IMES

FPGA-BASED ACCELERATOR FOR POST-QUANTUM SIGNATURE SCHEME SPHINCS-256

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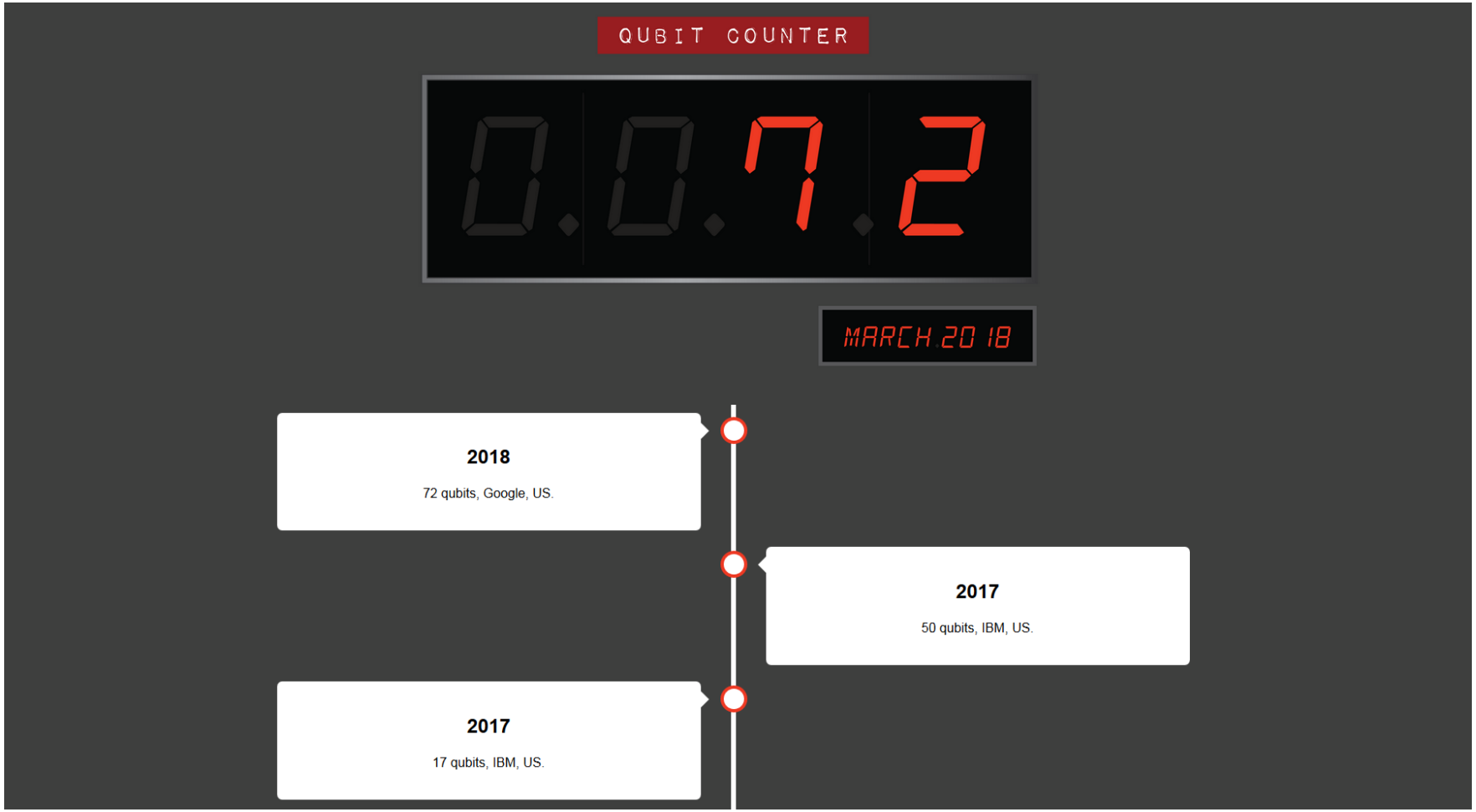
Quantum Computer Progress



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Impact on Current Algorithms

Function	Algorithm	Key length/ Hash length (bits)	Security level (bits)		Quantum Algorithm
			Classical	Quantum	
PKI: Signing, Key Exchange....	RSA-3072	3072	128	0	Shor
	ECC-256	256	128	0	Shor
Symmetric Encryption	AES-128	128	128	64	Grover
	AES-256	256	256	128	Grover
Hash	SHA-256	256	256	128	Grover
	SHA3-512	512	512	256	Grover

Agenda

- **Hash-based signatures**
  - OTS (one-time signature)
  - Merkle trees
  - SPHINCS-256
- **SPHINCS-256 FPGA implementation**
- **Adjustments to SPHINCS+**
- **SPHINCS+ FPGA implementation**
- **Performance results**

} **New, unpublished results!**

Post-Quantum Signature Algorithms…

- **…enable secure signing while an adversary has a quantum computer**
- **Several approaches:**
  - Lattice-based
  - Code-based
  - Supersingular isogeny
  - Others

