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Faster Hash-based Signatures with Bounded Leakage

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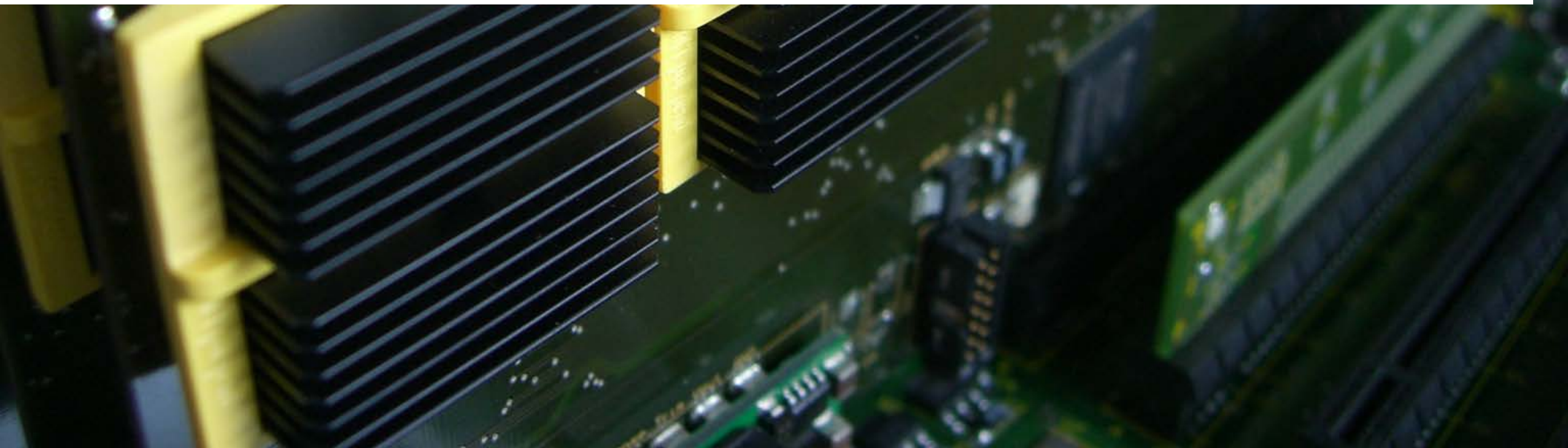

Motivation

Status quo

- Providing efficient PKC in embedded systems is challenging
- Side-channel attacks are a serious threat, protection is costly
- RSA, ECC, (EC-)DSA, …, breakable by quantum computers

→ Need for an efficient, post-quantum signature scheme with limited side-channel leakage

Idea

- Leakage-resilient schemes aim for inherent SCA resistance
- Candidate: Merkle signature scheme (MSS) with Winternitz one-time signatures (W-OTS)
  - Efficient in embedded systems [RED+08, HBB12]
  - Possible choice for a time-limited signature scheme
  - No efficient attacks on quantum computers (with right parameters)

Overview

Motivation

Background

Optimized Authentication Path Computation

Implementation and Leakage Analysis

Conclusions

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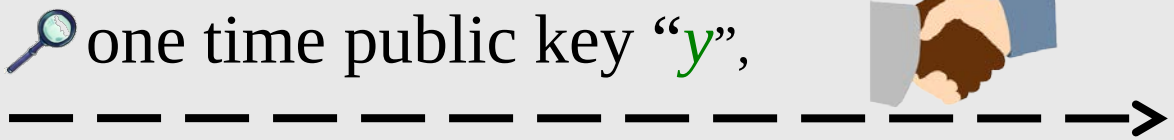
Hash-based Signatures: Principle



Key Setup

1. Select random x
2. Calculate: $y = f(x)$

Choice: disclose x?

How much information is signed?

One-time Signature Scheme

one time public key "$y_1, y_2, \ldots, y_n$",

 , "x_1, x_4" → signature of "1 , 0"

Key Setup

1. Select random $x_1, x_2, \ldots, x_n$
2. Calculate: $y_i = f(x_i)$

$$\left.\begin{matrix} y_1 \\ y_2 \end{matrix}\right\} \stackrel{?}{=} f(x_1)$$

$$\left.\begin{matrix} y_3 \\ y_4 \end{matrix}\right\} \stackrel{?}{=} f(x_4)$$

$= \overbrace{1}\ \overbrace{0}$

$= \overbrace{x_1, \not{x_2}}, \overbrace{\not{x_3}, x_4}$

Winternitz One-Time Signatures

- Uses hash chains to sign chunks of bits at once
- Reduces signature length (main drawback of Hash-based OTS)

Feature?

