Falcon

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PQShield

Journées du PEPR PQ-TLS du PEPR Quantique (29/06/2023)

Roadmap

This talk:

- ✔ High-level description
- ✔ Implementation
- ✔ Side-channel security
- ✔ Deployment
- ✘ ~~Algorithmics~~
- ✘ ~~Cryptanalysis~~

Hash-then-Sign

Initial attempts: NTRUSign (1997), GGHSign (2003)

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Keygen(1^λ)

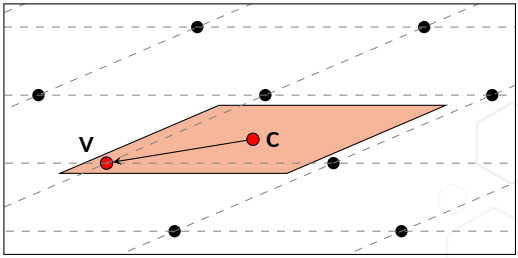
1. Gen. matrices $\mathbf{A}, \mathbf{B}$ such that:
   - $\mathbf{A}$ is pseudorandom
   - $\mathbf{A} \cdot \mathbf{B} = \mathbf{0}$
   - $\mathbf{B}$ has small coefficients
2. $\mathsf{pk} := \mathbf{A}, \mathsf{sk} := \mathbf{B}$

Sign(msg, sk = $\mathbf{B}$)

1. Compute $\mathbf{c}$ such that $\mathbf{A} \cdot \mathbf{c} = H(\mathsf{msg})$
2. $\mathbf{v} := \mathbf{B} \lfloor \mathbf{B}^{-1}\mathbf{c} \rceil$
3. $\mathsf{sig} := \mathbf{s} = (\mathbf{c} - \mathbf{v})$

Verify(msg, pk = $\mathbf{A}$, sig = $\mathbf{s}$)

Check ($\mathbf{s}$ short) & ($\mathbf{A} \cdot \mathbf{s} = H(\mathsf{msg})$)



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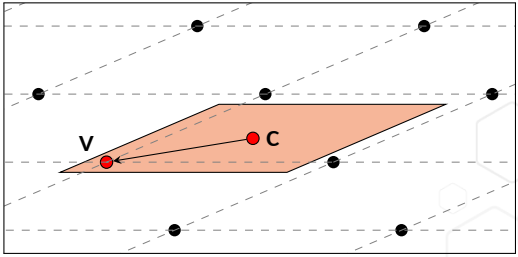


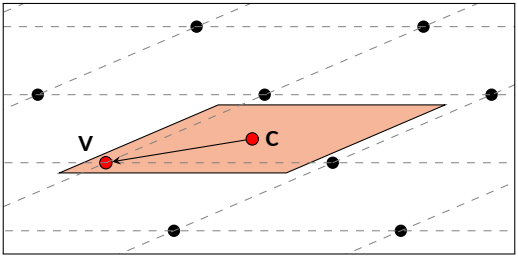
→ **Correctness:** easy

→ **Security:** Finding a short preimage $\mathbf{s}$ of $H(\mathsf{msg})$ should be difficult... or is it?

The parallelepiped attack

Problem: The distribution of the signature **s** is correlated to **B**

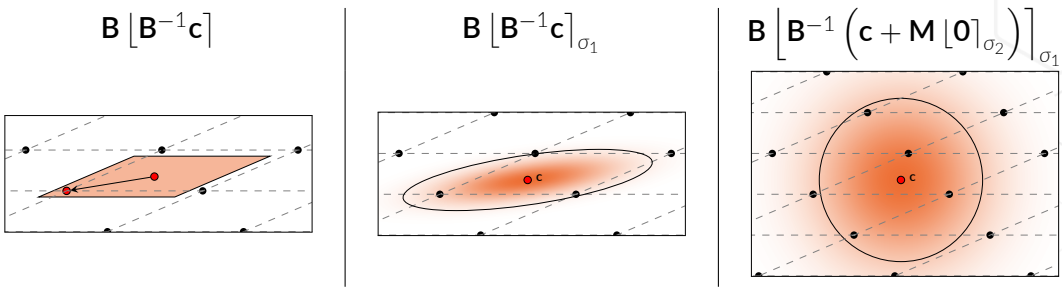
$$\mathbf{s} = \mathbf{c} - \mathbf{B}\left\lfloor \mathbf{B}^{-1}\mathbf{c} \right\rceil \in \left[-\frac{1}{2}, \frac{1}{2}\right) \cdot \mathbf{B} \tag{1}$$



Given many signatures, **B** can be recovered using techniques from Independent Component Analysis (ICA)