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  } **All signing protocols need a hash function (message digest)**
- **Hash based signature schemes**
  - Security relies on hardness of (second-) pre-image attack
  - Cryptanalysis: Hash functions are very well analyzed and understood
  - If hash functions are broken, all signing protocols are broken

  => Simply the most conservative choice in terms of security

Lamport One-Time Signature (OTS)

Example: OTS with 256 bit security

1. **Generate 2x256 random numbers, each 256 bits long**
   - $X_{0,0}, X_{0,1}, X_{2,0} \ldots X_{255,1}$
   - $X_{i,j}$ = private key

rand 0		rand 1	
$X_{0,0}$		$X_{0,1}$	
$X_{1,0}$		$X_{1,1}$	
$X_{2,0}$		$X_{2,1}$	
$X_{\ldots,0}$		$X_{\ldots,1}$	
$X_{255,0}$		$X_{255,1}$	

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   - $Y_{0,0} = h(X_{0,0}), Y_{0,1} = h(X_{0,1}), \ldots, Y_{255,1} = h(X_{255,1})$
   - $Y_{i,j}$ = public key

rand 0	*h*(rand 0)	rand 1	*h*(rand1)
$X_{0,0}$	$Y_{0,0}$	$X_{0,1}$	$Y_{0,1}$
$X_{1,0}$	$Y_{1,0}$	$X_{1,1}$	$Y_{1,1}$
$X_{2,0}$	$Y_{2,0}$	$X_{2,1}$	$Y_{2,1}$
$X_{\ldots,0}$	$Y_{\ldots,0}$	$X_{\ldots,1}$	$Y_{\ldots,1}$
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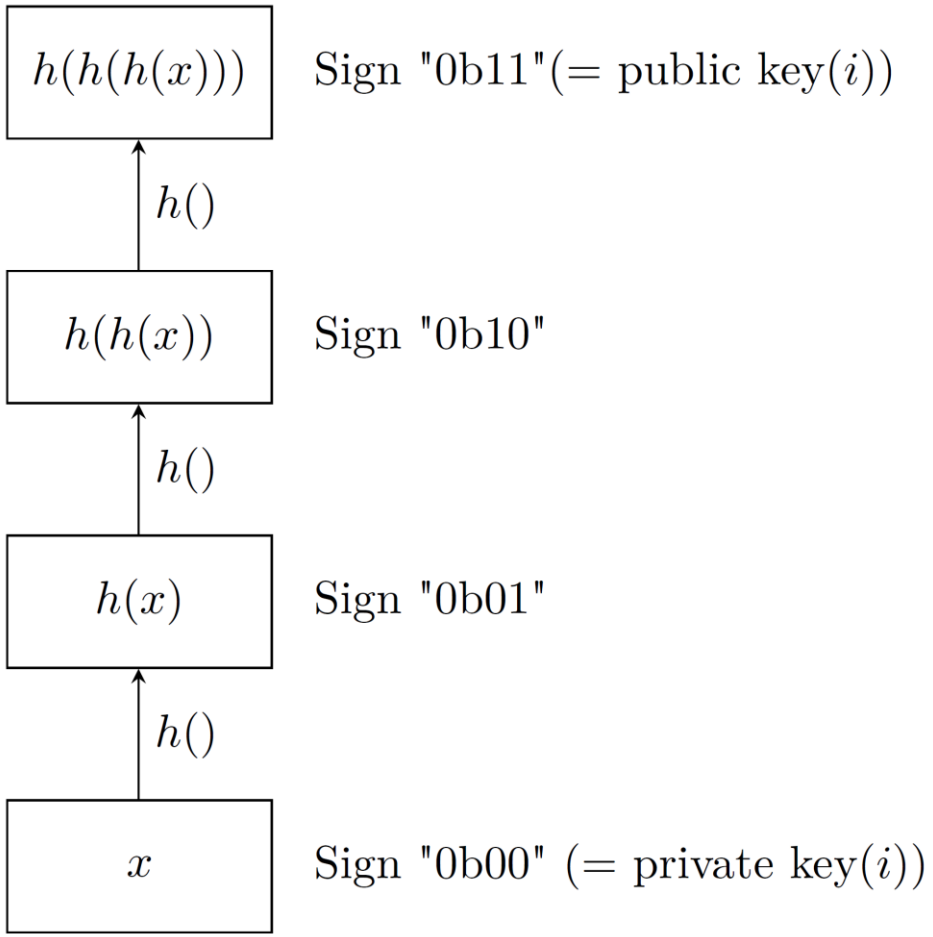
3. **Sign:**
   1. Calculate digest from message $d = h(m)$
   2. For $i = 0$ to 255
      1. If $d_i = 0$, then $\upsilon_i <= X_{i,0}$
      2. Else $\upsilon_i <= X_{i,1}$

rand 0	*h*(rand 0)	rand 1	*h*(rand1)
$X_{0,0}$	$Y_{0,0}$	$X_{0,1}$	$Y_{0,1}$
$X_{1,0}$	$Y_{1,0}$	$X_{1,1}$	$Y_{1,1}$
$X_{2,0}$	$Y_{2,0}$	$X_{2,1}$	$Y_{2,1}$
$X_{\ldots,0}$	$Y_{\ldots,0}$	$X_{\ldots,1}$	$Y_{\ldots,1}$
$X_{255,0}$	$Y_{255,0}$	$X_{255,1}$	$Y_{255,1}$

