# Integrating Security Constraints into Fixed Priority Real-Time Schedulers

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**Abstract**

Traditionally, most real-time systems (RTS) we considered to be invulnerable to security breaches and external attacks. This was mainly due to the use of proprietary hardware and protocols in such systems along with physical isolation. Hence, security and RTS were considered to be separate domains. This assumption is being challenged by recent events that highlight the vulnerabilities in such systems. In this paper, we focus on how to integrate security as a first-class principle in the design of real-time systems. We demonstrate how certain security requirements can be cast as real-time scheduling constraints. We use information leakage as a motivating problem to illustrate our techniques and focus on the class of fixed-priority (FP) real-time schedulers. We evaluate our approach both analytically as well as using simulations and discuss the tradeoffs in using such an approach. Our work shows that many real-time task sets can be scheduled using our methods without significant performance impact.

## I. Introduction

Embedded real-time systems (RTS) are used to monitor and control physical systems and processes in varied domains, *e.g.,* aircraft including Unmanned aerial vehicles (UAVs), submarines, other vehicles (both autonomous as well as manual), critical infrastructures (*e.g.,* power grid and water systems), spacecraft and industrial plants to name but a few. The next-generation of real-time control systems will need to support numerous interconnected, complex functions that include (but are not limited to) mission control, data acquisition, processing and communication [27]. To reduce cost, power consumption and weight for such systems, designers are progressively moving towards integrated architectures – all such functionalities are implemented as separate, yet inter-dependent, real-time tasks on individual processing nodes. This implementation possibly uses commercial-off-the-shelf (COTS) technology.

Until recently, most such RTS were considered to be invulnerable to security breaches because such systems were *(a)* physically isolated from the outside world, *(b)* executed on dedicated hardware and *(c)* used specialized protocols. Of late, such systems are increasingly being connected together, sometimes through the use of unsecured networks such as the Internet. Furthermore, sophisticated adversaries and malware developers are able to overcome air-gaps and physical isolation. This is evident from recent successful attacks on automobiles [3], [16], industrial control systems [7], malicious code injection into the telematics units of modern demonstration of potential vulnerabilities in avionics systems [35] and attacks on UAVs [28].

The vulnerabilities in RTS differ considerably from those of traditional enterprise systems due to the time and resource constraints under which RTS operate. The threats faced by RTS could also vary in scope and effect: from the leakage of critical data [30] to hostile actions due to lack of authentication [3], [16], [35]. It could be argued that some of the above-mentioned attacks succeeded because the original systems were not designed to be secure against attacks. However, simply tacking on security mechanisms that provide confidentiality (*e.g.,* encryption), integrity protection (*e.g.,* message authentication) and availability (*e.g.,* replication) without considering the embedded and real-time nature of such systems will not be effective. Researchers have proposed the addition of security as a new dimension to the design of embedded systems [14]. There also exists work reconciling security mechanisms with real-time properties [17], [33], [38]. Specifically, researchers proposed changes to the EDF scheduler [17], [38] – this was to optimize the level of security achieved while ensuring that real-time deadlines were met (the measurement was in the strength of security keys and primitives).

We consider the issue of *information leakage between real-time tasks* with different security levels. It is fairly well understood that the use of shared resources can lead to information leakage among programs without the use of explicit communication [15], [24]. Researchers have also studied the use of covert timing channels between tasks of differing security levels in the rate monotonic (RM) scheduler [30]. In contrast, we are focusing on information leakage due to the sharing of resources[1] such as

**Note:** This paper is an extended version of one that was previously published in ECRTS 2014 [21]. The main changes/differences are: *(a)* we elaborate more on the adversary model, the system model and motivations for both in Sections II and III; *(b)* we have updated the analysis in Section IV – the graph-based algorithm now computes the upper bounds on the number of invocations of the flush task in polynomial time instead of pseudo-polynomial time (as was the case with the previous paper); *(c)* a new section (VI-D) compares the performance of the two graph algorithms – the original one [21] and the more efficient one presented in this paper and *(d)* other textual changes to most sections, especially the introduction, abstract and conclusion.

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[1]Other than the processor core of course.

caches, DRAMs and I/O buses. Hence, every time there is a switch between tasks belonging to different security levels, there is a distinct possibility that information could leak through shared resources.

*Our aim is to reduce the potential for such information leakage through shared resources by integrating security at the design phase for RTS – in the form of intelligent scheduling constraints.* We present various methods for integrating such constraints into real-time scheduling policies (Sections III, IV and V). We also derive analytical bounds for the same (Section IV)[2]. In particular, we focus on the class of fixed priority (FP) scheduling algorithms [19]. These scheduling algorithms cover a large class of real-time systems.

The high-level contributions of this paper then are:

1) demonstrate the use of constraints on real-time schedulers as a means of enforcing security properties (mitigating information leakage through storage channels over implicitly shared resources[3] in this case) – presented in Section III;
2) discuss enhancements to the FP scheduling algorithms for the integration of such constraints (Sections III, IV and V) and provide analysis bounds for an instance of the problem (non-preemptive FP algorithm) – see Section IV; and
3) present additional ideas for the integration of such constraints for other instances of the problem that aim to improve performance compared to non-preemptive FP (Section V).

We first present the adversary and system model in Section II. We also carried out an extensive evaluation of the methods presented here (Section VI).

## II. Adversary and System Model

In complex real-time systems issues of information leakage arise when tasks at different security levels or from different security domains share the computing platform. Such situations can arise in multi-level security systems or when modules sourced from different providers are integrated together. For example, consider an avionics system designed as per the DO-178B model [6]. The navigation system which is less critical may be sourced from a less trustworthy vendor and can be placed at a lower confidentiality level than the flight control system to which it provides information. In such a case even if the navigation system were to be compromised it will not be privy to the critical data from the latter [35].

Another example is of unmanned aerial vehicles (UAVs) where: *(a)* a set of real-time tasks/components, $\{R\}$, are employed to control the UAV and *(b)* another set of tasks, $\{I\}$, are employed to gather, processes and communicates information back to the base station. $\{R\}$ could include tasks to calculate the flight path and control code to manage the engines. $\{I\}$ could include software components that control a camera to capture images, one or more tasks to process the images and another component to communicate the processed/raw images back to the command center. Now, the components in $\{R\}$ will have a higher criticality in terms of the real-time requirements while those in $\{I\}$ will have higher security requirements in terms of confidentiality, *i.e.,* the information that the UAV captures may be considered very security sensitive. Security levels could also vary within each set of tasks. For instance, the information being processed by the task that calculates the flight path of the UAV may be considered more secure sensitive than the information being processed by the control task (essentially the low level sensory/actuation information).

Another scenario is one where legacy applications are moved over to modern computing platforms due to the obsolescence of older processor architectures, *e.g.,* the "RePLACE" system from Northrup Grumman [9], [10], [26]. Such solutions take legacy applications and execute them on modern processors by providing emulation frameworks so that the application still believes it executes on the original platform. However, due to lack of physical isolation that they relied on before, leakage of information across applications due to the underlying shared resources is a real possibility. This could be exacerbated if the original applications processed information with different levels of sensitivity.

### *A. Adversary Model*

We assume that an adversary was either able to insert a task (that respects the real-time guarantees of the system to avoid immediate detection) or compromised one or more existing tasks at a lower security level. For example, the task set from the less trusted vendor in the previously discussed example could contain a task that is compromised. The main objective of this attacker is to passively glean secure information by observation of shared resource usage. Also, while the adversary can observe the usage of shared resources (like caches), it cannot snoop on the RAM contents of other tasks (due to the existence of virtual memory and/or memory controllers). Active adversaries that can tamper with the system operation are out of scope for this work. This is a reasonable adversary model as evidenced by attacks discovered in recent years, such as the Student [7] attack against process control systems, that show adversaries were passively gleaning information about the system long before active steps were initiated. Similarly, in high-target system such as UAVs, it may often be more important from an adversary's point of view to remain undetected than to actively interfere and be detected.

### *B. System Model*

We consider a uniprocessor system following the Liu and Layland task model [18] that contains a set of sporadic tasks, $\{\tau\}$ where each task $\tau_i \in \{\tau\}$ has the parameters: $\{p_i, c_i, d_i\}$, where $p_i$ is the period, $c_i$ is the worst-case execution time and $d_i$ is the deadline, with $d_i \leq p_i$. We also assume that (for the FP scheduling policy), the set of real-time priorities, $\{Pri\}$ are fixed such that, $\forall \tau_i, \tau_j \in \{\tau\}$ and $pri_{\tau_i}, pri_{\tau_j} \in \{Pri\}$ then either $pri_{\tau_i} \prec pri_{\tau_j}$ if $\tau_i$ has a higher priority than $\tau_j$ or $pri_{\tau_i} \succ pri_{\tau_j}$

[2]While earlier work [21] presented these methods and analyses, we expand on this to improve the efficiency of the analysis – see Section VI-D.

[3]Sometimes referred to as "storage channels with timing exploitation".

if $\tau_j$ has a higher priority than $\tau_i$. Of course, it is also possible that $pri_{\tau_i}$ and $pri_{\tau_j}$ share the same priority level. For the sake of simplicity, we write $pri_{\tau_i}$ as $pri_i$. Let $hep_i$ be the set of tasks with a higher or equal priority than a given task $\tau_i$ (excluding $\tau_i$ itself) and $lp_i$ be the set of tasks with lower priority than $\tau_i$. We also assume that time is measured in *integral quantities* and not as a continuous value.

