# Real-Time Systems Security through Scheduler Constraints


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# Introduction

- Real-time systems (RTS) considered to be invulnerable to external security attacks
  - Due to use of proprietary hardware/protocols
  - Physical isolation
- Above assumptions are being challenged
  - Subsystems interconnected with each other (even through the Internet)
  - Malware developers able to overcome air gaps
  - Attacks demonstrated on automobiles, avionics systems, UAVs, power grids, etc.
- Security violations in real-time systems could be more catastrophic than other systems
  - Loss of life, physical harm to humans, system & environment, etc.
- Cannot tack on regular security mechanisms without concern for real-time properties

# Contributions



- Problem: Information leakage in real-time systems
  - Use of shared resources (e.g.: caches, DRAMs, etc.) to leak critical data
  - Between tasks with *different security levels*
- Contribution: *integrate security at design phase of RTS using* ***intelligent scheduling constraints***
- Fixed-priority (FP) scheduling schemes
- Analysis bounds for the integration of such constraints in FP algorithms

# Outline



- System model, adversary model, assumptions
- Security problem, Outline of our Solution
- Scheduling constraints: PreFlush, Half-PF, Constrained PreFlush
- Analysis
- Further scheduling considerations: Ordering
- Evaluation
- Conclusion

# Assumptions, adversary model, etc.



- Information leakage possible in systems with *multiple levels of security*
  - E.g.: DO-178B style avionics system with navigation system (low) and flight control (high)
- Security levels could *differ* from real-time priorities
  - E.g.: UAV with camera and real-time control tasks
  - Image capture and processing tasks → higher requirements for confidentiality
  - Real-time control tasks (flight path, engine control, etc.) → higher real-time priorities

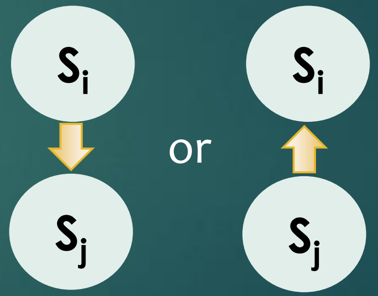
- **Adversary**
  - Can insert new tasks or compromise existing tasks → respects RT guarantees to avoid detection
  - Passively gleans secure information → by observation of shared resource usage
  - *Cannot* observe RAM contents of other tasks
  - *Cannot* tamper with system operation

# System Model



- Real-Time
  - Liu and Layland task model
  - Set of sporadic tasks
  - Fixed-priority (FP) scheduling algorithm

- Security
  - Set of security 'levels' of tasks forms a *total order*
  - Given any two tasks, $\tau_i$ and $\tau_j$, 'security ordering' can be one of →



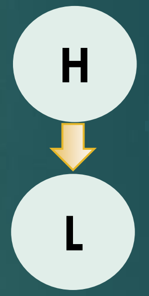

  - Will generalize to a partial order in future work

# Security problem

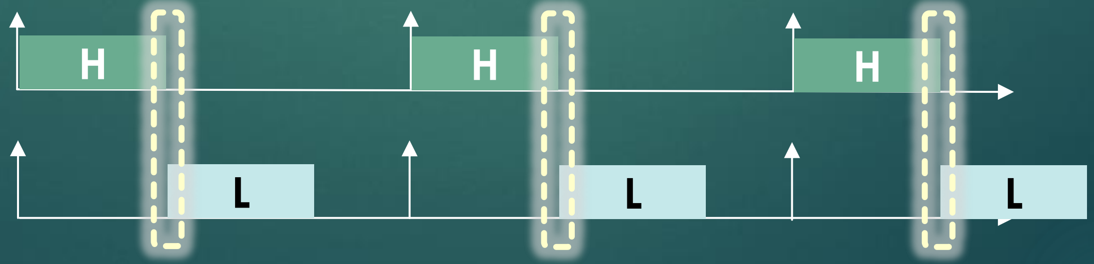


- *Information leakage through storage channels over implicitly shared resources*

- Consider two tasks, **H** and **L** such that
  - H has higher real-time priority than L
  - H is also at a higher security level than L
  - Hence, L *should not* be privy to H's information/internal state




- If **L** follows **H** at any point, then there is potential that a compromised **L** can snoop upon **H**
- Consider:



