Tampere University

ACCELERATING SLH-DSA BY TWO ORDERS OF MAGNITUDE WITH A SINGLE HASH UNIT

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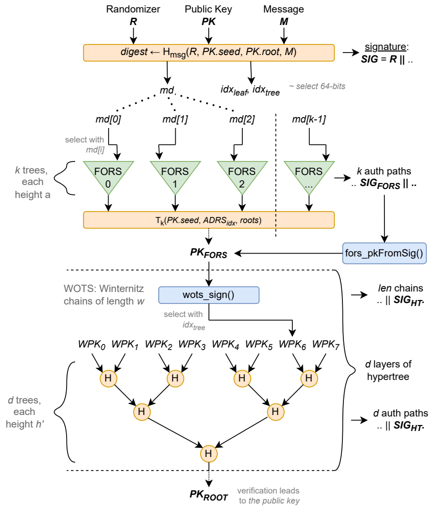
FIPS 205, SLH-DSA (Stateless Hash-Based Digital Signature Standard)

SLH-DSA is the NIST-standardized version of the **SPHINCS**$^+$ scheme by Andreas Hülsing and others.

Stateless hash-based signature scheme:
No need to keep track of signing state / index.
Each secret key can be used for 2^{64} signatures.

Relatively complex, multi-stage algorithm.
Forest of Random Subsets (FORS), Winternitz One-Time Signature Scheme (WOTS$^+$), eXtended Merkle Signature Scheme (XMSS) hypertree.

FIPS 205 came into effect on August 13, 2024.
Only change in final: Domain-separating $M \rightarrow M'$ padding for different input hashing methods.



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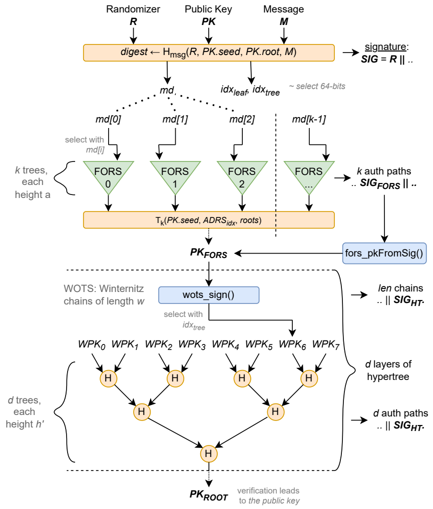

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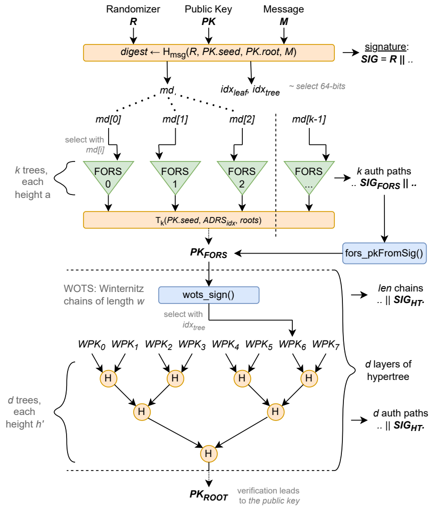

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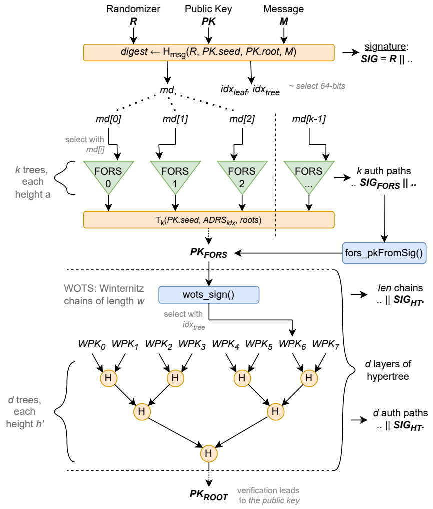
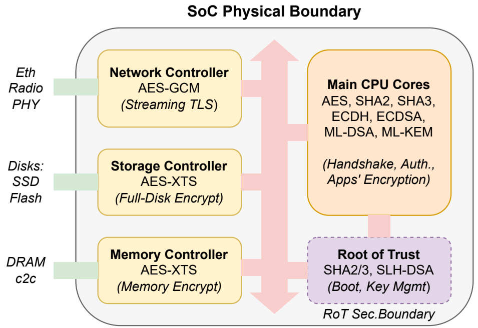


