: the application layer, the kernel layer, and the architecture layer. In the application layer, the user can model a set of processes. A process can be a single job instance (named ST in Fig. 1), a Periodic Task (PT) of which job instances are invoked periodically, or a process with execution precedences modeled by a DAG, as will be explained in Section IV.

The application layer interacts with the RTOS kernel layer. The application informs the kernel of its execution states, while the kernel model returns task scheduling decisions. We model four functionalities of the OS kernel, namely process management, resource management, interrupt handling and real-time scheduling. A queue in the OS kernel is used to order the tasks that become ready for execution. The OS kernel further has a resource manager sub-module that controls access to resources shared between tasks. The resource block queues store tasks waiting to get access to a particular resource due to mutual exclusion. Moreover, interrupt service routines are defined in the OS kernel model. When an interrupt is generated, either from software or hardware, the OS kernel schedules the corresponding interrupt handler depending on the handler priority. Different real-time (preemptive) schedulers are implemented in the scheduling module of the OS kernel model. The architecture layer models the hardware computing platform. It specifies the number of cores in the SoC platform, the interconnection between the cores, and the hardware interrupt interfaces. The current architecture model mainly accounts for the scheduling overhead including migration and context switching overhead after a scheduling decision is made by the OS kernel. The implementation details of the architecture model are beyond the scope of this paper.

![Fig. 1: Simulation framework of SysRT.](image)

Application layer, OS kernel layer and architecture layer are implemented on top of the basic classes and primitives provided by SystemC. We use event-driven simulation, where events are modeled by the sc_event class. This class allows explicit triggering of events by means of a notification method. The Event.notify(sc_time t) method notifies or posts an event after time t. If a simulation process is set to be sensitive to an event, then this process acts as the corresponding event handler. When an event occurs, the corresponding event handler is invoked and scheduled by the SystemC simulation kernel. Scheduled events may be canceled with the event.cancel() method.

Modelling preemption is always a challenging topic for a RTOS simulator. Most RTOS simulators that are built on top of SystemC use wait(sc_time time) to model task execution latency. If a task is preempted for some time, then the preemption time is counted as extra task execution latency, resulting in another execution of wait(sc_time time) for that task. However, this approach comes with a speed penalty due to the frequent computations of the preemption time and the frequent executions of wait(sc_time time). Unlike this approach, SysRT adopts an event-driven approach that uses only sc_event to model preemption. Events are extracted from the task execution states, which will be discussion soon. Once a task is preempted, the only work to do is to cancel the task finishing event. When this task is scheduled again, a new task finishing event is posted after the remaining execution time. compared with the wait(sc_time time) method, this event-driven approach introduces less simulation overhead.
IV. APPLICATION MODEL

The Application is a program that contains a set of coordinated tasks modeled by the user through the Task module. In this work, the actual task functionality is abstracted away, and only the timing of task execution is simulated. Here, we assume that timing information of task execution latencies are estimated or known a priori.

A. Task Model

In the task model, three kinds of constraints specified on real-time tasks are considered: timing constraints, precedence relations, and access control on shared resources. Timing constraints, such as execution times and job deadlines, are specified at the creation of a real-time task object. Precedence constraints are realized by a DAG task model [12]. Contention on shared resources is simulated by adding wait/signal instructions in the task execution routine, as will be explained below.

A task module contains a list of high-level instructions that are executed in sequence. Instruction sub-modules are added to a task module by the InsertCode method. For example, consider a task \( T_1 \) that computes for 500 milliseconds, then tries to get access to a shared variable \( R_1 \) after which it occupies the resource for 50 milliseconds once the access is granted, and after releasing the shared resource the task finishes its current job by computing for another 300 milliseconds. This can be modeled by: \( T_1\text{.InsertCode("execute(500); wait(R_1); execute(50); signal(R_1); execute(300)")}. \) Details about the instruction module will be described in Section IV-B.