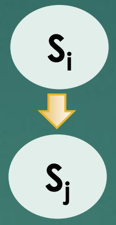
# Solution



1. **Clean up the shared resource** (eliminating storage channel) **SYNTHETIC FLUSH TASK (FT)**
   - Between every transition from/to H and L
   - E.g.: *flush the cache* after each task has completed
2. **Scheduling constraints** to prevent situations where leakage can occur
   - No instance of L can be scheduled after any instance of H
   - If an instance of L is preempted by H and then resumes later, leakage can still occur → avoid

- From an implementation perspective, the above constraints translate to:
  a. Flush/clean out shared resource on every transition of type H → L **PREFLUSH (PF)**
  b. ~~Ensure that all jobs of H complete before transitioning to L~~ ~~**MISSED DEADLINES**~~
  c. Prevent L from being preempted by H once it has started executing **CONSTRAINED PREFLUSH (CPF)**

# PreFlush (PF), Half-PF

- Rules for PF are
  1. For every pair of tasks, $\tau_i$ and $\tau_j$, such that 

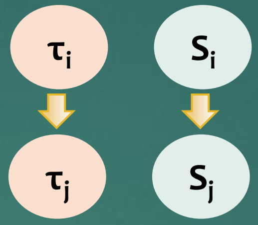
invoke **FT** on every transition, $\tau_i \rightarrow \tau_j$
  2. Invoke **FT** on every transition of type, $\tau_j \rightarrow \tau_i$

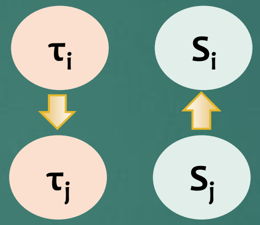
- Second rule prevents 'responses', i.e. confirmations in a covert channel setup
- If the first rule is active then even if the responses can be sent, it doesn't matter

- **HALF-PF**

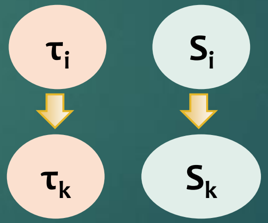
# Constrained PreFlush (CPF)



- Rules for CPF are
  1. For every pair of tasks, $\tau_i$ and $\tau_j$, such that 

  *prevent* $\tau_i$ from preempting $\tau_j$
  2. For every pair of tasks, $\tau_i$ and $\tau_j$, such that 

  *allow* $\tau_i$ to preempt $\tau_j$

- For the first rule, if there exist one or more tasks such that 

  - $\tau_i$ *is still allowed to execute* after $\tau_j$ → avoids situation where $\tau_i$ faces inordinate priority inversion
  - We are concerned more with *direct priority inversion* and not indirect ones

# FP and Security



- Fixed Priority (FP) Schedulers are a class of well known static scheduling algorithms
- We show how to integrate the Half-PF constraint into FP scheduling algorithms
  - Start with *non-preemptive* FP schedulers → one of the easier algorithms to implement/analyze
- Our techniques
  1. Provide insights into how security-related constraints can be integrated into scheduling algorithms
  2. Demonstrate how worst-case response-time analysis can be carried out for such situations
- Let
  - $\tau_i$ : task under analysis
  - $c_{ft}$ : execution time for one invocation of the flush task (FT)
  - FTs are executed non-preemptively

# Analysis



- Analysis strategy
  - Use standard response-time analysis for non-preemptive FP
  - Compute number of higher or equal priority jobs that interfere with $\tau_i$
  - Determine maximum number of FT invocations required by such jobs → increase response times
  - Iterate until convergence is achieved
- Worst-case response time of task $\tau_i$ at iteration '*k*',

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

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$I_j$: number of instances of higher or equal priority task $\tau_j$ that interfere with $\tau_i$

$$I_j = \left\lfloor \frac{R_i(k) - c_i}{p_j} + 1 \right\rfloor$$

---

$B_i$: max. blocking time

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

# Analysis (contd.)



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

- $N_{ft}$: worst-case number of FT required by interfering higher/equal priority tasks
- $N_{ft}$ derived only using
  - Ordering of security levels
  - Number of interfering jobs that are of higher or equal priority
  - No assumptions on arrival times or other parameters of higher/equal priority jobs
- In the paper → demonstrate how to compute $N_{ft}$ in *polynomial time in the number of jobs*