***h(m)* = 0b010…1**

=> Signature(m) = ($X_{0,0}, X_{1,1}, X_{2,0}, \ldots, Y_{255,1}$)

W-OTS+ Shorter Signatures for Hash-Based Signature Schemes

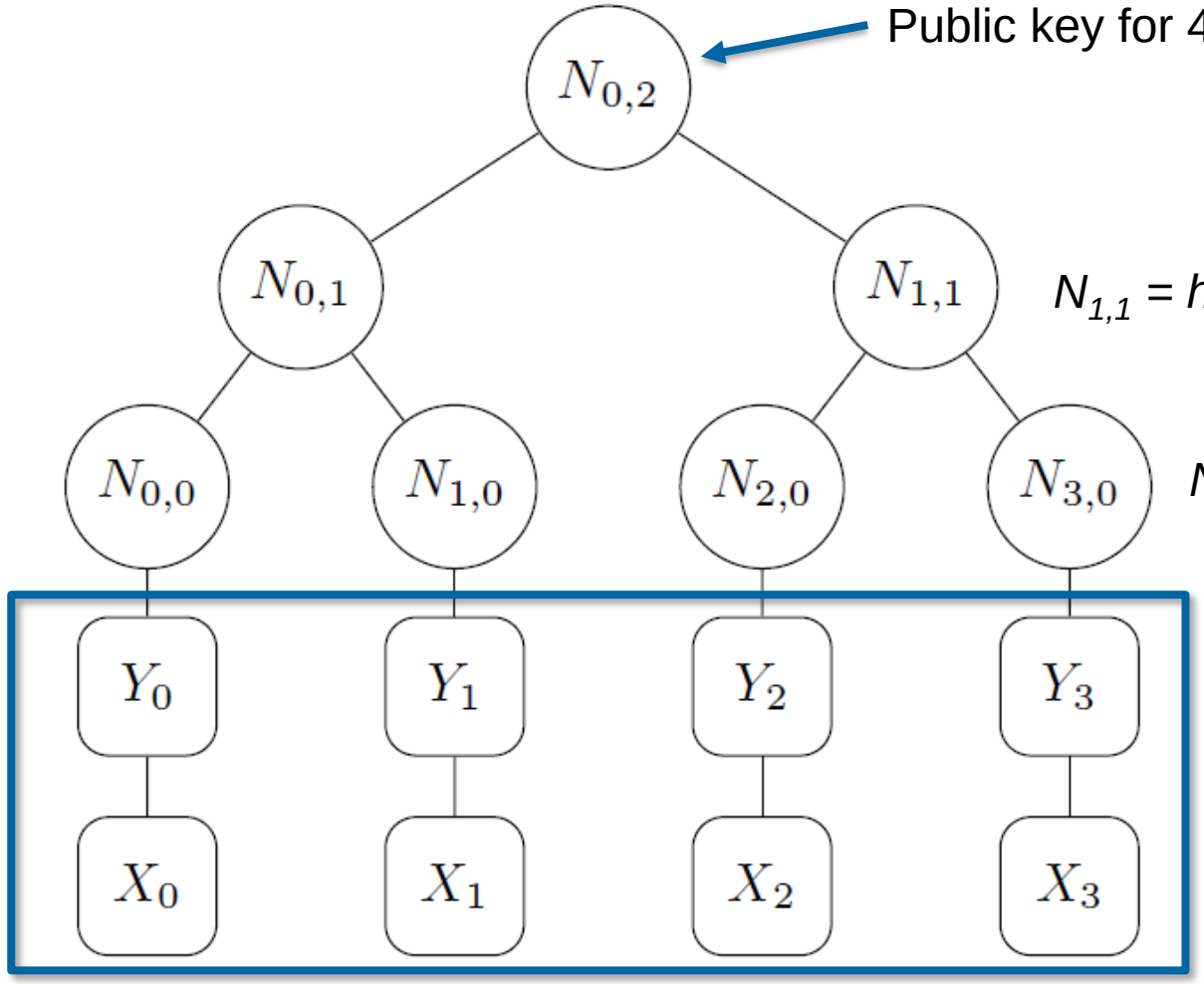


- **Sign a few bits per random number**
- **Increases processing time**
- **Decreases key and signature sizes**

W-OTS+

+ **Signature system which security is based only on security of hash function**
+ **Quantum secure**
+ **Very fast**
– **One signature per key pair**

