

# A New Covert Channel in Fixed-Priority Real-Time Multiframe Tasks

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**Abstract**—This study investigates the presence of illicit information flows in fixed-priority multiframe real-time systems. We identify an algorithmic covert channel (called FrameLeaker) that enables a low-priority task to deduce the execution patterns (frames) of a high-priority task. We show that the response time of a targeted low-priority task (receiver) can be used to extract the execution behavior of a high-priority task (sender). We further introduce a metric called “inference precision ratio” to evaluate the efficacy of the received information.

**Index Terms**—Covert Channel, Real-time System, Multiframe.

## I. INTRODUCTION

In high-assurance systems such as those with real-time requirements, information flows must be *explicit* (i.e., passed through authorized channels.). Any communication between real-time tasks must be known and configured a priori. As third-party vendors often supply various applications in modern real-time systems, it is challenging to thoroughly trust or verify them, leading to new vulnerabilities. A covert timing channel refers to an unauthorized communication path where one entity (sender) transmits information to another entity (receiver) in violation of security policies. In safety-critical real-time systems (e.g., avionics, automotive, industrial control systems), it is of utmost importance to provide strong isolation among applications that require different levels of criticality to limit interference among them. Hence, there must not exist any illicit information flow (viz., covert channels) between tasks. We identify that the deterministic nature of real-time schedulers can contribute to one such channel in multiframe fixed-priority systems.

Multiframe real-time tasks [1] are used in many industrial applications where execution time is different from one phase to another of its execution. For instance, a periodic task in a control system may collect a small amount of data collection in each period that takes a small execution time but then summarize and store this data every  $k$  cycle using a sophisticated algorithm that takes a larger execution time. Another example is in real-time multimedia encoding, where different encodings may take a variable time.

This research is partly supported by the US National Science Foundation (Award 2312006). Any findings, opinions, recommendations, or conclusions expressed in the paper are those of the authors and do not necessarily reflect the sponsor's views.

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The research aims to formally analyze the creation and investigation of a covert timing channel by a high-priority sender task and a low-priority receiver task in the presence of a third-party task under the rate-monotonic scheduling. We show that by analyzing the response time of the receiver, it is possible to signal the execution behavior of the high-priority sender. By exploiting this channel, a rogue task can *signal its frame patterns* to another task. We name this covert channel vulnerability FrameLeaker. Knowing such information can leak critical information to other parties. For instance, in the control task example, frame patterns can leak whether a task is performing data collection or logging/processing. Our analysis shows an illegitimate communication path between a high and low-priority task, even with the presence of other benign tasks. We formally show that the receiver task can predict at least one of the frames from the sender from its runtime delay (viz., response time). We further introduce a metric (called *inference precision ratio*) that quantify the goodness of received information.

In this paper, we made the following contributions.

- We propose an analytical model that finds the *existence of an algorithmic covert channel* (named FrameLeaker) for a set of multiframe tasks running using the rate monotonic scheduling policy (Section III);
- We formally characterize the channel and prove that it will *always* be possible for a low-priority receiver task to infer at least one frame of the sender task (Section III); and
- We devise a *metric* (called inference precision ratio) to determine the chances of successful inference (Section IV).

## II. BACKGROUND AND MODELS

### A. Preliminaries: Covert Channels

A covert channel is a hidden communication channel. Such channels are not intended to exist in the system and are created furtively by untrusted entities using techniques antithetical to the system's intended design. From a real-time perspective, we investigate how malicious tasks can exploit deterministic scheduling policies to illicitly transfer information (frame patterns in our context).

A covert channel can be classified into two major categories: (a) noiseless channel and (b) noisy channel. A covert communication path can be represented as a *discrete*

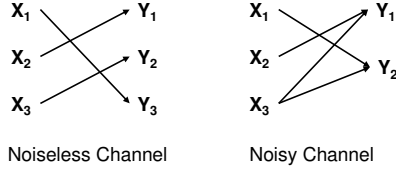


Fig. 1. Types of covert channels: (a) output alphabets directly map a particular input alphabet (noiseless channel, left); and (b) multiple input alphabets can result in the same output alphabets (noisy channel, right).