The simulation is driven by events generated by the first job of each task. The typical events generated for a task are illustrated in Fig. 2. A job_arrival event is posted at the activation offset (start time) \( \phi_i \) by the start_of_simulation() method in the Task module which is called at the beginning of the simulation. A job_arrival event is notified every time when the task becomes ready to execute. Between the job arrival time and finish time, a job may miss its relative deadline. For such cases, a deadline_miss event is posted at time \( \phi_i + D_i \), where \( D_i \) is the relative deadline of task \( i \). The action of the deadline_miss event handler is specified by the user. Possible actions are to kill the job instance, to ignore the deadline miss or even to stop the simulation. Once a job starts its execution, a job_end event is posted at time \( \phi_i + C_i \), where \( C_i \) is the execution latency of task \( i \). The responsibility of the job_end event handler is to cancel the pending deadline_miss event and to call the kernel interface to inform it to schedule another task. A schedule event is posted by the OS kernel to a specific task if it was selected to be scheduled. The schedule event handler schedule() then schedules the instructions of the task. A deschedule event is generated if a task is preempted by another task with a higher priority. The deschedule event handler deschedule() cancels the pending job_end event, records the current time stamp and computes the executed job length. When the task is re-scheduled, a new job_end event is posted for the job’s remaining execution time.

The UML class diagram of task modules is shown in Fig. 3(a). AbsTask defines the interface that must be implemented by a general task. It includes an activate() method, which activates the task, as well as schedule()/deschedule() methods, which modify the task state and related variables when a task is scheduled/descheduled. AbsRTTask defines the interface that should be provided by a real-time task and contains methods for getting the absolute and relative deadline of a task.

Periodic Task Model: Periodic tasks consist of a number of instances or jobs that are regularly activated at each period. Periodic tasks are reactivated by the job_arrival event handler, which posts a new job_arrival event at the next period.

DAG Task Model: A DAG is a graph of real-time subtasks (also called nodes) that captures their execution precedences. The subtasks share the same deadline and period but differ in their WCET. The DagNode module is used to construct a DAG application model in SysRT.

B. Instruction Model

Instructions inside tasks are modeled using the Instruction class. There are two kinds of instructions. First, execute(sc_time time) is used to model the execution time required to execute a real code segment in an application. It can be described by a random variable, making it is possible to model a portion of code with an arbitrarily distributed random execution time. The other instruction type is wait(Resource res)/signal(Resource res), which models the request or release of a shared resource. A task executes all the instructions in sequence. A job instance is completed only after its last instruction was executed. If a task is activated again (i.e. firing
a new job), then the instruction pointer is reset to the first instruction.

The schedule/deschedule event propagates from a task to its instructions. If a task is selected to execute at time \( t \), the task calls its instruction interface and notifies a schedule event in the Instruction module. Suppose that the execution duration of the instruction is \( \text{instr}_{\text{time}} \), the schedule event handler in the Instruction module will post an end instr event at time \( t + \text{instr}_{\text{time}} \). The end instr event handler increments the instruction pointer to the next instruction in the task and posts a new end instr event for the next instruction. If there are no more instructions to execute, the interface of the task module is invoked and a job end event is posted. During instruction execution, a task may be preempted and rescheduled. A similar event propagation mechanism between a task and its instructions applies to the deschedule event.

Based on the assumption that the actual requesting and releasing of a resource takes zero time, the end instr event is notified immediately if the current scheduled instruction is wait or signal. The end instr event handler for the wait instruction communicates with operating system kernel by calling the interface request resource (Kernel, Resource, resource quantity). As a result, the task gets the resource if a sufficient quantity of that resource is available. Otherwise, the task is blocked by the operating system kernel. For the signal instruction, the end instr event handler invokes the interface release resource (Kernel, Resource, resource quantity) in the operating system kernel module. The task releases the resource quantity used.

V. RTOS Kernel Model

Fig. 3(b) shows the UML class diagram of the OS kernel module. The AbsKernel class is an abstract class that defines the minimal functionality of a kernel. The UNPKernel and SMPKernel classes are implemented to model an OS kernel running on a uniprocessor system (UNP) or a symmetric multiprocessor system (SMP), respectively. Traditional real-time multiprocessor schedulers can be classified in two categories: global and partitioned schedulers. Global Earliest-Deadline-First (G-EDF) and Partitioned-EDF (P-EDF) are examples of each category. The SMPKernel class models a general OS kernel with a global scheduler, whereas the PartiKernel class models an OS kernel with partitioned schedulers.