SLotH: SLH-DSA Architecture for SoC Root-of-Trust (RoT) Units

Typical Use Case:


SoC Physical Boundary
Eth Radio PHY
Disks: SSD Flash
DRAM c2c
Network Controller AES-GCM (Streaming TLS)
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Main CPU Cores AES, SHA2, SHA3, ECDH, ECDSA, ML-DSA, ML-KEM (Handshake, Auth., Apps' Encryption)
Root of Trust SHA2/3, SLH-DSA (Boot, Key Mgmt)
RoT Sec.Boundary

SLH-DSA can be used by RoTs for boot signatures, updates, and attestation.

SLotH Features:

- Keccak (SHAKE) and SHA2 (256/512): Supports all parameter sets of SLH-DSA in FIPS 205 ("internal" functions in the final version.)
- Not much larger than existing Root-of-Trust hash accelerators.
- But often 10 times faster due to SLH-DSA specific optimizations.
- Side-channel countermeasures.
- (Passes TVLA leakage assessment.)

(Full software and hardware source code: `https://github.com/slh-dsa/sloth`)

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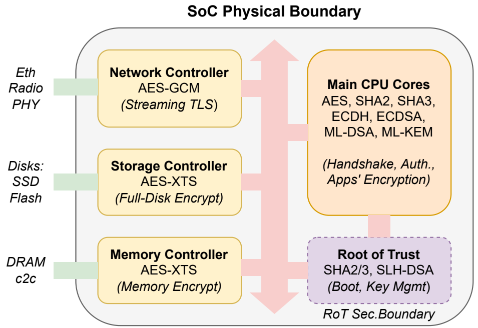
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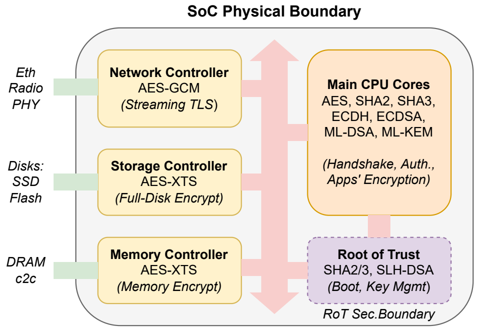

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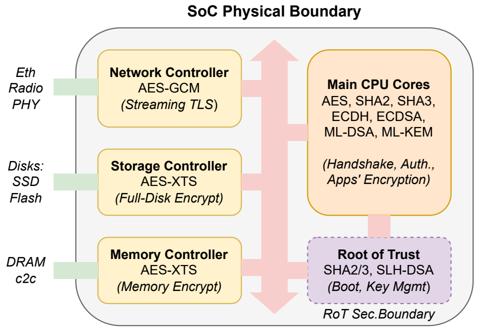

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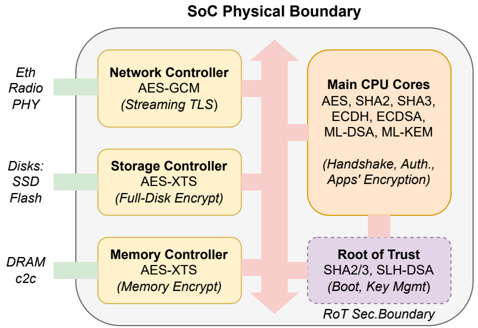

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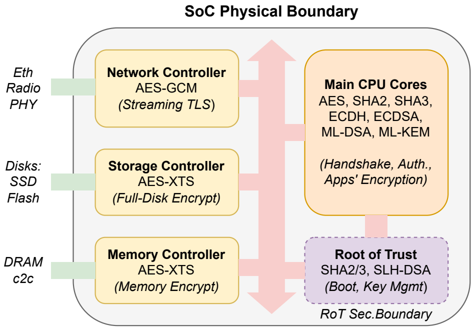

