CaSA

End-to-end Quantitative Security Analysis of Randomly Mapped Caches

Thomas Bourgeat, Jules Drean, Yuheng Yang, Lillian Tsai, Joel Emer, Mengjia Yan

Presented by Peter Deutsch
MIT 6.888 - Secure Hardware Design

Motivation

It is well known that caches can be used to exfiltrate secrets through ***timing side channels*** such as Prime + Probe.

Micro-architects have attempted to mitigate side-channel leakage through the use of ***randomly mapped caches***, which aim to increase the difficulty of an attack.

Many of these mitigation schemes make bold (***and ultimately quite fragile***) security claims based on varying attack strategies.

It is apparent that a unified framework is required to thoroughly evaluate cache security across proposed designs!

Threat Model

CaSA assumes that an attacker can:

- Observe the latency of its own memory accesses
- Reside in a user-level process or secure enclave
- Use more than one thread to control multiple cores
- Leverage speculative execution to provoke the victim

CaSA does not reason about:

- Attacks mounted in an SMT context
- Flush and occupancy based cache attacks

Overview - Primary Contributions

CaSA (Cache Security Analyzer) **provides the following contributions:**

1. **Demonstrates** a three-step, end-to-end communication paradigm which better evaluates the security properties of caches *beyond eviction set generation*
2. **Formulates** the security analysis of randomized caches into a statistical problem, allowing quantitative analysis through a novel framework
3. **Evaluates** existing randomly mapped caches and provides new insights regarding noise and communicating across cache epochs

Any Initial Thoughts? Strengths? Weaknesses?

My Thoughts

Strengths

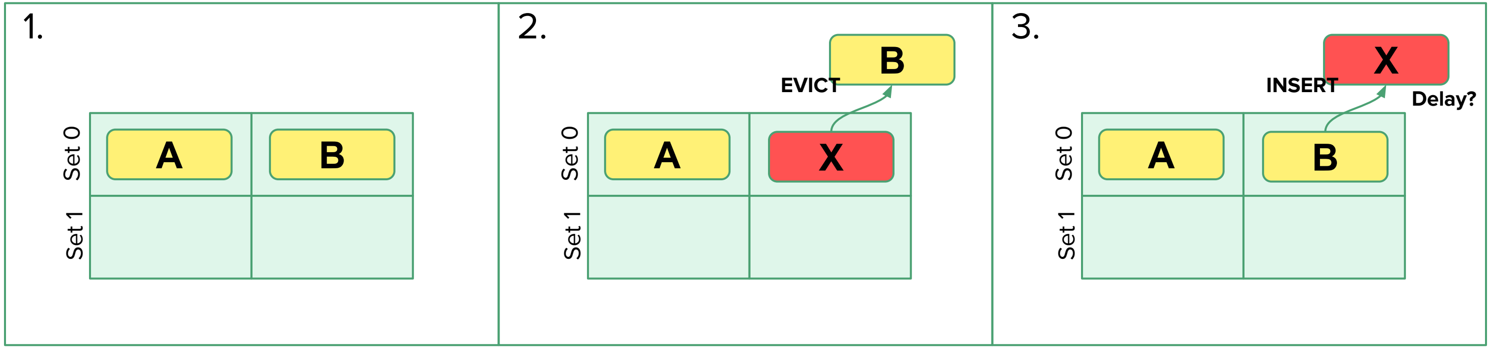
- Provides the first framework which allows for a fair comparison of the security of contemporary secure/randomized caches
- Is very flexible, and can analyze a wide variety of potential cache configurations, allowing for design space exploration
- Clearly expresses and justifies surprising results (such as the impact of noise)

Weaknesses

- Doesn't provide a tool to determine upper bounds for side-channel *bandwidth*
- Fails to formulate statistical representations for multi-way caches
- Doesn't consider communications schemes which use multi-bit symbols

Background - Cache-Based Side Channel Attacks

In cache-based side channel attacks, the cache is used as a **communication channel**, where each line can be viewed as a **sub-channel.**