- **Can only be used once → leaks information only once**

Practicalities

- Secret signing key X is generated using PRNG
- Generation of public verification key Y requires generation of X and all hash chains

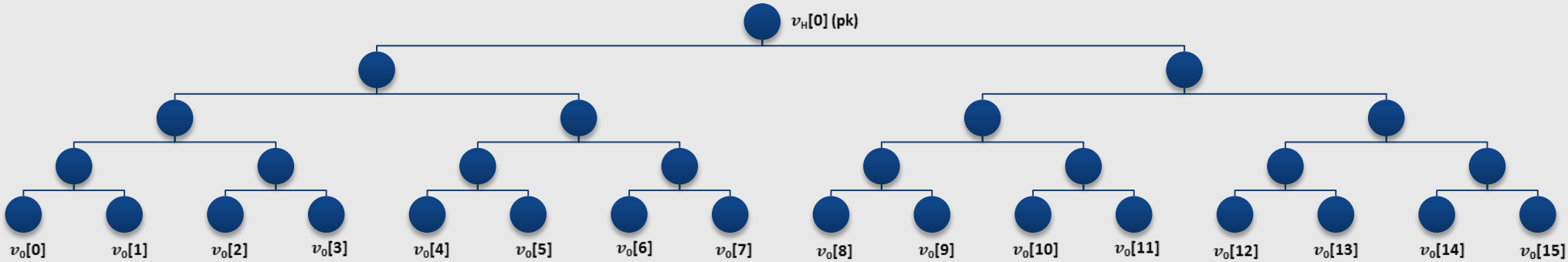
→ **Leakage:** Each generation of Y causes one full leakage of X

Background on Hash-based Signatures

- Given some one-time signature scheme (OTSS)
- Hash together OTS verification keys in a binary hash tree
- Cryptographic hash function $g : \{0,1\}^* \rightarrow \{0,1\}^m$
- Choose tree height H, allows 2^H signatures

MSS Key Generation

- Leaves are hashed one-time verification keys $\nu_0[i] = g(Y_i)$
- Generate root of Merkle tree (MSS verification key)



Background on Hash-based Signatures

MSS Signature Generation

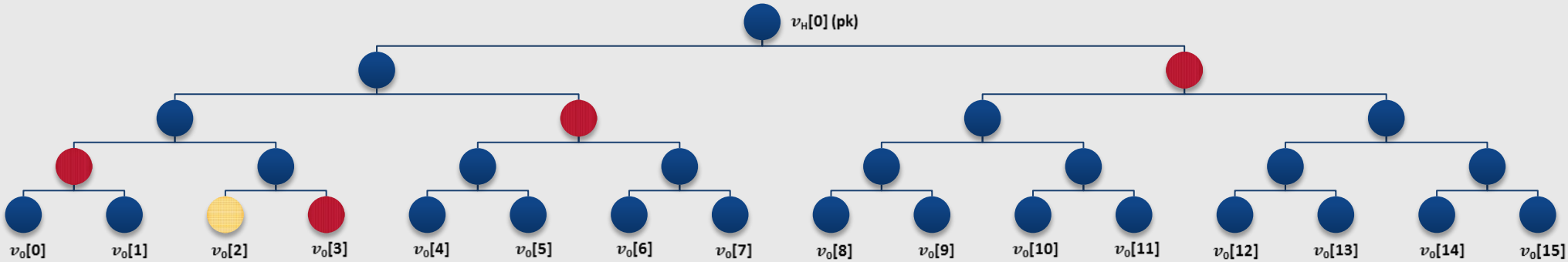
- Compute message digest $d = g(M)$, choose signature index s
- Compute OTS $\sigma_{\mathrm{OTS}} = \mathrm{Sign}_{\mathrm{OTS}}(d, X_s)$ under signing key X_s
- Find all sibling nodes on the way to the root $(\mathrm{AUTH}_0, \ldots, \mathrm{AUTH}_{H-1})$

$$\sigma_s(d) = (s, \sigma_{\mathrm{OTS}}, Y_s, (\mathrm{AUTH}_0, \ldots, \mathrm{AUTH}_{H-1}))$$