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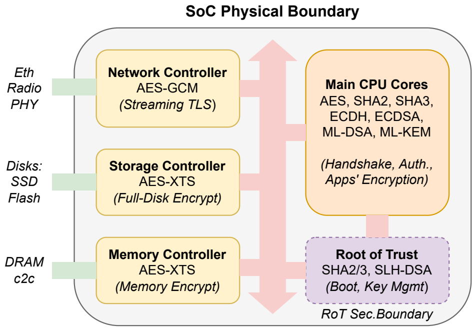

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10 × Faster than big CPUs, over 100 × Faster than Embedded SW

Example: SLH-DSA-SHAKE-128f (SPHINCS$^+$-SHAKE-128f-simple) cycle counts.

Implementation	KeyGen	Sign	Verify
pqm4: Embedded SW [1]	59,759,081	1,483,676,214	83,065,165
avx2: Main CPU SW [2]	2,249,444	56,933,788	3,346,068
shake256_lsu HW [3]	1,724,534	42,597,665	2,457,742
SLotH [this work]	176,552	4,903,978	440,636
Gain over embed SW [1]	338.5×	302.5×	188.5×
Gain over AVX2 SW [2]	12.7×	11.6×	7.6×
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Why is current software and hardware so much worse?

- Hashes are very fast in hardware, and very slow on CPUs:
  SHA3/SHAKE (Keccak f1600) is 24 cycles in HW, 2,000 (..10,000+) cycles on CPUs.
  SHA2 (256/512 compr. func) is 64/80 cycles in HW, 1,000+ cycles on CPUs.
- Hash accelerators are designed to hash data, not to hash other hashes.
- A lot of cycles are wasted with CPU setting up new data to be hashed.

How did we make it faster: *(Perform quantitative analysis, remove bottlenecks.)*

- Automate hash primitive formats in hardware, minimizing CPU involvement:
  Hold keys (PK.seed and SK.seed) and ADRS fields in hardware registers.
- Automate Winternitz iteration – most of SLH-DSA is performing iteration (2):

$$X^0 = \mathrm{PRF}(\mathrm{PK.seed}, \mathrm{SK.seed}, \mathrm{ADRS} = \texttt{WOTS\_PRF}) \tag{1}$$

$$X^j = \mathrm{F}(\mathrm{PK.seed}, \mathrm{ADRS} = \texttt{WOTS\_HASH}(j), X^{j-1}) \text{ for } j \geq 1. \tag{2}$$

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Why is current software and hardware so much worse?

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SLH-DSA Hash Primitives: Public and Secret Variables (1/2)

$\underline{\mathrm{H}_{\mathrm{msg}}(R, \mathrm{PK} = (\mathrm{PK.seed} \parallel \mathrm{PK.root}), M)}$	*(PQ-ITSR)*	Used in:
$= \mathrm{SHAKE256}(R \parallel \mathrm{PK} \parallel M, 8m)$		*SHAKE, all*
$= \mathrm{MGF1\text{-}SHA\text{-}256}(R \parallel \mathrm{PK.seed} \parallel \mathrm{SHA\text{-}256}(R \parallel \mathrm{PK} \parallel M), m)$		*SHA2*, $n = 16$
$= \mathrm{MGF1\text{-}SHA\text{-}512}(R \parallel \mathrm{PK.seed} \parallel \mathrm{SHA\text{-}512}(R \parallel \mathrm{PK} \parallel M), m)$		*SHA2*, $n \geq 24$
$\underline{\mathrm{PRF}(\mathrm{PK.seed}, \mathrm{SK.seed}, \mathrm{ADRS})}$	*(PQ-PRF)*	Used in:
$= \mathrm{SHAKE256}(\mathrm{PK.seed} \parallel \mathrm{ADRS} \parallel \mathrm{SK.seed}, 8n)$		*SHAKE, all*
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}256}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 64 - n) \parallel \mathrm{ADRS}^c \parallel \mathrm{SK.seed}))$		*SHA2, all*
$\underline{\mathrm{PRF}_{\mathrm{msg}}(\mathrm{SK.prf}, opt\_rand, M)}$	*(PQ-PRF)*	Used in:
$= \mathrm{SHAKE256}(\mathrm{SK.prf} \parallel opt\_rand \parallel M, 8n)$		*SHAKE, all*
$= \mathrm{Trunc}_n(\mathrm{HMAC\text{-}SHA\text{-}256}(\mathrm{SK.prf}, opt\_rand \parallel M))$		*SHA2*, $n = 16$
$= \mathrm{Trunc}_n(\mathrm{HMAC\text{-}SHA\text{-}512}(\mathrm{SK.prf}, opt\_rand \parallel M))$		*SHA2*, $n \geq 24$

