LLCWhisp: Feasibility of Occupancy Attacks on Fully Associative LLCs with Random Eviction

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Background & Motivation

- **Last-Level Cache (LLC)** is commonly shared across cores in multi-core systems.
- Such shared caches are vulnerable to **timing and conflict-based side-channel attacks**.

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- Such shared caches are vulnerable to **timing and conflict-based side-channel attacks**.
- Fully Associative LLCs with **Random Eviction Policy (RFA-LLC)** is a proposed mitigation for conflict-based side-channel attacks.
- But **RFA-LLC** is vulnerable to **occupancy-based attacks**.

Background & Motivation

- These attacks use:
  - **Cache fills**
  - **Difference in hit and miss latency**
  - **Disturbance measurements due to different Eviction patterns**

Problem Statement

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- **Real-world systems** include:
  - **OS scheduling noise**
  - **Interrupts and background tasks**
- These introduce significant **noise and uncertainty** in attack performance.

Objective

- Evaluate the feasibility of **occupancy-based attacks** on RFA-LLCs in real system setting
  - In the presence of realistic OS and system-level interference
  - Using **gem5 full-system simulation** with Linux OS

Occupancy-Based Attack Model

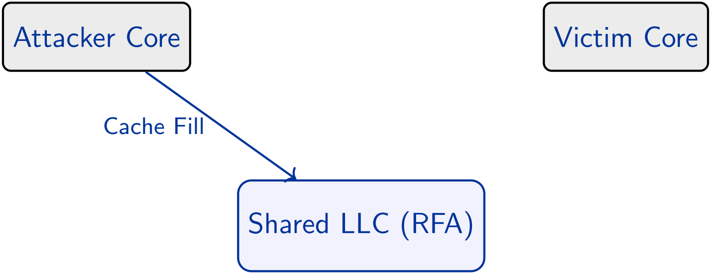
Attacker Core

Occupancy-Based Attack Model

Attacker Core

Victim Core

Occupancy-Based Attack Model



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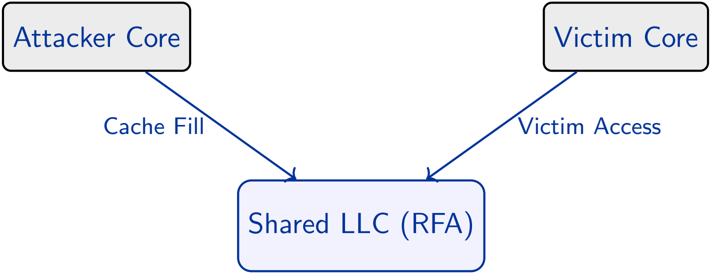

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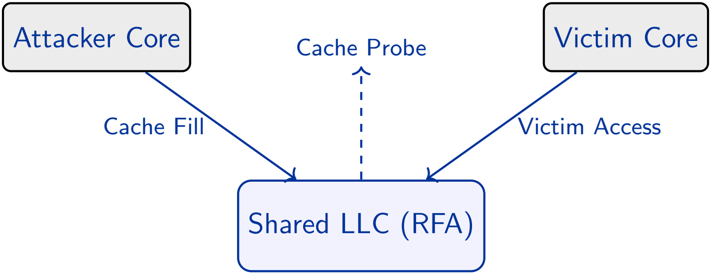

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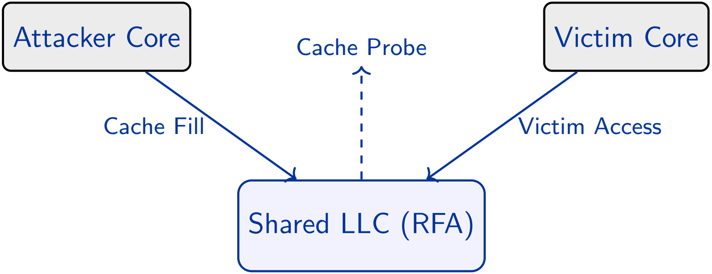

Attack Steps:
1. Attacker fills the LLC
2. Victim evicts some cache lines
3. Attacker probes occupancy
4. Inference via disturbance

Project Contributions

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Experimental Setup and Implementation

- **Simulator:** Experiments are conducted on the **gem5 full-system simulator** using the **Linux operating system**.
- **System Noise:** All experiments are conducted in presence of **realistic OS scheduling and background activity**, to evaluate feasibility of occupancy attacks in realistic settings.