Prime
Pre-Condition

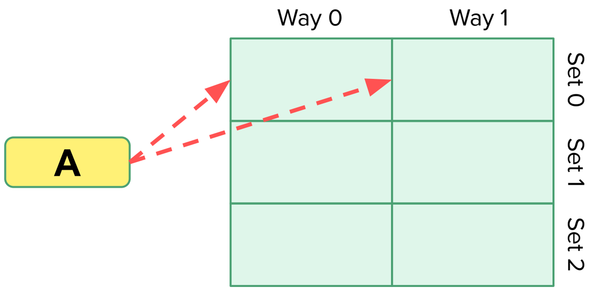
Wait
Modulate

Probe
Detect

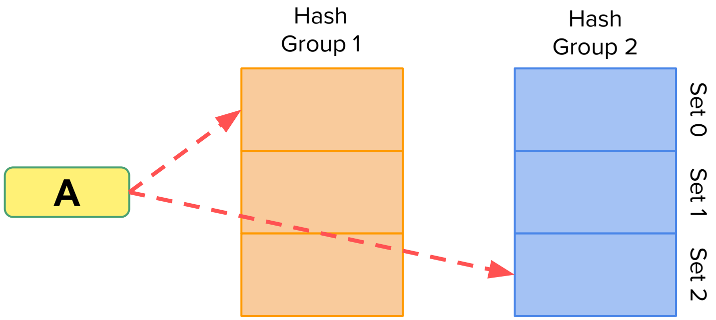
Takeaway: We would like a cache where it is difficult to *concretely* know which channels are pre-conditioned by an attacker, and which channels are modulated by a victim.

Background - Randomly Mapped Caches

By introducing randomness into mapping functions, we can significantly increase the difficulty for an attacker to create an eviction set.



Single Hash Group - Static Mapping
(ex. Standard Set-Associative Cache)



Multiple Hash Groups - Dynamic Mapping
(ex. Skewed CEASAR[1])

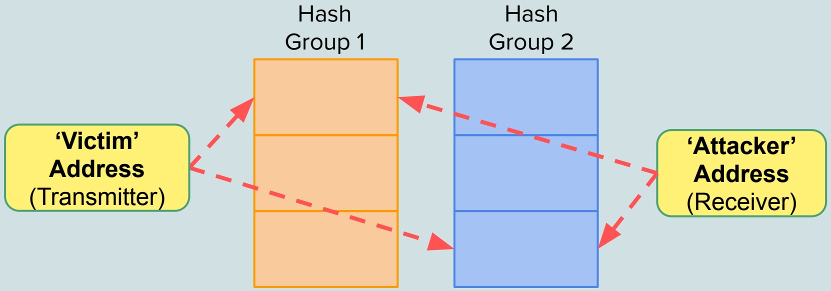
Q: Do randomized caches protect against Flush + Reload attacks? Why or why not?

[1] New Attacks and Defense for Encrypted-Address Cache - Qureshi et al.

Background - Hard and Soft Conflicts

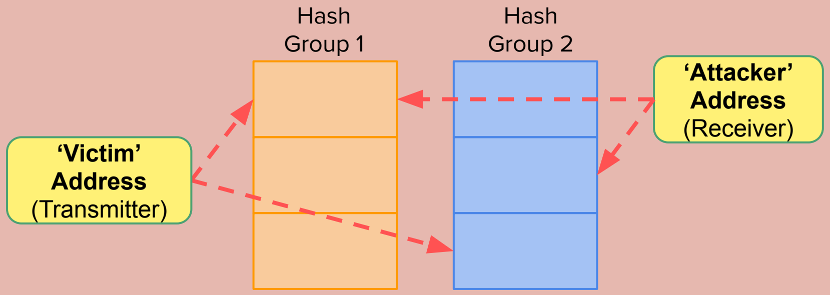
In prior work, signalling is accomplished through abusing set conflicts with the victim

Hard Conflict Eviction



Receiver maps to same set as transmitter in ***every*** hash group

Soft Conflict Eviction



Receiver maps to same set as transmitter in ***at least one*** hash group

Motivation - Limitations of Prior Work

Prior work makes ***differing assumptions*** on attacker strategies!

