

SCHEDULEAK

[RTAS 2019]

- Exfiltration of critical information
- Reconnaissance

“given knowledge of the scheduling algorithms used in the system, can we recreate its exact timing schedule?”

SYSTEM MODEL & REAL-TIME SCHEDULES

SYSTEM MODEL & REAL-TIME SCHEDULES

- Consider three periodic real-time tasks

	Period
1	5
2	6
3	15

SYSTEM MODEL & REAL-TIME SCHEDULES

- Consider three periodic real-time tasks
- Their relative priorities are: **1** > **2** > **3**

	Period
1	5
2	6
3	15

SYSTEM MODEL & REAL-TIME SCHEDULES

- Consider three periodic real-time tasks
- Their relative priorities are: **1** > **2** > **3**

	Period
1	5
2	6
3	15

- Their initial execution pattern would look like:

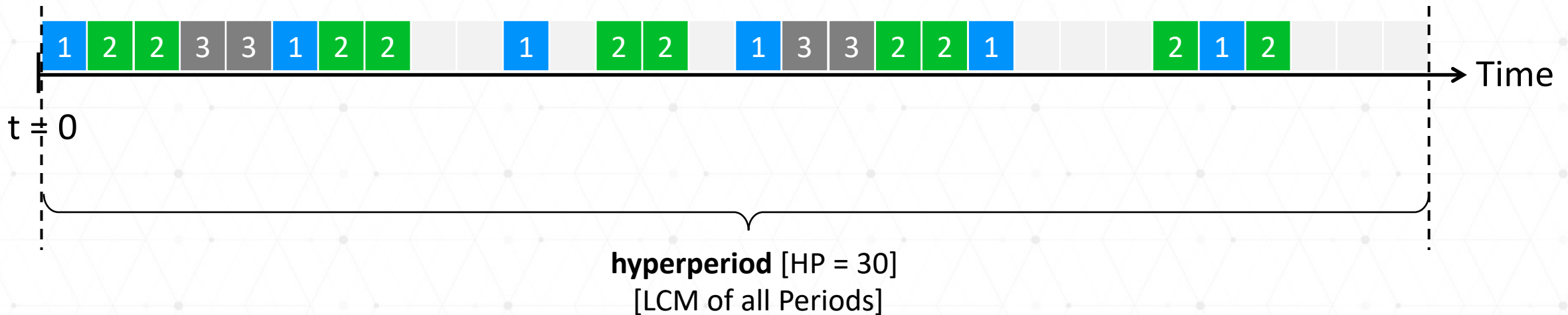


SYSTEM MODEL & REAL-TIME SCHEDULES

- Consider three periodic real-time tasks
- Their relative priorities are: **1** > **2** > **3**

	Period
1	5
2	6
3	15

- Their initial execution pattern would look like:



SYSTEM MODEL & REAL-TIME SCHEDULES



SYSTEM MODEL & REAL-TIME SCHEDULES

HP 1	1	2	2	3	3	1	2	2			1		2	2		1	3	3	2	2	1					2	1	2			
HP 2	1	2	2	3	3	1	2	2			1		2	2		1	3	3	2	2	1					2	1	2			
HP 3	1	2	2	3	3	1	2	2			1		2	2		1	3	3	2	2	1					2	1	2			
HP 4	1	2	2	3	3	1	2	2			1		2	2		1	3	3	2	2	1					2	1	2			
HP 5	1	2	2	3	3	1	2	2			1		2	2		1	3	3	2	2	1					2	1	2			
⋮																															

PROBLEM STATEMENT

HP 1	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1					2	1	2									
HP 2	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1					2	1	2									
HP 3	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1					2	1	2									
HP 4	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1					2	1	2									
HP 5	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1					2	1	2									
⋮																																						

PROBLEM STATEMENT

HP 1	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1			2	1	2			
HP 2	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1			2	1	2			
HP 3	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1			2	1	2			
HP 4	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1			2	1	2			
HP 5	1	2	2	3	3	1	2	2			1		2	2			1	3	3	2	2	1			2	1	2			
⋮																														

Can we predict **future** execution time points for critical task(s)? 1

PROBLEM STATEMENT



Can we predict **future** execution time points for critical task(s)? 1



PROBLEM STATEMENT

We use knowledge of the **regular execution patterns** in real-time systems

HP 1	1	2	2	3	3	1	2	2		1	2	2		1	3	3	2	2	1		2	1	2
HP 2	1	2	2	3	3	1	2	2		1	2	2		1	3	3	2	2	1		2	1	2
HP 3	1	2	2	3	3	1	2	2		1	2	2		1	3	3	2	2	1		2	1	2
HP 4	1	2	2	3	3	1	2	2		1	2	2		1	3	3	2	2	1		2	1	2
HP 5	1	2	2	3	3	1	2	2		1	2	2		1	3	3	2	2	1		2	1	2
⋮										⋮													

Can we predict **future** execution time points for critical task(s)? 1



PROBLEM STATEMENT

We use knowledge of the **regular execution patterns** in real-time systems

HP 1	1	2	2	3	3	1	2	2	1	2	2	1	3	3	2	2	1	2	1	2
HP 2	1	2	2	3	3	1	2	2	1	2	2	1	3	3	2	2	1	2	1	2
HP 3	1	2	2	3	3	1	2	2	1	2	2	1	3	3	2	2	1	2	1	2
HP 4	1	2	2	3	3	1	2	2	1	2	2	1	3	3	2	2	1	2	1	2
HP 5	DEMONSTRATED A CRITICAL SIDE CHANNEL IN REAL-TIME SYSTEMS																			
⋮	⋮																			

Can we predict **future** execution time points for critical task(s)? 1



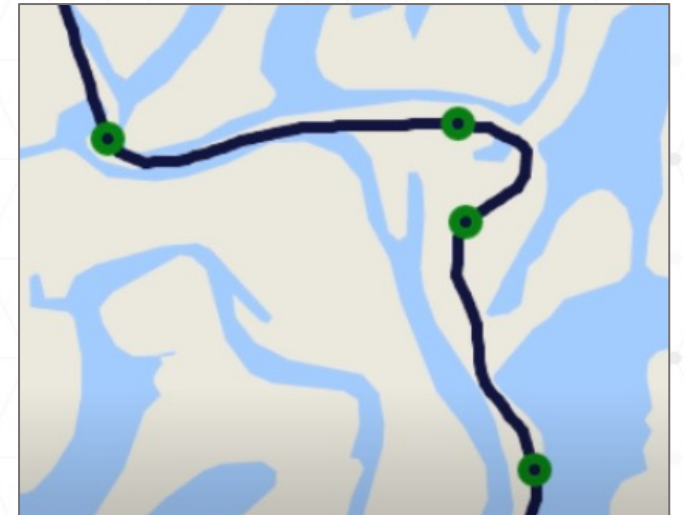
WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- **Consider a UAV on a mission**



• *true locations of interest*

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- Consider a UAV on a mission
- Takes [high-res] photos → points of interest [green]
- Camera → off or low-res mode otherwise



● *true locations of interest*

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

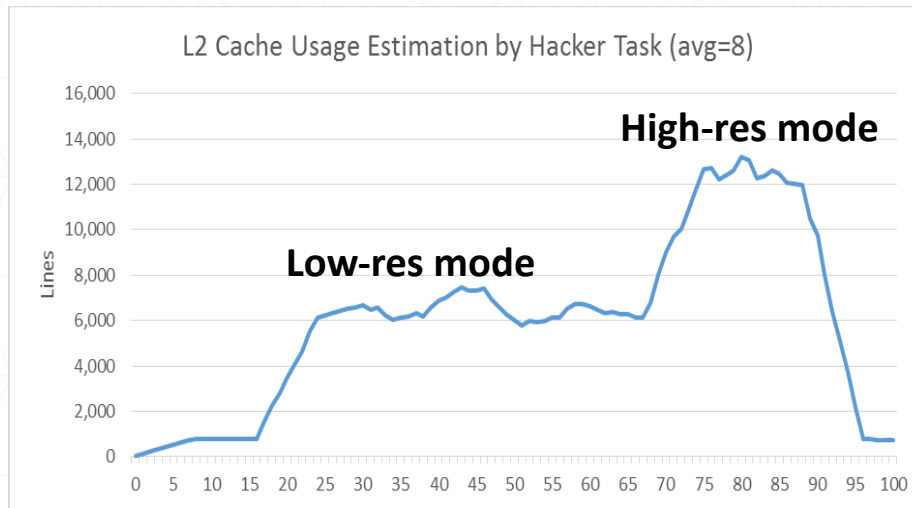
DEMONSTRATION 1

- **Attacker's goal**
 - **Recover location of interest points where memory usage [of victim] is high**

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- **Attacker's goal**
 - **Recover location of interest points where memory usage [of victim] is high**



Measurements on Xilinx Zedboard Zynq-7000, FreeRTOS,
[CPU Freq: 666MHz, L2 Cache: 512KB, 32 byte line size]





● *true locations of interest*

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1



- **Attacker's goal**
 - Recover location of interest points where memory usage [of victim] is high
- **Cache-timing side-channel attacks**

 Attacker: 2
 Target: 1 cache usage

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- **Attacker's goal**
 - Recover location of interest points where memory usage [of victim] is high
- **Cache-timing side-channel attacks**