- 2006: key-recovery on NTRUSign and GGHSign
- 2012: key-recovery against NTRUSign countermeasures

Design-level solution: trapdoor sampling à la "GPV"



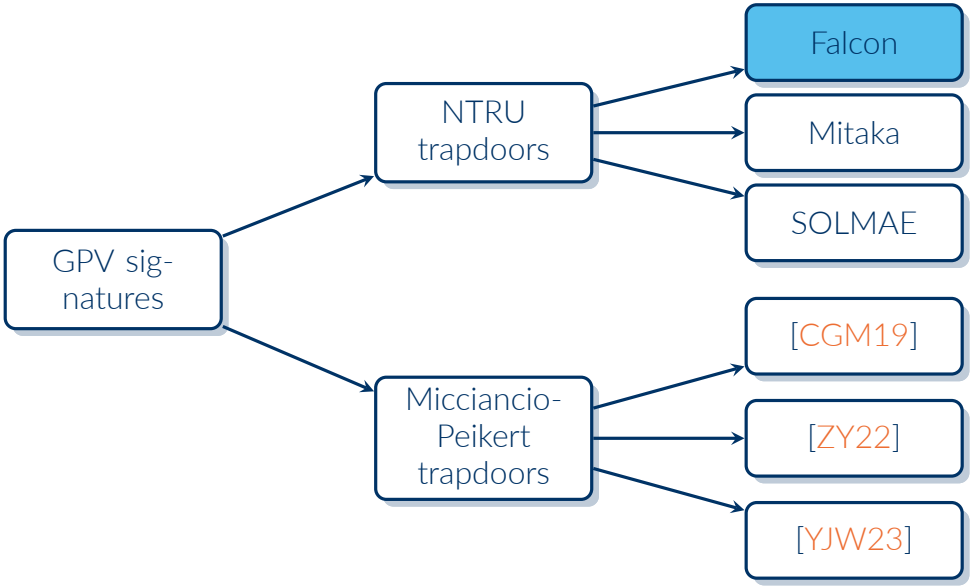
Indistinguishability: For appropriately chosen parameters, the rightmost procedure outputs a distribution close to a perfect Gaussian $D_{\Lambda(\mathbf{B}),\mathbf{c},\sigma}$.

Consequence: these two worlds are indistinguishable (in the ROM)

1. Sample a short vector $\mathbf{s}$, then set $H(\mathbf{msg}) = \mathbf{A} \cdot \mathbf{s}$
2. Compute $H(\mathbf{msg})$, then use $\mathbf{B}$ to sample a short preimage $\mathbf{s}$ of $H(\mathbf{msg})$

Falcon adds many refinements that make this blueprint more efficient, but more complex to implement.