- Authentication path independent of message → precomputable

Current (hashed) verification key

Authentication nodes



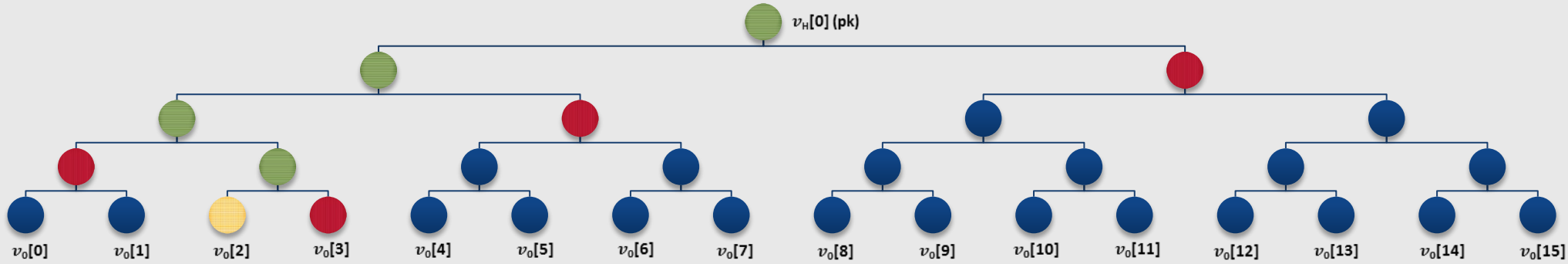
Background on Hash-based Signatures

MSS Signature Verification

- Given digest $d = g(M)$ and signature $\sigma_s(d)$
- Verify underlying one-time signature

→ Reconstruct root of the Merkle tree

- Current (hashed) verification key
- Authentication nodes
- Reconstructed nodes



Practical MSS

Leakage Resilient MSS

- Simply generating and storing all OTS keys independently will yield a leakage resilient signature scheme
- All computations in Merkle tree are public ➔ **No Leakage**
- Memory consumption is too high, so:

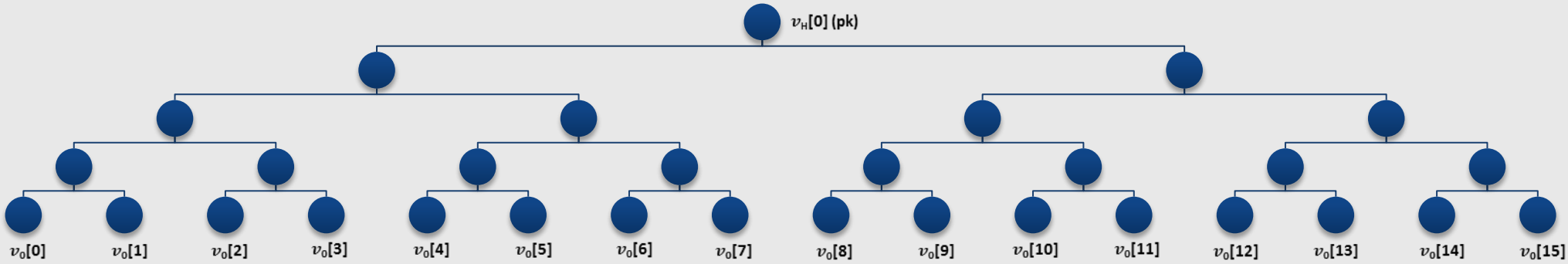
Practical MSS

- Uses PRNG to generate OTS keys
- Allows for just-in-time generation of OTS verification keys for authentication path
- Several optimized algorithms for efficient authentication path generation have been proposed

Authentication Path Computation

Currently best solution: BDS algorithm [BDS09]