 Attacker: 2
 Target: 1 cache usage

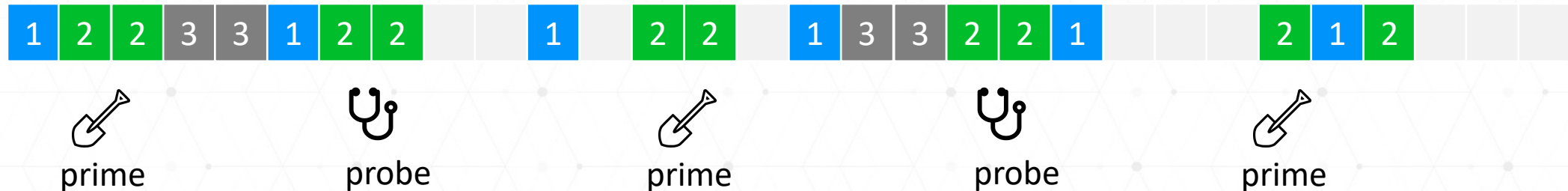


WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- **Attacker's goal**
 - Recover location of interest points where memory usage [of victim] is high
- **Cache-timing side-channel attacks**

 Attacker: 2
 Target: 1 cache usage



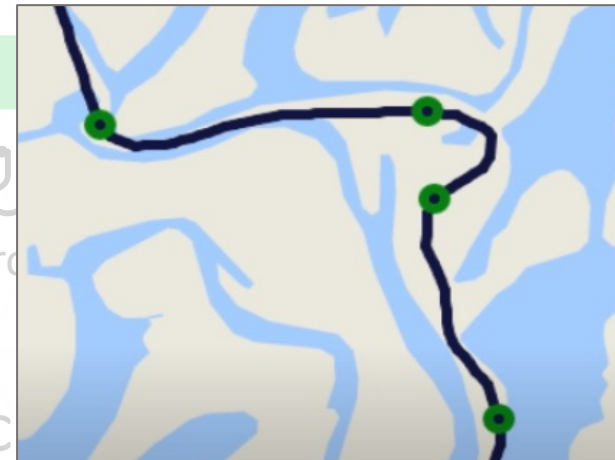
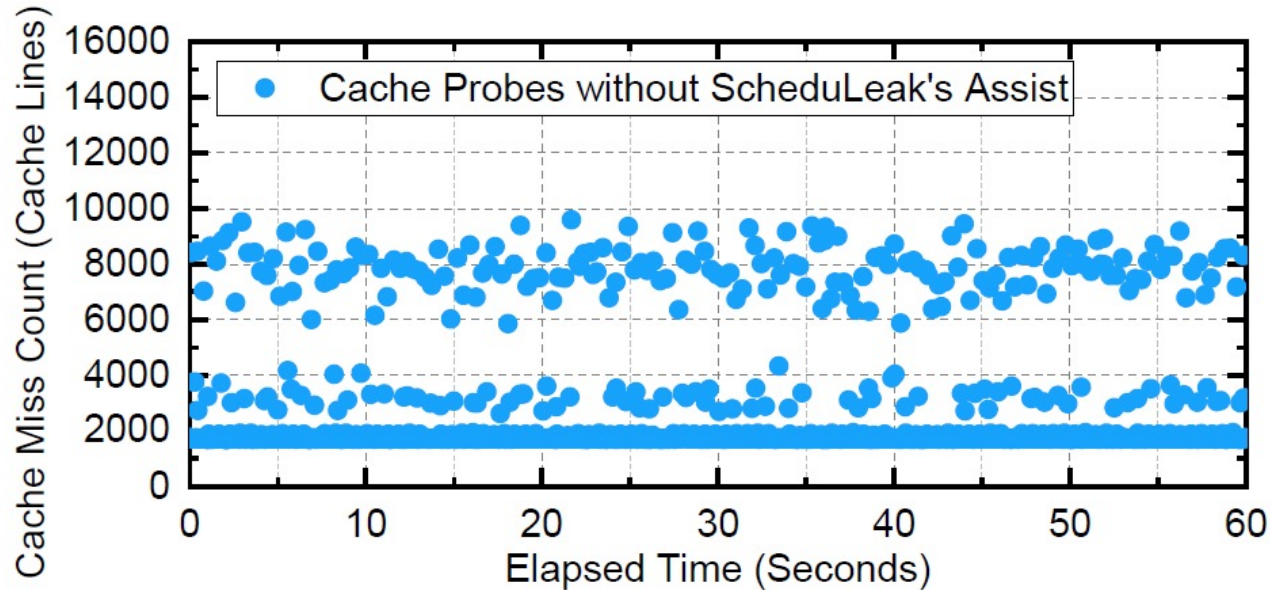
[Note: **no** information about future execution of victim task]

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

DEMONSTRATION 1

- Attacker's goal
 - Recover location of interest points where memory usage [of victim] is high
- Cache-timing

Cache usage probes are indistinguishable





WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

- With **precise timing information** from the side-channel
 - Launch cache-timing attack at more precise points

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

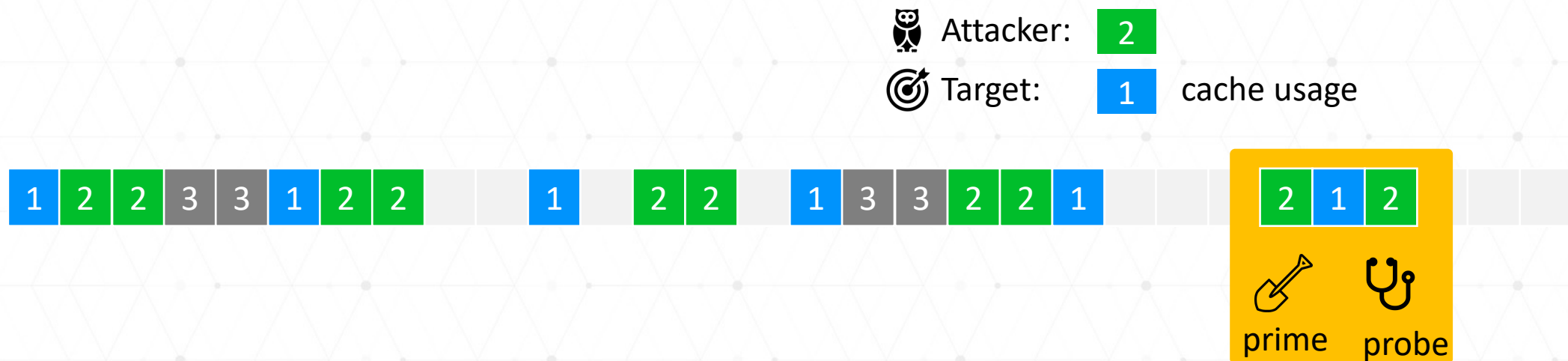
- With **precise timing information** from the side-channel
 - Launch cache-timing attack at more precise points

 Attacker: **2**
 Target: **1** cache usage



WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

- With **precise timing information** from the side-channel
 - Launch cache-timing attack at more precise points

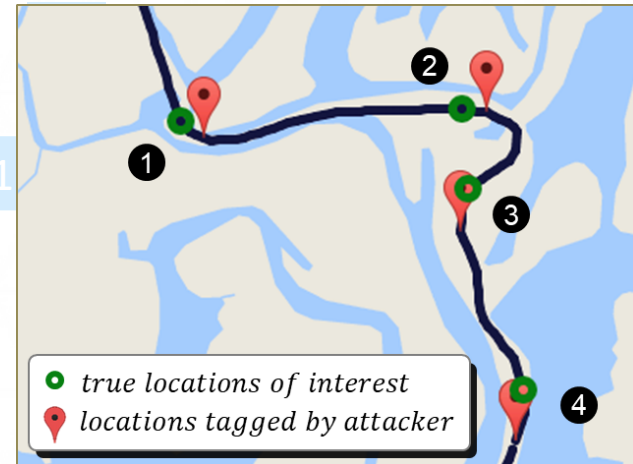
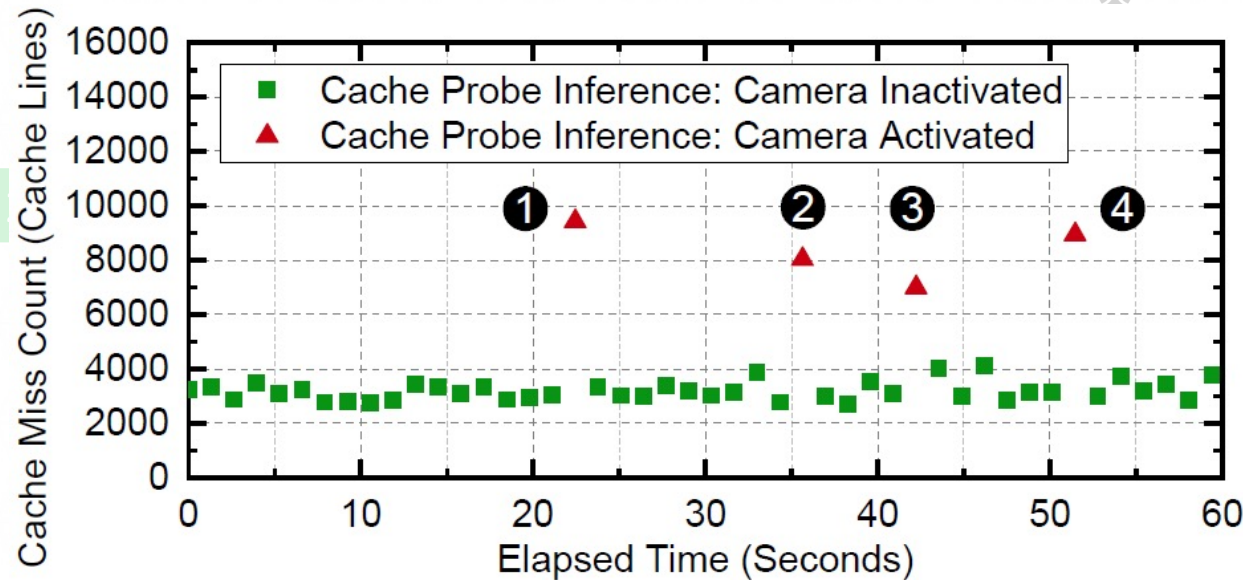


[Note: **very close** to the execution of victim task]

WHAT CAN WE DO WITH FUTURE EXECUTION INFORMATION?