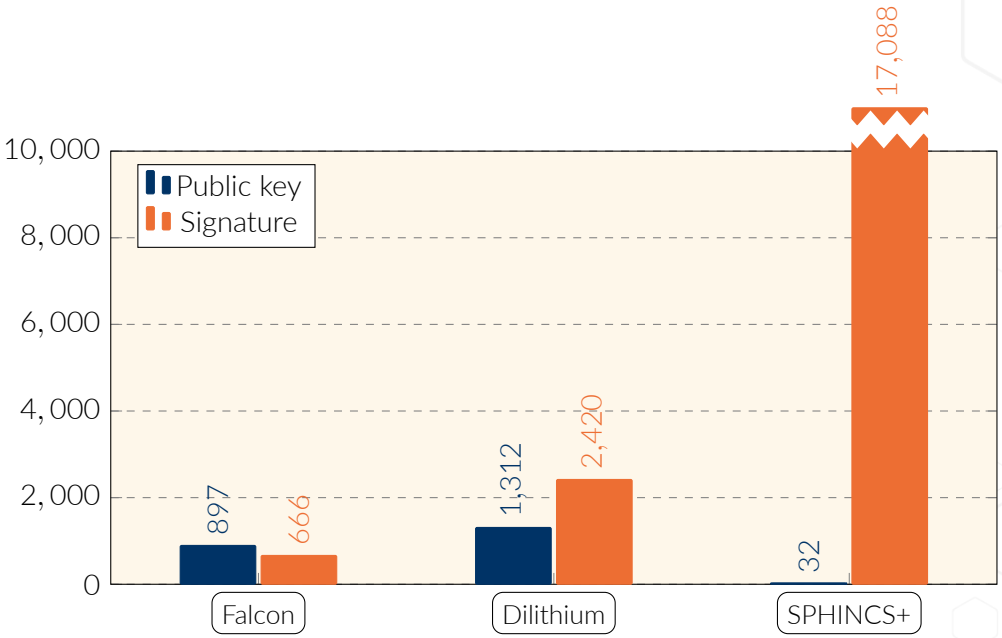
Signature schemes in the GPV family



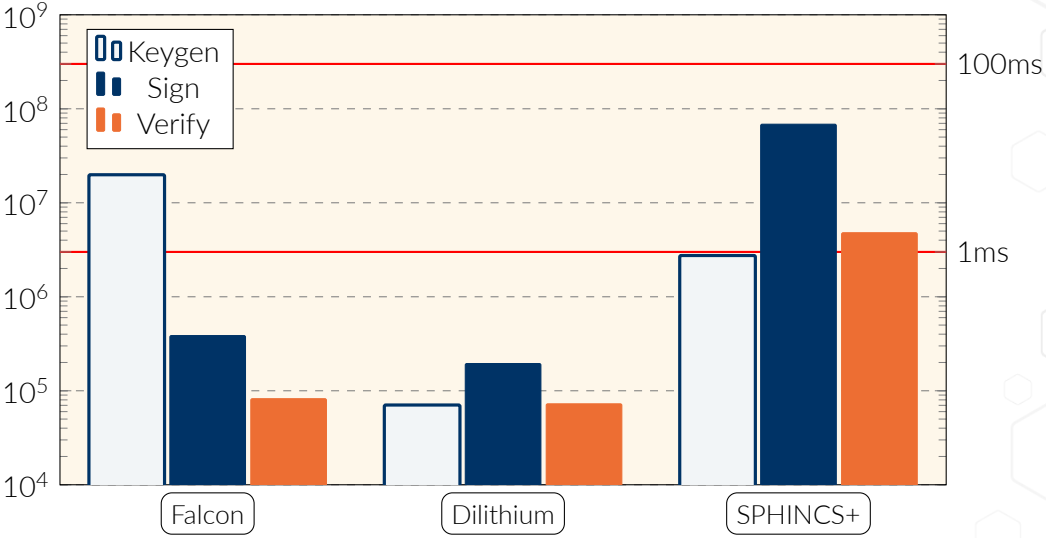
Falcon = GPV framework + NTRU trapdoors + Fast Fourier sampler + optimizations

Efficiency and Implementation

Sizes in bytes



Running time in cycles (from spec.)



Some implementations

- **GPU acceleration:**
  - *High Throughput Lattice-based Signatures on GPUs: Comparing Falcon and Mitaka* [LZS+23]
- **ARM Cortex:**
  - *New Efficient, Constant-Time Implementations of Falcon* [Por19]
  - *Fast Falcon Signature Generation and Verification Using ARMv8 NEON Instructions* [NG23]
- **FPGA and ASIC (verification only):**
  - *FPGA Energy Consumption of Post-Quantum Cryptography* [BKG22]
  - *Post-Quantum Signatures on RISC-V with Hardware Acceleration* [KSFS23]

Notes:

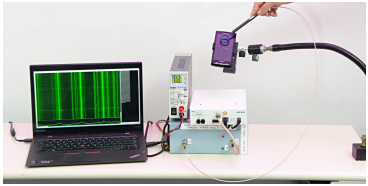
- Floating-point arithmetic (FPA) is a huge limiting factor
- Bottlenecks in KeyGen: arithmetic over large integers
- Bottlenecks in Signing: FFT-style operations and Gaussian sampling (in $\mathbb{Z}$)

Side-Channel Attacks

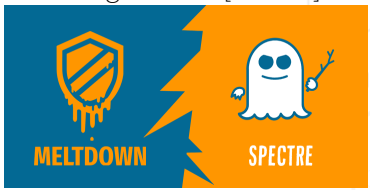
Side-channel attacks in cryptography

Power analysis attacks [KJJ99]

Electromagnetic attacks [Eck85]



Timing attacks [Koc96]



Acoustic attacks [AA04]

Visual attacks [NIC+23]

And more...

The return of the parallelepiped attacks

In Falcon, a signature **s** is distributed as a Gaussian.
The power consumption leaks information about the dot product $\langle \mathbf{s}, \mathbf{b}_0 \rangle$, or **s** itself.