*memoryless* channel, where information flows from a *sender* to a *receiver*, as illustrated in Figure 1. The channel is *discrete* when the input alphabets  $X = \{x_1, \dots, x_j\}$  and the output alphabets  $Y = \{y_1, \dots, y_j\}$  are finite. It is *memoryless* when the current output depends only on the current input. When noise occurs during the transmission, it affects the output the receiver observes. The behavior of a noisy channel can be nondeterministic, meaning that the output observed by the receiver is no longer solely determined by the input symbol transmitted. For instance, in the noisy channel depicted in Fig. 1, upon receiving  $y_1$ , the receiver cannot reliably determine which value ( $x_2$  or  $x_3$ ) was the input transmitted by the sender.

### B. System Model

We consider a uniprocessor real-time system with three periodic multi-frame tasks i.e.,  $\tau_H$ ,  $\tau_N$ , and  $\tau_L$ . A task  $\tau_H$  intends to secretly leak its execution behavior to a  $\tau_L$  in the presence of a high-priority task  $\tau_N$ . Hence,  $\tau_N$  acts as a “noise” in the covert channel between  $\tau_H$  and  $\tau_L$ . We denote  $hp(\tau_i)$  as the set of high-priority tasks than  $\tau_i$ . By assumption,  $hp(\tau_L) = \{\tau_N, \tau_H\}$  and  $\tau_N$  is the highest-priority task. We further assume that the tasks are scheduled using rate monotonic [2] scheduling policy.

Each task  $\tau_i$  is characterized by  $\tau_i = \{C_i, T_i, D_i, n_i\}$ , where  $C_i$  is the set of worst-case execution times of the task,  $T_i$  is the inter-arrival time (period),  $D_i$  is the relative deadline, and  $n_i$  denotes the repeating sequence of *frames* [1]. If a task has  $n_i \geq 1$  frames, then  $C_i = \{C_i^0, C_i^1, \dots, C_i^{n_i-1}\}$ . Each frame may have a worst-case execution time that may differ from other frames. All frames in the same task are released with the time interval  $T_i$  and have the same deadline  $D_i$ .

TABLE I  
MULTIFRAME TASKSET

Task	$T$	$C$	Priority
$\tau_1$	10	{1,3,5}	High
$\tau_2$	20	2	Low

Table I shows an example with 2 tasks  $\tau_1$  and  $\tau_2$  where  $\tau_1$  is a multi-frame task with 3 frames represented by the execution time values 1, 3, and 5; and  $\tau_2$  has just one frame. We further assume the tasks follow the implicit deadline model ( $D_i = T_i$ ), i.e., the tasks must complete before their next periodic arrival.

### C. Threat Model

We consider a noninterference model [3], i.e., the scheduling parameters, the scheduling algorithm, and the resulting schedule are publicly available to the adversary. Besides, all tasks have access to precise clocks. We aim to analyze whether a rouge task  $\tau_H$  can form a covert channel by exploiting the deterministic nature of real-time schedules. Particularly, the high-priority task ( $\tau_H$ ) wants to *leak* its execution patterns (frames) to a low-priority one ( $\tau_L$ ) in the presence of another benign task ( $\tau_N$ ).

## III. FRAMELEAKER: ALGORITHMIC COVERT CHANNELS IN MULTIFRAME REAL-TIME SYSTEM

We demonstrate a vulnerability in multiframe scheduling where a low-priority task can infer another high-priority task’s varying execution behavior by observing the impact that the low-priority task has on its own response time (i.e., the time between arrival and completion of a frame). We refer to this FrameLeaker. For instance, if  $\tau_H$  consists of  $n_H$  frames, by analyzing the response time of  $\tau_L$ , we infer what frames  $\tau_H$  is transmitting at a given point in time. In this case, the two parties do not require any explicit communication path. The receiver task ( $\tau_L$ ) can extract the sending signal by observing its completion time (say, by reading the system clock). Hence, we refer to this illegitimate information flow as *algorithmic covert channel*.

As an example, consider a taskset presented in Table II, where  $\tau_H$  has three frames (i.e.,  $C = \{1, 2, 3\}$ ). Depending on the  $\tau_H$ ’s frame execution, the response time of  $\tau_L$  varies. To illustrate, when the active frame is 3, the response time of  $\tau_L$  is 9, and when the active frame is 2, the response time of  $\tau_L$  is 8 (see Fig. 4). We represent the FrameLeaker covert channel vulnerability as a communication model described as a set with input-output binary relations. We do so by extending the response time analysis for multiframe task models considering *all possible invocations* of the receiver task, as we present below.