- With precise timing information from the side-channel
- Launch cache timing attack at very precise points

Four locations are **recovered** from cache usage probes



SYSTEM ASSUMPTIONS

Real-Time Tasks

- ▶ **Periodic**
 - ▶ Jobs released periodically
 - ▶ Relative deadlines
- ▶ **Sporadic**
 - ▶ Release/arrival times specified
 - ▶ Inter-arrival times
 - ▶ Absolute deadlines

worst-case execution times

SYSTEM ASSUMPTIONS

- **Assumption: Fixed-Priority Real-Time Systems [E.g. RM]**

 **Attacker's task (observer task)** *periodic* or *sporadic*

 **Victim task** *periodic*

Other tasks *periodic* or *sporadic*

Real-Time Tasks

▶ Periodic

- ▶ Jobs released periodically
- ▶ Relative deadlines

▶ Sporadic

- ▶ Release/arrival times specified
- ▶ Inter-arrival times
- ▶ Absolute deadlines

worst-case execution times

SYSTEM ASSUMPTIONS

- **Assumption: Fixed-Priority Real-Time Systems [E.g. RM]**

🦉 **Attacker's task (observer task)** *periodic* or *sporadic*

🎯 **Victim task** *periodic*

Other tasks *periodic* or *sporadic*

- **Requirements**

- The attacker knows the **victim task's period**
- The **observer task has lower priority than the victim task**

Real-Time Tasks

▶ Periodic

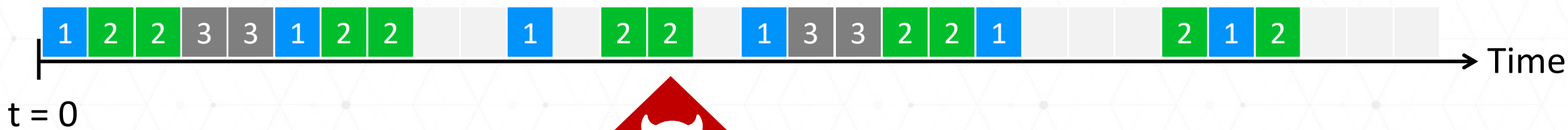
- ▶ Jobs released periodically
- ▶ Relative deadlines

▶ Sporadic

- ▶ Release/arrival times specified
- ▶ Inter-arrival times
- ▶ Absolute deadlines

worst-case execution times

WHY IS THIS HARD?



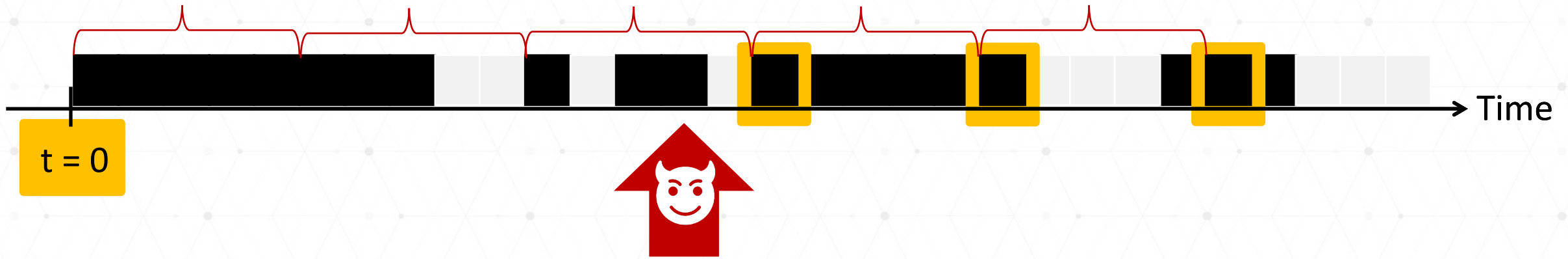
WHY IS THIS HARD?



WHY IS THIS HARD?



WHY IS THIS HARD?



WHY IS THIS HARD?



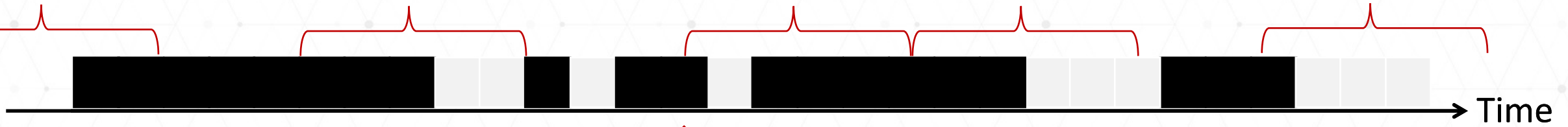
- **Attacker enters system at random point in time**

WHY IS THIS HARD?



- **Attacker enters system at random point in time**

WHY IS THIS HARD?



- **Attacker enters system at random point in time**

WHY IS THIS HARD?



- **Attacker enters system at random point in time**
- **Maybe look at the scheduler?**

WHY IS THIS HARD?



- **Attacker enters system at random point in time**
- **Maybe look at the scheduler? → need to break user/kernel boundary**

WHY IS THIS HARD?



- Attacker enters system at random point in time
- Maybe look at the scheduler? → need to break user/kernel boundary
- Attacker wants to stay undetected

ATTACK SCENARIO OVERVIEW

There is some schedule (on the victim system)



ATTACK SCENARIO OVERVIEW

There is some schedule (on the victim system)



The adversary **observes** and **analyzes** the schedule and **reconstructs** precise timing information



Inferring arrivals of a “victim” task



ATTACK SCENARIO OVERVIEW

There is some schedule (on the victim system)



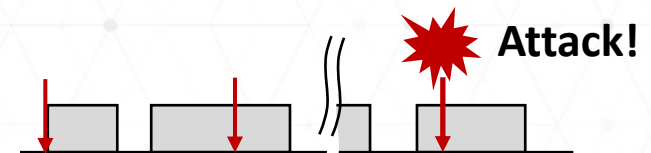
The adversary **observes** and **analyzes** the schedule and **reconstructs** precise timing information



The attacker can then launch a major attack at a future instant that can **cause the most amount of damage**



Inferring arrivals of a “victim” task



SCHEDULEAK ALGORITHMS

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

■ Observer Task τ_o ■ Other Tasks

SCHEDULELEAK ALGORITHMS

Observer task has **lower priority** than victim task

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

Observer Task τ_o Other Tasks

SCHEDULEAK ALGORITHMS

1

Reconstruct execution intervals of τ_v

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

Observer Task τ_o Other Tasks

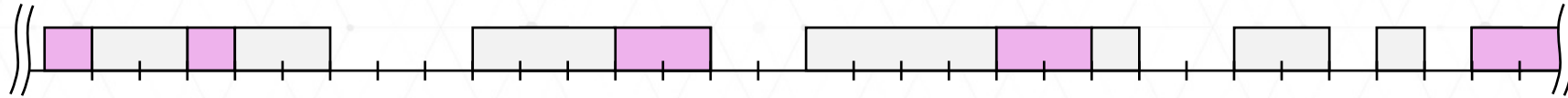
SCHEDULELEAK ALGORITHMS

1

Reconstruct execution intervals of τ_v

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

System Schedule Ground Truth:



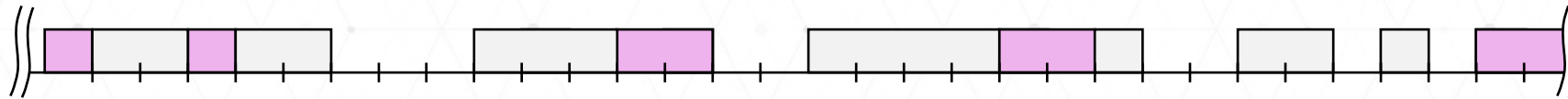
Observer Task τ_o Other Tasks

SCHEDULELEAK ALGORITHMS

1 Reconstruct execution intervals of τ_v

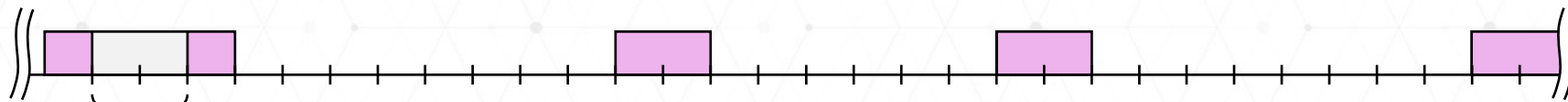
Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

System Schedule Ground Truth:



What the attacker can observe

Execution Intervals Reconstructed by the Observer Task:



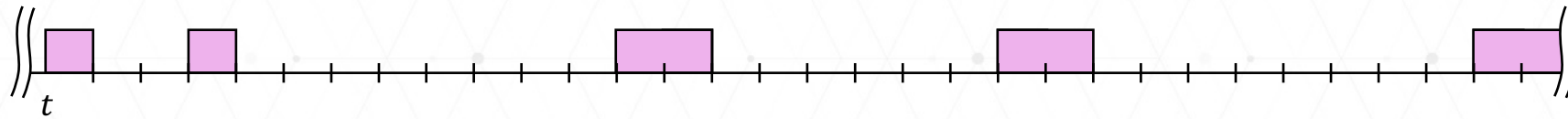
Some tasks preempted the observer task

Observer Task τ_o Other Tasks

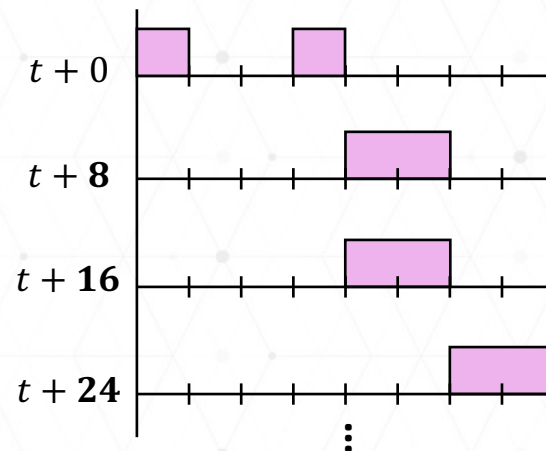
SCHEDULELEAK ALGORITHMS

2 Organize the execution intervals in a “schedule ladder diagram”

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



Place the intervals in a **ladder diagram** (width equals the victim task's period)



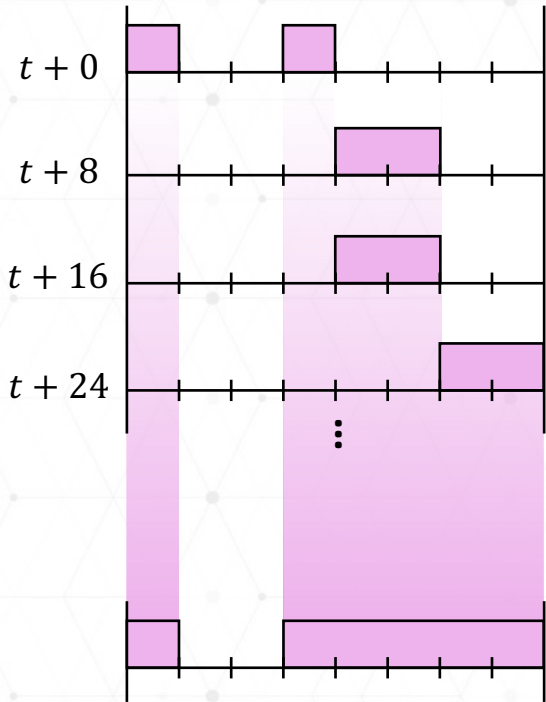
Still dealing with the Observer task executions

SCHEDULELEAK ALGORITHMS

2 Organize the execution intervals in a “schedule ladder diagram”

Take union of the execution intervals

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



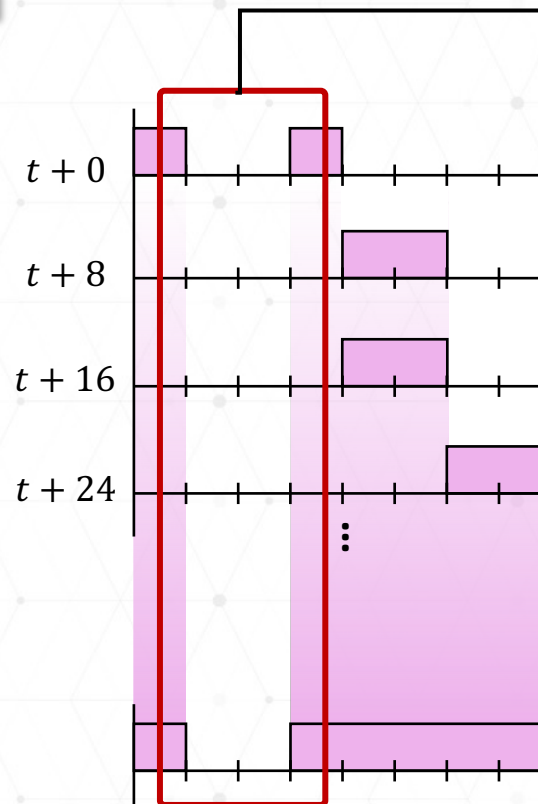
SCHEDULELEAK ALGORITHMS

2

Organize the execution intervals in a "schedule ladder diagram"

Take union of the execution intervals

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



TASKS WITH LOWER PRIORITIES (E.G. OBSERVER TASK) CANNOT APPEAR IN THIS COLUMN!

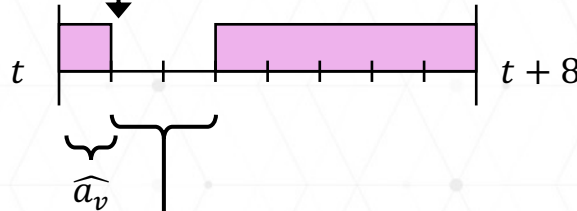
SCHEDULELEAK ALGORITHMS

3

Infer the victim task's initial offset

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1

We take the **starting point** of the empty column as the inference of the victim task's initial offset



TASKS WITH LOWER PRIORITIES (E.G. OBSERVER TASK) CANNOT APPEAR IN THIS COLUMN!

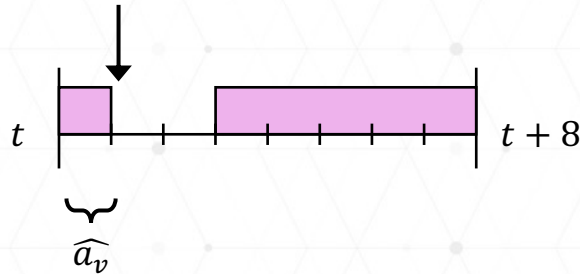
SCHEDULELEAK ALGORITHMS

3

Infer the victim task's initial offset

Predict the victim task's future arrivals

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



The **victim task's future arrival times** can be computed by

$$t + \widehat{a}_v + p_v * T$$

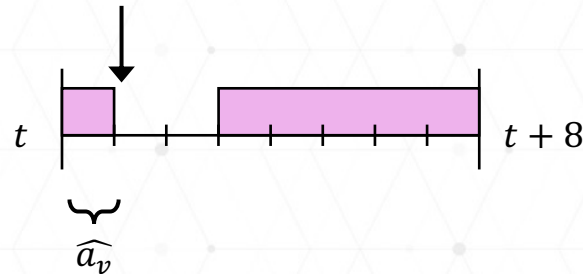
SCHEDULELEAK ALGORITHMS

3

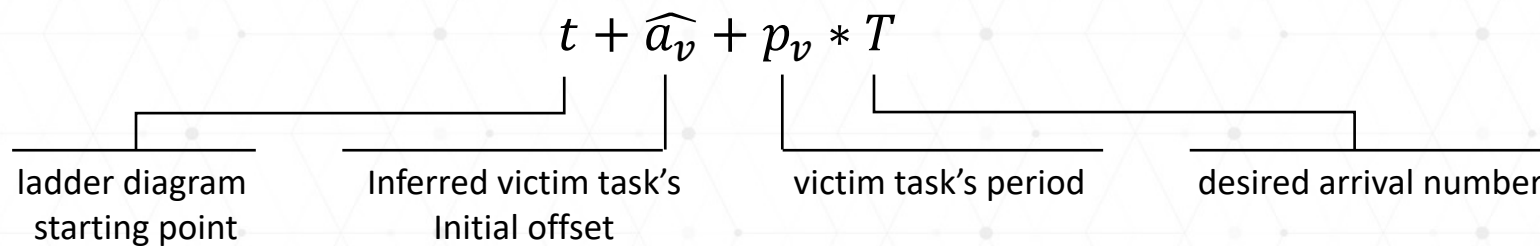
Infer the victim task's initial offset

Predict the victim task's future arrivals

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



The **victim task's future arrival times** can be computed by



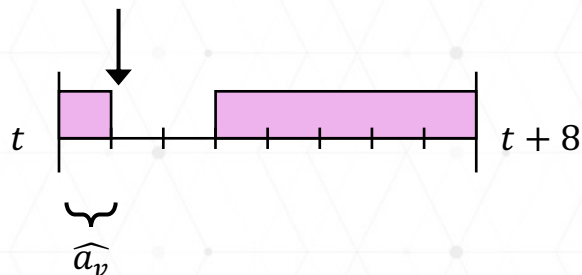
SCHEDULELEAK ALGORITHMS

3

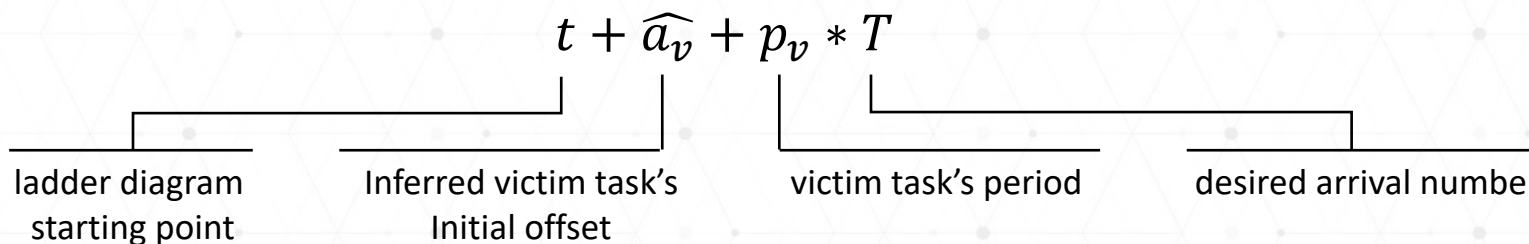
Infer the victim task's initial offset

Predict the victim task's future arrivals

Task ID	Period	Exec Time
Observer Task	15	1
Task 2	10	2
Victim Task (τ_v)	8	2
Task 4	6	1



The **victim task's future arrival times** can be computed by



CAN PREDICT, WITH HIGH PRECISION, **FUTURE** ARRIVAL TIMES OF VICTIM!