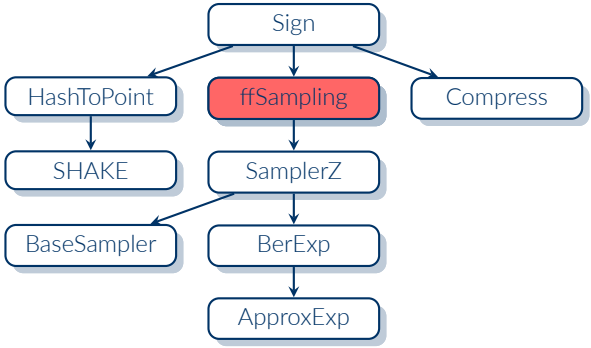
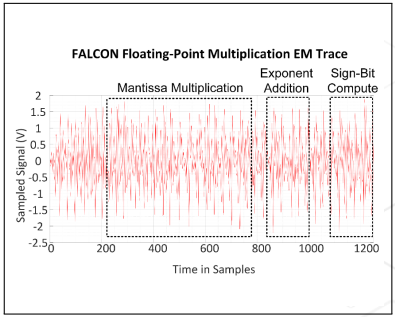


Figure 1: Flowchart of the signature



Learning **s** directly

[1] *FALCON Down: Breaking FALCON Post-Quantum Signature Scheme through Side-Channel Attacks* [KA21]

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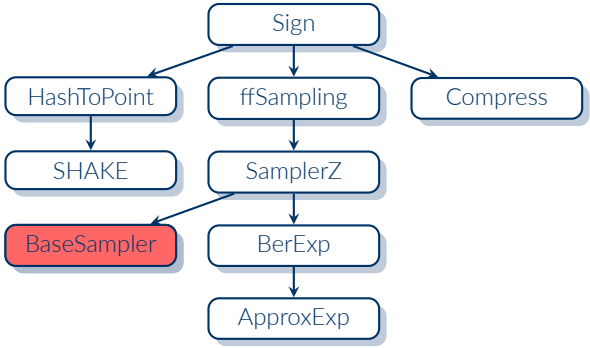

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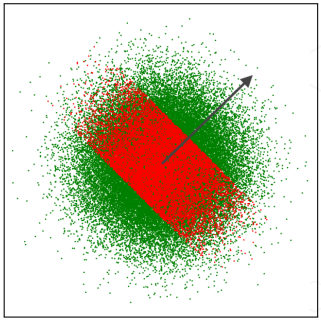

Filtering $\langle \mathbf{s}, \mathbf{b}_0 \rangle$ close to zero

[2] *The Hidden Parallelepiped Is Back Again: Power Analysis Attacks on Falcon* [GMRR22]

The return of the parallelepiped attacks

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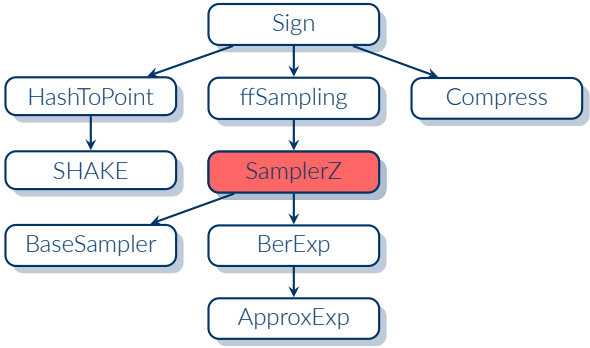

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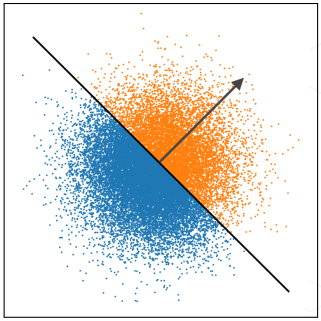

Filtering $\langle \mathbf{s}, \mathbf{b}_0 \rangle > 0$

[3] *Improved Power Analysis Attacks on Falcon* [ZLYW23]

Countermeasures (1/2)

Against timing attacks: make signing isochronous (“cryptographic constant time”)

- → BaseSampler reads a full table
- → BerExp implements rejection sampling via polynomial approximation

The signing procedure is isochronous assuming that some basic FPA operations are.

Protection beyond timing attacks?

- → [GMRR22, ZLYW23] propose countermeasures but they are ad hoc and only make their attacks more expensive to mount
- → In general, the most robust countermeasure is masking

Countermeasures (2/2)

Can we mask Falcon?