- **Fully-Associative LLC:**

$$\text{Set Associativity} = \frac{\text{Cache\_Size}}{\text{Block\_Size}}$$

so that the LLC becomes a single-set (fully associative) cache.

FA-LLC Configuration & Random Replacement

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- **Efficient Random Eviction:** In gem5 we maintain an **Invalid Blocks List** data structure that:
  - Tracks all cache lines invalidated
  - Allows constant-time insertion/removal as blocks become invalid/valid

Gem5 configurations

ISA	x86
Frequency	3GHz
Cores	2
L1-I, L1-D	32KB, 8-way, 64B line, 1 cycles, LRU, no prefetch
L2	256KB, 16-way, 64B line, 3 cycles, no prefetch, LRU
L3 (LLC)	2MB, 32768-way, 64B line, 15 cycles, no prefetch, RandomRP
DRAM	SingleChannelDDR3_1600 3GB

Table: Gem5 System Configurations

Cache Block Request Handling in gem5

Cache Block Request

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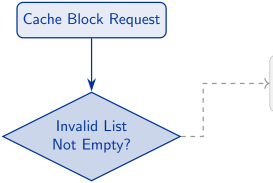

Data structure implemented in gem5:
Maintains "Invalid Blocks" list for efficient random eviction.

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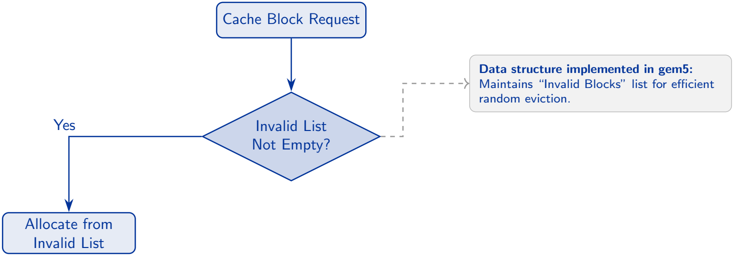

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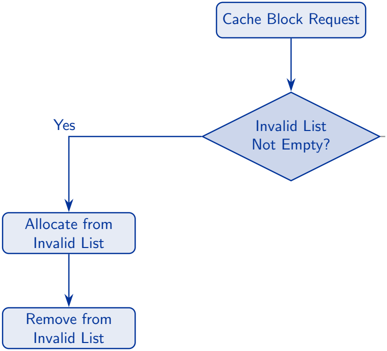

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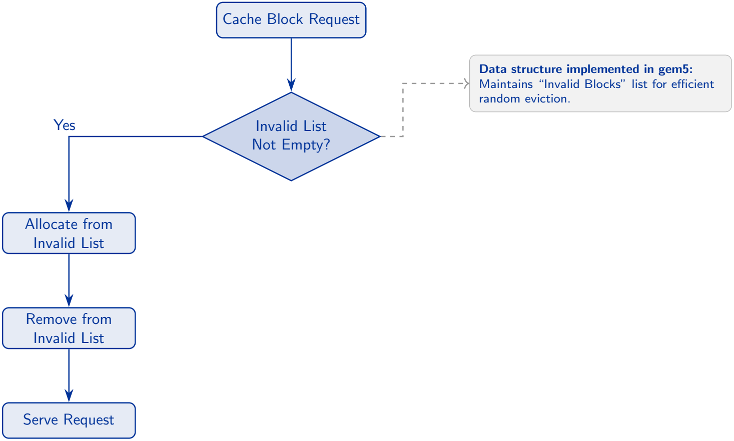