PERFORMANCE EVALUATION

- **Synthetic Task Sets**

6000 Task Sets:



Task Set Utilization
[0.01,0.1) ... [0.91, 1.0)
10 groups

×



The Number of Tasks
5, 7, 9, 11, 13, 15
6 groups

×

100

PERFORMANCE EVALUATION: METRICS



Inference Precision Ratio

the ratio of how close the inference to the true task starting point

PERFORMANCE EVALUATION: METRICS



Inference Precision Ratio

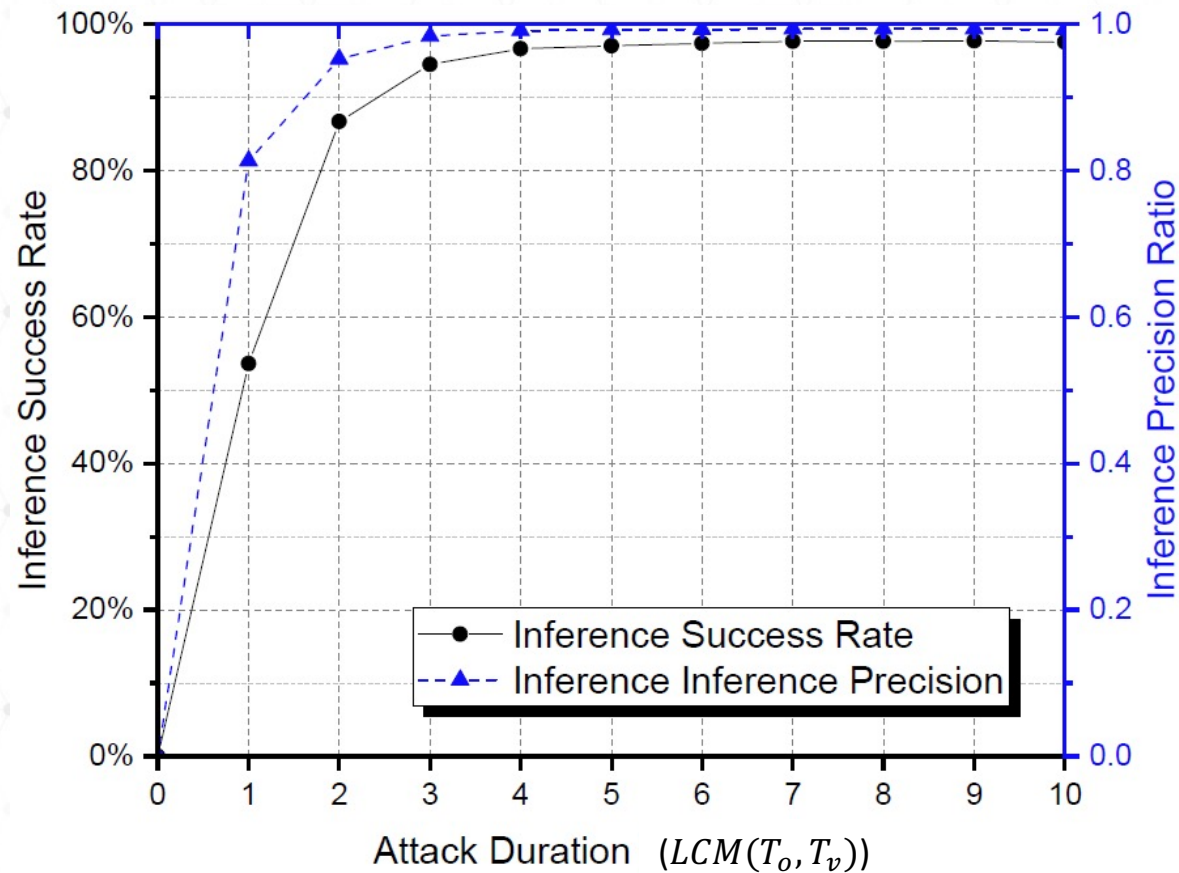
the ratio of how close the inference to the true task starting point



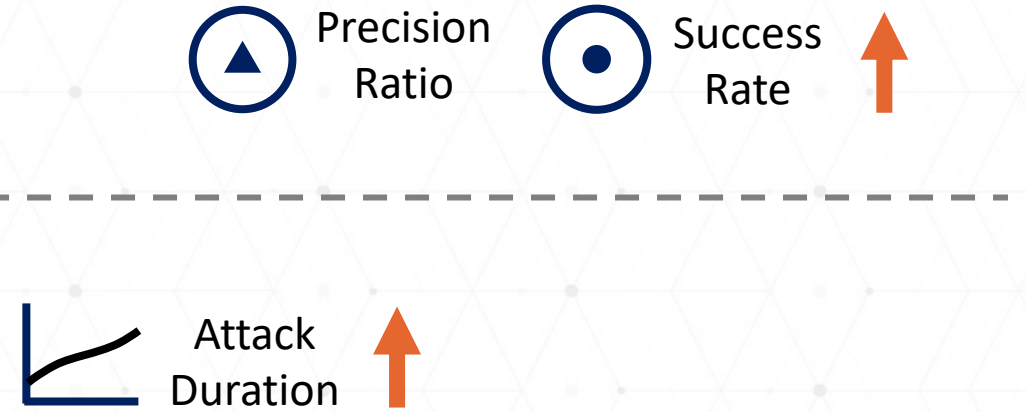
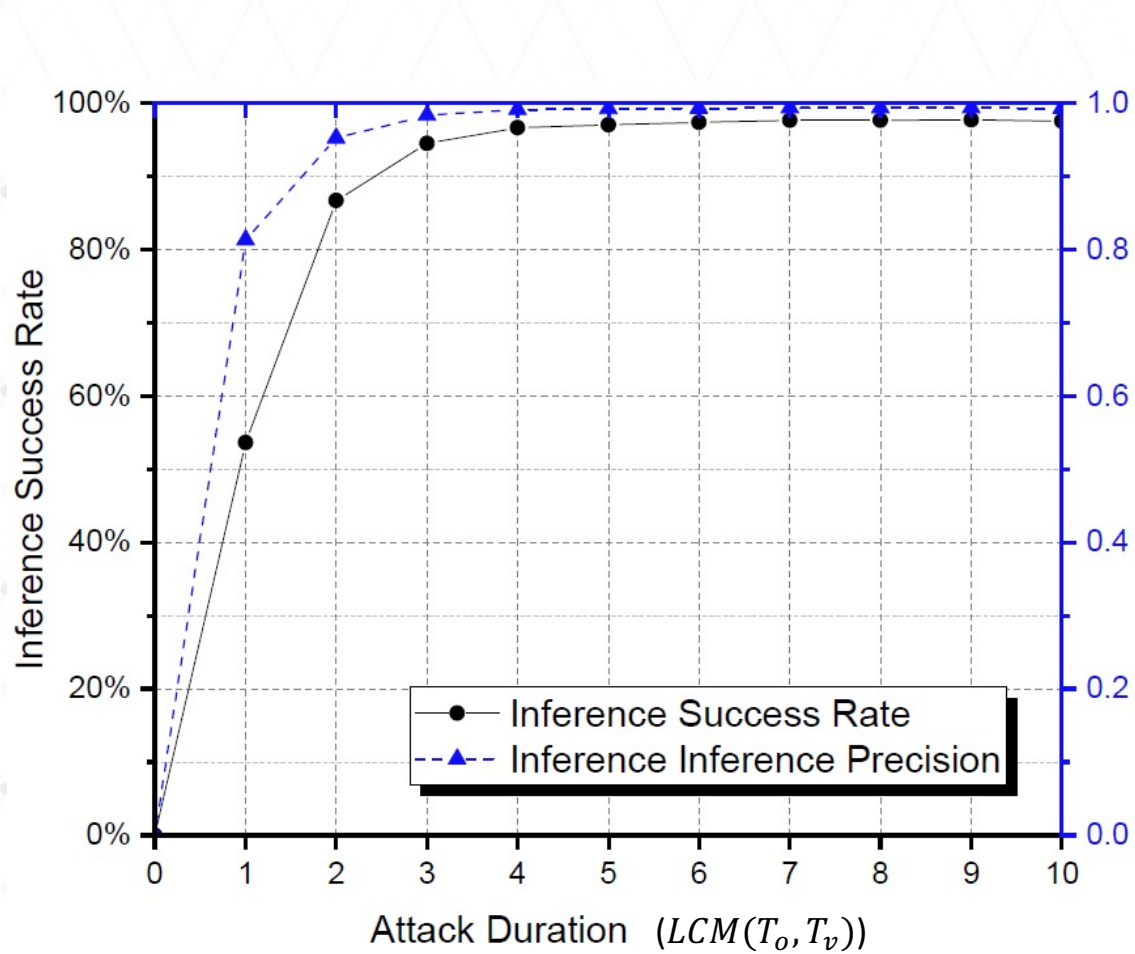
Inference Success Rate

an inference is successful if attacker can exactly infer the starting point of the victim task