In this work, we mainly consider services of process management, resource management, interrupt handling and real-time scheduling provided by the OS kernel. We have developed the modules of the OS kernel model with the aim to provide a flexible and extendable framework to facilitate implementation, testing and evaluation of different real-time schedulers with various resource sharing protocols.

A. UNPKernel Model

The UNPKernel module is developed to model a real-time OS kernel running on a uniprocessor. It contains sub-components such as the Scheduler module and the ResManager module that is responsible for performing resource access related operations. These sub-components are set through methods set_sched (Scheduler* s) and set_resmanager (ResManager* rm).

At initialization, a CPU pointer, which points to the modeled architecture, is created in the UNPKernel module to get information of the architecture platform. Since at most one task is allowed to execute at a time in a uniprocessor system, one pointer cur_exe is enough to track the current executing task.

For the communication with tasks, the UNPKernel module provides several functions. These include the functions Arrival (AbsRTTask* t) and End (AbsRTTask* t). The function Arrival (AbsRTTask* t) is called by the task arrival event handler. This method inserts the task in the ready queue, followed by a function call to make a schedule decision. End(AbsRTTask* t) is invoked by a task when the task completes its execution. This function removes the task from the ready queue and sets the cur_exe pointer to null. To suspend a task, the UNPKernel class implements a Suspend(AbsRTTask* t) function. This function removes the task from the ready queue. If the task was executing, then it will first be descheduled. When a task is resumed (from suspension by the OS or from being blocked on a resource), the kernelreactivates the task by calling Activate(AbsRTTask* t) which simply inserts the task in the ready queue and changes the task’s state to ready.

The operation of allocating the CPU for task execution is referred to as dispatching. The dispatching activity is simulated by the dispatch() function. Any circumstance that may change the current executing task should invoke dispatch() to make a scheduling decision:

- when a new task becomes ready;
- when a task finishes its current job;
- when a task is blocked;
- when an interrupt arrives, activating its corresponding interrupt handler.

On uniprocessor systems, just one execution flow can progress at a time. Therefore, dispatch() is simple in UNPKernel as compared with its implementation in other kernel modules. It simply compares the executing task with the first task in the ready queue. If they are different, it forces a context switch, which involves the participation of architecture model to simulate the context switch overhead. When the context switch has finished, the kernel schedules the newly dispatched task. Important to realize is that the dispatch() function has been decoupled from the scheduler that actually determines the order of the tasks in the ready queue, according to the implemented scheduling algorithm.

B. SMPKernel Model

The SMPKernel is a module modeling a real-time kernel with a global scheduler for (SMP) multiprocessor systems. On multiprocessor systems, multiple tasks are allowed to run concurrently. The SMPKernel module keeps track of the status of each individual processor, storing information about which task is executing on which processor, which tasks are about
to be dispatched to which processor, and whether or not processors are in the process of performing a context switch.

The functions provided to the Task module and methods related to process management in the SMPKernel module are similar to those in the UNPKernel module. However, the function to make a scheduling decision, dispatch(), is more complicated. Pseudocode 1 shows the procedure of the dispatch() method in SMPKernel. In this code, the variable newtasks denotes the number of tasks that are not executing but need to be scheduled. Assuming a simulated architecture with m processors, newtasks therefore equals to the number of tasks that are among the first m tasks in the task ready queue that are not yet executing or being dispatched. Newly scheduled tasks are dispatched to free processors if there are any available. If all processors are busy, then task preemption will take place.

Pseudocode 1: The procedure of dispatch() with a system architecture with m processors

1. while newtasks > 0 do
2. \( t^{new} \leftarrow \) first non-executing task in ready queue that needs to be scheduled (i.e., among the first m entries)
3. \( c \leftarrow \) find next free core {return NULL if no more free cores}
4. if \( c == NULL \) then
5. \( t_{remove} \leftarrow \) first executing task in ready queue not part of the first m entries ;
6. \( c \leftarrow \) get the index of core executing task \( t_{remove} \)
7. end if
8. dispatch_to_proc(\( t^{new}, c \))
9. newtasks ← newtasks - 1
10. end while

The dispatch() method decides on the index of the selected cores for task dispatch. By calling dispatch_to_proc(Task * newtask, CPU * c), the OS kernel also deschedules any task currently executing on processor c and computes the scheduling overhead including the context switch and task migration costs. The computed scheduling overhead is passed from the kernel layer to the architecture layer, which subsequently simulates this overhead. Hereafter, a newly dispatched task is selected to start execution on processor c. The procedure of dispatch_to_proc(Task * newtask, CPU * c) is shown in Pseudocode 2.