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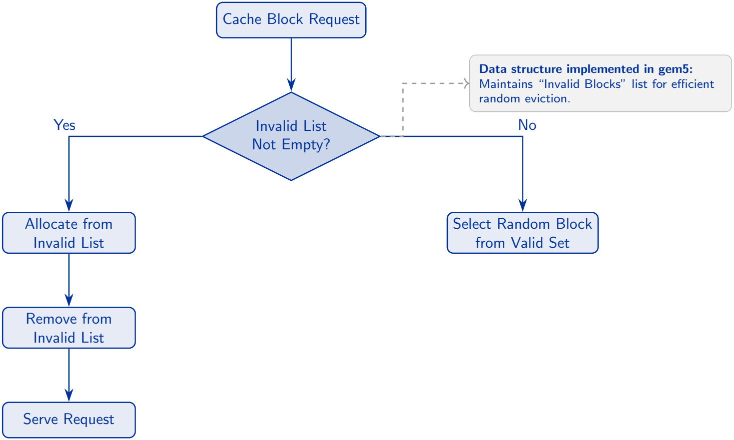

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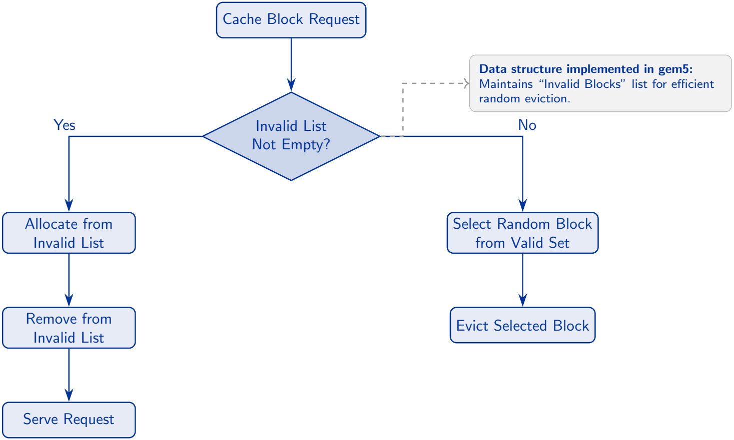

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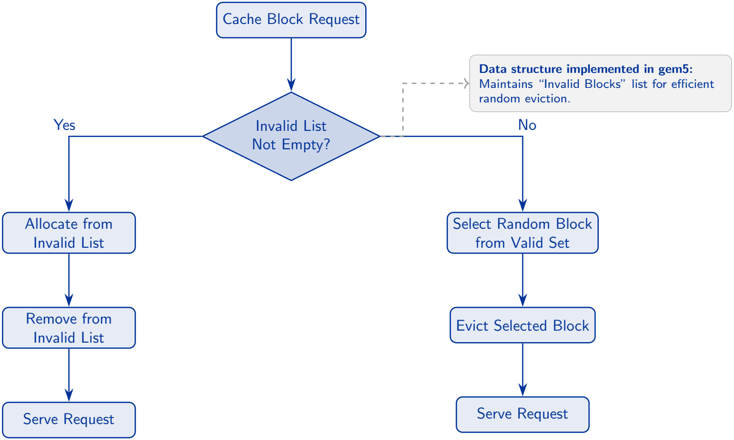

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CRFill and CRProbe: Overview

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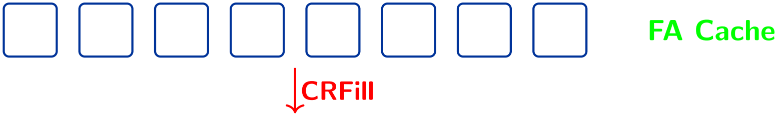
- **CRProbe:** Accessing data and using access latency to detect hit or miss which helps calculating occupancy.