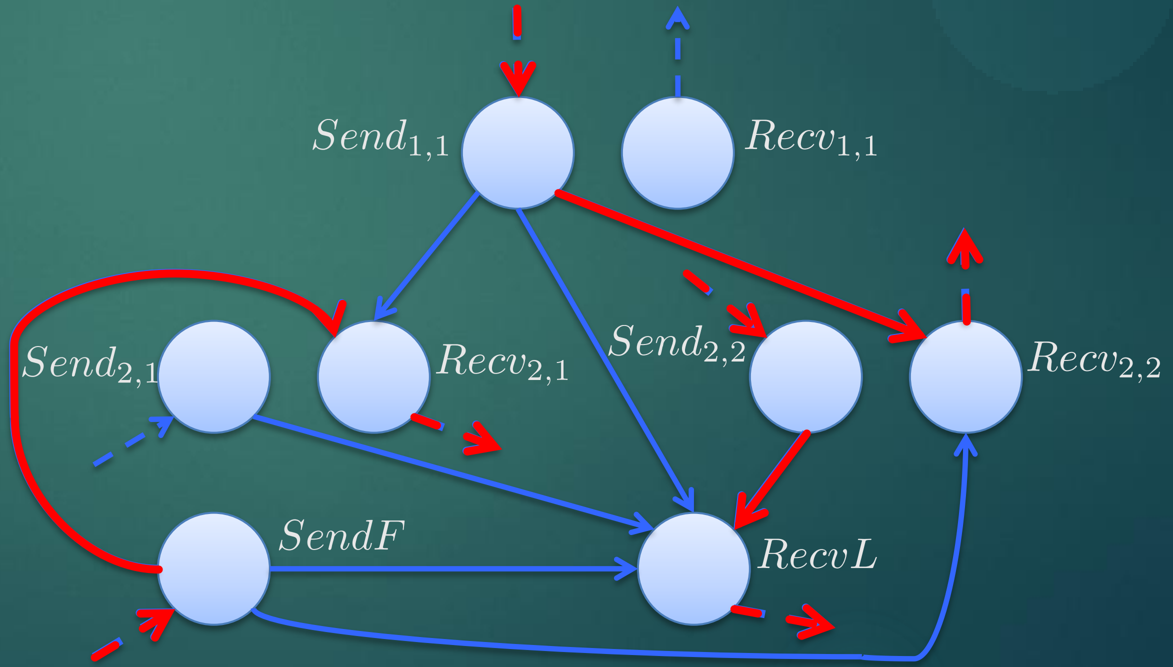
# Analysis (contd.)

- $N_{ft}$ computation: base idea
  - Create a flow graph where nodes represent jobs and edges represent FT
  - Each job is represented by a "sender" and a "receiver" node
  - SendF represents any job executed before the busy interval; RecvL is the job under analysis
  - Run max flow algorithm


$\tau_3$ under analysis

$I_1 = 1$

$I_2 = 2$

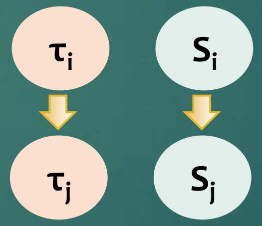


# Further Scheduling Considerations

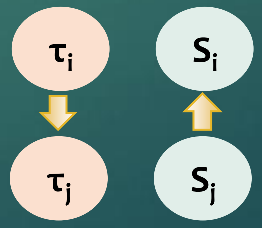


- Important issues arise when trying to integrate security into RT systems
  1. What is the best ordering of security levels?
  2. Is there such a thing as the "best" ordering of security levels?
  3. If it exists, is this "best" ordering in any way related to the real-time priorities of the system?
- Answer: *depends*!
  - Can provide some hints to designers

- *Forward Ordering*: For every pair of tasks, $\tau_i$ and $\tau_j$




- *Backward Ordering*: For every pair of tasks, $\tau_i$ and $\tau_j$




- *Random Ordering* :

  no real relationship between task priorities and security levels

# Ordering & Constraints



| | Forward Ordering | Backward Ordering |
|---|---|---|
| Half-PF | Every transition of type $\tau_i \rightarrow \tau_j$<br>• $\tau_i$ has higher priority than $\tau_j$<br>• will result in an FT invocation<br>• chances are high that most preemptions will result in FT | Least number of FT invocations<br>• Transition from higher to lower priority → transition from lower to higher security levels<br>• Execute FT at preemptions *only* |
| CPF | Prevents preemptions, but still suffers from overheads of many FT invocations | Same as Half-PF – all preemptions are by lower security tasks |

# Evaluation



- Set up *simulation* and *analysis engines*
- Generated and analyzed **2000** synthetic task sets
  - **10** base utilization groups: [0.02+0.1xi, 0.08+0.1xi] for i = 0 … 9
    [base utilization: total utilization for the tasks in set]
  - Task parameters:

| Parameter | Value |
|---|---|
| Number of tasks, **N** | [3, 10] |
| Task periods, $\mathbf{p_i}$ | [50, 100, 150, … 950, 1000] |
| Task execution times, $\mathbf{e_i}$ | [3, 30] |
| FT overhead | {1, 5, 10} |

- Task deadlines = periods
  - assigned priorities based on *Rate Monotonic* (**RM**) algorithm

Used same task sets for both

1. Evaluation of analysis bounds
2. Simulation-based evaluation

[1] computes worst-case response times based on analysis.