SLH-DSA Hash Primitives: Public and Secret Variables (2/2)

$\underline{\mathrm{F}(\mathrm{PK.seed}, \mathrm{ADRS}, M_1)}$	*(PQ-DM-SPR)*	Used in:
$= \mathrm{SHAKE256}(\mathrm{PK.seed} \parallel \mathrm{ADRS} \parallel M_1, 8n)$		*SHAKE, all*
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}256}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 64 - n) \parallel \mathrm{ADRS}^c \parallel M_1))$		*SHA2, all*
$\underline{\mathrm{H}(\mathrm{PK.seed}, \mathrm{ADRS}, M_2)}$	*(PQ-DM-SPR)*	Used in:
$= \mathrm{SHAKE256}(\mathrm{PK.seed} \parallel \mathrm{ADRS} \parallel M_2, 8n)$		*SHAKE, all*
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}256}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 64 - n) \parallel \mathrm{ADRS}^c \parallel M_2))$		*SHA2,* $n = 16$
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}512}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 128 - n) \parallel \mathrm{ADRS}^c \parallel M_2))$		*SHA2,* $n \geq 24$
$\underline{\mathrm{T}_\ell(\mathrm{PK.seed}, \mathrm{ADRS}, M_\ell)}$	*(PQ-DM-SPR)*	Used in:
$= \mathrm{SHAKE256}(\mathrm{PK.seed} \parallel \mathrm{ADRS} \parallel M_\ell, 8n)$		*SHAKE, all*
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}256}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 64 - n) \parallel \mathrm{ADRS}^c \parallel M_\ell))$		*SHA2,* $n = 16$
$= \mathrm{Trunc}_n(\mathrm{SHA\text{-}512}(\mathrm{PK.seed} \parallel \mathrm{toByte}(0, 128 - n) \parallel \mathrm{ADRS}^c \parallel M_\ell))$		*SHA2,* $n \geq 24$

Hash Primitive Counts: `slh_sign()`, Signature Generation

Distribution of hash primitive calls in SLH-DSA-SHA2- and SLH-DSA-SHAKE-* signining.*

Function	**128f**	**192f**	**256f**	**128s**	**192s**	**256s**
PRF	8,272	17,424	36,144	182,784	461,312	497,664
F	94,246	142,697	290,775	1,938,676	3,019,898	2,418,182
H	2,230	8,566	18,136	60,898	282,079	362,458
T_ℓ	176	176	272	3,584	3,584	2,048
Total	104,926	168,865	345,329	2,185,944	3,766,875	3,280,354
chain()	6,895	10,047	19,296	125,650	183,090	137,685
chain F	92,134	134,249	272,855	1,881,332	2,741,370	2,057,734
chain %	87.8%	79.5%	79.0%	86.1%	72.8%	62.7%

- A large majority of signing work is in F calls in chain() – Winternitz iteration.
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Function	128f	192f	256f	128s	192s	256s
PRF	0	0	0	0	0	0
F	5,908	8,620	8,633	1,886	2,751	4,067
H	264	330	383	231	301	372
T_ℓ	23	23	18	8	8	9
Total	6,196	8,974	9,035	2,126	3,061	4,449
chain()	770	1,122	1,139	245	357	536
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- More than 90% of verification work is in F calls in chain() – Winternitz iteration.
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On SLotH Hardware and Firmware