We assume that the set of security levels for tasks, $S$, forms a *total order*. Hence, any two tasks $(\tau_i, \tau_j)$ in the system may have one of the following two relationships when considering their security levels, $s_i, s_j \in S$: *(i)* $s_i \prec s_j$, meaning that $\tau_i$ has higher security level than $\tau_j$ or *(ii)* $s_j \prec s_i$. It is important to note that it is typical for security levels to be totally ordered. However, security labels that consider both the security level and the information compartment form a partial order [5]. We plan to generalize our system model to consider security labels that form a partial order in the future. Further, while it might be the case that the tasks with higher real-time priorities may also have the higher security levels, we do not limit ourselves to this assumption. While we do present cases where there exists a relationship between the priority levels and security levels, our techniques are more general than these special cases imply.

## III. Security and Scheduling

As stated in Section I, we propose to mitigate the problem of information leakage via shared resources among tasks of varying security levels, by placing constraints on scheduling algorithms. While there may be multiple ways to mitigate information leakage (*e.g.,* hardware-supported cache partitions), the approach of modifying or constraining scheduling algorithms is appealing because, *(a)* it is a software based approach and hence easier to deploy compared to hardware based approaches; *(b)* it allows for reconciling the security requirements with real-time or schedulability requirements; and *(c)* availability of extensive analytical tools for real-time systems allows for better evaluation and understanding of the trade-offs between the security and schedulability requirements.

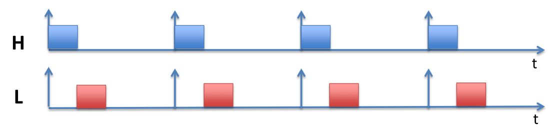

Fig. 1. Task Switches for a Two-Task System

We now present a simple example that is used to illustrate our ideas in this context. Consider the case of a simple RTS with just two periodic tasks, a high priority task $H\{p_H, c_H, d_H\}$ and a low priority task $L\{p_L, c_L, d_L\}$. Let us assume that the security levels for this system match the real-time priorities, *i.e.,* $s_H \prec s_L$; hence, information from H must not leak to L. Now, these tasks must be scheduled on a single processor, $P$, so that both deadlines $(d_H, d_L)$ are satisfied. Let the tasks be scheduled according to a Fixed Priority (FP) scheduling policy. If $L$ (or any part thereof) executes immediately after (any part) or all of $H$, then there is the potential for information leakage (*i.e.,* $L$ could inspect the shared resource contents that were recently used by $H$). Many attacks only need information about which cache lines were requested/evicted and the timing for such actions to be able to gather information about the data that the higher security level tasks used [24]. *The main intuition is that a penalty must be paid for each shared resource in the system, every time tasks switch between security levels.* In this case, *the cache must be flushed before a new task is scheduled*[4].

The solutions suggested in this paper are not specific to shared caches; we believe that the similar concepts are applicable to other shared resources as well. For instance, DRAMs or even the I/O bus could be shared resources that attackers may target to gather information (*e.g.,* it has been shown that the I/O bus can carry traffic related to a previously executing task even after a new task has been scheduled [22]). Hence, flushing mechanisms could be used for these other resources as well; *e.g.,* in the case of I/O buses, the "flushing mechanism" could just introduce a delay so that outstanding requests have time to complete before the new task starts up; in the case of a disk, the flushing task could reset the seek heads to some initial position. In general, there exist many resources in the system that are 'stateful'; hence, what one task does will have a timing effect on the next task. There exist ways to use this timing data to extract information about the previous executing task(s). Our solution is to add an operation (that has a fixed overhead) to "reset" the state of the device.

One point to note is that the flush task is not meant to immediately clear out the contents of the cache; the easiest way would have been to just supply a null voltage to the cache for a short duration. In fact, the flush task needs to ensure that the *system is left in a consistent state*. Any outstanding writebacks, bus write requests, data transfer, *etc.* need to complete before the contents of the cache are wiped. Hence, a finite amount of time must be spent in performing all of these operations.

### A. Scheduling Constraints

An initial analysis, then, yields the following constraints that can be applied to the real-time scheduler:

$C_1$ No instance of $L$ can be scheduled right after any instance of $H$

$C_2$ If an instance of $L$ is preempted by a job of $H$ and then resumes when $H$ completes then there is still a potential for information leakage – hence such a situation must be avoided.

Constraint $C_2$ is a special instance of $C_1$. Further analysis presents a few options for integrating these constraints into the scheduler:

[**A**] Since the shared resource is the offending party, we can ensure that it is always flushed/cleaned out whenever we see transitions of the type $H \rightarrow L$;

[4]We will discuss techniques to avoid an inordinate number of cache flushes later on in the paper.

[**B**] Ensure that all jobs of one kind ($H$ or $L$) complete before transitioning to the other; or
[**C**] prevent $L$ from being preempted by $H$ once it has been scheduled.

The first method, A, can be implemented by the use of a synthetic 'flush task' (FT) that is *always* executed once $L$ is scheduled after a job of $H$ – the job of the FT is to flush the contents of the shared resource; this ensures that any following task will not be able to access the contents of the resource. The problem with this method, of course, is that the synthetic task incurs an overhead (that may be small, yet still constant).

Of course, the problem with the use of an additional task to cleanse out the cache is that the overheads scale (often linearly) with the number of switches of the type $H \rightarrow L$ (Figure 1 where the horizontal axis is time; upward pointing arrows are new instances of tasks – also serve as deadlines for the previous invocations). Hence, the number of FT instances, $N_{ft} = N_H$, *i.e.,* the number of jobs for $H$. If we also assume that the FT is invoked on $L \rightarrow H$ switches (to prevent acknowledgements in covert channels[5]) then the number of FT instances is: $N_{ft} = N_H + N_L$, *i.e.,* the *total number of jobs*.

The second and third methods (B, C) will have to be used in conjunction with the first (A), since it is impossible to avoid the $H \rightarrow L$ transitions completely. These two techniques though, could significantly reduce the number of calls to the FT. Method (B) results in the least number of switches between tasks of $H$ and $L$ – just *one*. The problem, though, is obvious – one of the two tasks will very likely miss its deadline. Hence, for all practical purposes, we cannot use this method.

The final technique (C) is an additional constraint that is placed on the scheduling algorithm to handle constraint $C_2$. While this avoids situations where a preempted instance of $L$ resumes execution immediately after the completion of $H$ (thus reducing the number of preemptions and executions of FT), it could suffer from the problem of *priority inversion* where a high priority task is forced to wait for a low priority task to complete [25]. This technique could also result in lower utilization for some task sets (often resulting in task sets becoming unschedulable) since we are often forcing higher priority (critical) jobs to wait until an *entire lower priority job completes its execution*.

For the rest of this paper, we will refer to technique (A) as "`PreFlush`" (PF), *i.e.,* the basic scheduling algorithm with preemptions and FT, while technique (C) will be referred to as "`ConstrainedPreFlush`" (CPF), *i.e.,* the scheduling algorithm with a limited set of non-preemptions and (where necessary) FT invocations.

## B. PF and CPF for a Total Ordering of Security Levels

It is now easy to extrapolate PF and CPF to multiple tasks and security levels, $S$. The rules for **PF** are:

1) for every pair of tasks, $\tau_i, \tau_j |\ s_i \prec s_j$, invoke the FT on every transition of the type, $\tau_i \rightarrow \tau_j$;
2) also invoke the FT on every transition of the type, $\tau_j \rightarrow \tau_i$, *i.e.,* either on completion of $\tau_j$ or if $\tau_i$ preempts $\tau_j$.

The second rule ensures that the lower security task is not able to 'respond' (with acknowledgements) in case a covert channel is setup [5], [8], [30]. While this does cut down the efficiency of any such channels (and significantly reduces the possibility of information leakage), we can still get good protection and increased utilization by not enforcing this rule on most systems. If we prevent the flow of information between tasks by invoking the flush task on $\tau_i \rightarrow \tau_j$ transitions (where $s_i \prec s_j$), then even if a compromised $\tau_j$ is able to send back acknowledgements, it will not be effective. Hence, we present a simpler version of the PF mechanism called **Half-PF** *i.e.,* for every pair of tasks, $\tau_i, \tau_j |\ s_i \prec s_j$, invoke the FT on every transition of the type, $\tau_i \rightarrow \tau_j$ only. For the remainder of this paper, we focus on Half-PF rather than PF, unless explicitly mentioned[6].

The rules, then, for **CPF** are as follows:

1) for every pair of tasks, $\tau_i, \tau_j |\ pri_i \prec pri_j\ \&\ s_i \prec s_j$, *prevent* $\tau_i$ from preempting $\tau_j$; $\tau_i$ executes on the completion of $\tau_j$ if it is the highest priority task that is ready to execute at that point in time
2) for every pair of tasks, $\tau_i, \tau_j |\ pri_i \prec pri_j\ \&\ s_i \succ s_j$, *allow* $\tau_i$ to preempt $\tau_j$; this preemption is fine since the FT would have been invoked once anyways when $\tau_j$ completes execution

For the first rule, if there exist one or more tasks, $\tau_k$, such that $pri_i \prec pri_k\ \&\ s_i \prec s_k$ then $\tau_i$ is still allowed to execute after $\tau_j$ (even though we could further reduce FT invocations by not allowing it to). The reason is to avoid the situation where $\tau_i$ faces an inordinate priority inversion scenario. Hence, we are only concerned with direct preemptions and not indirect ones.

## IV. FP and Security

Fixed Priority (FP) schedulers [19] form a well known class of static scheduling algorithms. In this section we discuss how to combine the non-preemptive FP scheduler with our security-related constraint, Half-PF. We start with the non-preemptive FP scheduler because it is one of the easier algorithms to analyze and implement. We believe that the techniques in this paper will not only *(a)* provide insights into how such security-related constraints can be integrated into real-time schedulers but also *(b)* demonstrate how a worst-case response-time analysis can be carried out for such situations. We discuss CPF and other variations of FP later on.