Skewed-CEASAR[1] assumes the attacker uses hard-conflict receivers

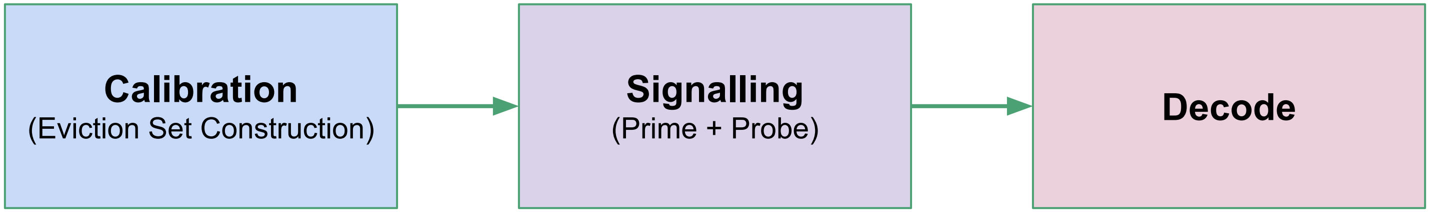
ScatterCache[2] assumes the attacker uses a large number of soft-conflict receivers

Which of these assumptions are valid?

What is the optimal attacker strategy?

[1] New Attacks and Defense for Encrypted-Address Cache - Qureshi et al.
[2] ScatterCache: Thwarting Cache Attacks via Cache Set Randomization - Werner et al.

Analysis - Proposed Communication Scheme



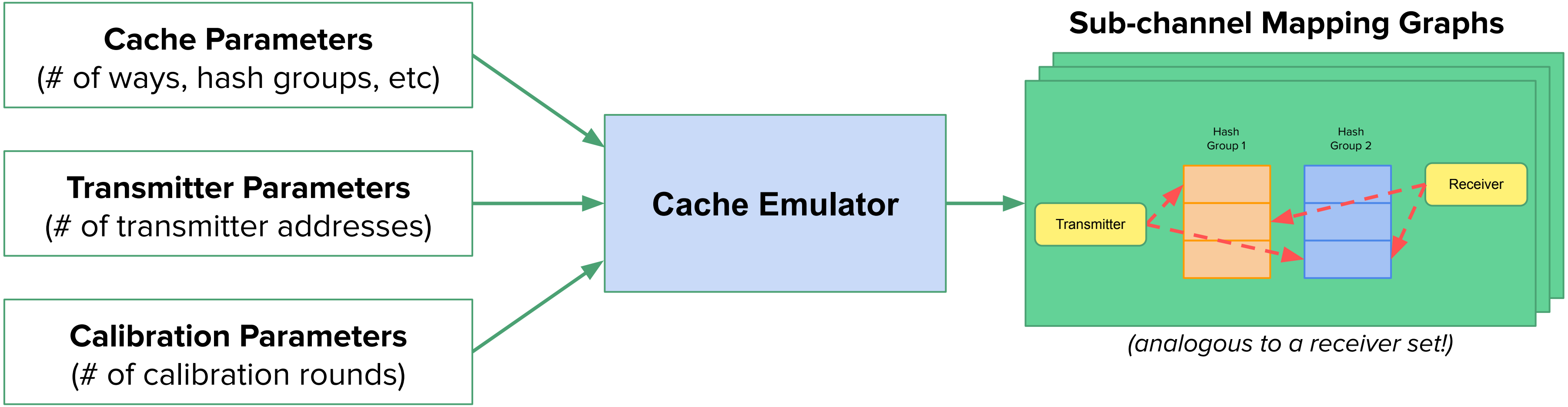
There exists a *tradeoff* between communications steps. An attacker can either:

- *Spend more time on calibration*, obtaining a large eviction set which can be used to detect modulations with a higher probability
- *Spend more time on signalling*, taking more measurements in order to better filter out noise and obtain a higher success rate

Q: How does this tradeoff relate to the epoch length of a randomized cache?