Full hardware and software for the prototype:
`https://github.com/slh-dsa/sloth`

Some Features and Notes:

- About 6,700 lines of bare metal ANSI C and 4,100 lines of Verilog.
- I wrote it mostly from scratch after the publication of FIPS 205 ipd.
- Actually Free: BSD 3-Clause License, no patent applications, etc.
- Shared implementation for all 12 parameters; 16.4kB binary “ROM” for all.
- Works with 64kB RAM (4kB stack – recall that signatures are up to 50kB).
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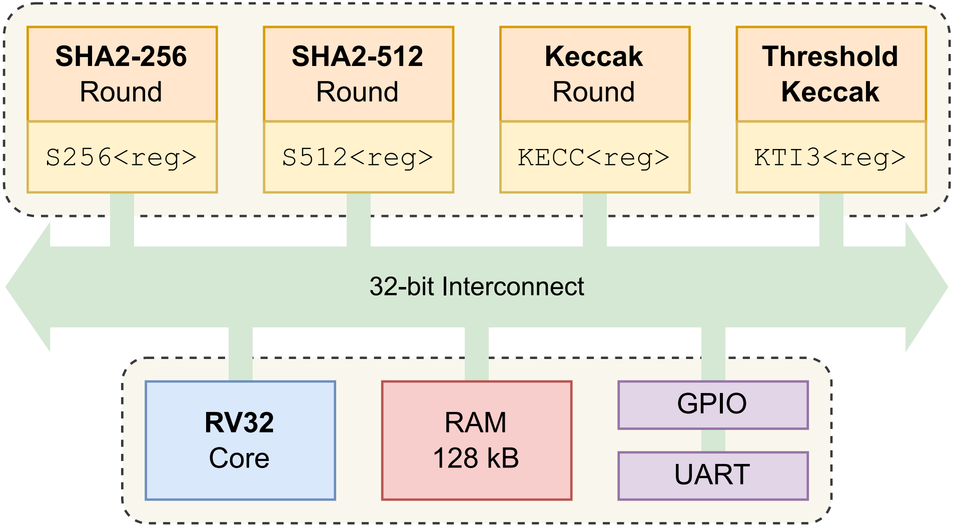
Block Diagram: Straightforward Memory-Mapped units (no DMA)



Example Register Map: KTI3_<reg> Threshold Keccak

Register Name	Offset	Bytes	Brief description
_BASE_ADDR	(0)	(1024)	Memory-mapped in prototype at 0x14000000.
KTI3_MEMA	0x0000	200	1600-bit Keccak permutation input-output state *A*.
KTI3_MEMB	0x00c8	200	Keccak secret state share B. *(Only in TI3.)*
KTI3_MEMC	0x0190	200	Keccak secret state share C. *(Only in TI3.)*
KTI3_ADRS	0x0260	32	32-byte ADRS structure for hash formatting.
KTI3_SEED	0x0280	32	Public key variable PK.seed for hash formatting.
KTI3_SKSA	0x02a0	32	Secret key SK.seed for PRF, share A.
KTI3_SKSB	0x02c0	32	Secret key SK.seed for PRF, share B. *(Only in TI3.)*
KTI3_SKSC	0x02e0	32	Secret key SK.seed for PRF, share C. *(Only in TI3.)*
KTI3_CTRL	0x03c0	4	Raw function control and status: Write 0x01 to start raw Keccak f1600, read for status (0x00=ready).
KTI3_STOP	0x03c4	4	Round count (for TurboShake / KangarooTwelve).
KTI3_SECN	0x03c8	4	Security / field length write $n \in \{16, 24, 32\}$.
KTI3_CHNS	0x03cc	4	Iteration count & trigger for hashing and chaining. - Set to s for s Winternitz F iterations. - Set to 0x40 + s for PRF + s Winternitz F iterations. - Set to 0x80 to perform initial padding for H or T_ℓ.