TABLE II  
EXAMPLE TASKSET 1

Task	$T$	$C$
$\tau_N$	5	2
$\tau_H$	10	{1,2,3}
$\tau_L$	20	2

### A. Response Time Analysis for Multiframe Tasks

The response time  $R_i$  of a task  $\tau_i$  consists of two types of execution: the task’s execution and the delay caused by the execution of other higher-priority tasks (called *interference*). Let  $\pi(\tau_i)$  represent a scheduling priority assigned to a task  $\tau_i$ . A taskset  $\Gamma$  running a fixed-priority scheduling policy will meet deadlines for all tasks if [4]:  $\forall \tau_i \in \Gamma, R_i \leq D_i$ , where  $R_i = C_i + \sum_{\tau_j \in hp(\tau_i)} \lceil \frac{R_i}{T_j} \rceil C_j$ .

Assume a multiframe task  $\tau_j$  with  $n_j$  execution frames  $\{C_j^0, C_j^1, \dots, C_j^{n_j-1}\}$ . Let us define a cumulative function

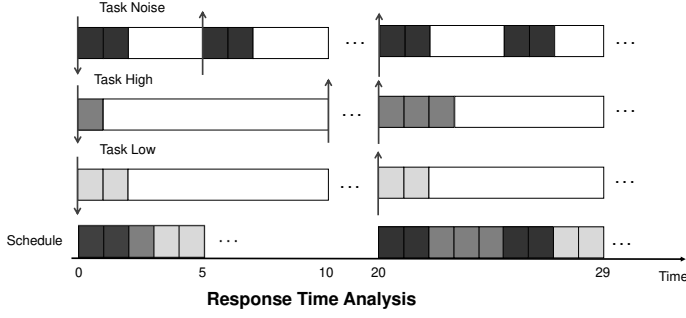


Fig. 2. Response time analysis of Task  $\tau_L$  for Taskset 1 (see Table II).  $\tau_L$  releases second instance at  $t = 20$ . Frame sequence of task  $\tau_H$  is  $\{3, 1, 2\}$ . We can see that  $R_L(1) = 9$  and high is transmitting frames where  $C_H = 3$ .

$\xi_j(k)$  that calculates the summation of the execution time of different frames of  $\tau_j$  up to a certain invocation  $k$  and is defined as follows [1]:

$$\xi_j(k) = \sum_{i=1}^{i=k} C_j^{i \bmod n_j}. \quad (1)$$

To illustrate, the value  $\xi_j(3)$  for task  $\tau_j$  whose execution times are  $\{5, 8, 3, 4, 2\}$  is 16. The value  $\xi_j(3)$  for task  $\tau_j$  whose execution times are  $\{5, 8, 2, 4, 2\}$  is 15. For a single-frame task, the cumulative function is  $\xi_j(k) = kC_j$  because of the constancy of  $C_j$  for all frames of the multiframe task.

Based on this function  $\xi_j(k)$ , the response time for the multiframe task model is represented as [1]:  $R_i = C_i^m + \sum_{\tau_j \in hp(\tau_i)} \xi_j(\lceil \frac{R_i}{T_j} \rceil)$ , where  $C_i^m \in \mathcal{C}_i$  is called the “peak frame” that leads to worst-case behavior. We can solve the above using the following standard recurrence process:

$$R_i^{w+1} = C_i^m + \sum_{\tau_j \in hp(\tau_i)} \xi_j(\lceil \frac{R_i^w}{T_j} \rceil), \quad (2)$$

where  $w = 0, 1, 2, 3, \dots$  and  $R_i^0 = C_i^m$ . The *worst-case* response time is obtained when  $R_i^{w+1} = R_i^w$  for the smallest value of  $w$ .

### B. Extended Timing Analysis for Multiframe Tasks

To expose FrameLeaker covert channel vulnerability (frame length) from  $\tau_H$ , we extend Eq. (2) to calculate all possible response times of  $\tau_L$ . Before we present details of our analysis, let us start with a definition.

**Definition 1 (Active Frame).** *The frames in a multiframe task arrive sequentially at regular intervals. The frame ready to be executed at a given time  $t$  is defined as the **active frame**. We denote the active frame of the  $k^{\text{th}}$  job of task  $\tau_i$  as  $C_i(k)$ .*

For example, if task  $\tau_i$  has three frames  $\{2, 3, 5\}$ , for the second job of  $\tau_i$ , the active frame is 3. Likewise, the active frame for the fourth job of  $\tau_i$  is 2.