Merkle Tree



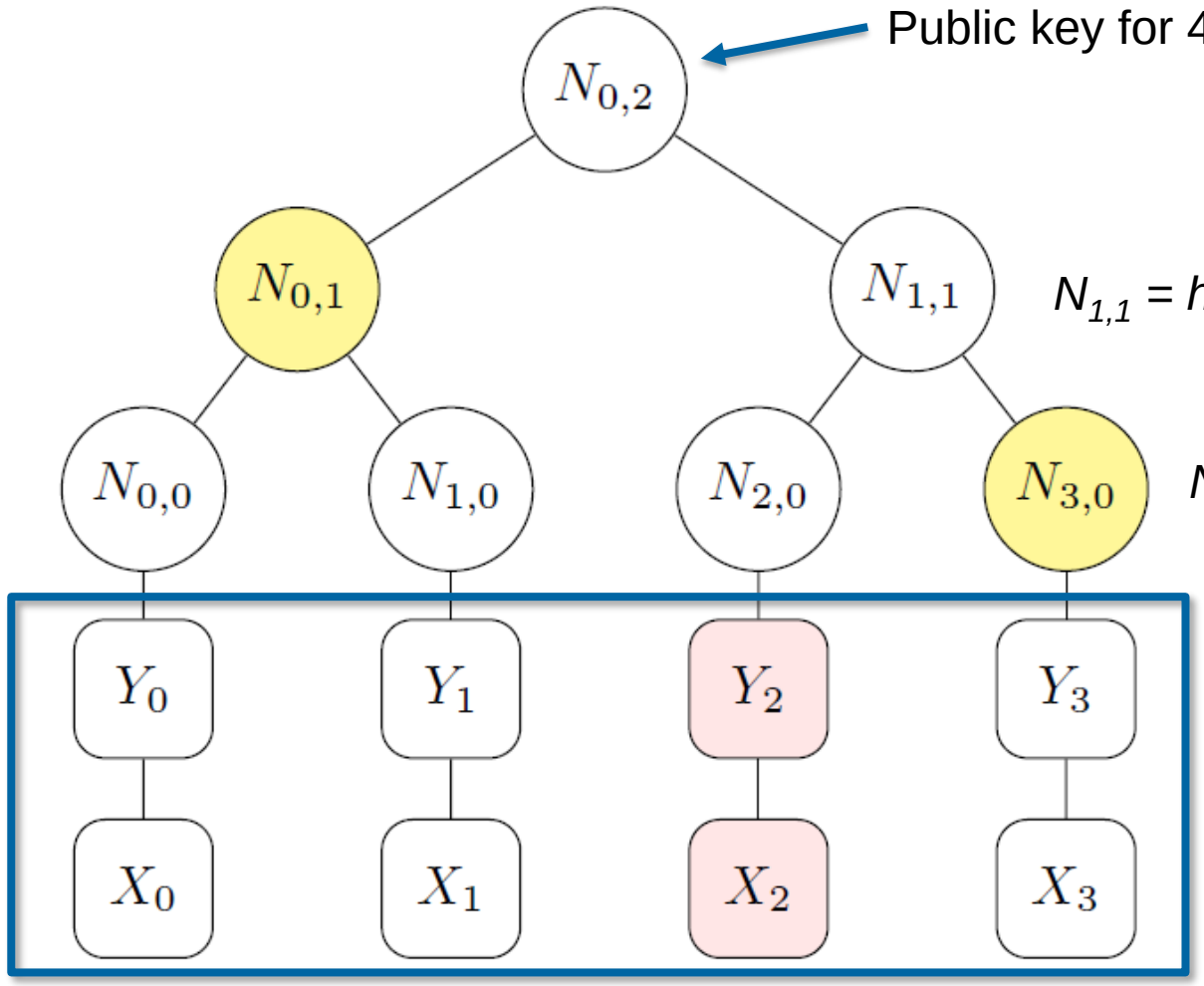
Public key for 4 signatures

$N_{1,1} = h(N_{2,0} \,||\, N_{3,0})$

$N_{3,0} = h(Y_3)$

4 W-OTS+ key pairs

Merkle Tree



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4 W-OTS+ key pairs

Merkle Tree

+ **Signature system which security is based only on security of hash function**
+ **Quantum secure**
+ **Fast operations**
– **State-based**

  => Check-list required: Which W-OTS+ key pairs (leaves of the tree) are already used?

SPHINCS

- **Make a hyper-tree (tree of trees)**
  - Increases number of leaves dramatically
- **Use a FTS (few-time signature) at bottom layer instead of OTS**
- **Choose starting point at random**