Configurable Hardware: Artix 7 FPGA LUTs / ASIC Gate Equivalents

CPU+IX RV32IMC	**Keccak** “plain”	**SHA2 -256**	**SHA2 -512**	**Keccak TI3**	**LUTs** XC7A100T	**kGE** Nangate45
yes	-	-	-	-	(3,023)	(31.36)
yes	-	yes	-	-	+2,463	+32.03
yes	yes	-	-	-	+5,582	+41.72
yes	yes	yes	-	-	+8.205	+73.52
yes	-	yes	yes	-	+5,942	+82.36
yes	yes	yes	yes	-	+10,857	+123.99
				Full system, all SLH-DSA parameters:	**14,428**	**155.35**
yes	yes	-	-	yes	+21,826	+173.22
yes	yes	yes	yes	yes	+27,694	+254.48
				Full system with Three-Share TI Keccak:	**30,717**	**285.84**

Configurable Hardware: Artix 7 FPGA LUTs / ASIC Gate Equivalents

CPU+IX RV32IMC	**Keccak** “plain”	**SHA2 -256**	**SHA2 -512**	**Keccak TI3**	**LUTs** XC7A100T	**kGE** Nangate45
yes	-	-	-	-	(3,023)	(31.36)
yes	-	yes	-	-	+2,463	+32.03
yes	yes	-	-	-	+5,582	+41.72
yes	yes	yes	-	-	+8.205	+73.52
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Side Channels: Sensitive Variable Leakage

- SLH-DSA's **master secret** is SK.seed (with randomization SK.prf is redundant.)
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- A major issue for SLH-DSA in a RoT are **fault attacks**. Genêt [1] shows that:
  A random bit-flip fault during signing can cause signatures to be generated that *will verify as correct* while containing hashes that allow *universal forgeries.*
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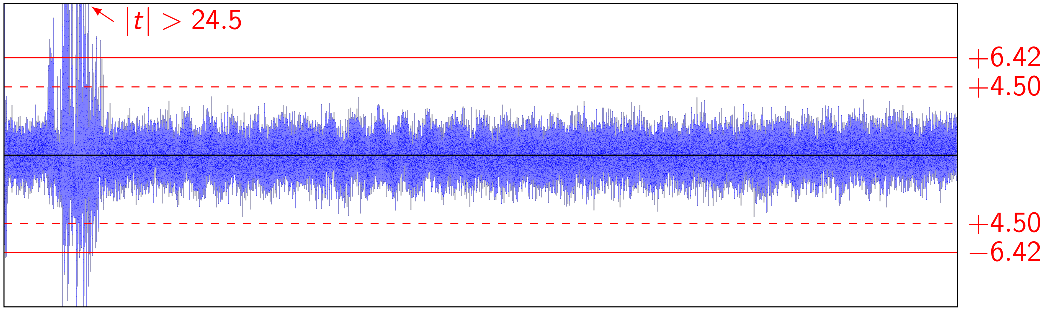
Unprotected CPU Implementations Leak **SK.seed**



Zoom of the first PRF in a non-accelerated TVLA shows strong leakage.

- Each SLH-DSA Signing operation has thousands of invocations of PRF, each using SK.seed. So even a 1-trace (horizontal) attack reveals secret key bits.
- Unaccelerated SLH-DSA; just demonstrating leakage from the first PRF.

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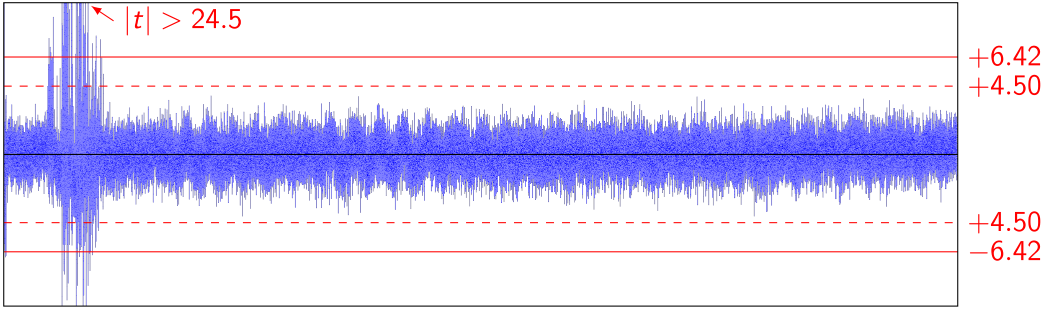