We measure the response time of jobs arriving at  $T_L$  interval to observe which frames of  $\tau_H$  transmit during that time.

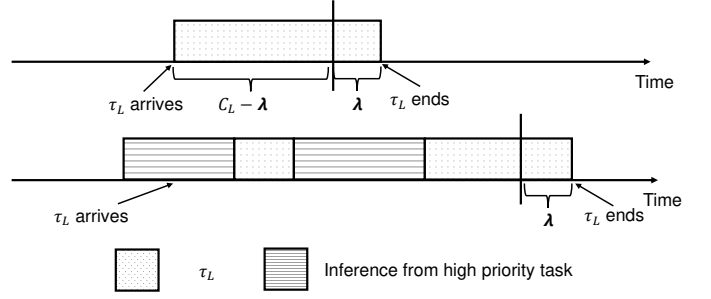


Fig. 3. Execution of  $\tau_L$  has  $C_L - \lambda$  unit of time for computation and  $\lambda$  time for response time calculation. The bottom part depicts high-priority tasks ( $\tau_N$  and  $\tau_L$ ) preempt  $\tau_L$ .

Hence, we calculate response time of  $k^{\text{th}}$  released task of  $\tau_L$  as follows:

$$R_L^{w+1}(k) = C_L(k) + \sum_{\tau_j \in \{\tau_N, \tau_H\}} \xi_j(\lceil \frac{R_L^w(k)}{T_j} \rceil) \quad (3)$$

Using Eq. (3), we deduce the response time of  $\tau_L$  at different instance, i.e.,  $R_i(k)$ , where  $k = 1, 2, 3, \dots$ . For the first instance of task  $\tau_L$  (i.e., first job), the response time is  $R_L(1)$ . Additionally, by assumption  $R_L \leq D_L$  (i.e., the task meets the deadline), and hence *schedulable*.

### C. Identifying Frame Signals

By leveraging the noninterference model, the receiver task keeps track of time read from the system time, including preemptions. For correct system operation (and remain stealthy)  $\tau_L$  should not run more than its worst-case execution time,  $C_L$ . Hence, it saves some budget for analyses to reconstruct (passive) information received from the sender. Hence, we define a parameter,  $\lambda$ , whose value is set by the receiver to limit the running time of the inference function in each period. This inference duration  $\lambda$ , is an integer in the range  $0 < \lambda < C_L$ , as shown in Fig. 3.

We use the active frames to deduce the signals from  $\tau_H$ . Hence, we calculate the response time of  $\tau_L$  when both  $\tau_H$  and  $\tau_L$  arrive simultaneously, i.e., at multiple of the least common multiple (LCM) of  $T_H$  and  $T_L$ . We then determine the response time of  $\tau_L$  at those points. Considering the response time of  $\tau_L$  at any other time may introduce interference from the previously released frame and the effect of the upcoming frame (i.e., create more noise in the inference). In contrast, the response time at the multiple of LCM of  $T_H$ , and  $T_L$  is *noiseless* as both  $\tau_H$  and  $\tau_L$  arrive simultaneously, and  $\tau_L$  can deduce the frame that  $\tau_H$  is transmitting correctly.

We use the following indexing to find the initial position of a multiframe of  $\tau_H$  at different times. If  $\tau_H$  has  $n_H$  frames, then for  $k^{\text{th}}$  release of the  $\tau_L$ , frame initial index  $p$  will be calculated as follows:

$$p = \lceil \frac{t}{T_L} \rceil \bmod n_H, \quad t = k \times T_{LCM}, \quad k = 0, 1, 2, 3, \dots, \quad (4)$$

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**Algorithm 1** FrameLeaker Inference: Inferring frames of high-priority task  $\tau_H$