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For the remainder of this section, let $\tau_i$ be the task under analysis and $c_{ft}$ be the execution time of one FT. III-B, We assume that each FT is executed together with the task that requires it: *i.e.,* if a job of task $\tau_j$ follows the execution of a job of task $\tau_i$, with $s_i \prec s_j$, a FT is invoked when the job of task $\tau_j$ is scheduled for execution, effectively increasing its execution time to $c_j + c_{ft}$. In other words, FT are also executed non-preemptively. Our analysis strategy is: we use standard response time analysis

[5]We will relax this assumption later in the paper to obtain tighter bounds.

[6]Note that a PF technique that invokes a FT both from high-to-low and low-to-high essentially can support security labels that from a partial order. This is because when $s_i$ is unrelated to $s_j$ information leakage should not be allowed in either direction.

for non-preemptive FP to compute, at each iteration, the number of higher or equal priority jobs that interfere with $\tau_i$. Then we determine the maximum number of FT invocations required by such jobs and we correspondingly increase the computed response times. As usual, we iterate until convergence is achieved.

Hence, the worst-case response time $R_i(k+1)$ of task $\tau_i$ at iteration $k$ can be computed [2] as:

$$R_i(k+1) = B_i + N_{ft}(S, \{I_j | \tau_j \in hep_i\})c_{ft} + \sum_{\forall j \in hep_i} (I_j c_j) + c_i, \tag{1}$$

where $B_i$ represents the maximum blocking time induced by lower priority tasks and their FT, $N_{ft}$ is the worst-case number of FT required by either interfering higher or equal priority tasks or by the task under analysis and $I_j$ is the number of instances of a higher or equal priority task $\tau_j$ that interfere with $\tau_i$, which for non-preemptive FP is:

$$I_j = \Big\lfloor \frac{R_i(k) - c_i}{p_j} + 1 \Big\rfloor. \tag{2}$$

The maximum blocking time $B_i$ can be computed as:

$$B_i = \max_{\forall \tau_j \in lp_i} \bar{c_j} - 1, \tag{3}$$

where $\bar{c_j} = c_j + c_{ft}$ if there exists a task $\tau_k \in S$ such that $s_k \prec s_j$ and $\bar{c_j} = c_j$ otherwise; *i.e.,* if there is any task that can cause a lower priority job of $\tau_j$ to suffer a FT then we need to add $c_{ft}$ to the blocking time generated by $\tau_j$. The $-1$ term accounts for the fact that the lower priority blocking task must arrive at least one time unit before the activation of $\tau_i$.

Note that we derive $N_{ft}(S, \{I_j | \tau_j \in hep_i\})$ based only on the ordering of security levels and the number of interfering jobs of each task in $hep_i$; in other words, we make no assumption on the arrival time or other timing parameters of higher or equal priority jobs within the busy interval. In the remaining of this section, we will show how to compute a bound to $N_{ft}$ in polynomial time in the number of tasks. We begin with some definitions. Intuitively, the concept of a *valid job sequence* captures all valid schedules based on the available information $S, \{I_j | \tau_j \in hep_i\}$, *i.e.,* all sequences of jobs that can invoke a FT during the busy interval for $\tau_i$.

**Definition 1** (Valid Job Sequence)**.** *A valid job sequence $\psi$ for $S, \{I_j | \tau_j \in hep_i\}$ is a sequence of $\sum_{\tau_j \in hep_i} I_j + 2$ jobs in $S$ such that: (a) the first job is a job of any task of $S$; (b) the last job is a job of $\tau_i$; (c) the sequence of $\sum_{\tau_j \in hep_i} I_j$ intermediate jobs is any permutation of the union of $I_j$ jobs for each task $\tau_j$ in $hep_i$. Let $\Psi(S, \{I_j | \tau_j \in hep_i\})$ be the set of all valid job sequences for $S, \{I_j | \tau_j \in hep_i\}$.*

**Definition 2** (Number of FT for $\psi$)**.** *$N(\psi)$ is the number of FT required by jobs of valid job sequence $\psi$, with the exclusion of the first job of the sequence; i.e., for any two successive jobs of any tasks $\tau_j, \tau_k$ in the sequence, a FT is required for $\tau_k$ if and only if $s_j \prec s_k$ in $S$.*

Let $t_0$ be the time at which a job of task $\tau_i$ arrives. Then a job of a task in $lp_i$ could be executing at $t_0$, but after this job completes, only higher or equal priority tasks can possibly execute before $\tau_i$. Furthermore, the processor could also be idle at $t_0$, in which case a job of any task (either higher priority, lower priority or $\tau_i$ itself) could have finished executing last before $t_0$. Hence, when considering the job sequence, we need to consider a job of any task as the first job in the sequence. Since we make no assumption on the arrival time of tasks in the busy interval, we then need to consider any possible permutation of the $\{I_j | \tau_j \in hep_i\}$ higher or equal priority jobs; finally, the job of $\tau_i$ must execute.

Since valid job sequences corresponds to valid schedules[7] for $S, \{I_j | \tau_j \in hep_i\}$, we can obtain the desired FT value as:

$$N_{ft}(S, \{I_j | \tau_j \in hep_i\}) = \max_{\psi \in \Psi(S, \{I_j | \tau_j \in hep_i\})} N(\psi). \tag{4}$$

Unfortunately, enumerating all possible permutations of higher or equal priority jobs would take factorial time. Hence, we now show how to transform the problem of computing the maximum $N(\psi)$ over all valid job sequences into a max flow problem on a graph derived from $S$ and $\{I_j | \tau_j \in hep_i\}$. Intuitively, we construct the graph by using "sender" and "receiver" nodes corresponding to tasks in a valid job sequence. We add an edge between a sender and a receiver representing tasks $\tau_j, \tau_k$ respectively to represent the fact that an FT is required if a job of $\tau_j$ is followed by a job of $\tau_k$ in the sequence. Note that in the following definition, we use the notation $v \to v'$ to denote an edge from vertex $v$ to $v'$.

**Definition 3** (FT Graph)**.** *The FT Graph for $S, \{I_j | \tau_j \in hep_i\}$ is a flow graph $(V, E)$ with the following set of vertexes $V$:*

*1) a* source *vertex and a* sink *vertex;*
*2) a* sender *vertex $SendF$ and a* receiver *vertex $RecvL$;*
*3) for each $\tau_j \in hep_i$, a* sender *vertex $Send_j$ and a* receiver *vertex $Recv_j$;*

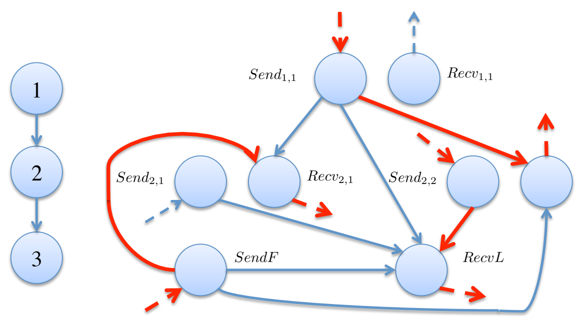
*and the following set of directed edges $E$, where $u(e)$ represents the capacity of an edge $e \in E$:*

*1) an edge from the source to every sender vertex, with $u(source \to SendF) = 1$ and $u(source \to Send_j) = I_j$;*
*2) an edge from every receiver vertex to the sink, with $u(RecvL \to sink) = 1$ and $u(Recv_j \to sink) = I_j$;*
*3) if there exists a task $\tau_k \in S$, $s_k \prec s_i$, an edge from $SendF$ to $RecvL$ with capacity $u = +\infty$;*

[7]Note that when considering the timing constraints of the jobs in $hep_i$, there are valid job sequences that are not valid schedules; however, we still compute a safe upper bound on the number of FT since every possible schedule is captured by a sequence $\psi$.

*4) for every task $\tau_j \in hep_i$, if there exists a task $\tau_k \in S$, $s_k \prec s_j$, an edge from $SendF$ to $Recv_j$ with capacity $u = +\infty$;*
*5) for every task $\tau_j \in hep_i$ such that $s_j \prec s_i$, an edge from $Send_j$ to $RecvL$ with capacity $u = +\infty$;*
*6) for every pair of tasks $\tau_j, \tau_k \in hep_i$ such that $s_j \prec s_k$, an edge from $Send_j$ to $Recv_k$ with capacity $u = +\infty$.*

In the following, let $f(e)$ denote the flow assigned to edge $e$ in a given flow assignment and $F = \sum_{e \in E} f(e)$ be the total flow value for that assignment. A flow assignment is valid if each flow $f(e)$ is between 0 and the edge capacity $u(e)$ and the flow conservation constraint is obeyed at all vertices except the source and sink: the sum of the flows on incoming edges to a vertex must be equal to the sum of flows on outgoing edges from that vertex.



(a) $S$ (b) Corresponding FT Graph

Fig. 2. Example: FT graph creation and max flow. $\tau_3$ is the task under analysis, with $I_1 = 2$ and $I_2 = 3$. Flow values $f$ represent a valid max flow assignment. Where not otherwise indicated, the edge capacity is $u = +\infty$ and the flow $f = 0$.

An an example, consider the security ordering in Figure 2(a). Let $\tau_3$ be the task under analysis and $I_1 = 2, I_2 = 3$. The equivalent FT Graph is shown in Figure 2(b). Note that for the sake of clarity we do not represent the source and sink vertices; all dotted lines directed towards a sender vertex represent edges originating from the source (edges of Type 1 in Definition 3) and all dotted lines going out of a receiver vertex represent edges ending in the sink (Type 2). Each higher or equal priority job is represented by two vertices, a sender and a receiver. An edge is added between $Send_j$ and $Recv_k$ if executing $\tau_j$ followed by $\tau_k$ would result in a FT (Type 6). $SendF$ represents the first job in a valid job sequence; it only has a sender vertex since it is not preceded by another job in the sequence, and based on Definition 1, it can represent any task in the system. Similarly, $RecvL$ represents the task under analysis, which must execute the last job in any valid job sequence. Edges of Types 3-5 represent FT required by $RecvL$ or by the job following $SendF$ (possibly $RecvL$ itself, Type 3). Note that each sender vertex can receive from the source and each receiver vertex can send to the sink a number of units of flow at most equal to the maximum number of times that jobs of the corresponding task appear in any valid sequence.