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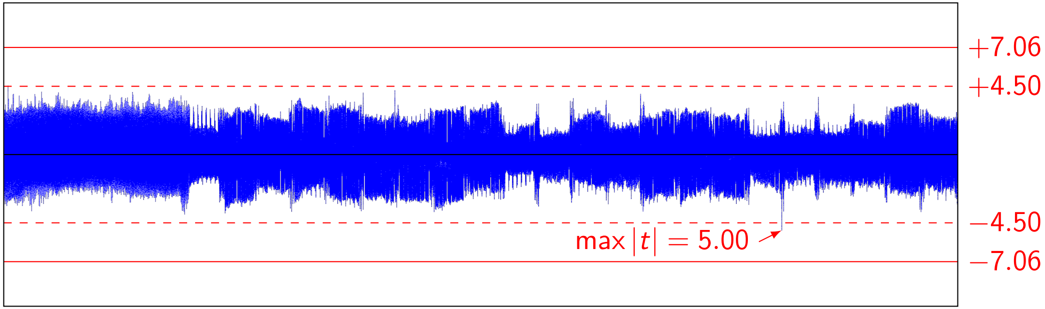

SK.seed autoloading + TI3 Keccak. TVLA: N = 100 000, L = 5 950 239, C = 7.06.

- TVLA with 3-share TI Keccak for PRF (SK.seed) and secret Winternitz hashes.
- Countermeasure doubles hardware size, but less than 25% performance hit.
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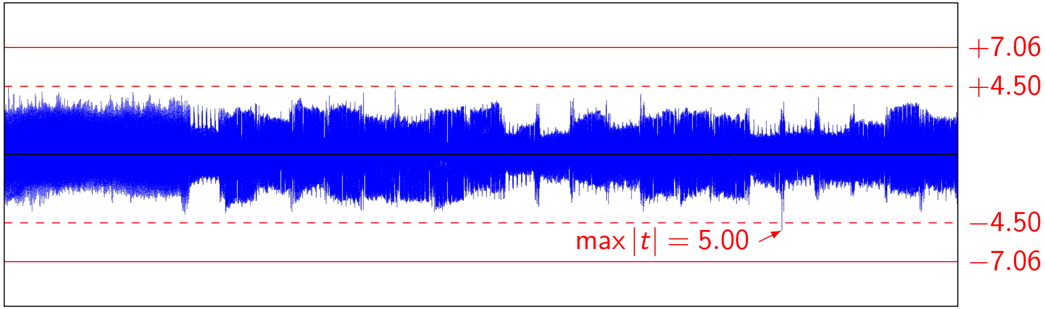

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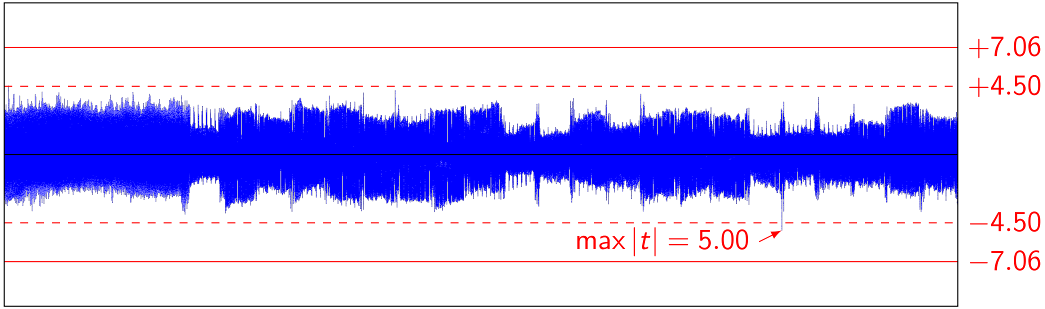

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Performance (1/2): "Fast signature" (**f**) parameter sets