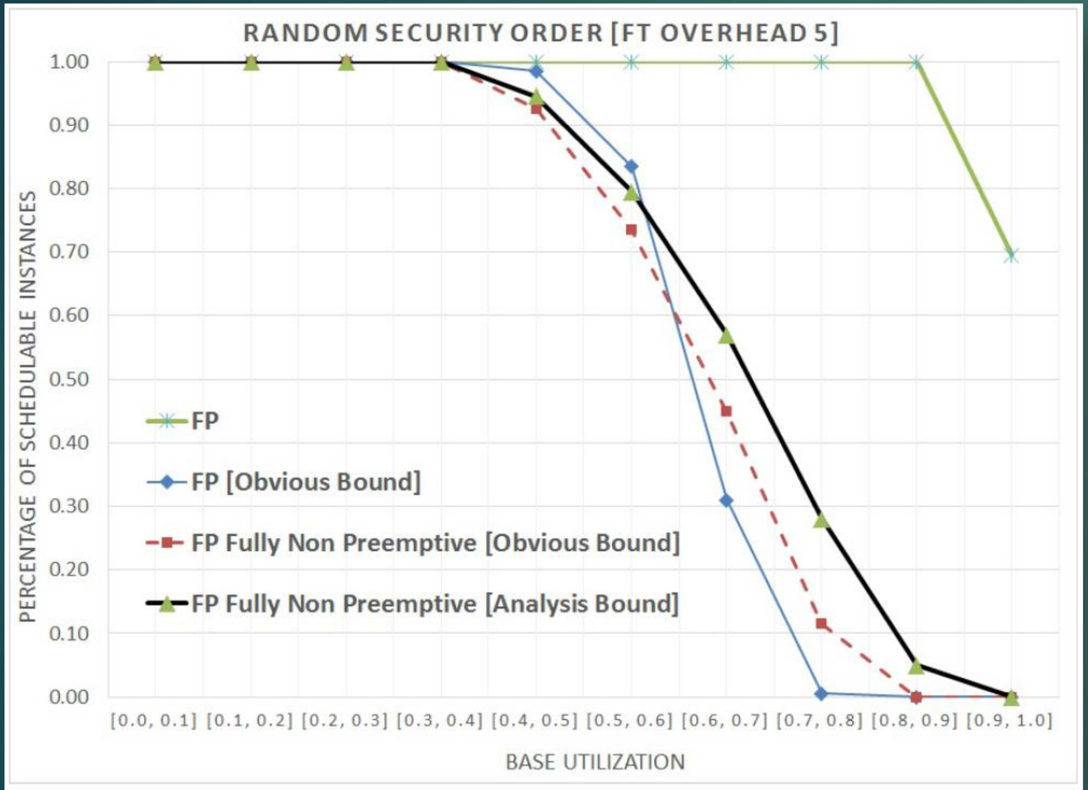
[2] executes task sets up to one hyperperiod; system tracks response times for each task.

On completion of a job, both check whether response times exceed task deadlines.

# Analysis-based Results



Non-Preemptive FP with Random ordering, Half-PF constraint



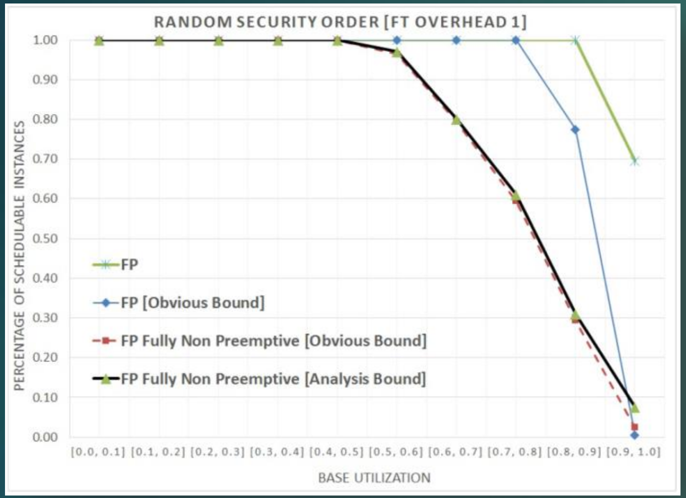

- Vanilla FP performs best → no constraints
- Our method [black line] → better than naïve bounds for number of FT invocations
- Designers can see effects of security constraints
- Reduced schedulability, but **increased security**