Analysis - Calibration Module

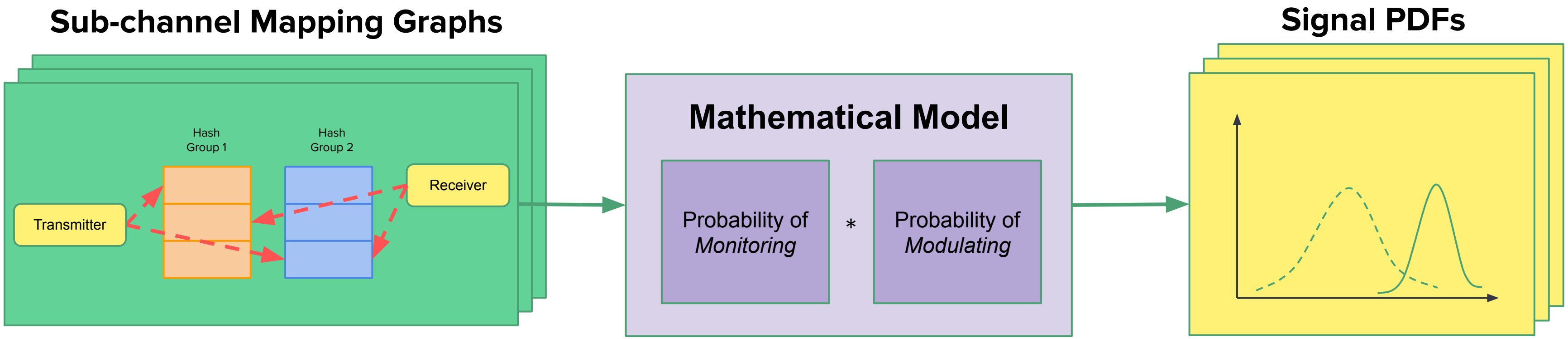
The **Calibration Module** attempts to establish a relationship between transmitter/receiver addresses and the subchannels to which they map to



Q: How do we know how many transmitter addresses there are?

Analysis - Signalling Module

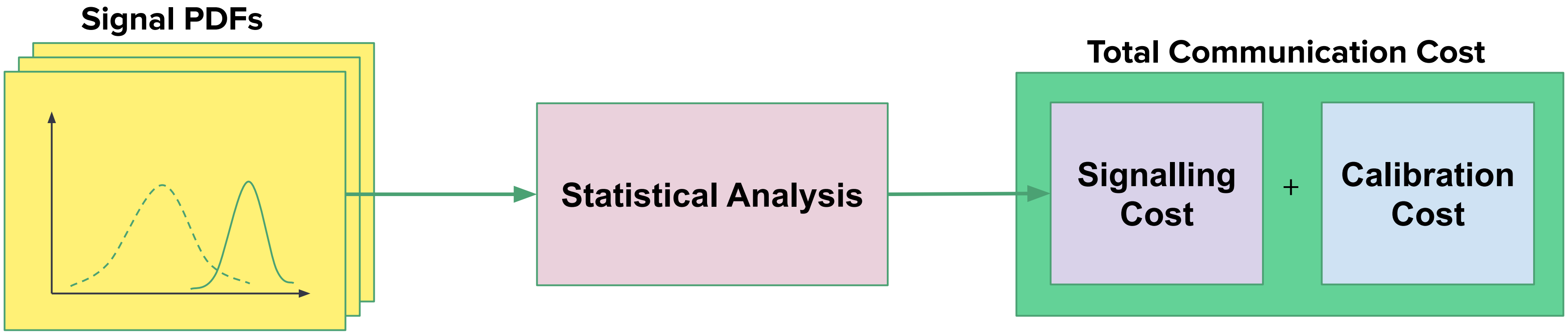
The **Signalling Module** attempts to model the distribution of the number of modulations observed by the receiver *for each possible value of the secret*



Q: Where is noise considered?