A valid max flow assignment is shown by the $f(e)$ values in Figure 2(b). One unit of flow is sent on edges $source \rightarrow SendF \rightarrow Recv_2 \rightarrow sink$ and $source \rightarrow Send_2 \rightarrow RecvL \rightarrow sink$, two additional units of flow on edges $source \rightarrow Send_1 \rightarrow Recv_2 \rightarrow sink$, and zero everywhere else, for a flow value $F = 4$. This flow assignment corresponds to the valid job sequence $\psi = (\tau_1, \tau_2, \tau_1, \tau_2, \tau_1, \tau_2, \tau_3)$, which similarly results in $N(\psi) = 4$, since FT are required in the transitions from $\tau_1$ to $\tau_2$ and $\tau_2$ to $\tau_3$. Note that the sequence can be constructed based on pairs of sender and receiver vertexes with non-zero flow, starting from $SendF$ (it can represent any task in the system, $\tau_1$ in the example) and ending with $RecvL$ ($\tau_3$). Finally, note that the max flow is strictly dependent on the number $I_j$ of jobs of each higher priority task $\tau_j$.

The following theorem formally proves that the maximum flow on the FT graph represents an upper bound to the number of FT for any valid job sequence. Furthermore, while the bound is not always tight, it is at most one higher than the maximum number of FT. Intuitively, the bound is one FT higher because there exist some integer flow assignments that do not correspond to a valid job sequence. In particular, an assignment might have flow both on the edge between $SendF$ and $RecvL$ and on other edges. This cannot result in a valid sequence, since it requires that the first job in the sequence is immediately followed by the job of task under analysis $\tau_i$, but at the same time, there must be other FT caused by intermediate higher priority jobs. However, we can show that we can always obtain a valid sequence by removing the flow on at most one edge.

**Theorem 1.** *Let $\bar{F}$ be the max flow value for the FT graph $(V, E)$ for $S, \{I_j | \tau_j \in hep_i\}$. Then:*

$$\bar{F} - 1 \leq \max_{\psi \in \Psi(S, \{I_j | \tau_j \in hep_i\})} N(\psi) \leq \bar{F} \tag{5}$$

*Proof:* Since all capacities in the FT graph are integers, there must exist an integer flow assignment with max flow value $\bar{F}$. We first show (Part A of the proof) that for any valid job sequence $\psi \in \Psi(S, \{I_j | \tau_j \in hep_i\})$, there exists a valid flow assignment with flow value $F = N(\psi)$; thus $\max_{\psi \in \Psi(S, \{I_j | \tau_j \in hep_i\})} N(\psi) \leq \bar{F}$. We then show (Part B of the proof) that for any valid integer flow assignment with flow value $F$, there exists a valid job sequence with $N(\psi) \geq F - 1$; thus $\max_{\psi \in \Psi(S, \{I_j | \tau_j \in hep_i\})} N(\psi) \geq \bar{F} - 1$. This concludes the proof.

**Part A:** Given job sequence $\psi$ and for ease of notation, assume that the first job in $\psi$ is a job of task $\tau_k$; based on Definition 1, $\tau_k$ can be any job in $S$. Also based on Definition 1, we use the term intermediate jobs to refer to jobs of tasks in $hep_i$, with the exclusion of the first job in $\psi$. We now show how to construct a flow $f$ such that $F = N(\psi)$. We consider two cases.

Case A.1: there are no tasks in $hep_i$. Then $\psi$ is composed of only two jobs, of $\tau_k$ and $\tau_i$ respectively. If $s_k \prec s_i$, we set of flow of 1 on edges $source \rightarrow SendF \rightarrow RecvL \rightarrow sink$, for a flow value $F = 1$ equal to $N(\psi)$; note that the flow is valid since there must be an edge $SendF \rightarrow RecvL$ in the FT Graph according to Definition 3. If instead it does not hold $s_k \prec s_i$, then we can simply set all flows to zero since $N(\psi) = 0$.

Case A.2: there is at least one task in $hep_i$. In this case, there must be at least one intermediate job of the task in $hep_i$ in $\psi$. We then construct $f$ by progressively adding flow to the graph one unit at a time in the following manner: A.2.1) Let the first intermediate job in the sequence be a job of $\tau_j$. Then if $s_k \prec s_j$, we add one unit of flow on edges $source \rightarrow SendF \rightarrow Recv_j \rightarrow sink$. A.2.2) For any two successive intermediate jobs of $\tau_j$ and $\tau_l$, if $s_j \prec s_l$ we add one unit of flow on edges $source \rightarrow Send_j \rightarrow Recv_l \rightarrow sink$. A.2.3) Let the last intermediate job in the sequence be a job of $\tau_l$. Then if $s_l \prec s_i$, we add one unit of flow on edges $source \rightarrow Send_l \rightarrow RecvL \rightarrow sink$. We now show that the flow is valid: first, note that we only send flow on edges that exist in the FT Graph according to Definition 3, and that flow conservation constraints are respected by construction. Furthermore, the maximum amount of flow sent from the source to $SendF$ and from $RecvL$ to the sink is one unit (A.2.1 and A.2.3). Finally, the maximum amount of flow sent from the source to a vertex $Send_j$ and from a vertex $Recv_j$ to the sink is equal to the number of intermediate jobs of $\tau_j$ in $\psi$, which is $I_j$; hence, all capacity constraints are respected, making the flow valid. Now note that an outgoing flow of 1 from the source (and incoming flow of 1 to the sink) is added every time it holds $s_j \prec s_l$ for any two successive jobs of $\tau_j, \tau_l$ in the sequence; hence, it must hold $F = N(\psi)$, concluding this part of the proof.

**Part B:** We need to show that given an integer flow $f$, we can construct a sequence $\psi$ such that $N(\psi) \geq F - 1$. If $F = 0$, the proof is trivial, so assume $F > 0$. We now define the concept of a minimal vertex sequence set for $f$ to help us construct $\psi$: B.1) a vertex sequence is an alternation of sender and receiver vertexes; B.2) a vertex sequence starts with a sender and ends with a receiver; B.3) if a receiver is followed by a sender in a vertex sequence, both vertexes must belong to the same task (i.e., $Recv_j$ and $Send_j$ for some task $\tau_j$); B.4) the number of times that a given sender vertex is followed by a given receiver vertex in all sequences in the set must be equal to the flow $f(e)$ on the edge between the sender and the receiver; B.5) for any task $\tau_j$, there cannot be two vertex sequences in the set such that one sequence ends with $Recv_j$ and another starts with $Send_j$. Essentially, vertex sequences represent "concatenations" of sender and receiver vertexes that exchange flow. It is easy to see that there must exist at least one minimal vertex sequence set: one can simply construct one by starting with a set of $F$ sequences of the form $(Send_j, Recv_l)$ (i.e., one sequence with two vertexes for each unit of flow in the graph), and then concatenating any two sequences that end/start with $Recv_j$ and $Send_j$, respectively, until condition B.5 is met. Further note that since $S$ is totally ordered, each $Send_j$/$Recv_j$ vertex can only appear once in each sequence in the set: otherwise, there would be a circular relationship among priority levels. Finally, we show that the number of sequences in the minimal vertex sequence set in which $Send_j$ or $Recv_j$ appear is at most equal to $I_j$. Clearly by B.4 and the fact that the amount of flow sent from source to $Send_j$ is at most $I_j$, it follows than $Send_j$ cannot appear in more than $I_j$ sequences; the same holds for $Recv_j$. Based on the total order of $S$ and B.5, it also follows that for a given task $\tau_j$, there could be one or more sequences that start with $Send_j$ (and hence has a $Send_j$ vertex but not a $Recv_j$ vertex) or one or more sequences that end with $Recv_j$ (and hence has a $Recv_j$ vertex but not a $Send_j$ vertex), but not both; otherwise the sequences could be concatenated. Based on these two observations, the property that the number of sequences in which $Send_j$ or $Recv_j$ appear is at most $I_j$ must then hold. **Example:** consider Figure 2. Since $F = 4$, one can construct a minimal vertex sequence set by considering the 4 sequences $\{(SendF, Recv_2), (Send_2, RecvL), (Send_1, Recv_2), (Send_1, Recv_2)\}$, and then concatenating $Recv_2$ and $Send_2$. Based on which sequences are concatenated, we can derive either of the following two valid minimal vertex sequence sets: set $\{(SendF, Recv_2, Send_2, Recv_L), (Send_1, Recv_2), (Send_1, Recv_2)\}$ or set $\{(SendF, Recv_2), (Send_1, Recv_2), (Send_1, Recv_2, Send_2, Recv_L)\}$.