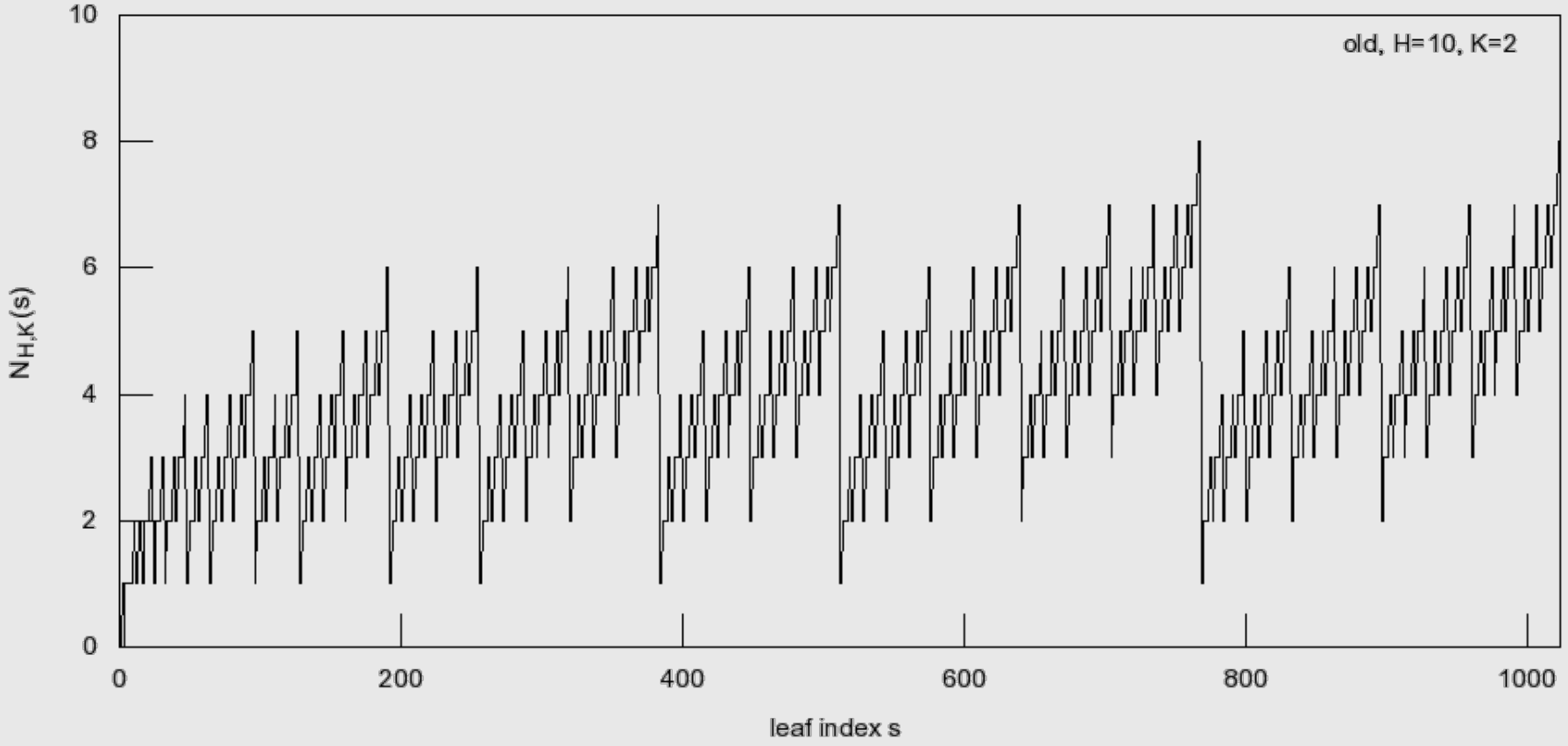
- *Left* authentication nodes are easy to compute:
  either leaf or both child nodes are part of previous authentication paths → store and reuse
- *Right* authentication nodes computed from scratch
- Two ways to determine right authentication nodes
  - Nodes close to the top are most expensive to compute → store them
  - Use instances of the Treehash algorithm [Mer89, Szy04] to compute lower right nodes — one instance per tree level



Drawbacks of the BDS Algorithm

Unbalanced leaf computations

- Some leaves are generated various times, others are barely touched
- Each computation means additional leakage!