FT = 5

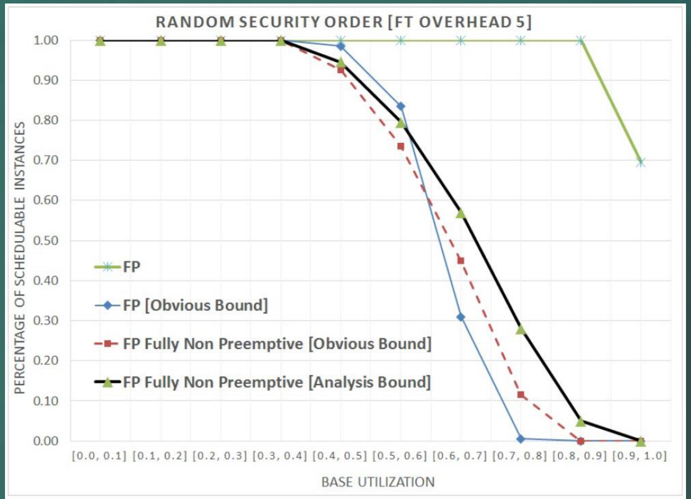
# Analysis-based Results (contd.)



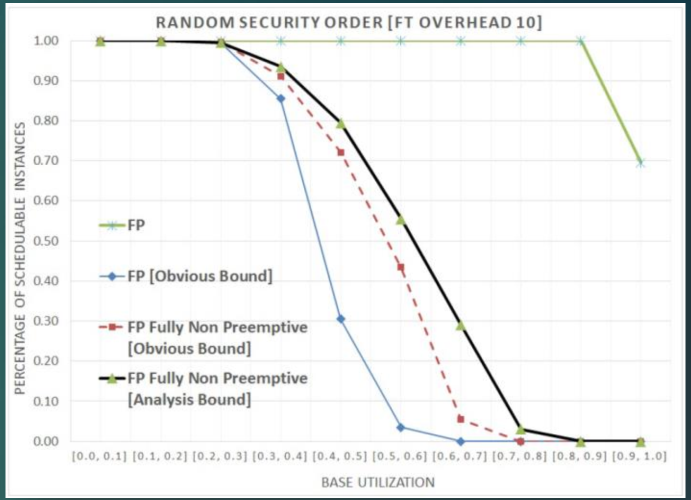
Varying FT Overhead Costs




FT = **1**




FT = **5**




FT = **10**

As FT overheads go up, our analysis-based methods perform better → compared to naïve bounds

As FT overheads go up, preemptive FP performs worse → more FT compared to non-preemptive