Analysis - Decode Module

The **Decode Module** computes the number of signal transfer rounds required to achieve a 99% success rate, then determines the ***total communication cost***



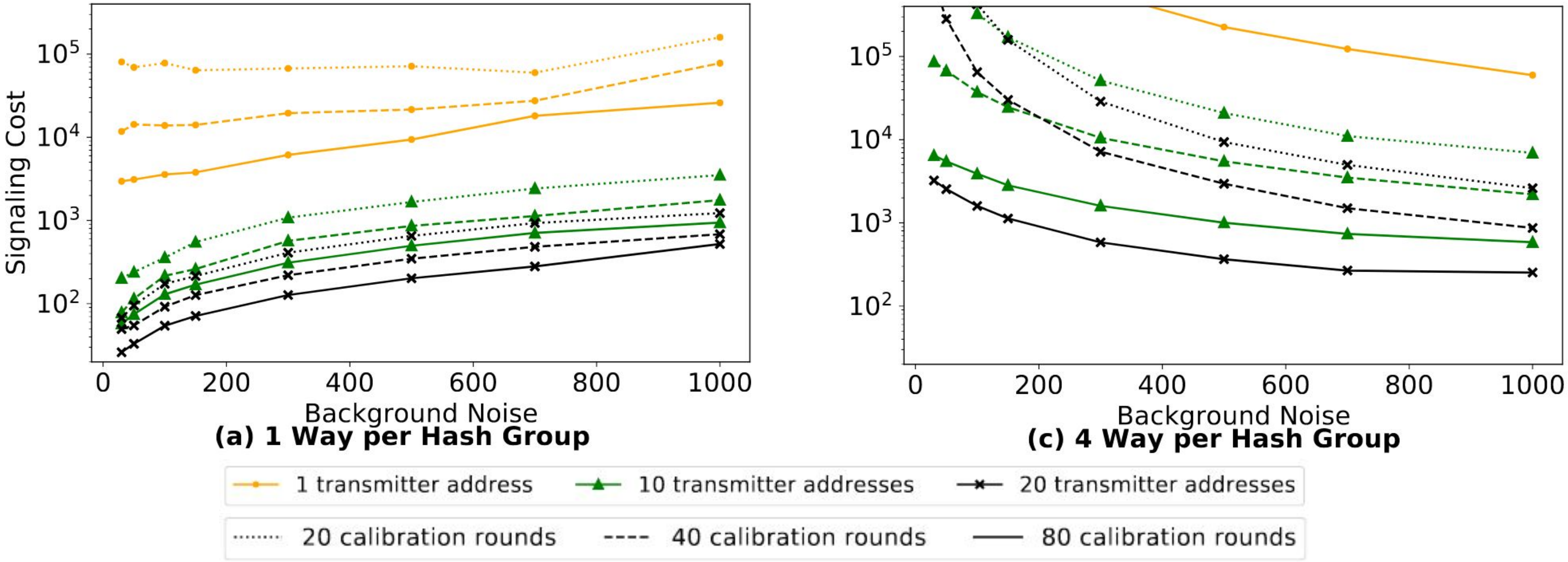
Key Insights

CaSA makes the following novel observations:

1. Spending the maximum amount of time in the calibration phase is not always the best strategy.
2. Noise can actually ***reduce*** our signalling cost in some cases!
3. Information can be leaked and accumulated across epochs, even when the mapping functions are changed.