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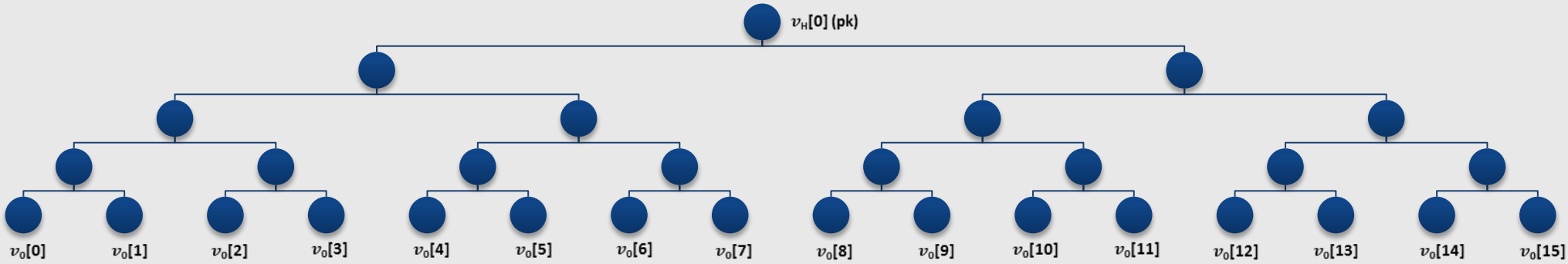
Optimized Authentication Path Computation

- Rightmost nodes of each Treehash instance are computed most frequently → store and reuse them in lower Treehash instances
- Excluding the root of each Treehash instance and Treehash_0
- Every second reinitialization of Treehash_h, $0 \leq h \leq H - K - 2$ can now directly copy the authentication node

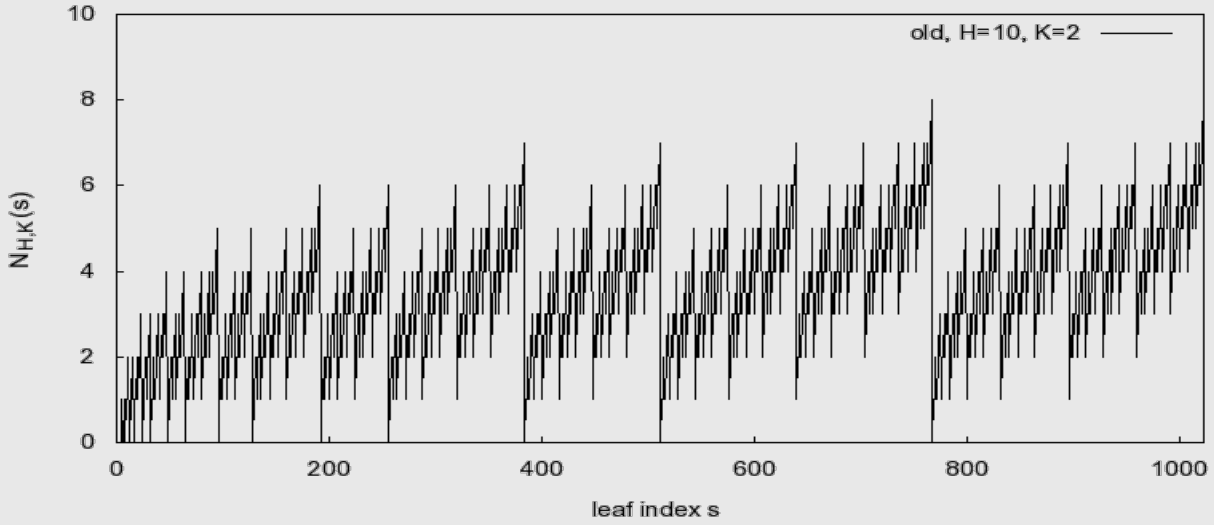
➔ Number of updates is (almost) **halved**!