CRFill and CRProbe Visualization

FA Cache

CRFill and CRProbe Visualization



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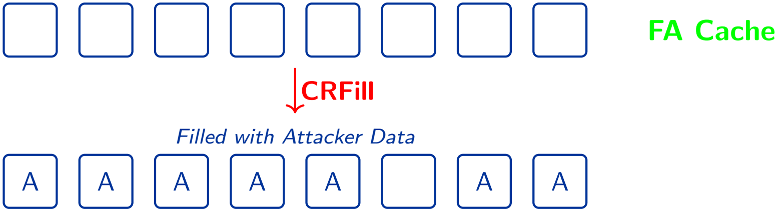

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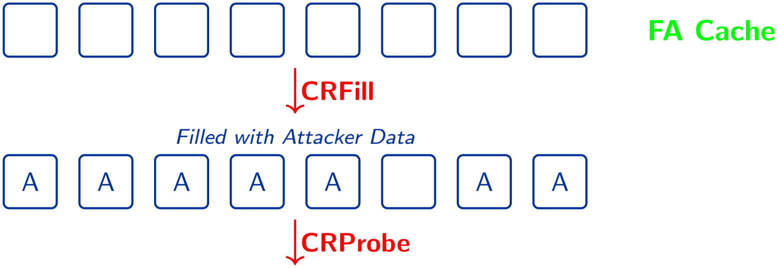

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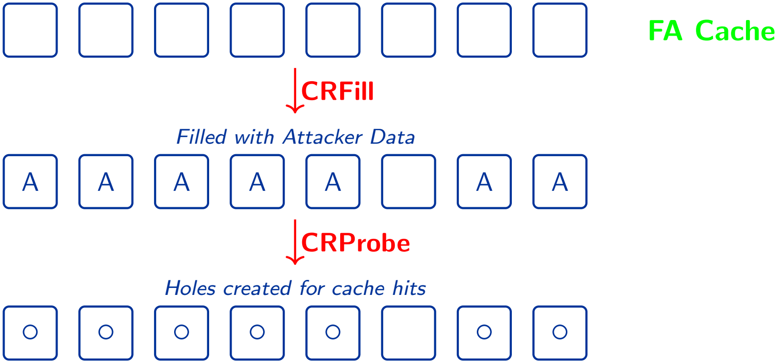

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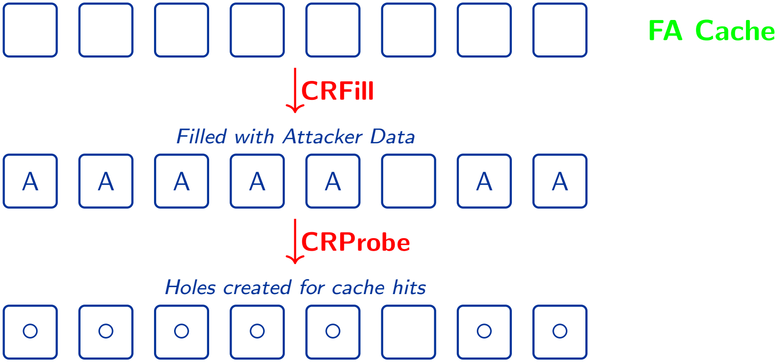