- → Good luck with that
- → Is Mitaka[1] a realistic masking-friendly alternative? No[2].
- → Dilithium is in a better place but still very expensive to mask

If you want a masking-friendly signature scheme, choose **Raccoon**[3]

[1] *Mitaka: A Simpler, Parallelizable, Maskable Variant of Falcon* [EFG+22]
[2] *A Key-Recovery Attack against Mitaka in the t-Probing Model* [Pre23]
[3] *Raccoon: A Side-Channel Secure Signature Scheme* (https://github.com/masksign/raccoon)

When to Deploy

Pros and cons

Pros

- Compact public key and signature sizes
- Very fast verification
- Signing is also fast, but less than Dilithium

Cons

- Key generation and signing require FPA
  - Be mindful on devices with non-existent or variable-time FPA units
  - Say goodbye to masking
- Key generation and signing are complex to implement
- Key generation is slow-ish

Mapping Falcon properties to applications

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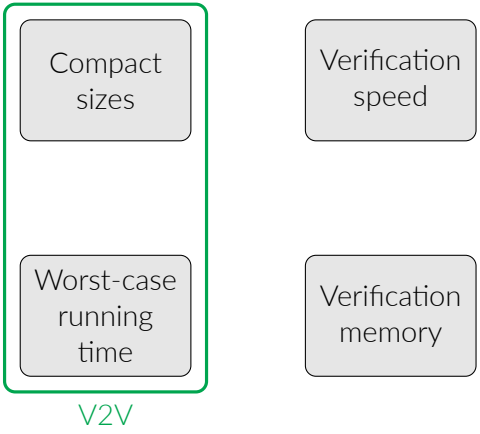
Compact sizes

Verification speed

Worst-case running time

Verification memory

Vehicle-to-vehicle (V2V) communications



Drive (Quantum) Safe! – Towards Post-Quantum Security for V2V Communications [BMTR22]

> " Only signature schemes whose explicit certificate can be sent in five or less fragments can be used in the *True Hybrid* design. [...] Falcon is the only viable scheme. "

TLS certificates

TLS

Compact sizes

Verification speed

Worst-case running time

Verification memory

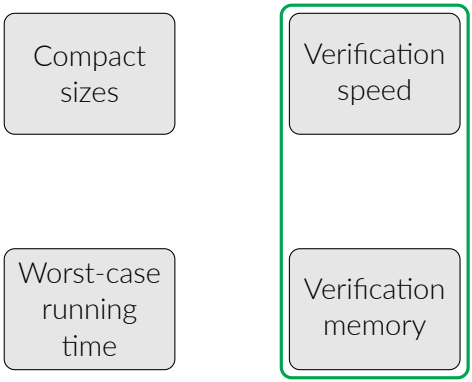
Post-Quantum Authentication in TLS 1.3: A Performance Study [SKD20]

> " The PQ algorithms with the best performance for time-sensitive applications are Dilithium and Falcon. "

NIST's pleasant post-quantum surprise [Wes22] recommends:

- → Falcon for offline signature
- → Dilithium for handshake

Verification on embedded devices

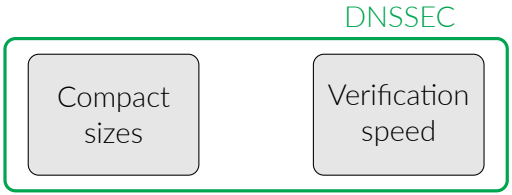


FPGA Energy Consumption of Post-Quantum Cryptography [BKG22]

> " For signature verification, Falcon provides the lowest energy consumption, highest throughput, and lowest transmission size [compared to Dilithium and SPHINCS+]. "

Verifying Post-Quantum Signatures in 8 kB of RAM [GHK+21]

> " On Cortex-M3, [Falcon's] overall memory footprint is about 6.5 kB. "



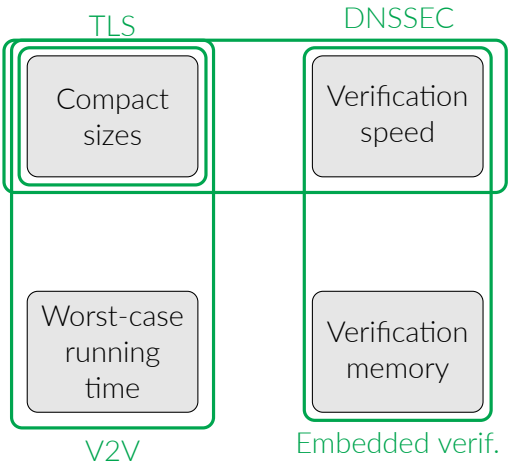
Retrofitting Post-Quantum Cryptography in Internet Protocols: A Case Study of DNSSEC [MdJvH+20]

> " [...] the performance of Falcon-512 is closest to the current algorithms and meets the requirements of DNSSEC. "

Post-Quantum Signatures in DNSSEC via Request-Based Fragmentation [GS22]

> " [...] Falcon-512 may be the most suitable option currently available to be standardized for DNSSEC. "

Summary



Suitable applications:

- V2V
- TLS certificates
- Verification on embedded devices
- DNSSEC
- ...

Questions?

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