- Additional storage requirement: $\binom{H-K}{2}$ nodes



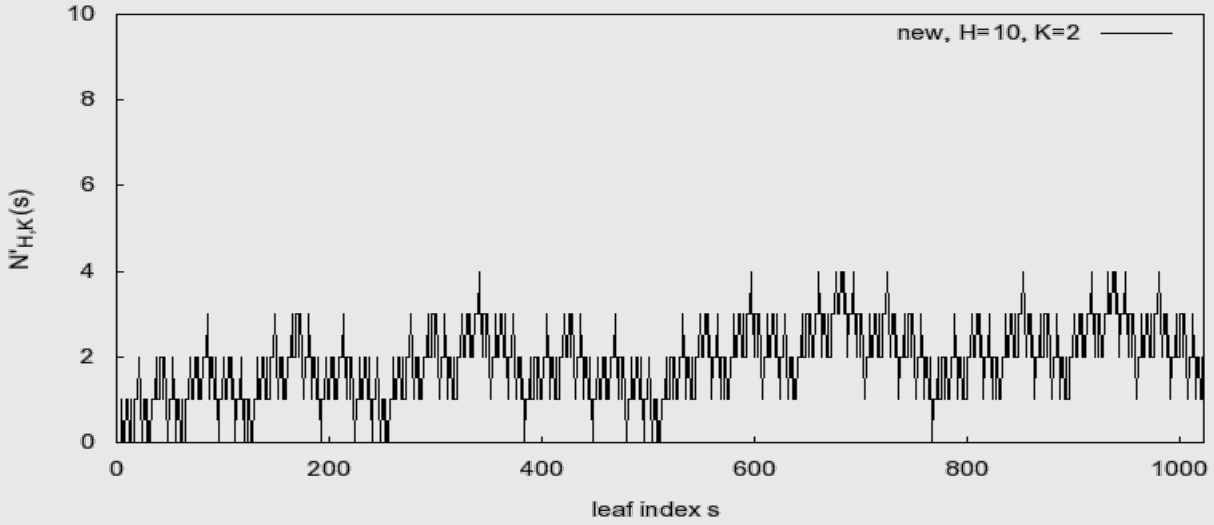
Comparison

Before



Average:
$\approx 1/2(H-K)$

Now



Average:
$\approx 1/4(H-K+1)$

Leakage is halved

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Implementation Choices

- General purpose hash functions have bad performance
- Block cipher constructions can make use of AES coprocessor

For Merkle Tree

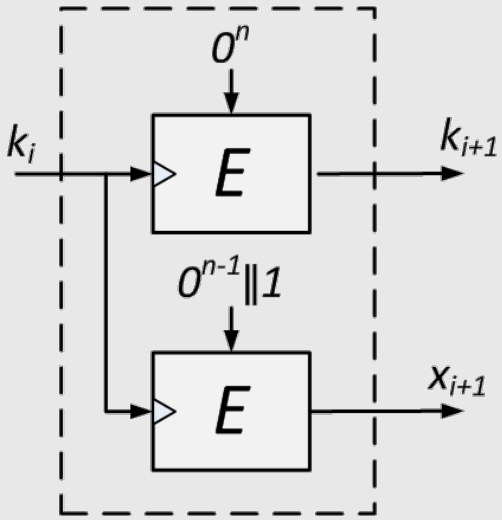
- g **uses AES-128 MJH construction** [LM11] w\ 256/160-bit output

For Winternitz OTS

- f **uses AES-128 MMO construction** [MMO85] w\ 128-bit output

PRNGs

- Leakage-2-limiting PRNG proposed in [SPY+10]
  - Each key used on 2 different inputs only
  - Only static (i.e. non-adaptive leakage allowed)