	SLH-DSA-SHAKE-*				SLH-DSA-SHA2-*			
	SLotH		*(PQM4)*		SLotH		*(PQM4)*	
Func.	clk average	clk/h	*clk/h*	×	clk average	clk/h	*clk/h*	×
128f KG	176,552	39.3	*13294.6*	*338.5*	358,494	79.8	*3423.4*	*42.9*
Sign	4,903,978	46.7	*14140.2*	*302.5*	9,127,150	87.0	*3645.8*	*41.9*
Verify	440,636	71.1	*13405.8*	*188.5*	691,186	111.5	*3413.5*	*30.6*
192f KG	284,238	43.4	*13500.4*	*310.8*	541,583	82.8	*3461.1*	*41.8*
Sign	10,596,236	62.7	*14267.0*	*227.4*	23,726,217	140.5	*3786.0*	*26.9*
Verify	711,431	79.3	*13744.0*	*173.4*	1,290,921	143.9	*3670.8*	*25.5*
256f KG	815,609	47.5	*13702.4*	*288.7*	1,454,706	84.7	*3480.7*	*41.1*
Sign	23,660,226	68.5	*14089.4*	*205.6*	50,240,516	145.5	*3710.5*	*25.5*
Verify	857,059	94.9	*14098.8*	*148.6*	1,419,466	157.1	*3646.5*	*23.2*

- SLH-DSA-SHAKE-128f signing is 4.9M cycles or 19.6ms @ 250 MHz (XCVU9P).
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Performance (2/2): “Small signature” (**s**) parameter sets

	SLH-DSA-SHAKE-*				**SLH-DSA-SHA2-***			
	SLotH		*(PQM4)*		SLotH		*(PQM4)*	
Func.	clk average	clk/h	*clk/h*	×	clk average	clk/h	*clk/h*	×
128s KG	11,180,642	38.9	*13294.3*	*342.1*	22,709,640	78.9	*3424.5*	*43.4*
Sign	102,346,701	46.8	*13306.1*	*284.2*	190,085,952	87.0	*3429.0*	*39.4*
Verify	179,603	84.5	*13870.8*	*164.2*	268,445	126.2	*3369.9*	*26.7*
192s KG	18,038,904	43.1	*13497.4*	*313.4*	34,280,105	81.9	*3462.3*	*42.3*
Sign	263,100,826	69.8	*13492.5*	*193.2*	626,858,593	166.4	*3654.0*	*22.0*
Verify	289,825	94.7	*13620.7*	*143.8*	641,048	209.5	*3843.6*	*18.4*
256s KG	13,003,653	47.3	*13691.4*	*289.5*	23,174,830	84.3	*3465.4*	*41.1*
Sign	296,265,468	90.3	*13674.5*	*151.4*	696,201,400	212.2	*3750.9*	*17.7*
Verify	469,973	105.6	*13993.7*	*132.5*	894,078	200.9	*3756.7*	*18.7*

- SLH-DSA-SHAKE-128s verificaton is only 179.6k cycles or 0.72ms @ 250 MHz.
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	SLH-DSA-SHAKE-*				**SLH-DSA-SHA2-***			
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Sign	296,265,468	90.3	*13674.5*	*151.4*	696,201,400	212.2	*3750.9*	*17.7*
Verify	469,973	105.6	*13993.7*	*132.5*	894,078	200.9	*3756.7*	*18.7*

- SLH-DSA-SHAKE-128s verificaton is only 179.6k cycles or 0.72ms @ 250 MHz.
- But signing with s variants is of course 20× slower than with f variants.
- Core hash utilization even with SHAKE is often within 50% of optimal.

Final Notes and Conclusions

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Findings:

- You can make SLH-DSA about 10× faster on hash accelerators by automating message formats (PK.seed, SK.seed, ADRS registers) and Winternitz chain().

  Useful reminder: Quantitative analysis is essential for understanding bottlenecks.

Side-Channel Security:

- Having a hardware SK.seed register, fast/parallel hash set-up helps a lot.
- SLotH has a 3-share TI Keccak option – very big, but fully KAT compatible.
- Custom PRF's can be considered – verification remains compatible.
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