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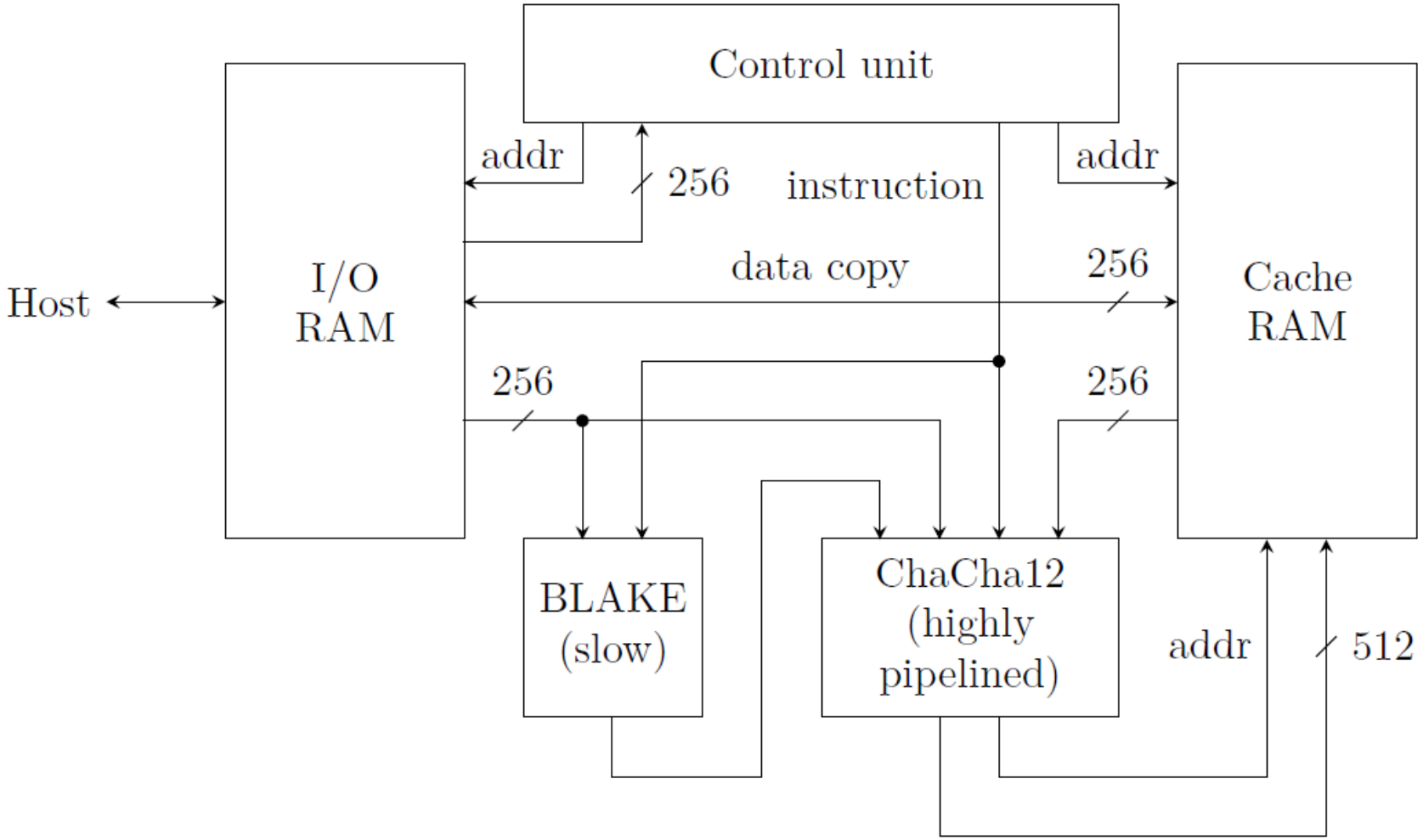
Source: https://sphincs.cr.yp.to/

=> Stateless, practical, hash-based, incredibly nice cryptographic signatures (SPHINCS)