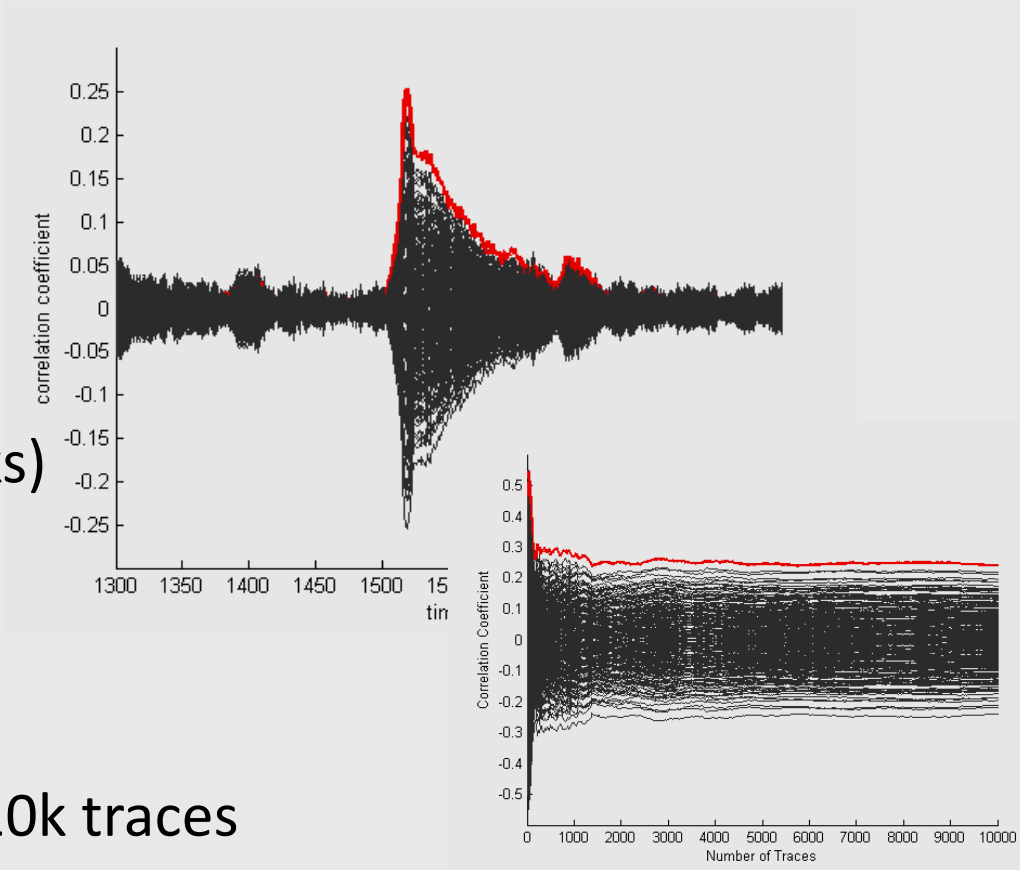


Side Channel Analysis of XMEGA-AES

- AVR XMEGA has unprotected AES co-processor

DPA results

- **[Kiz09]** suggests approx. 2500 traces for key recovery
- No strong leakage at S box output
- Instead HD of 2 inputs (ghost peaks)



- Our results match **[Kiz09]**
- Our correlation is slightly higher:

.27 instead of .18 @10k traces

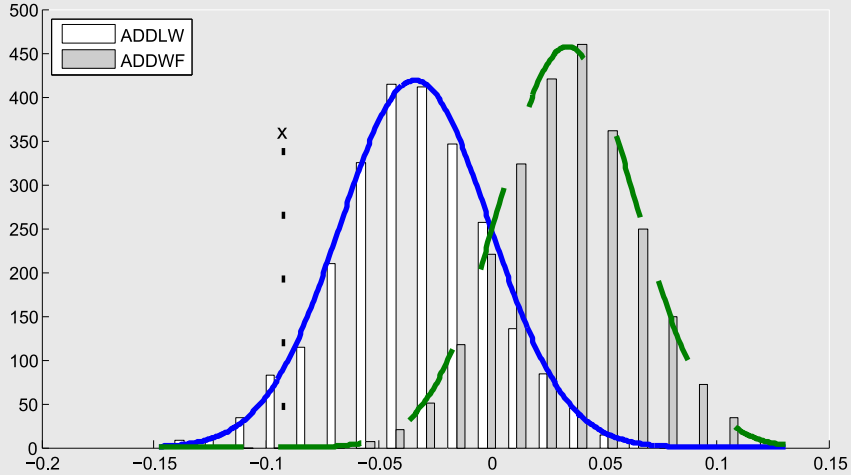
This implies slightly better measurement setup