PERFORMANCE EVALUATION: RESULTS

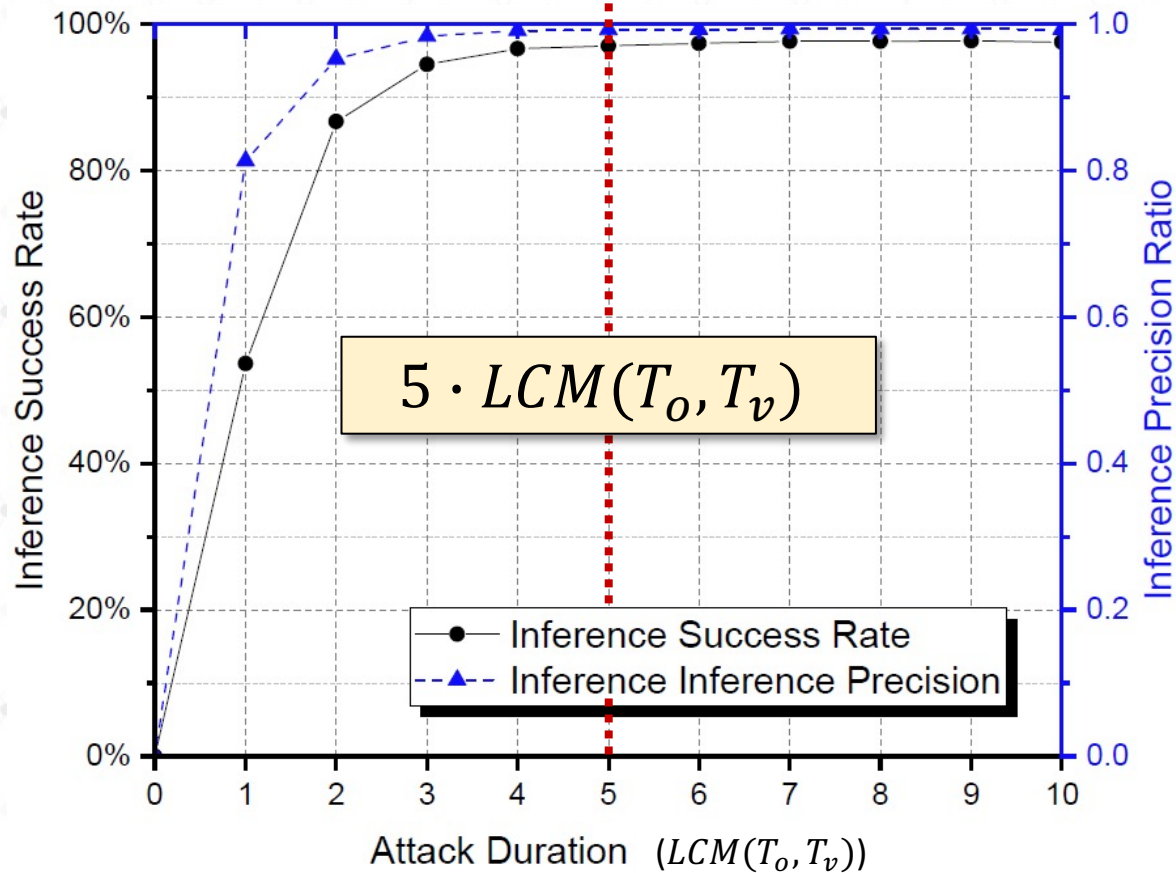


PERFORMANCE EVALUATION: RESULTS



PERFORMANCE EVALUATION: RESULTS

Precision Ratio = 0.99, Success Rate = 97%

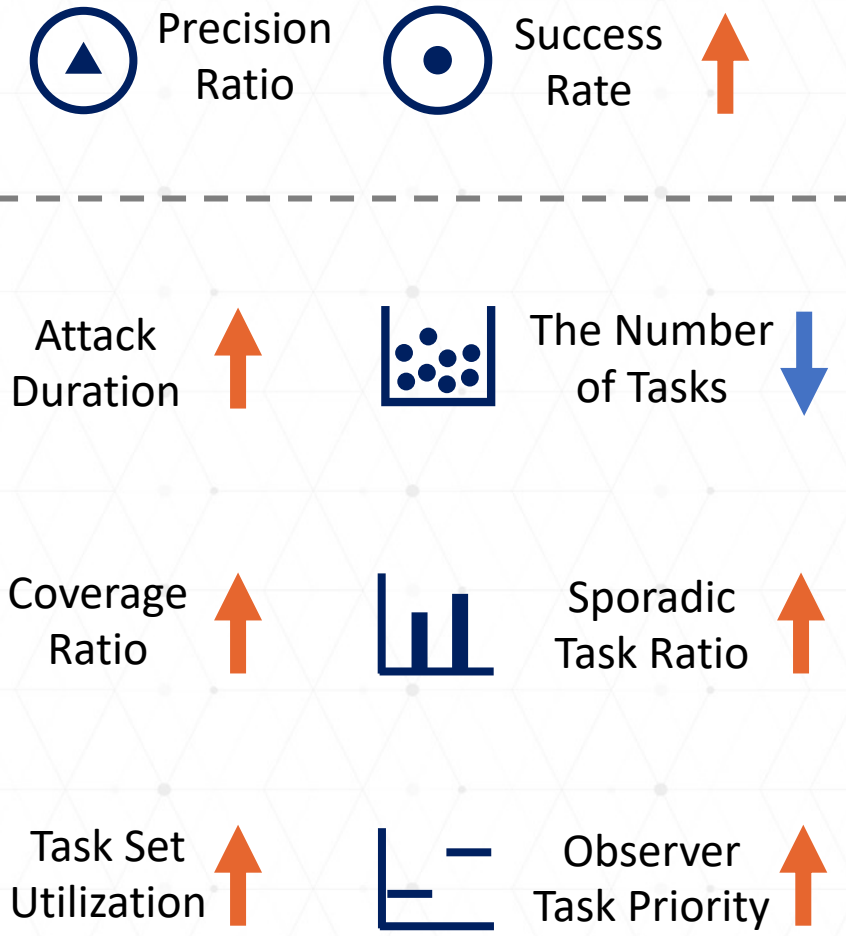
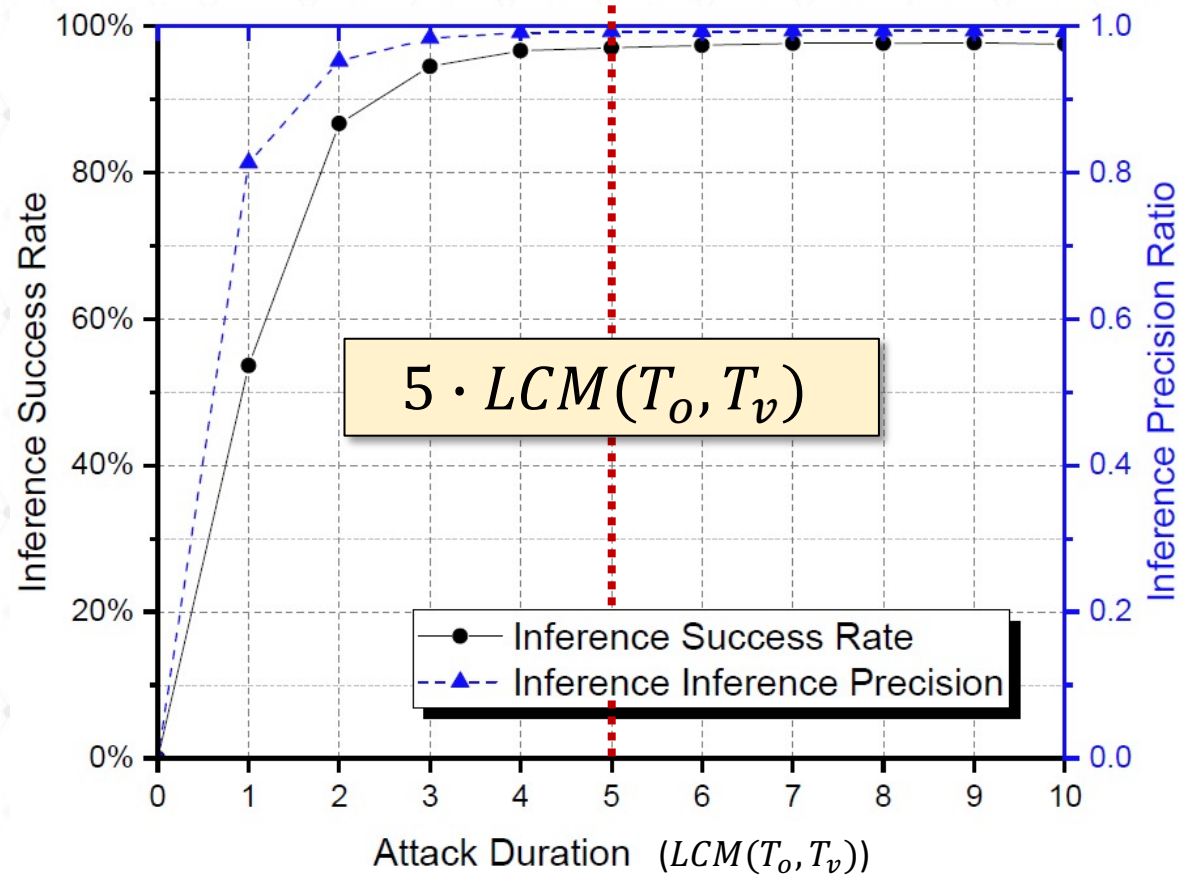