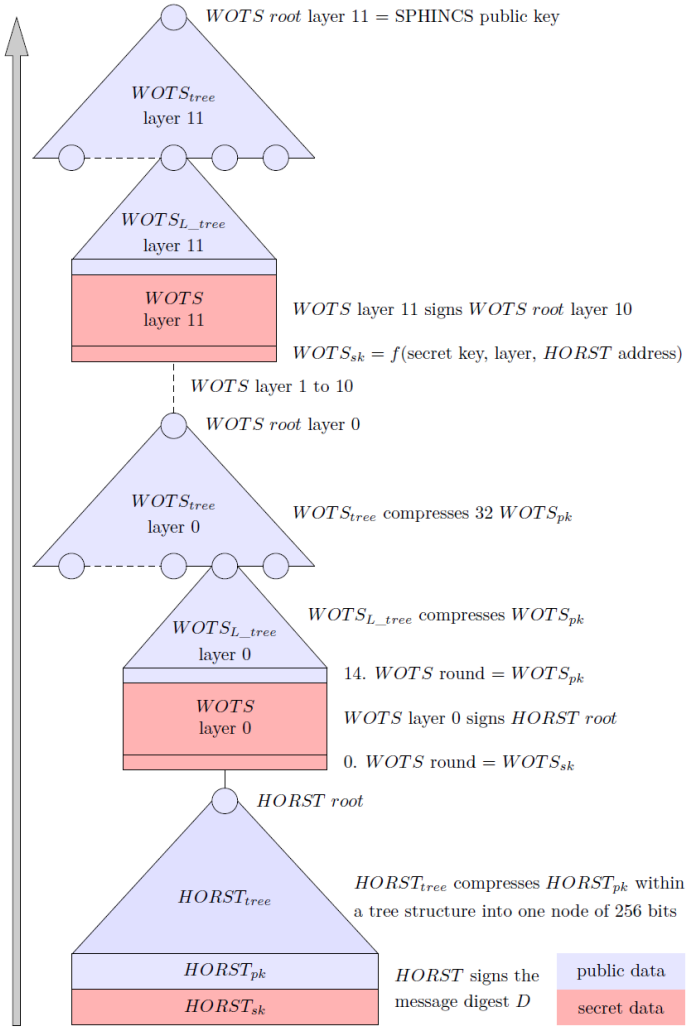
SPHINCS-256 Operation Count

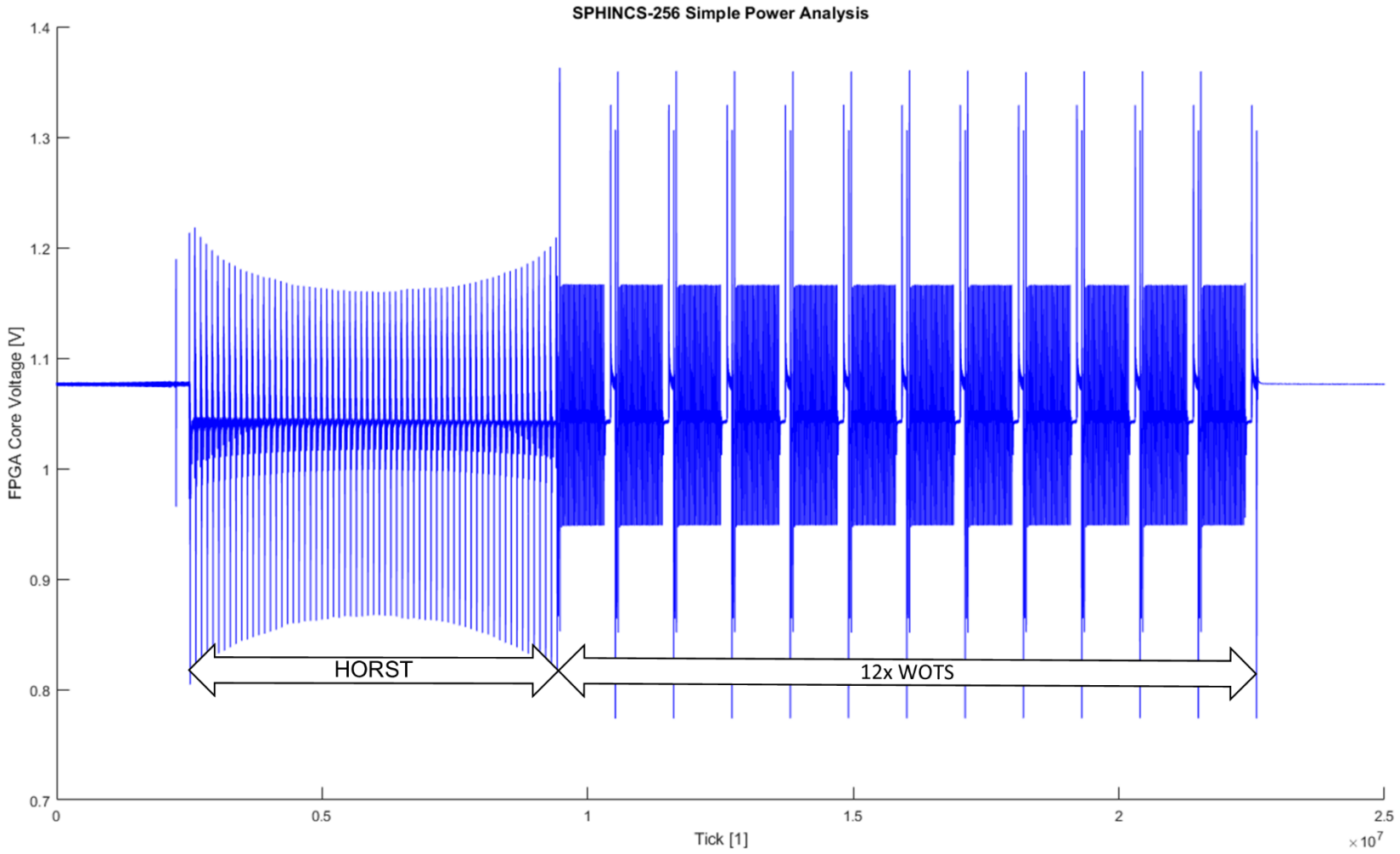
Function	Signing					Verification
Part	Start	HORST	WOTS	Overhead	Total	Total
BLAKE-256	0	1	384	12	**397**	0
ChaCha12	0	32,768	13,056	408	**46,232**	0
π_{ChaCha}	0	193,410	437,352	≈9000	**640,000**	≈9000
BLAKE-512	2	0	0	0	**2**	1