We can then construct $\psi$ based on any minimal vertex sequence set as follows: B.6) if there is any vertex sequence in the set that starts with $SendF$, pick any task $\tau_k$ such that $s_k \prec s_j$, assuming that $Recv_j$ is the second vertex in the sequence, and start $\psi$ with a job of $\tau_k$; note that there must be at least one such task $\tau_k$, otherwise according to Definition 3 there would be no edge between $SendF$ and $Recv_j$. Then add intermediate jobs to $\psi$ based on the vertex sequence (i.e., for each successive receiver and sender vertexes $Recv_j$ and $Send_j$, add one job of $\tau_j$, plus one job for the final receiver in the sequence). If there is no maximal vertex sequence that starts with $SendF$, start $\psi$ with a job of any task in $S$. B.7) For any vertex sequence in the set that does not start with $SendF$ or end with $RecvL$, add intermediate jobs to $\psi$ based on the vertex sequence as in the previous point. B.8) Let $x_j$ be the number of jobs of $\tau_j$ added to $\psi$ either in the previous rules B.6-B.7 or in the next rule B.9. Then add $I_j - x_j$ additional jobs of $\tau_j$ to $\psi$. B.9) If there is any vertex sequence that ends with $RecvL$, add intermediate jobs to $\psi$ based on the vertex sequence. Otherwise, simply add a job of $\tau_i$ as the last job in the sequence. Since each $Send_j$/$Recv_j$ vertex appears once in at most $I_j$ vertex sequences, it follows that $x_j \leq I_j$ in B.8, and the total number of intermediate jobs of $\tau_j$ in the sequence is exactly $I_j$. Since furthermore the first and last job in the sequence also respect Definition 1 based on B.6, B.9, it follows that $\psi$ is a valid job sequence. Finally, note that by construction we have added $F$ job transitions of the form $s_j \prec s_l$ to $\psi$ (one for each sender vertex followed by a receiver vertex in any vertex sequence); hence, $N(\psi)$ must be at least equal to $F$, satisfying the $N(\psi) \geq F - 1$ relation. However, we need to cover one final case: B.10) the minimal vertex sequence set might comprise at least two sequences, including one that starts with $SendF$ and ends with $RecvL$. In this case, we cannot construct a full sequence $\psi$ based on both vertex sequences, since a valid job sequence must start and end with jobs corresponding to vertexes $SendF$ and $RecvL$. However, we can still construct a sequence $\psi$ based on B.6 - B.9 by removing $SendF$ and $Recv_j$ from the vertex sequence, where $Recv_j$ is the second vertex in the sequence started with $SendF$. Using the same reasoning as above, this results in $N(\psi) \geq F - 1$, concluding the proof. **Example:** using the minimal vertex sequence set $\{(SendF, Recv_2), (Send_1, Recv_2), (Send_1, Recv_2, Send_2, Recv_L)\}$ for Figure 2 and following B.6-B.9, we construct the job sequence $\psi = \big((\tau_1, \tau_2), (\tau_1, \tau_2), (\tau_1, \tau_2, \tau_3)\big)$, as previously noted; the first two jobs are added based on B.6 and vertex sequence $(SendF, Recv_2)$, the second two jobs based on B.7 and vertex sequence $(Send_1, Recv_2)$, and the last three jobs based on B.9 and vertex sequence $(Send_1, Recv_2, Send_2, Recv_L)$. Note that since we already added a number of intermediate jobs (again, the first job in the sequence, corresponding to $SendF$, is excluded) equal to $I_1, I_2$ for $\tau_1$ and $\tau_2$, we do not need to add any job in B.8. Finally, note that if we were to use the other valid minimal vertex sequence set for the example in the figure, we would have to apply rule B.10, resulting in $N(\psi) = 3$ rather than 4. ■

## *Computational Complexity and Previous Work*

The max flow value can be computed by any max flow algorithm. In particular, the Orlin+KRT algorithm [23] has a complexity $O\big(|E||V|\big)$. Note that since the FT Graph has an edge between any sender and receiver vertexes for tasks $\tau_j, \tau_k$ with $s_j \prec s_k$, the number of edges is $O(|V|^2)$. Let $n$ be the number of tasks in the system; given that the number of vertexes is $O(n)$, it follows that the max-flow value can be computed in $O(n^3)$ time.

Note that in previous work [21], we first proposed a graph-based algorithm to compute a bound on $N_{ft}(S, \{I_j | \tau_j \in hep_i\})$. The bound derived in that paper [21] has the same tightness as in Theorem 1, that is, the bound is at most one higher than the worst-case number of FT. However, the graph algorithm in [21] has pseudo-polynomial complexity in the number of tasks, since the constructed graph has a number of vertices proportional to the number of jobs $I_j$ in the busy interval. In contrast, our new algorithm runs in *polynomial time in the number of tasks*. We evaluate (and compare) the running times for both algorithms in Section VI through a set of synthetic task sets.

## V. Further Considerations for Scheduling

Designers of real-time systems must work towards optimizing a large number of parameters to ensure the (functional & temporal) correctness of the system. Security constraints are additional parameters that they must now be considered as part of this process. This begets the following questions:

1) What is the best ordering of security levels?
2) In fact, is there such a thing as the "best ordering" for security levels in RTS?
3) Is this "best ordering" related, in any way, to the real-time priorities of the task sets?

The most obvious answer, of course is *depends* – this is entirely up to the particulars of the system (what tasks are in the system, their properties, functionality, *etc.*). But perhaps we can provide some hints to designers so that if they have a choice, then they could tune their system to improve not just real-time performance but also security. We present two examples to highlight some of these issues. While our analysis (Section IV) has focused on non-preemptive scheduling algorithms, in the examples and discussion presented in this section, we will also talk about issues related to preemptive scheduling methods.

**Example 1**: Consider a security ordering for three tasks, $s_1 \prec s_2 \prec s_3$ where the real-time priorities are: $pri_1 \prec pri_2 \prec pri_3$; we also assume that all tasks are released at the same time (at least for this example). Now, consider the Half-PF and CPF constraints:

**Half-PF**: Under this constraint, every time there is a change of the type $pri_i \rightarrow pri_j$ (where $pri_i \prec pri_j$) there will a FT invocation. Hence, for the current set of ready jobs, *every time* a task completes and a new one is scheduled, it will result in a FT invocation. The only time that a FT will not execute is when a new instance of a higher priority task preempts a lower priority task. Also, it is often the case that higher priority tasks have shorter periods (*e.g.,* in RM [18] scheduling) – hence, the jobs of the higher priority tasks will often preempt the lower priority jobs and every time the latter resume their executions, a FT invocation will take place. It is also typical that lower priority jobs, while having the longer periods, also have longer execution times. Hence, the chances of such preemptions, followed by FT invocations, will be high.

**CPF**: even though tasks cannot be preempted by higher priority tasks for this example (see the definition of CPF in Section III-B), it still suffers from the overheads of many FT invocations. Every time a higher priority task is scheduled and then is followed by a lower priority task the FT must execute. This seems to result in the most number of FT executions for a set of ready tasks at any point in time as we see in Section VI. We refer to this ordering (where priorities and security levels are ordered along the same direction) as *forward ordering*:

**Definition 4.** *For any two tasks, $\tau_i, \tau_j$ with priority ordering $pri_i \preceq pri_j$, a* **forward ordering** *states that the security levels will be $s_i \prec s_j$.*

**Example 2**: Now, let us change the security ordering of tasks from Example 1 to be $s_1 \succ s_2 \succ s_3$ while still preserving the real-time priorities as before, *i.e.,* $pri_1 \prec pri_2 \prec pri_3$; we also assume, as before, that all tasks are released at the same time. Now, consider Half-PF and CPF for this updated example:

**Half-PF**: In this case, since all the tasks are released at the same time, the highest priority task $\tau_1$ will execute first, followed by $\tau_2$ and then $\tau_3$ will execute; during this sequence of executions, *the FT was never invoked*. The reason is simple – though the higher priority tasks have a lower security level, the number of transitions of the type $s_i \rightarrow s_j$ where $s_i \prec s_j$ is reduced (reduced to zero for these invocations in Example 2). The only instances when we need to execute the FT is when a preemption takes place or if a high priority task follows a low priority task. As mentioned above, most of the time (in a typical RTS) low priority tasks execute and though preemptions can occur, they only result in one additional FT.

**CPF**: the CPF constraint is able to do better than Half-PF at reducing the number of FT executions (for this example), since lower priority tasks cannot be preempted once they start. Hence, higher priority job can cause only *one* FT invocation (and that too only if it immediately follows a task with lower priority). Hence, this particular ordering of tasks seems to bring out the best behavior in the scheduling algorithms when the constraints Half-PF and CPF are applied (more in Section VI). We call this a *backward ordering*, where priorities and security levels are in the seemingly opposite directions; it is defined as:

**Definition 5.** *For any two tasks, $\tau_i, \tau_j$ with priority ordering $pri_i \preceq pri_j$, a* **backward ordering** *states that the security levels will be $s_i \succ s_j$.*

We also introduce the notion of "random ordering" where two tasks, $\tau_i, \tau_j$ with priority ordering $pri_i \preceq pri_j$ could exhibit any one of the following two behaviors regarding security level ordering: $s_i \prec s_j$, or $s_i \succ s_j$. Considering the varied nature of RTS and security constraints, it may often be the case that task sets will fall into this particular ordering.

**Definition 6. Random ordering***: Given a set of tasks $\{\tau\}$, it not possible to establish an exact relationship between their priority ordering and their security ordering.*

**Note:** By "random ordering" we do not mean that the ordering is random. It is a convenient phrase to describe the fact that we do not assign a specific order, ahead of time, to the tasks.

Definitions 4, 5 and 6 provide insights into the what could possible be the worst, best and average case situations for real-time systems with security constraints.

## VI. EVALUATION

We now evaluate the constraint-driven FP schedulers introduced in the previous sections. We first present our experimental setup, discuss the evaluation of the response time-based analyses (from Section IV) and present a set of simulations for other combinations of FP schedulers and security constraints. We also discuss some limitations for our work.