# Simulation-based Results



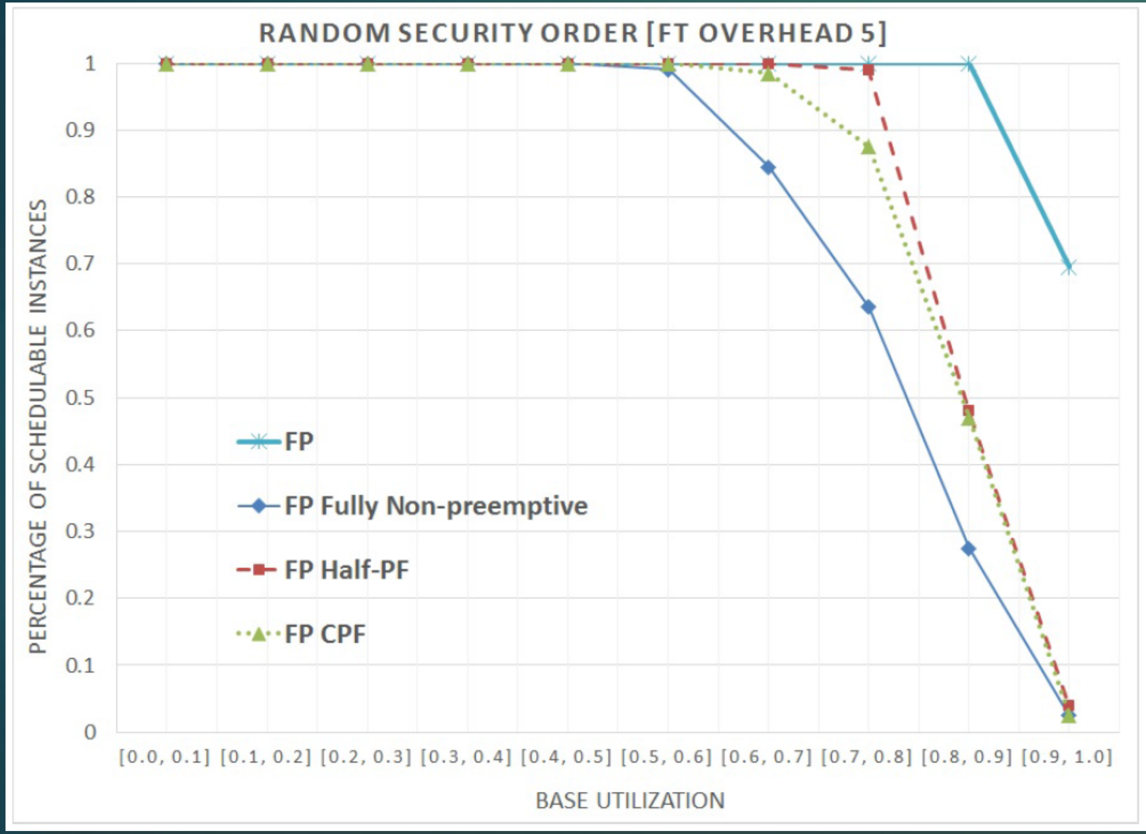
- Use a simulator that schedules task sets according to one of the following:
  1. Preemptive (vanilla) FP: preemptions allowed, no FT invocations [**FP**]
  2. NonPreemptive FP: FP no preemptions; FT allowed between high → low security level transitions [**FP FULLY NON-PREEMPTIVE**]
  3. Preemptive FP with flush tasks: FT invoked on transitions from high → low; Half-PF constraint [**FP HALF-PF**]
  4. Preemptive FP with resource flush under certain conditions [**FP CPF**]