CRProbe Pseudocode

CRProbe Algorithm

```
int i = arr_size - 1
while i ≥ 0 do
    t1 = rdtsc
    load(arr[i])
    delay = rdtsc - t1
    clflush(arr[i])
    if delay < hit_miss_threshold OR i == arr_size-1
then
        occ++
    i = i - 1
done
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Note: Misses are handled carefully to avoid evicting filled lines—crucial in random eviction LLCs.

Evaluating Cache Fill Effectiveness

- Goal: To study the effectiveness of cache filling under realistic OS scheduling and background activity.
- Setup: Multiple access patterns tested with data sizes and access counts denoted as x^a — where data size is x times of LLC size and a is the number of iterations over the data..

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Occupancy values reflect the ability of attacker to maintain control over cache blocks despite system noise.

Static CRFill

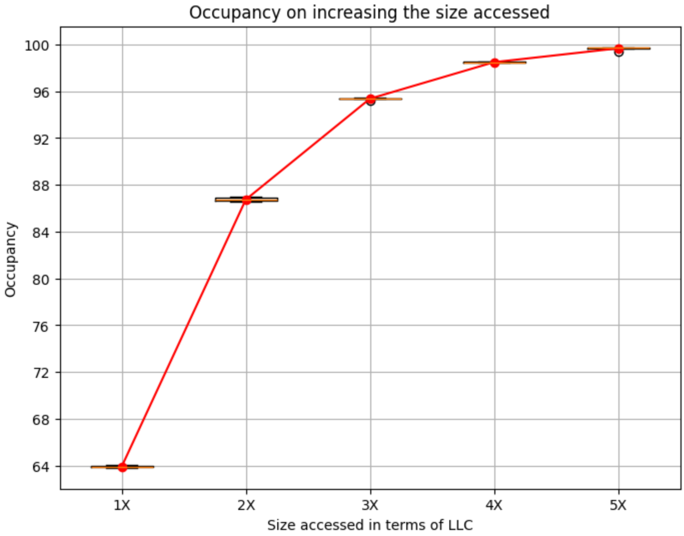

Figure: CRFill step

Static CRFill

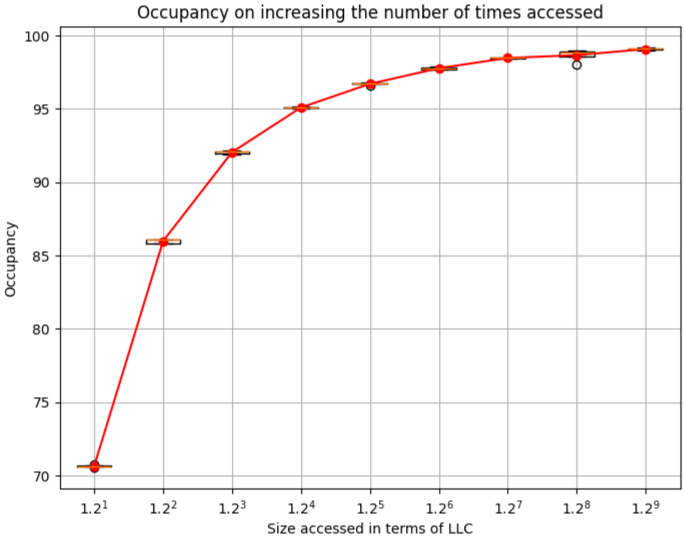

Figure: CRFill step

Dynamic CRFill

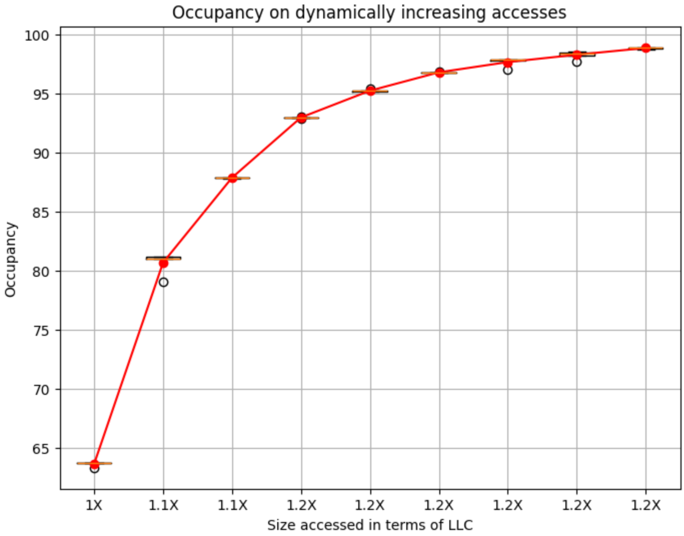

Figure: CRFill step

Key Observations

Inference

Occupancy-based attacks are practically feasible even in noisy, full-system environments. Minimal OS-induced disturbance observed, with attackers consistently achieving high occupancy across patterns.