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1: Input:  $\Gamma = \{\tau_1, \tau_2, \dots, \tau_n\}$ 
2: Output: Deduced frame of  $\tau_H$  by  $\tau_L$ 
3:  $Length$  of multi-frame of sender task  $\leftarrow n_H$ 
4:  $T_{LCM} \leftarrow LCM(T_L, T_H)$ 
5:  $t_{max} \leftarrow n_H \times T_{LCM}$ 
6:  $t \leftarrow 0$ 
7:  $\mathcal{C}_{deduce} \leftarrow \{\}$   $\triangleright$  Store the deduced frame of  $\tau_H$ 
8:  $R_L \leftarrow \{\}$ 
9: while  $t < t_{max}$  do  $\triangleright$  Each job of  $\tau_L$  will calculate response
   time  $R_L$  till  $t_{max}$ 
10:    $index = \lceil \frac{t}{T_H} \rceil \bmod n_H$   $\triangleright$  index flag is used to detect the
       active frame of  $\tau_H$ 
11:    $R_L \leftarrow R_L(t/T_L)$   $\triangleright$  Calculate  $R_L(t/T_L)$  using Eq. (3)
12:    $\mathcal{C}_{deduce} \leftarrow \mathcal{C}_H[index]$ 
13:    $t \leftarrow t + T_{LCM}$   $\triangleright$  Response times at multiple of  $T_{LCM}$ 
14: end while
15: set( $\mathcal{C}_{deduce}$ )  $\triangleright$  Getting the deduced frame comparing  $R_L$  &
     $\mathcal{C}_{deduce}$ . set() returns distinct elements

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where  $T_{LCM}$  is  $LCM(T_L, T_H)$ . To illustrate, let us assume  $\tau_H$  has three execution frames (e.g.,  $\{1, 2, 3\}$ ) and for 2<sup>nd</sup> release of  $\tau_L$ , frame sequence of  $\tau_H$  will be 3, 1, 2,  $\dots$  and so on.

#### D. Algorithm

FrameLeaker's inference process is presented in Algorithm 1. The variable  $T_{LCM}$  stores the LCM of  $T_L$  and  $T_H$  (Line 4). We calculate the response time of  $\tau_L$  at a multiple of  $T_{LCM}$  until a timeout period,  $t_{max}$  (Line 5). We store the deduced frame of  $\tau_H$  in  $\mathcal{C}_{deduce}$  (Line 7) and response time of  $\tau_L$  in  $R_L$  (Line 8). We find the active frame index of  $\tau_H$  (Line 10) and calculate  $R_L$  using Eq. (3) (Line 11). We store the deduced frame of  $\tau_H$  in  $\mathcal{C}_{deduce}$  (Line 12) and infer the deduced frame comparing  $R_L$  and  $\mathcal{C}_{deduce}$  (Line 15).

#### E. Examples and Illustrations

We illustrate the inference process with a few examples.

**Example 1.** Assume we have three tasks  $\tau_N, \tau_H, \tau_L$  with periods 5, 10, and 20.  $\tau_H$  has three frames 1, 2, and 3, as listed in Table II. Response time of  $\tau_L$  varies because of the multiframe nature of the  $\tau_H$ . We infer which frame  $\tau_H$  is transmitting by analyzing the response time of  $\tau_L$ . To evaluate the response time of  $\tau_L$ , we need to find the frame sequence of  $\tau_H$  at the time of  $k^{\text{th}}$  arrival of  $\tau_L$ . We can see the frame sequence of  $\tau_H$  at  $t = 0, 20, 40$  in Fig. 4. Using Eq (3), we calculate the response time of the first instances of  $\tau_L$ .  $R_L(k)$  denotes the response time of  $\tau_L$  at  $k^{\text{th}}$  release. Using Eq. (3),  $R_L(1) = 5$ ,  $R_L(2) = 9$ ,  $R_L(3) = 8$ .

**Example 2.** Assume we have three tasks  $\tau_N, \tau_H, \tau_L$  with periods 4, 8, and 12.  $\tau_H$  has three frames with durations  $\{1, 2, 3\}$  as listed in Table III.  $\tau_L$  calculates the frame sequence of  $\tau_H$  at the time of  $k^{\text{th}}$  arrival of  $\tau_L$ . In this example, the frame sequence of  $\tau_H$  at  $t = 0, 24, 48$  (multiple of LCM of  $T_L, T_H$ , see Fig. 5). Using Eq. (3),  $R_L(1) = 5$ . In this case,  $\tau_L$  can only infer  $\tau_H$ 's frame duration when  $\tau_H$  transmits its first

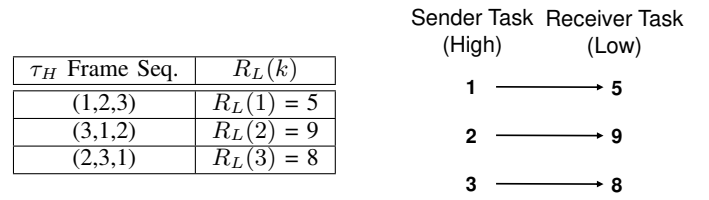


Fig. 4. Response times and input/output signal mapping for Taskset 1.