SPHINCS-256 Core Top



Simple Power Analysis

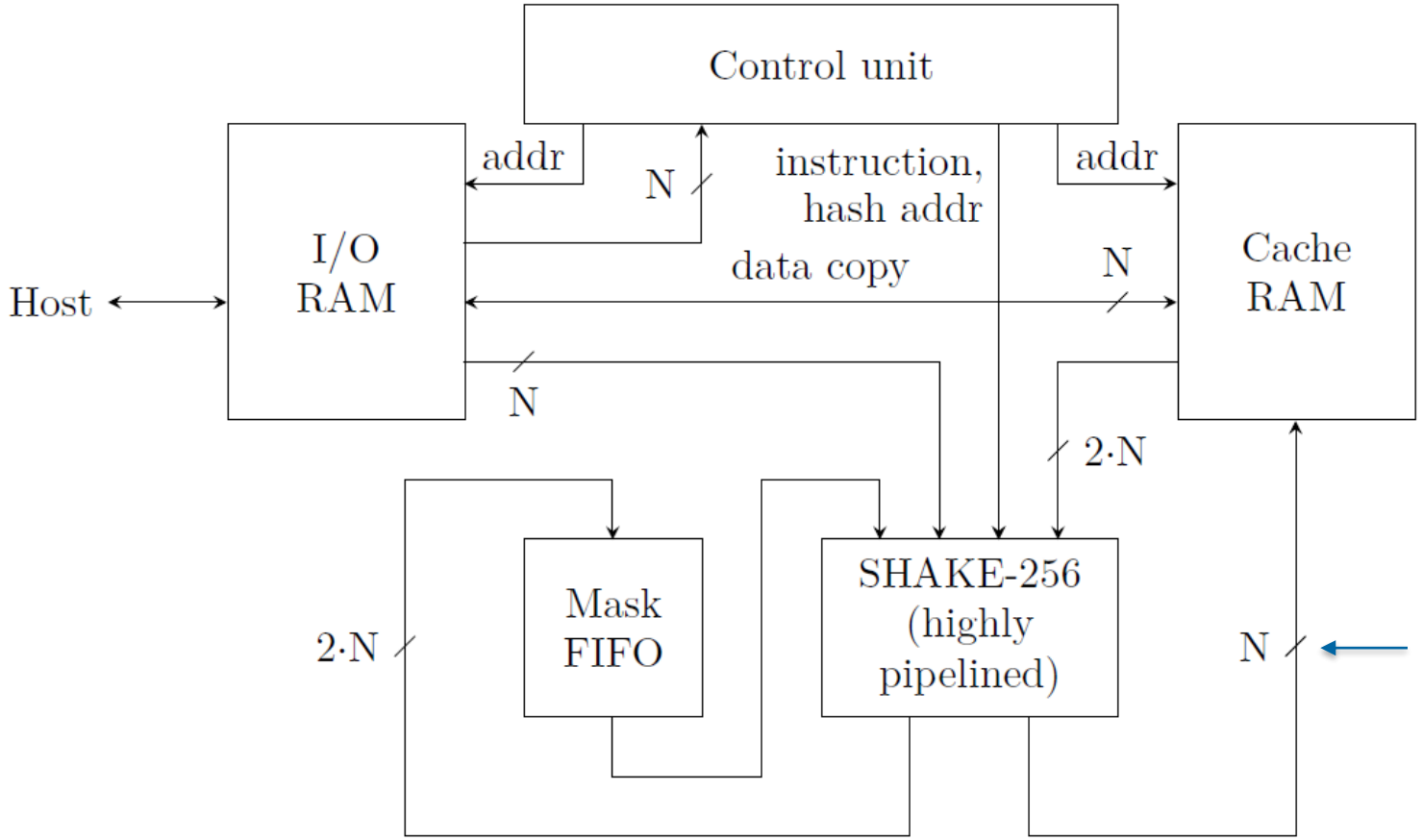




SPHINCS+

- **Submitted to the NIST post-quantum project**
- **Some adjustments to SPHINCS-256**
  - Few-Time signature is now more efficient (security, processing time, signature size)
  - Change underlying hash function
  - Masks are generated (PRNG) => reduces key sizes
- **Several instances**
  - Security level 1, 3, and 5 (≙ 128, 192, and 256 bit)
  - Different hash functions
    - SHAKE-256 (SHA-3)
    - SHA-256
    - Haraka
  - Always a fast (larger signature) and a small (slower processing) version