300 traces suffice

Quantifying Single Measurements

Template Attack

- Univariate templates
- Built from 10k traces
- Point selection via DPA

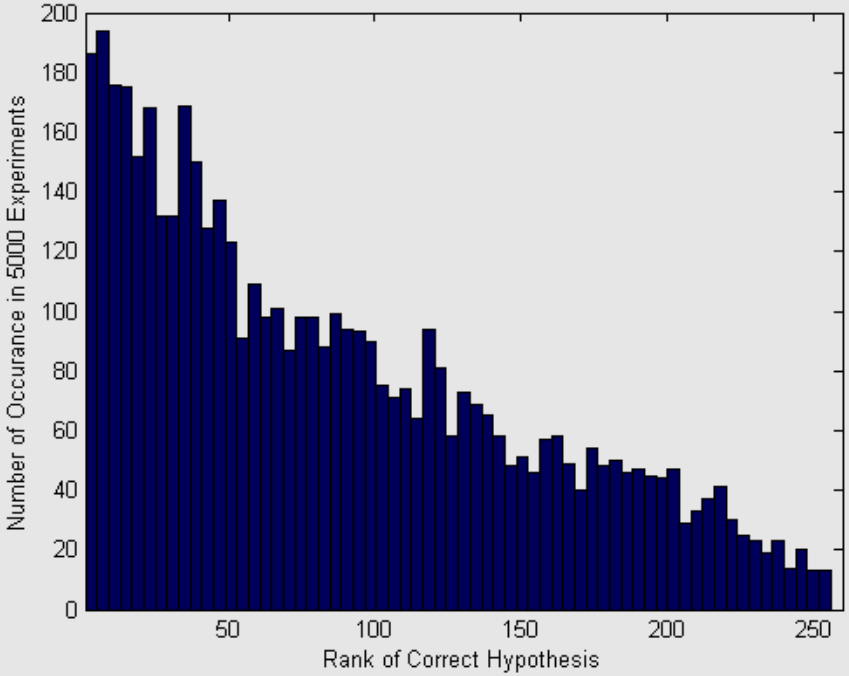


PRNG Leakage Quantification

- 10 leakages on 2 different inputs
- 5000 experiments
- **Guessing Entropy** (av. key rank)

  85.06 or 6.41 bit

→ **Less than one bit per byte**



Implementation Results

CPU Performance (Intel Core i7-2620M, 64-bit)

- Parameters $H = 16, K = 2, w = 2$
- Disabled Turbo Boost and Hyper-threading

Microcontroller Performance (Atmel AVR ATxmega128A1, 8-bit)

- Parameters $H = 10, K = 2, w = 2$
- KeyGen infeasible for reasonable tree heights

Hash g		MJH-256 w/ AES-128			MJH-160 w/ AES-128		
Target		[22]	our	impr.	[22]	our	impr.
Core i7	KeyGen	6546.9 ms	6037.5 ms	8%	4218.7 ms	3886.3 ms	8%
Core i7	Sign	743.9 us	401.3 us	46%	487.1 us	256.2 us	47%
Core i7	Verify	76.1 us	78.1 us	-3%	50.8 us	49.3 us	3%
AVR	Sign	110.0 ms	64.9 ms	41%	70.7 ms	41.7 ms	41%
AVR	Verify	18.4 ms	18.4 ms	0%	11.0 ms	11.0 ms	0%

Conclusions

- Algorithmic improvement for auth. path computation in MSS
- Balanced leaf computations→Reduced side-channel leakage
- Efficient implementations on two common platforms
- Practically verified the theoretic performance gains and bounded leakage on an embedded device

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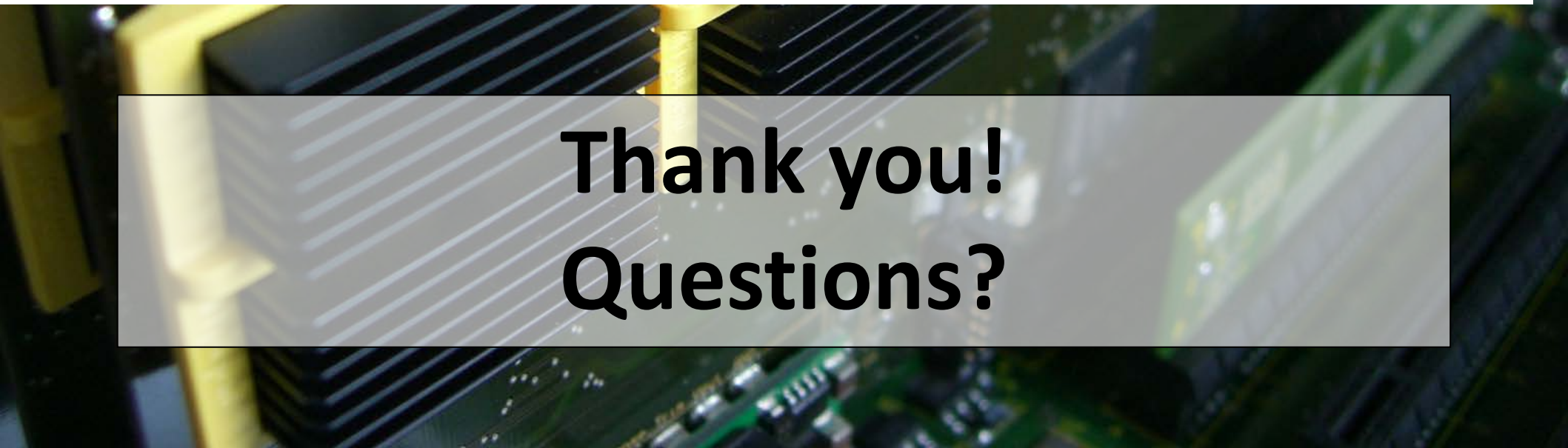

Thank you!
Questions?

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