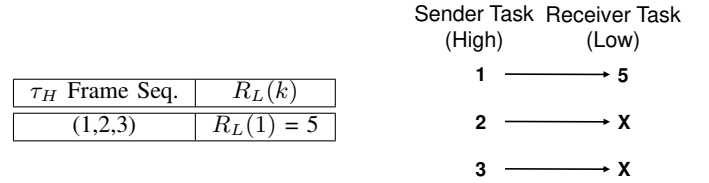


Fig. 5. Response times and input/output signal mapping for Taskset 2.

TABLE III  
EXAMPLE TASKSET 2

Task	$T$	$C$
$\tau_N$	4	1
$\tau_H$	8	$\{1,2,3\}$
$\tau_L$	12	2

frame. Due to the parameters of the system (i.e., period and number of frames), we cannot extract more than one frame. For instance, in this taskset  $\frac{LCM(T_H, T_L)}{T_H} = n_H$ . As a result, at each checking point (i.e., multiple of  $LCM(T_L, T_H)$ ),  $\tau_H$  transmits the same frame. Thus,  $\tau_L$  cannot infer more than one frame.

#### F. Characterizing the Channel

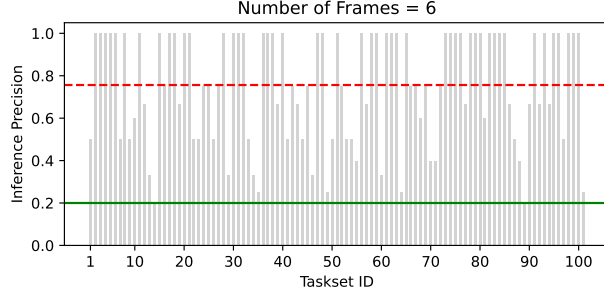
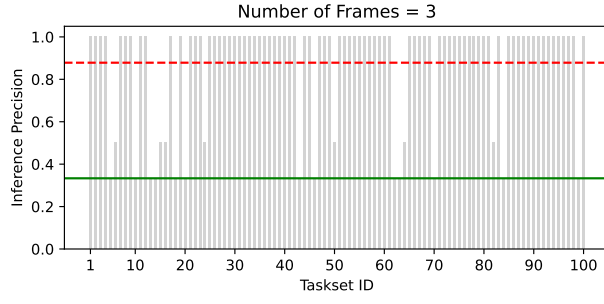
We now characterize the FrameLeaker covert channel. Let us introduce two definitions.

**Definition 2** (Channel Deducibility). A channel is **fully deducible** if task  $\tau_L$  can infer all the frames of task  $\tau_H$ . Likewise, a channel is **partially deducible** if task  $\tau_L$  can infer some, but not all, frames of task  $\tau_H$ .

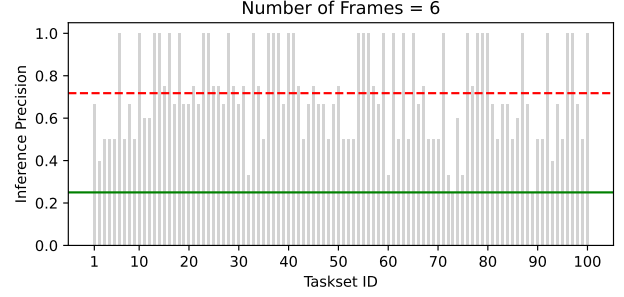
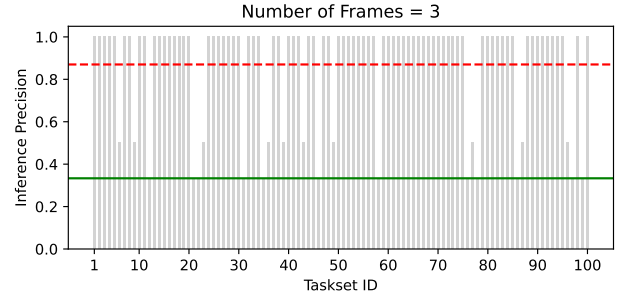
By observing its response time,  $\tau_L$  can infer which frame is transmitted by the task  $\tau_H$ . For instance, as in Example 1,  $\tau_L$  can map the frame sequence  $\tau_H$  and the corresponding response time (Fig 4). As we shall present below, it is always possible to extract information about at least one frame, and hence, the covert channel we discovered is *partially deducible*.