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Fingerprinting using Cache Footprint

Holes after CRProbe (Hit->flush->hole)

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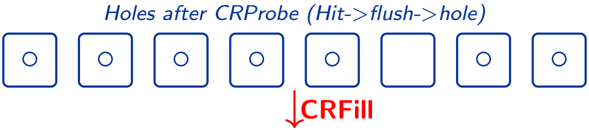

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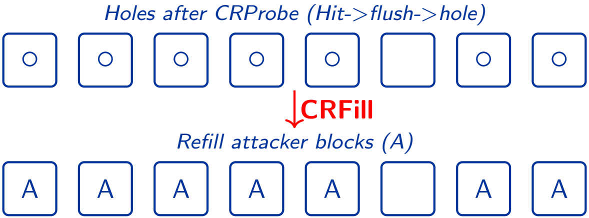

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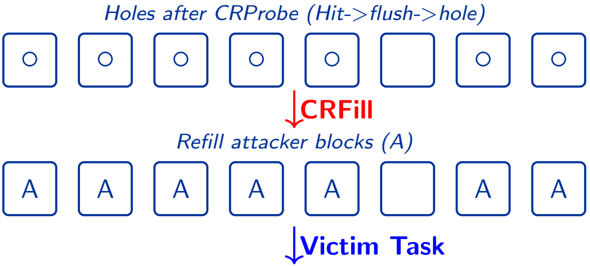

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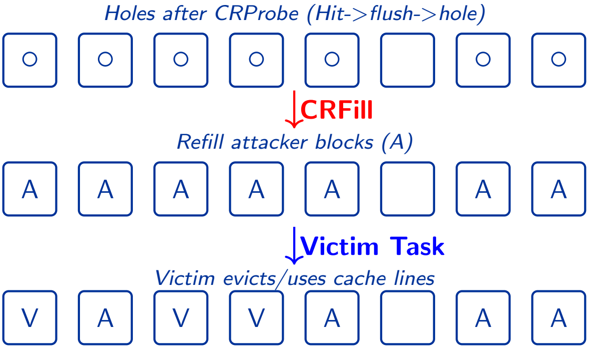

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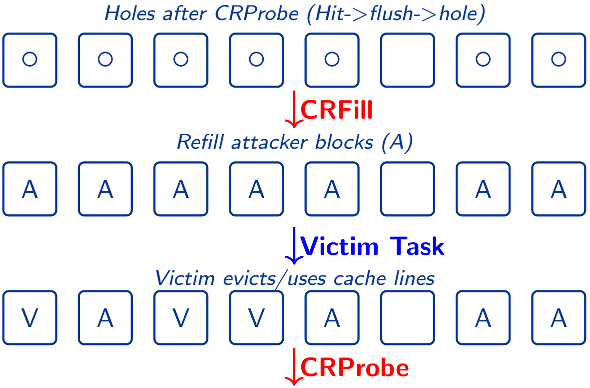

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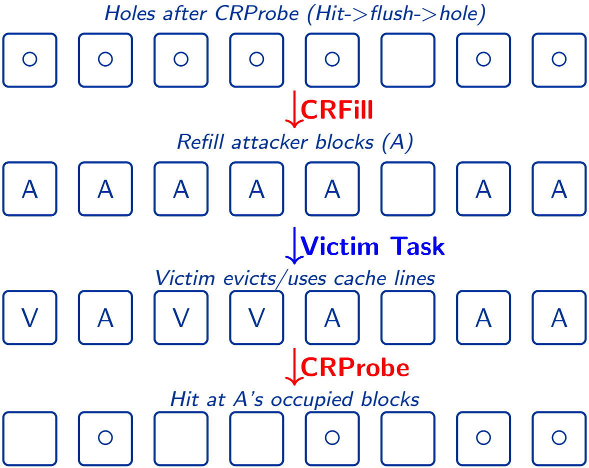

Exploring Fingerprinting in RFA-LLCs

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Key Challenge in Realistic Setups

Realistic setups introduce **non-deterministic noise** due to OS and background processes.

Experimental Procedure: OS Noise Analysis

- Attacker executes **CRFill** and **CRProbe** to occupy a significant portion of the LLC.
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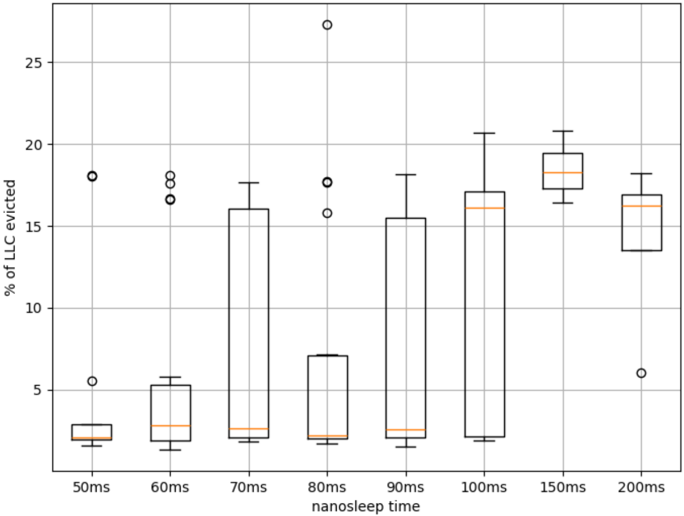
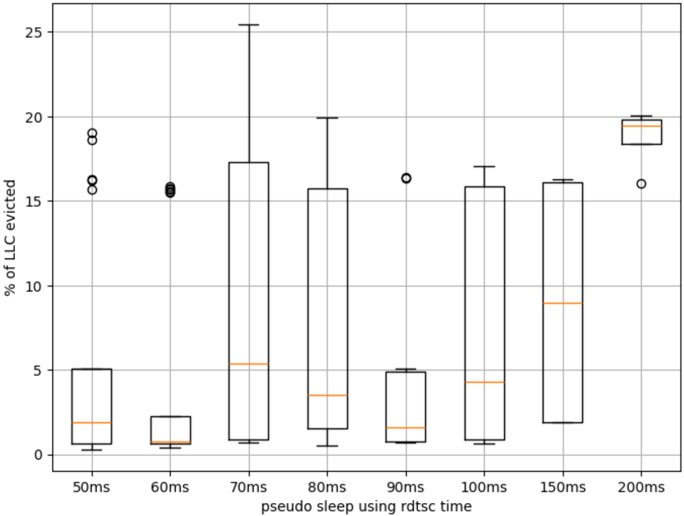
- We conduct this using **two methods of inactivity**:
  - `nanosleep()` system call
  - `rdtsc`-based busy wait using a `while` loop
- After x ms, attacker **probes** the cache again to estimate how many of its blocks were disturbed.
- This helps infer the **extent of OS-induced eviction** over time.

Footprint due to sleep



Footprint due to pseudo sleep



Experimental Procedure: OS Noise Analysis

Observation

A longer idle interval $\rightarrow$ more blocks disturbed $\rightarrow$ higher system activity footprint.

However, **the presence of OS noise introduces considerable variability** in the observed cache behavior, impacting the consistency of attack performance.

Conclusion

Key Takeaway

Operating system noise significantly increases variability in cache occupancy, leading to observable degradation in attack performance.

- The attacker can still achieve **substantial occupancy** across diverse access patterns even in nosiy settings.
- However, **system-level interference** introduces **non-determinism** in cache behavior, impacting repeatability and effectiveness of occupancy-based attacks.

Future Work

Next Steps

- Investigate techniques to **mitigate the impact of OS-induced noise** on cache behavior to carry out cache occupancy based attacks.
- Explore **adaptive or noise-resilient attack strategies** that can maintain effectiveness even under significant system-level interference.

Thank you for Attending!

Questions and Answers!