Precision Ratio Success Rate

Attack Duration

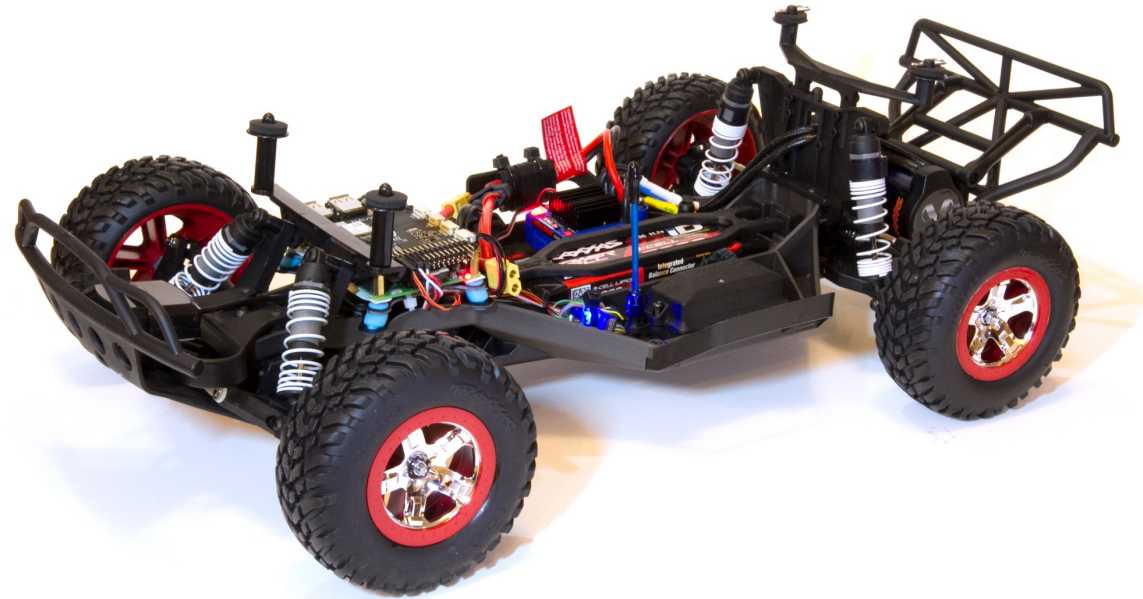
PERFORMANCE EVALUATION: RESULTS

Precision Ratio = 0.99, Success Rate = 97%



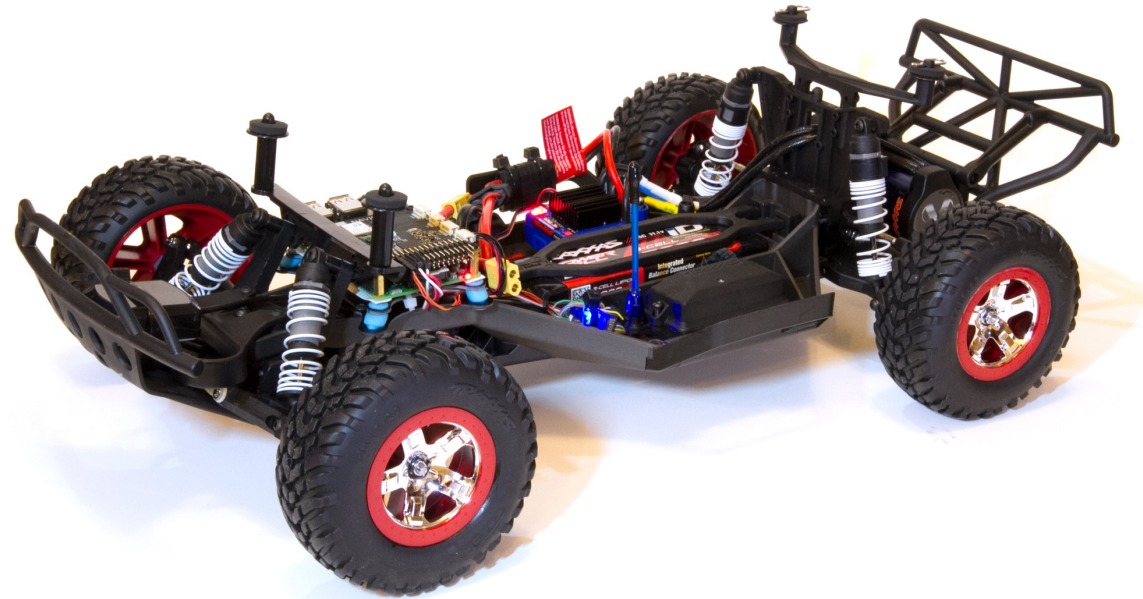
WHAT CAN WE DO WITH INFORMATION
GLEANED USING SCHEDULEAK?

DEMONSTRATION 2



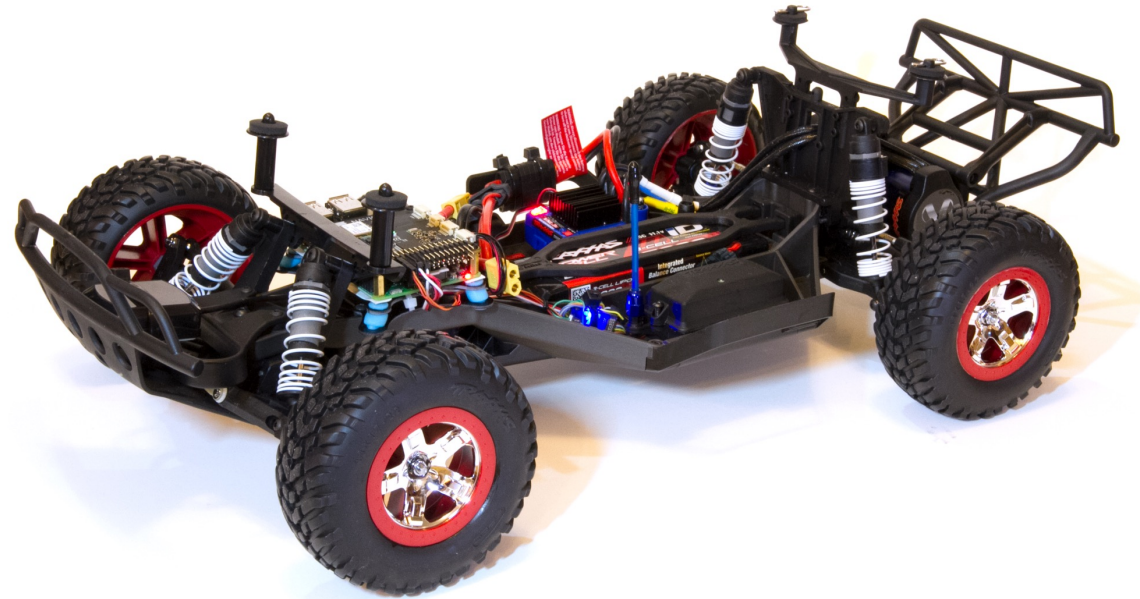
DEMONSTRATION 2

- **Imagine attacker controls a real-time task in an autonomous system**



DEMONSTRATION 2

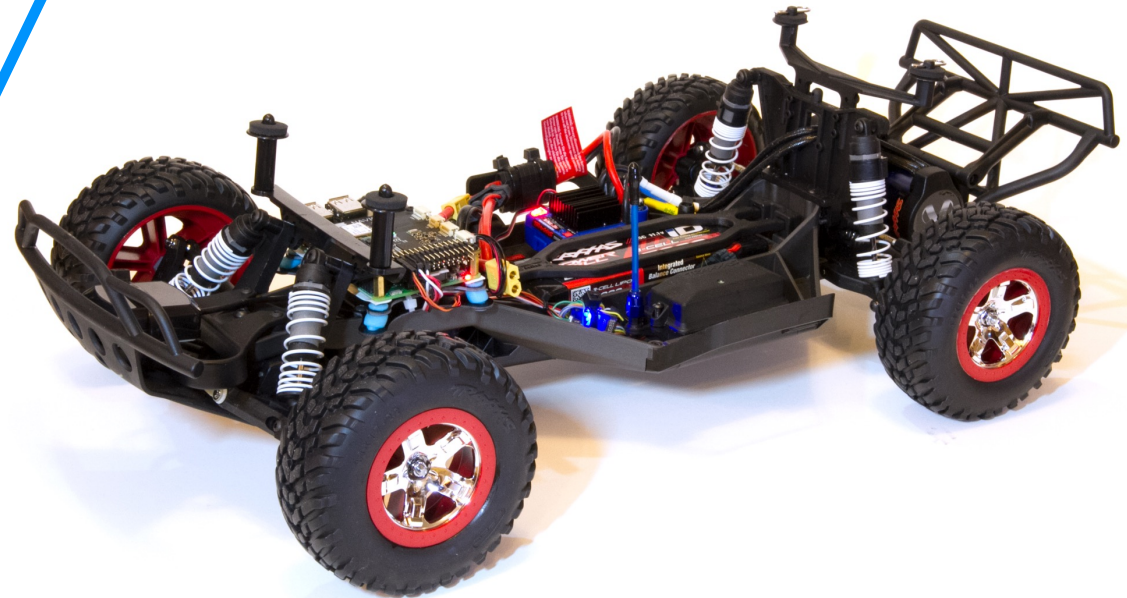
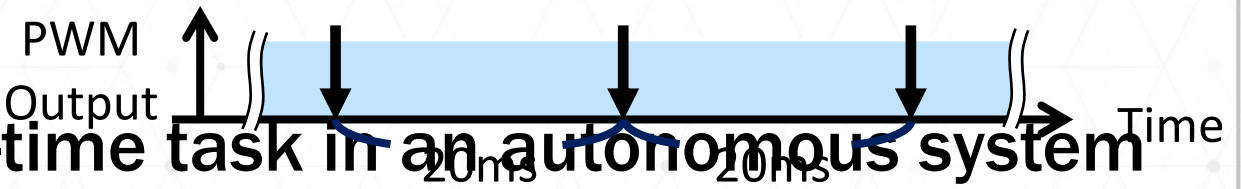
- **Imagine attacker controls a real-time task in an autonomous system**