**Lemma 1.** The noisy channel in FrameLeaker is always at least partially deducible for a schedulable taskset.

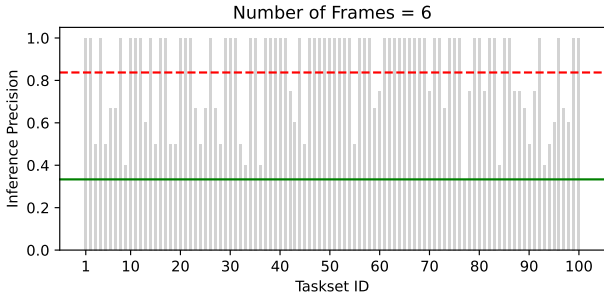
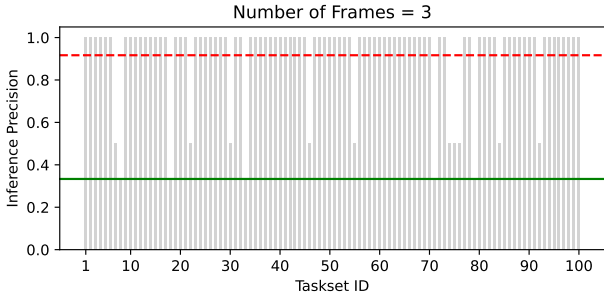
*Proof.* We deduce the frame of sender task  $\tau_H$  using the response time of  $\tau_L$  at a multiple of LCM of  $T_L$  and  $T_H$ , i.e.,  $T_{LCM} = LCM(T_L, T_H)$ . We check response time at  $t = k \times T_{LCM}$ ,  $k = 0, 1, 2, 3, \dots$ , when both  $\tau_L, \tau_H$  arrive simultaneously. In these values of  $t$ , the response time of  $\tau_L$



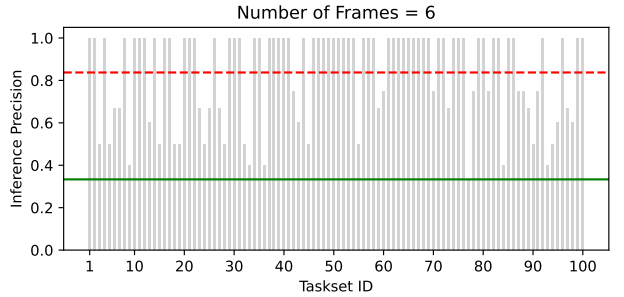
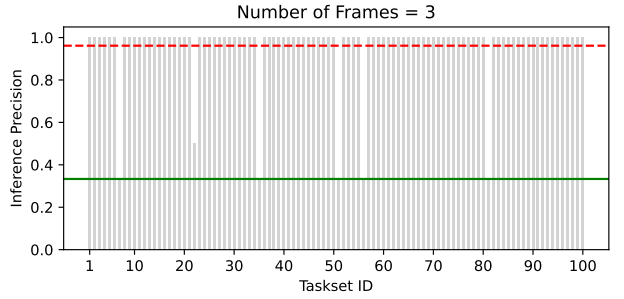
(a) Inference precision: periods of  $\tau_H$  and  $\tau_L$  generated randomly.



(b) Inference precision: periods of  $\tau_H$  and  $\tau_L$  are harmonic.



(c) Inference precision: fixed the period of  $\tau_L$  with varying period of  $\tau_H$ .



(d) Inference precision: fixed the period of  $\tau_H$  while  $\tau_L$ 's period is varied.