- FT overhead was set to **5** for all simulation experiments

# Simulation-based Results (contd.)



Random Security Ordering, FT = 5



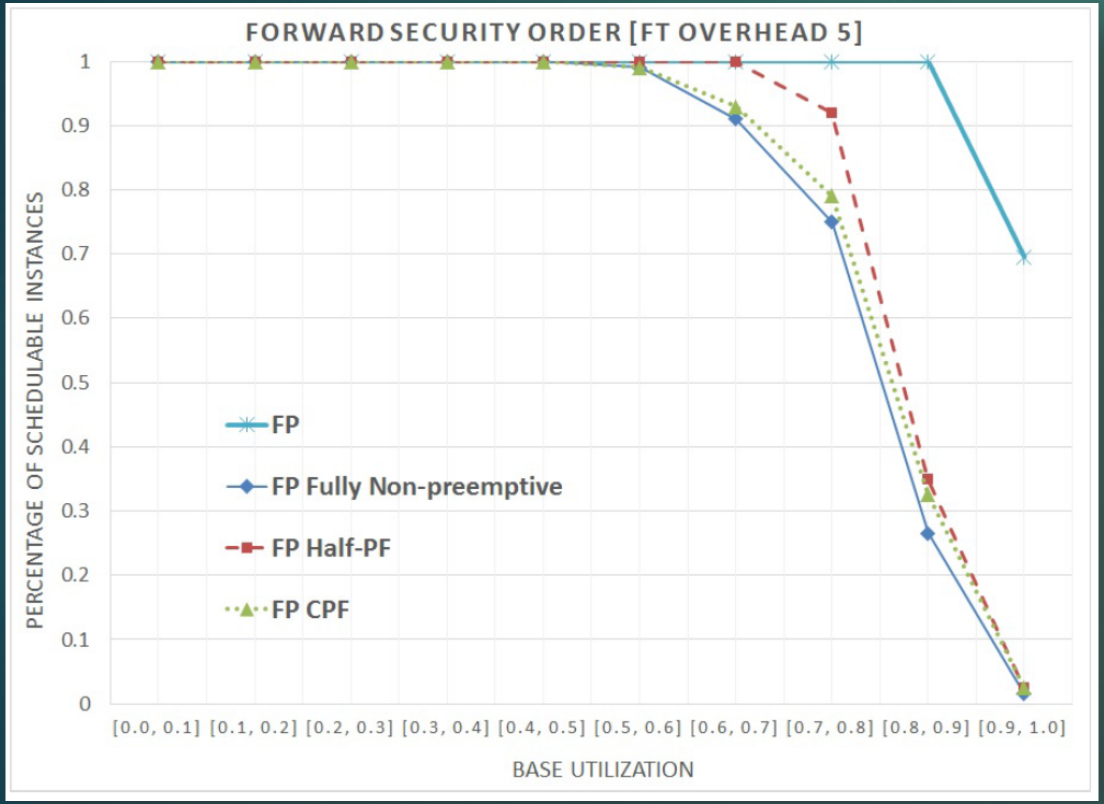

- Vanilla FP performs best → no constraints
- **FP FULLY NON-PREEMPTIVE** → worst
  [no preemptions at all]

- **FP HALF-PF** and **FP CPF** perform much better
- Both start dropping off around 75 % utilization