- **It wants to take over control of the steering and throttle**

DEMONSTRATION 2

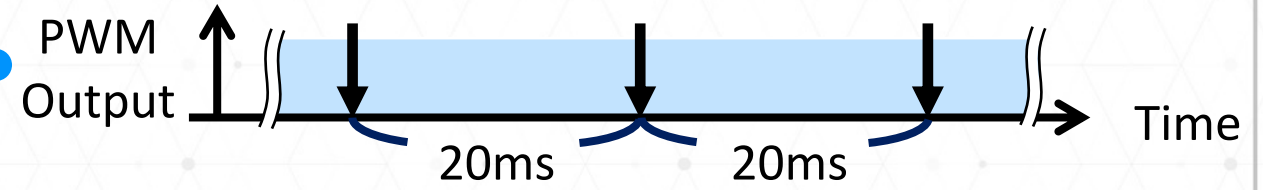
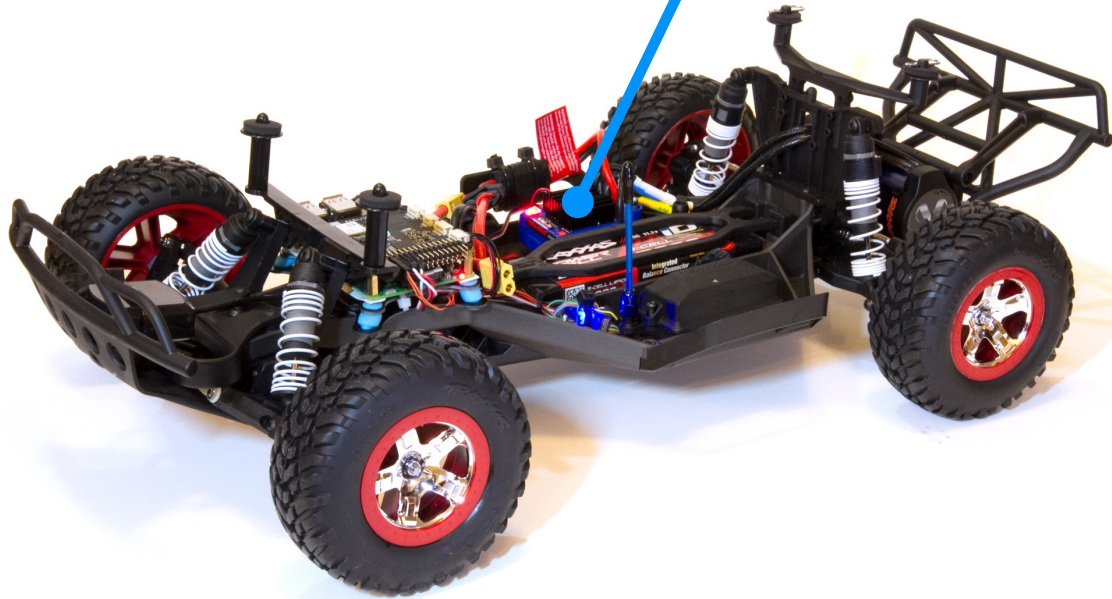
- Imagine attacker controls a real-time task in an autonomous system



- It wants to take over control of the steering and throttle

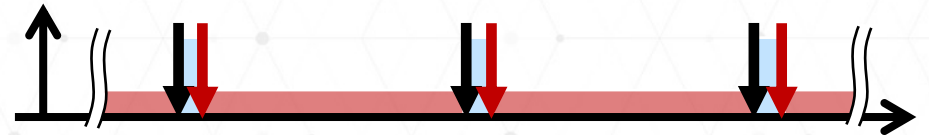
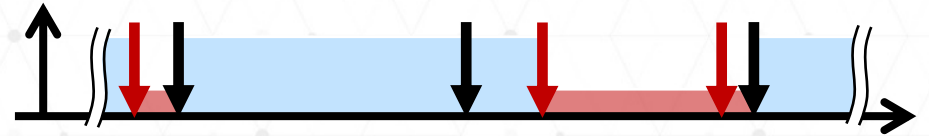
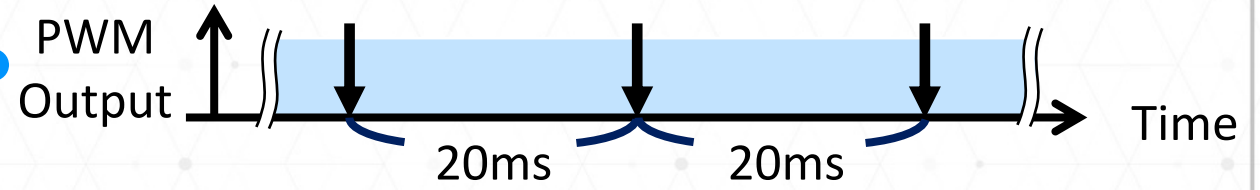
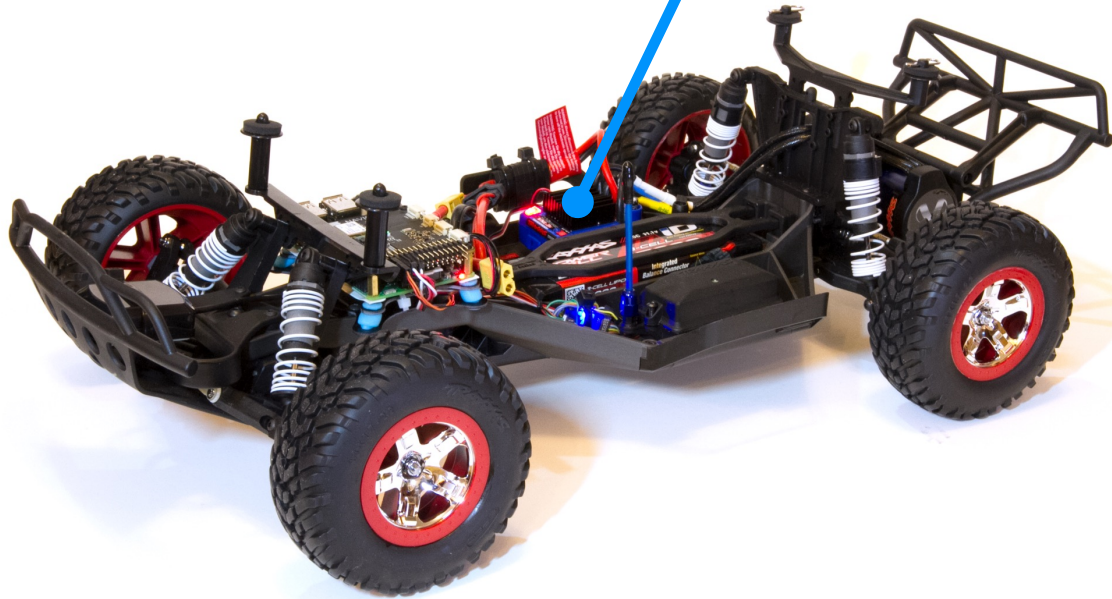


DEMONSTRATION 2



↓ PWM Update Task ↓ Attacker's Task

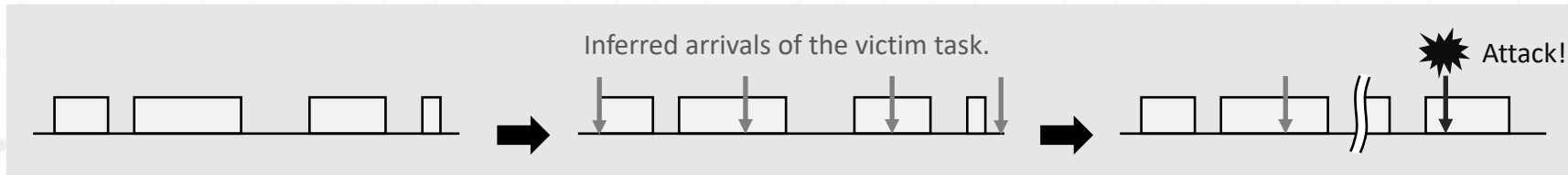
DEMONSTRATION 2



↓ PWM Update Task ↓ Attacker's Task

SCHEDULEAK SUMMARY

- **Reconnaissance attack algorithms**
- **Targeting sporadic and mixed real-time CPS**
- **Stealthy and Effective**
- **No root privileges required for ScheduLeak**



More videos [including cache attack demo]: <https://scheduleak.github.io>