Fig. 6. Inference precision for 100 randomly generated tasks with fixed frame length (3 and 6) for four different cases: (a)  $T_L$  and  $T_H$  are randomly generated, (b)  $T_L$  and  $T_H$  are harmonic, (c) Fixed  $T_L$  and varied  $T_H$ , and (d) Fixed  $T_H$  and varied  $T_L$ . The red line indicates the average precision value, while the green line indicates the minimum precision value.

has no interference from the previous frame of  $\tau_H$ . At each multiple of  $T_{TCM}$ ,  $\tau_L$  may receive different frames of  $\tau_H$ . But in the worst case scenario, the frame of  $\tau_H$  comes in such a way that where at each multiple of  $T_{LCM}$ , exactly the same frame of  $\tau_H$  arrives. This happens when  $\frac{T_L}{T_H} = n_H$ . Thus, we can conclude that even in the worst-case scenario,  $\tau_L$  can deduce at least one frame of  $\tau_H$ .  $\square$

#### IV. EVALUATION

We measure the information leakage in FrameLeaker using synthetically generated workloads. We evaluated using 100 randomly generated task sets under the following setups: (a)  $T_L$  and  $T_H$  are randomly generated, (b)  $T_L$  and  $T_H$  are harmonic, (c) Fixed  $T_L$  and varied  $T_H$ , and (d) Fixed  $T_H$  and varied  $T_L$ . In randomly generated case, the task periods are

TABLE IV  
SIMULATION PARAMETERS

Parameters	Value
Period $T_H$	[10, 15] ms
Period $T_L$	[30, 50] ms
Number of frames, $n_i$	{3, 6}
Number of taskset for each utilization, $N_u$	100

TABLE V  
AVERAGE AND MINIMUM PRECISION

Case	No. of Frames	Avg. Precision	Min. Precision
Random	3	0.88	0.33
Random	6	0.75	0.20
Harmonic	3	0.87	0.33
Harmonic	6	0.72	0.25
Fixed $T_L$	3	0.92	0.33
Fixed $T_L$	6	0.84	0.33
Fixed $T_H$	3	0.96	0.33
Fixed $T_H$	6	0.83	0.25

randomly selected from [15, 30] ms for  $\tau_H$  and [50, 70] ms for  $\tau_L$ . Table IV lists the key simulation parameters. In the harmonic period case, we vary the ratio of  $\frac{T_L}{T_H}$  in the range of [2, 5]. In the fixed  $T_L$  case, we set  $T_L = 120$  and vary  $T_H$  in the range of  $\frac{T_L}{[2, 5]}$  (i.e.,  $T_H < T_L$ ). In the fixed  $T_H$  case, we set  $T_H = 30$ .

**Metric: Inference Precision Ratio.** We propose a *metric* to measure the successful inference of receiving frames. This metric represents the ratio of detectable frames to the total frame length and is calculated as follows:

$$Q = \frac{\text{Total number of deducible frames } (n_d)}{\text{Total number of frames } (n_j)}$$

For instance, in Example 1,  $Q = 3/3 = 1$ , while in Example 2,  $Q = 1/3 = 0.33$ . These relative quantities can serve as effective metrics for comparing the deducibility levels of two noisy channels. For instance, when the  $Q$  of noisy channel  $A$  for a given task set exceeds that of channel  $B$  for another one, we may conclude that the receiver can deduce more information about the frame sequence.

## A. Results

We include the average inference precision (red line) and minimum precision (green line) in each plot (see Fig. 6). The average precision and minimum precision values for all four cases are listed in Table V. Inference is better for lower frame numbers (see Figs. 6). When we fix  $T_H$  and vary  $T_L$ , the best average precision value is achieved (i.e., 0.96). Based on the minimum precision value and also from Lemma 1, we can conclude it is possible to deduce at least one frame in the worst-case scenario (i.e., inference precision value is always greater than 0). In all of our experimental cases, we observed that the 90<sup>th</sup> percentile value is 1, indicating that our framework achieves very high inference precision.

## V. RELATED WORK AND CONCLUSION

While some work exists on securing real-time systems [5]–[7], there has not been much work on exploring attack surfaces. Perhaps the closed work is Son et al. [8] that identified timing covert channels for rate monotonic schedulers. However, this early work does not provide any analytical verification. There exists other work [3], [9]–[13] for discovering side and covert channel leakages, but none of them have considered multi-frame scenarios.

FrameLeaker exposes an algorithmic covert channel in multi-frame task scenarios. Under the assumption that  $\tau_L$  is a task with the longest period, we show that the low-priority task least infers the transmission of one frame of a multi-frame task while in the best case, we can infer all of them! Our findings will help designers to be cognizant of covert channel leaks and modify schedulers to prevent such information flows.

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