Pseudocode 2: The procedure of dispatch_to_proc(Task * newtask, CPU * c)

1. AbsRTTask current_task \( \leftarrow \) the task currently executing on core c
2. if current_task \( \neq NULL \) then
3. deschedule current_task
4. end if
5. if newtask == NULL then
6. RETURN
7. else
8. prepare newtask to execute on core c
9. end if
10. Compute the scheduling overhead
11. Send the overhead to architecture model

functions related to process management in the PartiKernel module are slightly different than those in SMPKernel due to task affinity. However, the dispatch() method has been completely re-implemented. If a task is inserted to or is removed from a local queue, instead of calling dispatch(), PartiKernel invokes a dispatch(CPU * cpu) function that passes the task affinity as a parameter to make a local rescheduling decision for the processor in question. Changes on a local queue have no effect on the ordering of other local queues. In this sense, the dispatch(CPU * cpu) function is similar to dispatch() in UNPKernel.

D. Scheduler Model

When a task becomes ready to execute, it is inserted to the ready queue managed by the scheduler, which is a sub-component of a kernel module. The ready queue is ordered by task priority assigned by the scheduling algorithm. At a scheduling point, the scheduler (i.e. dispatcher) is responsible for selecting the task(s) at the front of the ready queue to execute. In SysRT, the following schedulers have currently been implemented:

- Global Earliest Deadline First [13] (G-EDF)
- First Come First Out (FIFO)
- Fixed Priority Scheduler (FPS)
- Rate Monotonic Scheduler (RMS)
- Round Robin (RR).
- Proportional Fairness [14] (P-FAIR)
- Partitioned-based Scheduler (PS) including P-EDF
- Non-Preemptive EDF (NP-EDF)

E. Resource Management Model

The Resource module models a resource shared by two or more tasks. It provides an interface to the OS kernel module to, for example, perform locking operations for providing access to these shared resources. The resource availability is checked by the method IsAvailable(int amount). It returns false if the quantity of a certain resource is not sufficient. Every task uses resources through a critical section surrounded by wait and signal instructions. If the executing task requests/releases a certain resource quantity, the resource
manager in the OS kernel invokes the interface of the resource, lock(int amount), unlock(int amount), to decrease/increase resource availability for that particular resource.

The ResManager module models a resource manager that implements the resource accessing protocol. It contains multiple block queues, each associated with a particular resource to store tasks blocked on that resource. These block queues are ordered by task priority. Different resource sharing protocols can be implemented by the ResManager module. Taking the Priority Inheritance Protocol [15] as an example, requesting a resource is implemented by first checking the availability of the requested resource. If there are not enough available resources, the resource manager calls the kernel interface to suspend the task that is requesting the resource. Furthermore, the priority of the resource owner is changed to the maximum priority of those tasks that are blocked for the resource. If the requested resources are available, the resource manager invokes the unlock interface of the resource and grants the resources to the task. Releasing a resource unlocks the resources and changes the priority of the releasing task back to its original priority, after which it checks if the resource block queue is empty. If the queue is not empty, the resource manager removes the first task from the block queue, and activates the task through the kernel interface and locks the resource for the new owner.

VI. EXPERIMENTAL RESULTS

In this section, we evaluate the accuracy and simulation performance of SysRT, and demonstrate its flexibility and benefit in DSE. All experiments were conducted on a 3.4GHZ Intel Core i5. The default time unit of the task parameters in the following experiments is the simulation resolution set by SystemC.

A. Simulation performance and accuracy

The first experiment is to evaluate the accuracy and simulation performance of SysRT by comparing it with four other simulators: the state-of-art (prediction-based) HCSim simulator [10] and three conventional quantum-granularity based simulators (also described in [10]) with a simulation quantum of 1ms, 10ms and 100ms, respectively. All simulators model a Partitioned-Fixed Priority scheduler, where tasks have been uniformly partitioned over the simulated processors. Task execution costs and periods, priorities are randomly distributed over the intervals [50ms, 150ms], [100ms,10s] and [1, 100], respectively. The simulated time is 10 minutes. Note that all these tasks are not necessarily real-time tasks.