SPHINCS+ Core Top



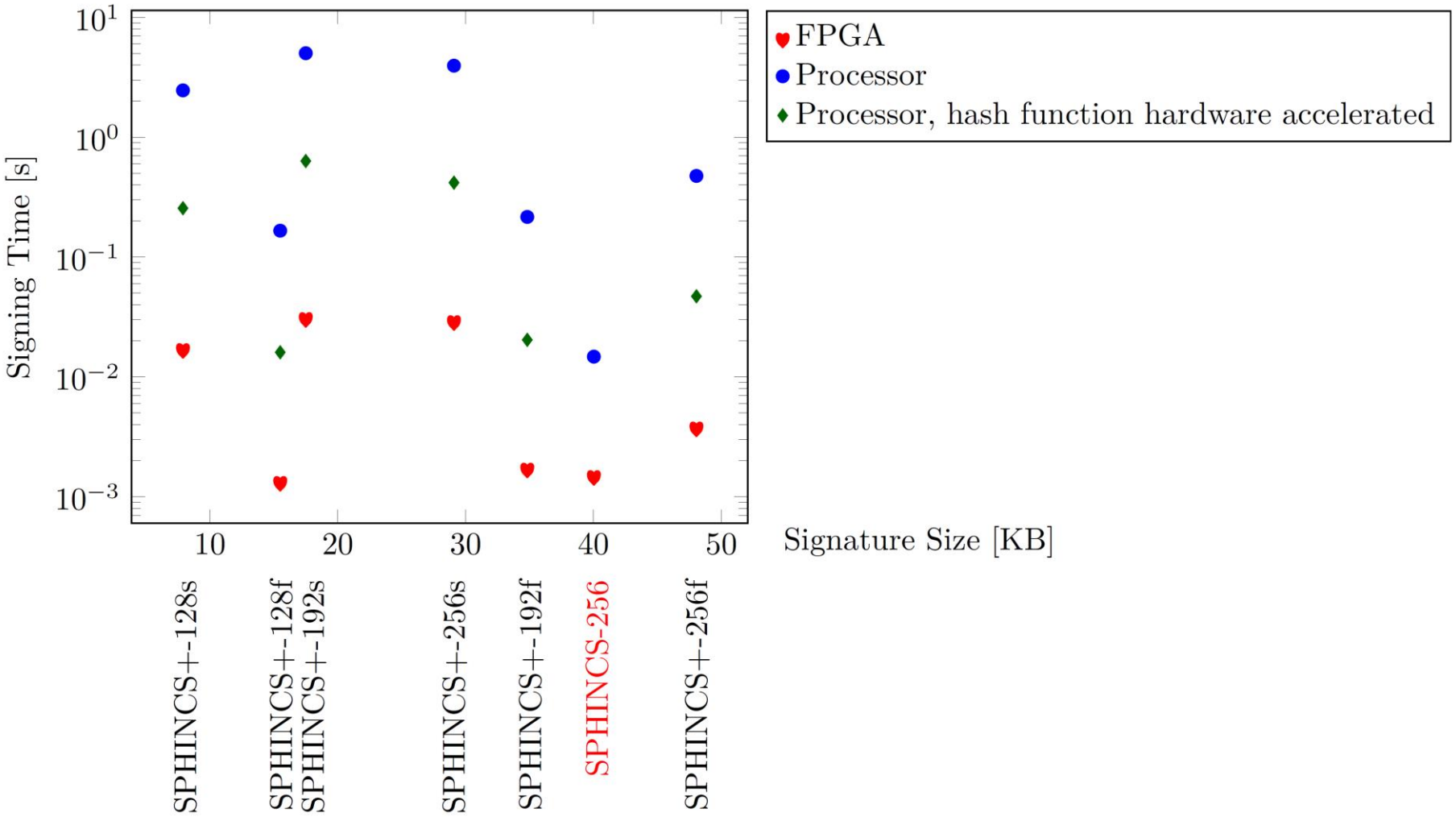
Performance Results

Instance	Sign	FPGA Resources			Sign	Clock	T sign	T verify
	[KByte]	LUT	FF	BRAM	[clks]	[MHz]	[ms]	[ms]
SPHINCS-256	40	19k	38k	36	805k	525	1.53	0.07
SPHINCS+-SHAKE256-128s	7.9	49k	73k	15.5	5,275k	300*	17.58	0.09
SPHINCS+-SHAKE256-128f	16.6	47k	73k	15.5	410k	300*	1.37	0.19
SPHINCS+-SHAKE256-192s	16.7	50k	74k	22.5	9,569k	300*	31.90	0.12
SPHINCS+-SHAKE256-192f	34.8	50k	74k	22.5	530k	300*	1.77	0.25
SPHINCS+-SHAKE256-256s	29.1	50k	76k	30	9,025k	300*	30.08	0.17
SPHINCS+-SHAKE256-256f	48	52k	76k	30	1,169k	300*	3.90	0.28

*Clock frequency of SHAKE-256 pipeline runs at 600 MHz

All results are related to Xilinx Kintex-7 device (XC7K325T-2)

Performance Comparison



Summary

- **FPGA Implementation SPHINCS-256**
  - >600 sign/s, >15000 verifications/s for SPHINCS-256
- **FPGA Implementation SPHINCS+-SHAKE256-128f**
  - >700 sign/s, >5000 verifications/s for
- **SPA: Protected**
- **DPA: Robust**
  - We tried hard, but could not extract any key bits.

Thank you

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Innosuisse – Swiss Innovation Agency

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Why is SPHINCS+ slower than SPHINCS-256?

- **Factor two is lost due to the mask computation**
- **The hash function SHAKE-256 needs more computational effort than ChaCha12**
- **L-tree computation is faster than the calculation of SHAKE-256 with a long input.**
  - The latter holds only for our highly pipelined FPGA implementation and is caused by pipeline stalls.

Implementation Results

Ref	Scheme	Security Classic	Security PQ	FPGA	Area LUT/FF/DSP/BRAM	f MHz	t ms	t·area s·LUT
this	SPHINCS-256	256	128	K7	19,067/38,132/3/36	525	1.53	29.4
[PDG14]	BLISS-IV	192	?	S6	6,438/6,198/5/7	135	0.35	2.25
[ACZ16]	ECDSA-256	128	0	V7	6,816/4,442/20/0	225	1.49	10.2
[ACZ16]	ECDSA-521	256	0	V7	8,273/7,689/64/0	161	5.02	41.5
[SA14]	RSA-2048	112	0	V7	3,558 slices/54/0	399	5.68	≈60
[BHH+15]	SPHINCS-256	256	128	Haswell CPU E3-1275 (1 core)		3500	14.7	-