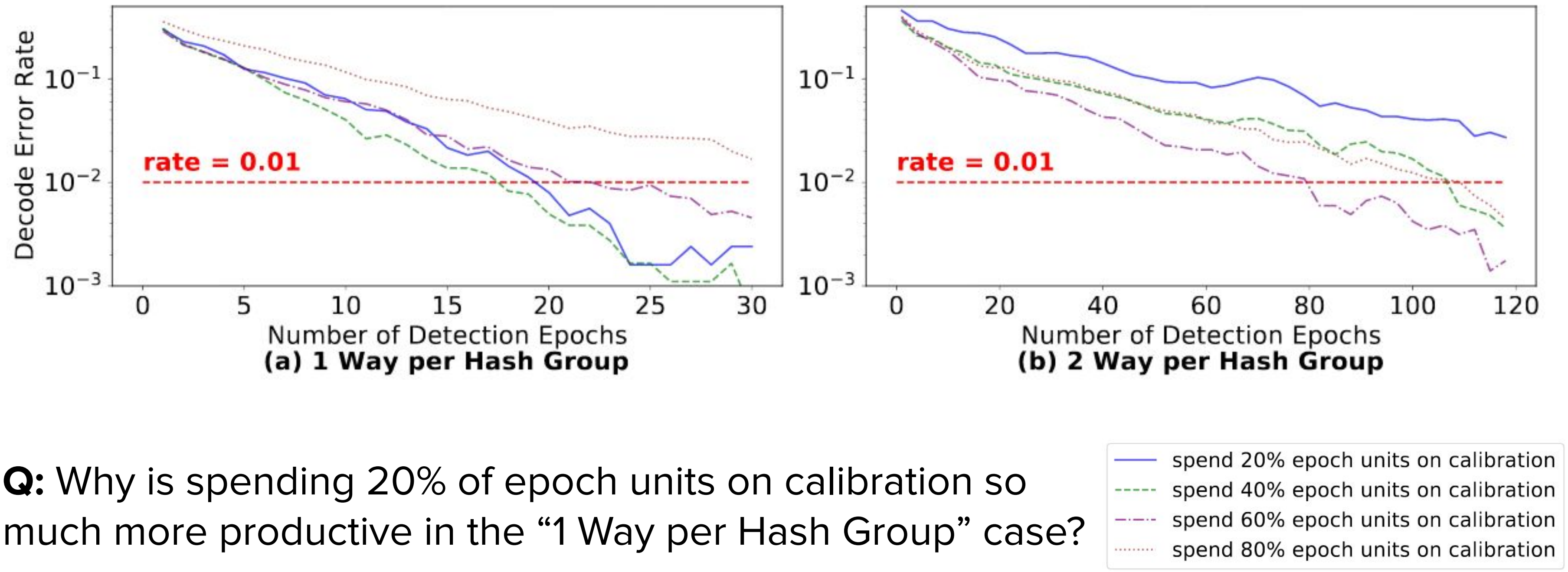
Evaluation - Signalling Cost + Noise

Q: Can noise be beneficial when there is only one way per hash group?



A: No.

Evaluation - Communications Costs



Q: Why is spending 20% of epoch units on calibration so much more productive in the “1 Way per Hash Group” case?

Discussion Questions

Discussion Questions - Cache Hardening

- Can hash mechanisms be devised to minimize collisions between programs and provide better results than random mapping?
- It's important during the calibration step to only choose addresses from the candidate set that are useful - how does this factor into the calibration efficiency?
- How can the attacker determine when a new epoch has started? Is intermittently randomizing the epoch length a viable option to improve security?
- This is a side channel and not a covert channel - what's the guarantee that the transmitter will access the same specific address as many times as you need?

Discussion Questions - Future Work

- What can be done in the future to avoid making the same mistakes as the previous security analyses and making incorrect security guarantees?
- Can an analysis framework similar to CaSA be applied to other structures within the CPU? Could it be applied to multi-level caches in an SMT context?
- How would CaSA need to be adapted in order to consider multi-bit symbol transmissions?
- Is it feasible (or worth attempting) to determine lower bounds for communications costs?
- Are we “doomed” to a future where caches must have tunable parameters (such as epoch lengths and hash groups) to remain secure?