Figures 4 (a), (b) and (c) show the simulation times taken by each simulator simulating a different number of processors, ranging from 1 to 16, where the number of tasks is 16, 100 and 1000. Figure 4 clearly shows that SysRT achieves the fastest simulation speed in these experiments. Both SysRT and HCSim are scalable with respect to the number of processors and the number of tasks. The simulation speed of the conventional simulator with largest simulation quantum is similar to that of HCSim and SysRT. However, it suffers from a lower accuracy, as will be discussed later on. Conventional simulators get much slower if the simulation quantum size decreases.

To derive a reference for the task response times, we have also performed the experiment with the same task sets on a real Linux-based RTOS, i.e. Litmus [16], varying the number of active processors from 1 to 4. For each task, we calculate the relative errors between the response times obtained from simulators and the actual response times from Litmus. The accuracy is measured by the average error of all tasks in the testing task set.

Table I is the average simulation error of those tests. The number of active processors and the number of tasks in different testing sets is not reported since it turns out that these factors have little effect on the relative error of each individual task. SysRT, HCSim and conventional simulation with the smallest simulation quantum yield high accuracy, whereas conventional simulators with a larger simulation quantum suffer from degraded accuracy.

### TABLE I: Average Simulation Error of Five Simulators

<table>
<thead>
<tr>
<th></th>
<th>HCSim</th>
<th>SysRT</th>
<th>Quantum:1ms</th>
<th>Quantum:10ms</th>
<th>Quantum:100ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>0.166%</td>
<td>0.166%</td>
<td>0.166%</td>
<td>4.182%</td>
<td>&gt;100%</td>
</tr>
</tbody>
</table>

Note that, although SysRT and HCSim are supposed to be theoretically accurate, several factors in Litmus such as context switches and kernel tasks with high priorities could lead to small simulation errors. Fortunately, both SysRT and HCSim provide support to model the scheduling overhead to improve accuracy.

B. Flexibility of SysRT

As most prediction-based RTOS simulators do not support simulating real-time resource access protocols due to difficulties in predicting preemption points, we show the flexibility of SysRT by simulating a set of four periodic tasks \( T_1, ..., T_4 \) that exclusively access two shared resources \( R_1 \) and \( R_2 \). Task parameters are listed in Table II. \( P_i \) is the task activation period and \( C_i \), the execution time. Variable \( \xi_{j,i} \) denotes the duration of the critical section that \( T_i \) occupies \( R_j \). The value 0 for \( \xi_{j,i} \) means that \( T_i \) does not use \( R_j \). Tasks are scheduled on an uniprocessor by a RM scheduler with priority inheritance as resource sharing protocol.

### TABLE II: Task Parameters and Theoretical WCRT.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>( P_i )</th>
<th>( C_i )</th>
<th>( \xi_{1,i} )</th>
<th>( \xi_{2,i} )</th>
<th>WCRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 )</td>
<td>100</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>110</td>
<td>16</td>
<td>3</td>
<td>3</td>
<td>71</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>200</td>
<td>70</td>
<td>20</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>350</td>
<td>102</td>
<td>0</td>
<td>30</td>
<td>310</td>
</tr>
</tbody>
</table>

The analytically calculated Worst Case Response Time (WCRT) for each task is given in the last column of Table II. We have run the simulation for 80000 time units. The simulated response time of the first 200 jobs of each task are shown in Fig. 5. As can be seen from Fig. 5, the response times obtained from simulation are consistently lower than...
the theoretical WCRTs. Thanks to the modular and flexible implementation of SysRT, the resource sharing protocol is correctly simulated.

C. Benefit of SysRT in DSE

The second experiment demonstrates the flexibility of SysRT and its benefits for early DSE. An embedded system with a mixed application workload is simulated. The task set is composed of three Hard Real-Time (HRT) tasks, five Soft Real-Time (SRT) tasks and three Best-Effort (BE) tasks. Task types, parameters and utilization ($P_i$ divided by $C_i$) are listed in Table III. If an interval $[a, b]$ is assigned to $P_i$ (or $C_i$), then $P_i$ (or $C_i$) is a random variable uniformly distributed in that interval. This models workload variations.