### *A. Experimental Setup*

TABLE I. EXPERIMENTAL PARAMETERS.

| Parameter | Value |
|---|---|
| Number of tasks, $N$ | $[3, 10]$ |
| Task period, $p_i$ | $[50, 100, \ldots, 950, 1000]$ |
| Task execution time, $e_i$ | $[3, 30]$ |
| FT overhead | $\{1, 5, 10\}$ |

Part of the process of integrating the Half-PF and CPF into FP is to gain an understanding of the behavior of the modified algorithm(s). For this purpose, we set up simulation and analysis engines and analyzed thousands of task sets. Table I summarizes the parameters used for the generation of task sets used in our evaluation. We generated 2000 random, synthetic, task sets evenly from *ten* base utilization groups, $[0.02{+}0.1{\cdot}i, 0.08{+}0.1{\cdot}i]$ for $i = 0, \ldots, 9$, *i.e.,* 200 instances per group. The base utilization of an instance is defined as the total sum of the task utilizations. Each input instance consists of $[3, 10]$ tasks, each $\tau_i$ of which has a period $p_i \in [50, 100, \ldots, 950, 1000]$ and an execution time $c_i \in [3, 30]$. The deadline of each task is set to be equal to its period, *i.e.,* $d_i = p_i$. Since deadlines are equal to periods, we decided to assign task priorities according to the Rate Monotonic (RM) algorithm [18]. While we acknowledge that RM is not an optimal priority assignment algorithm for our task model, we point out that optimizing the priority assignment is outside the scope of this work.

The overheads for the FT instances would depend on the actual resources, *e.g.,* in the case of a cache[8], it will be: $\frac{sizeof(cache)}{cache\_refill\_bandwidth}$; hence we use the values in the table ($[1, 5, 10]$) as placeholders. The values of $c_{ft}$ (relative to the task execution times) might seem a little high but it depends on the system under consideration. Sure, if the highest value for execution time (30) is equated to say, 10 ms, then $c_{ft}$ ranges from 0.3–3.3ms. This value does seem inordinately high considering that, for many architectures, the values lie in the 100's of microseconds range for cache flushes[9]. Of course things change if we were to assume that say, $30 = 1ms$ for the task execution times. Then the values of $c_{ft}$ range from $33\mu s$ to $333.33\mu s$; admittedly the latter is a little high (relative to the task execution times), but the purpose of choosing this value is to show what happens if we end up using shared resources that have high associated costs for cleaning out their state. Typically we would see $c_{ft}$ values closer to the lower end of the spectrum (*i.e.,* between $33 - 167\mu s$). The techniques presented in this paper would still be valid with other values for FT overheads.

For each task set instance, an ordering of security levels ($S$) is constructed: for each task $\tau_i$, a task $\tau_j | s_i \prec s_j$, where $i < j$, is added to $S$ with a probability of 0.5. Thus, in the resulting set, any $\tau_i$ can never have a lower security level than $\tau_j$. This prevents the formation of cyclical security relationships.

We use the same generated task sets for both, *(a)* the evaluation of the analysis bounds from Section IV and *(b)* the simulation-based evaluation of the other techniques (in Section V). All tasks are released at time $t = 0$ and each simulation executes for the duration of the hyper-period $HP$ of the given task set. The system keeps track of the response time of each job, denoted by $r_i^k$, that is calculated by the time duration that the $k^{th}$ job of $\tau_i$ took to complete its execution $e_i$. The analysis engine, on the other hand, computes the worst-case response time based on the iteration from Section IV. Upon completion of a job, the simulation/analysis engine checks whether the response time exceeds its deadline. A task set is said to be *unschedulable* if there exists any $\tau_i$ such that $r_i^k > d_i$ for $k = 1, \ldots, \frac{HP}{p_i}$.

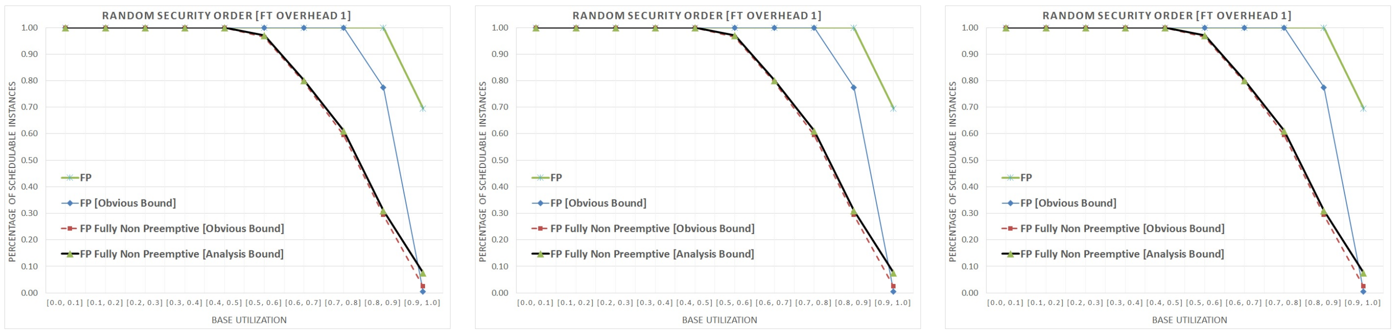
**Note:** we used the Ford-Fulkerson algorithm [4] to compute the max-flow.

### *B. Evaluation of Response-Time Based Analysis*

We first evaluate the Non-Preemptive FP+Half-PF combination (analyzed in general for FP in Section IV). We focus on the random ordering of security levels (Definition 6) since it represents the general case. Consider Figure 3(b) that shows results for an FT execution time of 5. The X-axis plots the utilization "bins" (or ranges) for the experiments while the Y-axis represents the total percentage of schedulable task sets for each bin. The various plots represent the FP variants: *(a)* the (vanilla) FP (thick green line); *(b)* FP with the obvious bounds (blue solid line) and two versions of the Non-Preemptive FP algorithm, *(c)* one based on the obvious/worst-case bound (red dotted line) and *(d)* one based on the worst-case response time analysis from Section IV and Equations 1 and 2 (thick black line). In the case of the "obvious bound" for both vanilla FP and non-preemptive FP, we refer to time taken by the worst-case number of FT invocations, $N_{ft}$. For the former, $N_{ft} = 2 * N_{hep_i} + 1$ and for the latter,

[8]Essentially to flush and refill the cache.

[9]As an example, a typical Intel Core i7 processor has an 8 MB Level 3 cache and up to 21 GB/s memory bandwidth. This results in a theoretical worst-case time $c_{ft} = 380\mu s$ to flush the entire L3 cache content to main memory. We further experimented with a Xilinx FPGA platform using an ARM Cortex A9 hard core processor to obtain experimental measurements on an embedded system. Using the available flushing functionality in the cache controller, we measured a worst-case running time for FT equal to $380\mu s$.



(a) FT=1 (b) FT=5 (c) FT=10

Fig. 3. Analysis-based Results [Random Ordering]

$N_{ft} = N_{hep_i} + 1$ ($N_{hep_i}$ is the number of higher or equal priority jobs for each task $\tau_i$[10]). **Note**: vanilla FP does not suffer from any FT overheads – it does not implement the security constraints.

The random ordering of security levels provides insights into the typical performance for the scheduling algorithms. As expected, `FP` (the vanilla version) performs the best, simply because it does not implement any of the constraints from Section III-B. This is evident from the graphs where the bar for FP is at the top and schedules most task sets. Of course, the ability to schedule task sets drops as we reach the higher utilization values (above $90\%$[11]).

From this graph we observe that our analysis (black line) is able to obtain tighter bounds than the naive (obvious) bounds. Hence, following the max-flow based graph algorithm presented in Section IV, we are able to schedule more task instances. While the performance may not be as good as vanilla FP, designers of such systems can now choose to increase the security, albeit at reduced schedulability levels (for task sets with higher utilizations), of real-time systems.

We also analyzed the effects of variability in the execution time of FTs on the schedulability of task sets (Figures 3(a) and 3(c)). As expected, the overall performance (relative to basic FP) drops as the FT execution time increases. When FT overheads are low, the naive analysis (obvious bounds) comes close to the response-time-based analysis while the relative differences increase as the FT overheads go up. The exception is shown in Figure 3(a) where the naive method performs much better (getting much closer to vanilla FP in fact). The reason is that the FT overhead ($c_{ft} = 1$) is *much* lower than the execution times of the tasks; the scheduling algorithm is not hindered all that much by these low overheads and hence seems to perform much better when compared to the analysis-based results. When the FT overheads are closer to the typical values ($c_{ft} = 5$ in Figure 3(b)) we see that performance of the naive analysis-based results drops (in comparison with the calculated worst-case bounds; *i.e.,* the black line). The relative performance drops further when $c_{ft}$ increases further (Figure 3(c)).

Hence, our techniques perform better when the overheads for flushing shared resources increase. This is quite important, since different shared resources (caches, DRAMs or even I/O buses) will demonstrate varying degrees of overheads for flushing their state and our methods are never worse (and usually better) than the typical conservative estimates.

One important observation is that *the modified algorithms (i.e., the ones with the security constraints integrated) are still able to schedule a large number of task sets*. The algorithms without these constraints start differentiating themselves only for the higher utilization values when the FT overheads become a factor for the modified algorithms. Hence, we can still implement many real-time systems that meet both the timeliness guarantees as well as the security requirements.

## C. Simulation Results for Other Schemes

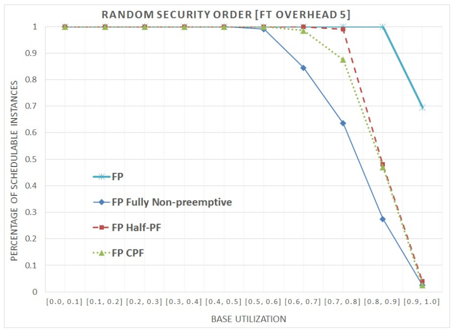
While section IV presented the analysis for one instance of an FP algorithm (non-preemptive) and a scheduling constraint (Half-PF), other combinations are possible as well (enumerated below). We believe that performing similar analyses for all of these combinations, while laborious, is still feasible and builds upon the intuition(s) provided in this paper. We are currently working on these analyses. In the meantime, we carried out a variety of simulations for these other combinations so that designers of secure real-time systems can gain a better understanding of the effect of the various parameters. In this section we enumerate the results from these simulations.