# Ordering + Simulation Results

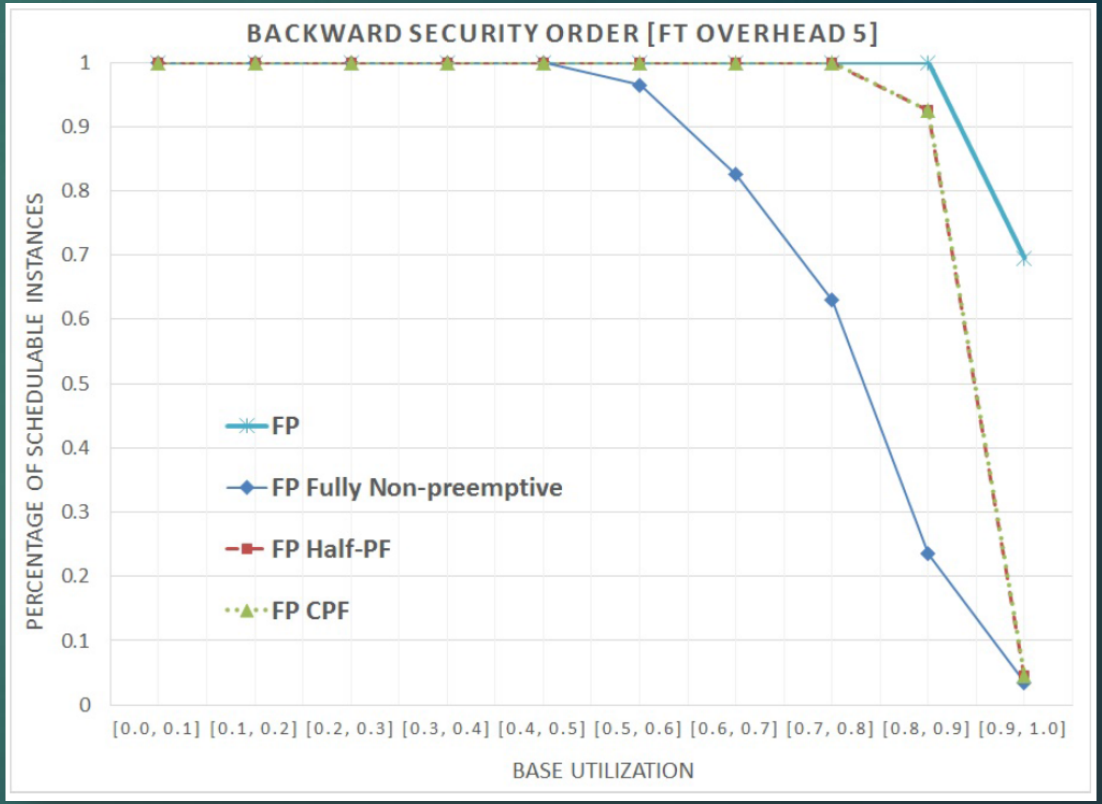


**Forward** Security Ordering, FT = 5




Performs the worst → more FT invocations

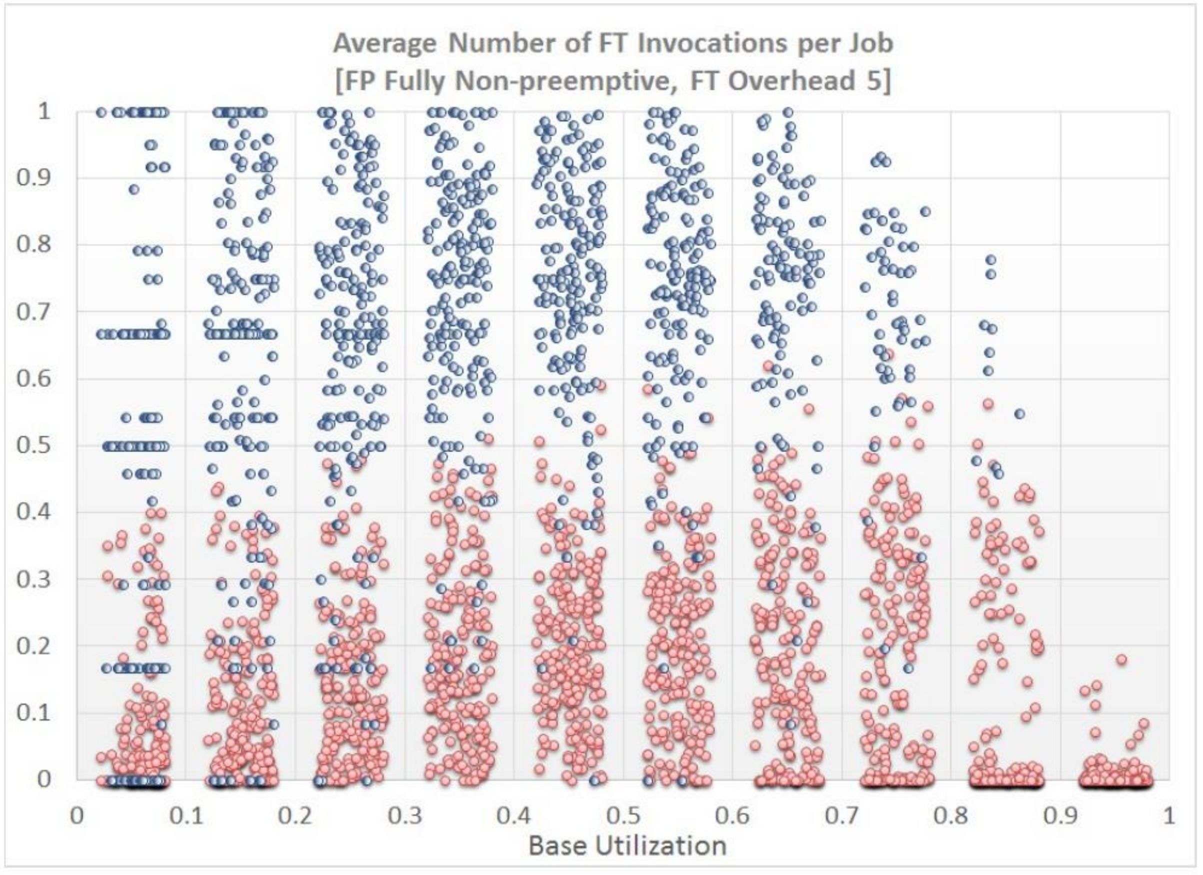
**Backward** Security Ordering, FT = 5




Performs the best → least FT invocations

# FT: Simulation vs Analysis






- Number of FT invocations normalized to number of jobs
- Red dots: FT invocations [simulation]
- Blue dots: FT invocations [analysis]

Hence

1. Num. FT invocations much less than number of jobs
2. For most task sets, number of actual FT invocations lower than calculated values
3. True *even for higher utilization task sets!*

# Limitations



- Transforming security requirements into scheduling constraints
  - Our solution for *one* problem → information leakage through storage channels
  - Not a silver bullet for all security problems in real-time systems
- Many security properties may not be amenable to being cast as scheduling constraints
  - E.g.: communication-related vulnerabilities
- Performance overheads could inhibit adoption in many RTS
  - May be mitigated by careful design process

# Conclusion



- Presented methods to integrate security properties into real-time systems
- Techniques to amend FP algorithms to reduce information leakage through shared resources
- Designers of real-time systems can now consider such security properties
  - Can assess tradeoffs between security requirements and real-time guarantees
- Future Work
  - Analysis for other scheduling policies / constraints
  - Case study
  - Architectural mechanisms?

# Thanks!

- Questions?