The application requirement for hard real-time tasks is to guarantee that deadlines are always met. SRT tasks are allowed to miss deadlines, thus their performance is measured by the deadline miss ratio. For best-effort tasks, the performance is calculated by their average response time. We have run simulations with three kinds of schedulers on different architecture models. EDF and FPS schedulers are tested with systems containing 2 to 8 processors, and a partitioned-based scheduler (PS) has been tested for systems with 3 to 5 cores. For the latter, Table IV lists the local scheduling policies and scheduled task(s) on each processor. The simulation is aborted if a HRT task misses a deadline.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Type</th>
<th>$P_i$</th>
<th>$C_i$</th>
<th>$U_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>HRT</td>
<td>50</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>$T_2$</td>
<td>HRT</td>
<td>90</td>
<td>30</td>
<td>0.33</td>
</tr>
<tr>
<td>$T_3$</td>
<td>HRT</td>
<td>140</td>
<td>50</td>
<td>0.35</td>
</tr>
<tr>
<td>$T_4$</td>
<td>SRT</td>
<td>190</td>
<td>30</td>
<td>0.15</td>
</tr>
<tr>
<td>$T_5$</td>
<td>SRT</td>
<td>350</td>
<td>80</td>
<td>0.22</td>
</tr>
<tr>
<td>$T_6$</td>
<td>SRT</td>
<td>500</td>
<td>170</td>
<td>0.34</td>
</tr>
<tr>
<td>$T_7$</td>
<td>SRT</td>
<td>1000</td>
<td>[200, 700]</td>
<td>[0.2, 0.7]</td>
</tr>
<tr>
<td>$T_8$</td>
<td>SRT</td>
<td>1300</td>
<td>[500, 900]</td>
<td>[0.385, 0.692]</td>
</tr>
<tr>
<td>$T_9$</td>
<td>BE</td>
<td>[1000, 5000]</td>
<td>200</td>
<td>[0.04, 0.2]</td>
</tr>
<tr>
<td>$T_{10}$</td>
<td>BE</td>
<td>[3000, 9000]</td>
<td>500</td>
<td>[0.056, 0.167]</td>
</tr>
<tr>
<td>$T_{11}$</td>
<td>BE</td>
<td>[5000, 15000]</td>
<td>1500</td>
<td>[0.1, 0.3]</td>
</tr>
</tbody>
</table>

The average deadline miss ratio of the five SRT tasks is shown in Fig. 6(a). The deadline miss ratio decreases as the number of processors increases and becomes 0 for five processors. HRT tasks are not schedulable under EDF if the number of processors is less than four, thus no results are available for those cases.
plotted for EDF for 2 and 3 processors.

Fig. 6(b) shows the scheduling overhead including the total number of context switches and task migrations. It is interesting to observe that partitioned schedulers have no task migration but suffer from a large number of context switches incurred by P-FAIR, which serves as a local scheduler.

Fig. 7 illustrates the average response times of the BE tasks. As the number of processors increases, the average response time becomes smaller. The response times are very large if the number of processors is less than 4, thus they are not plotted. Evidently, such system performance estimates as obtained by SysRT are helpful to make design decisions at the very early system design stages.

VII. CONCLUSION

In this paper, we presented SysRT, a generic and high-level SystemC-based multiprocessor RTOS simulator. It provides the unique and novel combination of being highly accurate, efficient and easy to extend to facilitate early DSE. To this end, it contains different types of application models and a modular RTOS kernel model. Efficient and precise modeling of preemptive scheduling is achieved via an event-driven simulation approach. Its modular design allows for easy plug-in of new schedulers as well as new resource sharing protocols. Comparing SysRT with state-of-art simulators, it achieves faster simulation speeds with the same small simulation error. We demonstrated the flexibility of SysRT by experiments with a mixed workload executing on multiprocessor platforms with different numbers of cores.

For future work, we plan to establish co-simulation with more advanced hardware simulators developed in SystemC. Moreover, we are interested in designing and studying new schedulers for mixed application workloads executing on embedded platforms.

REFERENCES