Given the set of generated tasks from Section VI-A, we use a simulator that schedules task sets using scheduling policies obtained by combinations of basic FP and Non-Preemptive FP with the constraints from Section III-B:

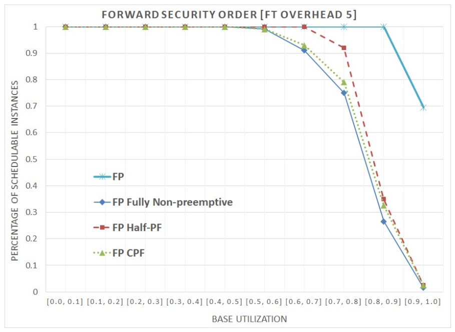
- Preemptive (or vanilla) FP (`FP`): tasks are scheduled by the basic FP scheduling policy. Preemptions are allowed with no FT invocations.
- NonPreemptive FP (`FP Fully Non-Preemptive`): It is the same as `FP` mentioned above, except that no preemptions are allowed but we do allow FT invocations when changing from high to low security levels.
- Preemptive FP with FT (`FP PF` but actually `FP Half-PF`): same as `FP`, however a resource flush task (FT) is executed whenever a higher security level task is being preempted by a task having a lower security but higher priority level.

[10]We get these bounds based on the upper bounds on the number of preemptions for basic and non-preemptive FP algorithms.

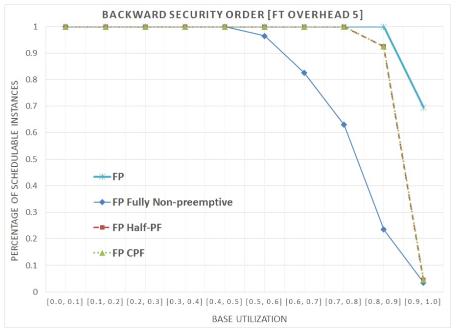
[11]While the typical schedulability tests for FP put the theoretical upper bound at $69\%$ [18], it is possible for FP to schedule task sets with higher utilizations – *e.g.,* if they are harmonic in nature.



(a) Random Ordering



(b) Forward Ordering



(c) Backward Ordering

Fig. 4. Simulation-based Results [FT = 5]

- Preemptive FP with Resource Flush under certain conditions (`FP CPF`): Preemptions are not allowed when the preempting task has a higher security level than the one currently running; otherwise preemptions are allowed.

Figure 4(a) presents results for the performance analysis of the "random ordering" method (Definition 6) for the above algorithms. For the following discussion, the execution overhead for each FT invocation, unless otherwise stated, is 5 time units[12].

As before, the vanilla FP performs the best. At the other extreme, we have the `FP Fully Non-Preemptive` algorithm that doesn't allow any preemptions. As expected, it has a tougher time in keeping up with `FP`, especially when the utilization values increase. These are the endpoints that we will use for comparing the remaining constraint-based algorithms.

Figure 4(a) shows that while `FP Half-PF` performs fairly well at scheduling most task sets, `FP CPF` is also able to match its performance, for the most part. `Half-PF` drops more task sets (as compared to `FP`) – its performance starts to degrade around the 75% utilization mark. It is interesting to note that this algorithm and `FP CPF` are still able to schedule some task sets as the utilization grows, at which point, interestingly, `FP CPF` catches up with `FP Half-PF`. Of course, both of these still perform much better than the `FP Fully Non-Preemptive` algorithm. The chief benefit of all three of these modified FP algorithms is that the overall *security is increased*. Now RTS designers can make choices based on quantifiable information – increased security versus a little drop in real-time utilization.

We conducted similar experiments for the Forward and Backward ordering of security levels (see Figures 4(b) and 4(c)). As expected, the forward ordering performs worse than the random ordering. The `FP Half-PF` and `FP CPF` algorithms are similar in performance for the forward ordering – they both start dropping out earlier than random (around 65% and 55% respectively) and are closer to the `FP Fully Non-Preemptive` version. Hence, our conjecture that the forward ordering results in bad (potentially worst) behavior is confirmed.

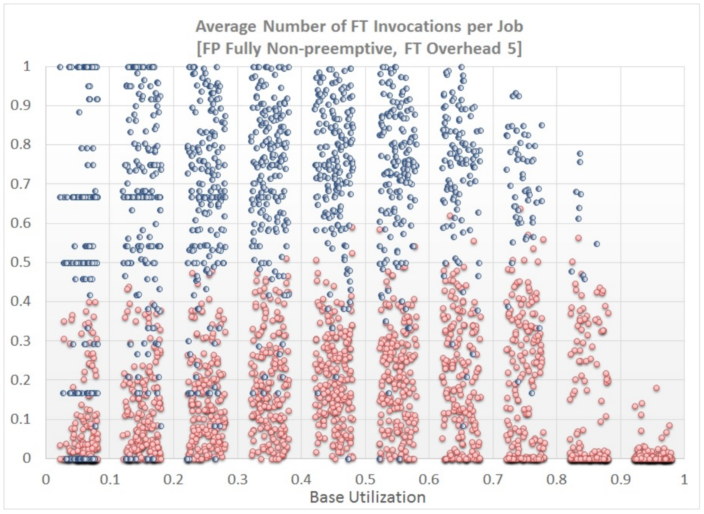


Fig. 5. Avg. #FT per Job for Analysis & Simulations [FP + Half-PF]

The backward ordering (Figure 4(c)), on the other hand, seems to be the *best* performer of the lot. In fact, its performance matches that of `FP` for the most part, dropping down (albeit a little) only for the really high utilization values. Again, this seems to underscore our claim that a backward ordering of security levels will be the best way to obtain the highest performance, while still guaranteeing the security properties. One interesting observation: for the backward ordering of security levels, `FP CPF` *is transformed into* `FP Half-PF`. The reasoning is simple: remember that CPF disallows preemptions when the higher priority task has a higher security level but allows preemptions in the opposite case. In the backward ordering, a higher priority task *always* has a lower (or equal) security level as the currently executing task – hence, preemption are always allowed. In Figure 4(c) the two lines are indistinguishable.

An important point to note though: for the lower utilization levels (typically below 50%), all of the modified algorithms perform just as well as FP in scheduling the task sets. *Hence, for many real-time systems, these algorithms are able to not just improve the security properties of the systems, but do so without any observable drop in performance*.

We can definitely think of ways to reduce the number of FT invocations based on the following insights: **(1)** Consider the `PF/Half-PF` constraints; in any given task set $\tau$ and security ordering $S$, a particular task $\tau_i$ will cause a FT invocation iff it

[12]We also saw similar trends for other values of $c_{ft}$ but omit them here since they don't really add any new information.

is preempted by a task, $\tau_j |\ pri_j \prec pri_i\ \&\ s_j \succ s_i$; hence all other preemptions will not result in FT executions – depending on the task set characteristics, this could potentially reduce a large number of preemptions; **(2)** `CPF` reduces many preemptions (and FT invocations) by definition; it also ensures that a lower priority job will experience a FT execution only *once* due to higher priority, higher security level tasks, thus reducing the total number of FT invocations; **(3)** All lower priority jobs, with higher security levels than the current job will only increase the number of FT executions for that job by *one* – essentially before it is scheduled to run. Once the job starts executing, it cannot be preempted by lower priority jobs (even with higher security levels); the latter cannot be scheduled as long as the current job has leftover execution.

The above rules show that the actual number of FT invocations due to these scheduling constraints could be reduced, perhaps even more aggressively than the bounds presented in Section IV. Results in Figure 5 also validate this observation. For each task set, on the Y-axis, the graph measures the number of FT invocations normalized to the total number of jobs, *i.e.,* the average number of FT executions per job. The X-axis represents the various utilization ranges/bins. This graph shows the results for the `FP Half-PF` algorithm for a random security ordering. The red dots (on the lower part of the graph) show the results we obtained from the simulations while the blue dots (on the upper parts of the graph) show the results for average number of FT invocations per job from the worst-case response time analysis. From this graph, we observe that: *(i)* the total number of FT invocations is typically *much less* than the number of jobs; *(ii)* this is also true as we reach the higher utilization task sets; *(iii)* the graph also shows that, for most tasks sets, the number of simulated FT executions is lower than the values calculated from our worst-case response time analysis. Hence, there is significant scope for reduction in these overheads and for corresponding increases in the schedulability of task sets. Other combinations of FP scheduling algorithms and security constraints also show similar behavior; they are omitted here due to space considerations.

## *D. Performance Evaluation of Graph Algorithms*

As mentioned earlier, our initial efforts to compute a bound on the number of invocations of the flush task, *i.e.,* $N_{ft}(S, \{I_j | \tau_j \in hep_i\})$ was based on the use of a graph-based algorithm [21]. However, that graph algorithm has a pseudo-polynomial complexity in the number of tasks. In this paper though, we have developed a new algorithm (see Section IV) that runs in *polynomial time in the number of tasks*. In this section we evaluate the performance of both algorithms by calculating the running times for both algorithms using sets of synthetic tasks. The previous version of the graph algorithm will be referred to as `Original` while the algorithm that we present in this paper is referred to as `New`.

TABLE II. EXPERIMENTAL PARAMETERS FOR PERFORMANCE EVALUATION OF GRAPH ALGORITHMS.

| Parameter | Value |
|---|---|
| Number of tasks, $N$ | $[5, 49]$ |
| Task period, $p_i$ | $[50, 100, \ldots, 950, 1000]$ |
| Task execution time, $e_i$ | $[1, 10]$ |
| Base utilization | $[0.3, 0.5]$ |
| FT overhead | 3 |

We generated a new set of synthetic tasks for analyzing the performance of the two algorithms. Table II summarizes the parameters used for generating these task sets. The method for generating the new task sets is similar to what was presented in Section VI-A[13]. We generated 1800 random, synthetic, task sets evenly from 9 groups that are defined by the number of tasks per set, *i.e.,* $[5, 9]$, $[10, 14]$, $\ldots$, $[45, 49]$ tasks. For instance, $[5, 9]$ indicates that the generated task sets will have anywhere from $5 - 9$ tasks in the set. The ranges for the task periods remain the same as before, that is, each task has a period $p_i \in [50, 100, \ldots, 950, 1000]$. Since there are more numbers of tasks per set than the previous experiment, the range of possible execution times is narrowed to $[1, 10]$ from $[3, 30]$. Then, we fix the range of possible base utilizations (*i.e.,* the total sum of the task utilizations) of a set to $[0.3, 0.5]$. We also fix the FT overhead to 3. As before, the deadline of each task is set to be equal to its period, and we use RM to assign task priorities. Furthermore, the security level relations are determined randomly as explained in Section VI-A. All the results that we now present are based on the task sets that are schedulable – *i.e.,* 1797 instances out of the total 1800 generated sets. **Note:** We used the Ford-Fulkerson algorithm [4] to compute the max flow here as well (in the same manner that it was used for the original tasks in Section VI-A).

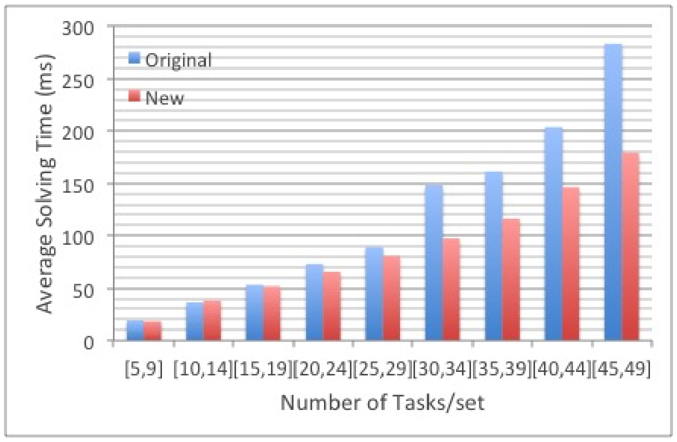
Figure 6(a) shows the average differences in time (for the two algorithms, `Original` and `New`) to solve a task set, *i.e.,* to test the schedulabilities for all tasks in a set. From this graph, we see that times required to solve `Original` grows at a much faster rate than `New`. The gap between the two algorithms grows with the number of tasks per set.

Next, we evaluate how efficient the `New` algorithm is in terms of the number of edges (that is dependent on the number of vertices) created by the flow graphs while calculating the worst-case $N_{ft}$ bound calculation. We first executed the `Original` algorithm for each of the 1797 schedulable task sets and get the *total number of edges* that are created for *all* the tasks in each set. Hence, we collected 1797 such samples (one for each schedulable task set) from this experiment. Then, for each task set, we obtain another, similar, sample with the new algorithm. The *reduction in the number of edges for a task set* is defined by: $(N_{e,org} - N_{e,new})/N_{e,org}$, where $N_{e,x}$ is the number of edges created by either `Original` or `New`. Figure 6(b) shows the average reduction in the number of edges for each group of tasks (defined by the number of tasks per set). We see that the `New` algorithm is more efficient in that it *generates fewer edges* for the flow graphs for each task set – this results in lower computation times for $N_{ft}(S, \{I_j | \tau_j \in hep_i\})$. Overall, the maximum reduction for the 1797 task sets was around 77%.

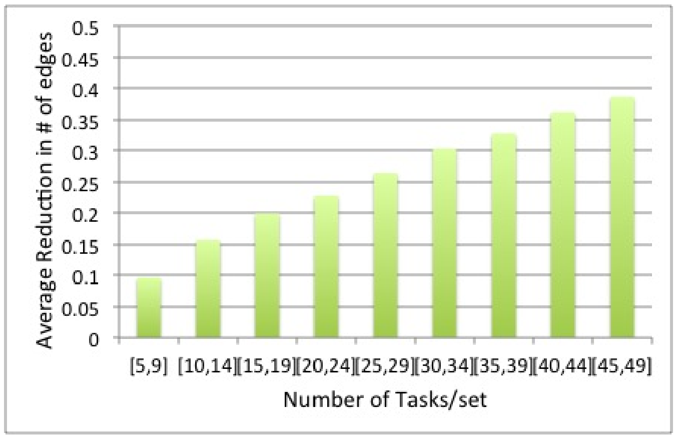
## *E. Limitations*

While we are able to show the value of, and methodology for, transforming security requirements (in this case prevent information leakage) into constraints for real-time scheduling, this is obviously not a silver bullet for solving all security problems.

[13]We generated new task sets since the *number* of task sets in the original evaluation was not enough to show the differences in running times.



(a) Solving time



(b) Number of edges

Fig. 6. (a) Average time to test the schedulabilities of a task set with the original algorithm [21] and the one being proposed in this paper and (b) Average reduction in the number of edges created for flow graphs from `Original` to `New`.

Many security requirements may not be amenable to being cast as scheduling constraints, *e.g.,* communication vulnerabilities. Also performance overheads due to such constraints could inhibit their adoption in many high utilization RTS, though with careful design processes this could be mitigated. The exact constraints depend on the system parameters.

## VII. Related Work

There is a large body of work on identification, analysis and mitigation of covert side channels (*e.g.,* [11]–[13], [15], [24]). In particular, Hu [12] assumes a similar security model and mitigation strategy (cache flushing) and discusses how scheduling algorithms can be modified to minimize the number of flushes. However, tasks have no real-time requirements and the scheduler does not support any service guarantee. Hence, in the following we only focus on those works that are relevant to real-time systems. For example, it has been shown that scheduling of (real-time) tasks can be a source of information leakage; Son *et al.* [30] showed that a covert timing channel can be established in the rate-monotonic scheduler. Völp *et al.* [37] discuss unauthorized information flows obtained through altered scheduling behavior (*e.g.,* delayed preemption). They also showed how to modify a fixed-priority scheduler to reduce the effect of such malicious alterations. They also studied the effect of timing channels introduced by real-time resource locking protocols and addressed them by transforming the relevant protocols [36]. In contrast, we do not focus exclusively on timing channels but rather on the approach of transforming security properties into real-time scheduling constraints; we use information leakage as an example to illustrate our techniques. The above techniques are orthogonal to ours (we intend to combine them in the future).

There has been some work on reconciling the addition of security mechanisms into real-time systems: Xie *et al.,* [38] and Lin *et al.* [17] considered periodic task scheduling where each task requires a security service whose overhead varies according to the (quantifiable) level of the service. They propose new schedulers [38] and enhancements to existing schedulers (*viz.,* EDF [17]) to meet real-time requirements while maximizing the level of security achieved. In contrast, we study enhancements to FP to reduce information leakage through shared resources while meeting real-time requirements.

The issue of information leakage in real-time database systems with multi-level security constraints has been considered [1], [31], [32]. Son *et al.* [31] focus on transaction scheduling and concurrency control algorithms to meet both security and real-time requirements. This includes metrics to measure fulfillment of security requirements and a concurrency control algorithm that can trade-off of security and real-time requirements [1]. Son *et al.* [32] resolve the conflict between real-time and security requirements by defining a notion of partial security and trading-off between the two.

There also exists recent work on developing architectural frameworks for solving security problems such as intrusion detection [20], [29], [34], [40], [41], among others. They aim to create hardware/software mechanisms to protect against security vulnerabilities while our work aims at the scheduler level. It is not inconceivable that the two sets of approaches could be combined to make the system more resilient to attacks.

Finally, in the case of our PF and CPF algorithms, the issue of computing the number of FT invocations is related to computing the number of preemptions suffered by a task or group of tasks. Existing work [39] discusses how to compute the exact cost of preemptions for a task under fixed-priority scheduling by accounting for the exact number of times that the task is preempted by higher priority tasks. The fundamental difference compared to this work is: according to our Half-PF constraint we only invoke a FT on a transition from a higher security to a lower security task, *not on every preemption*. Furthermore, a FT must be invoked even if a higher security task is simply followed by a lower security task, *i.e.,* without a need for preemption (as discussed in Section IV, which details the analysis for non-preemptive FP). Hence, the strategy detailed in [39] is not directly applicable. Having said that, that work [39] does present some interesting ideas for extending our analysis and we intend to use it as part of future work.

The work presented in this journal paper is an extended version of our paper that was published earlier [21]. As mentioned in the first page, we have made numerous additions/changes to the content in the conference version.

## VIII. Conclusion

We presented methods for integrating security constraints into real-time scheduling algorithms. In particular, the problem of information leakage via implicitly shared storage channels was used to illustrate our methods. The main idea was to modify the real-time scheduling algorithms to include security-oriented constraints to mitigate information leakage problems. The class of fixed priority scheduling algorithms was used to demonstrate our methods – *i.e.,* show how to block information leakage between tasks of differing security levels with acceptable performance overheads (or impact on schedulability). The proposed approach enables designers of real-time systems to carry out a proper assessment of the inherent tradeoffs between security requirements and real-time guarantees.

We are working on extending this in multiple directions – *(a)* improve the analysis to include other variants of FP; *(b)* extend the work to other classes of scheduling algorithms such as EDF; *(c)* consider multiple shared resources instead of just one; *(d)* generalize our system model (*i.e.,* relax the requirement for a total order of security levels) and finally *(e)* we intend to demonstrate these methods on realistic platforms.

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