Lattice-based NIST Candidates

Abstractions and Ninja Tricks

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PQShield

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- II Key Encapsulation Mechanisms
- III Signatures
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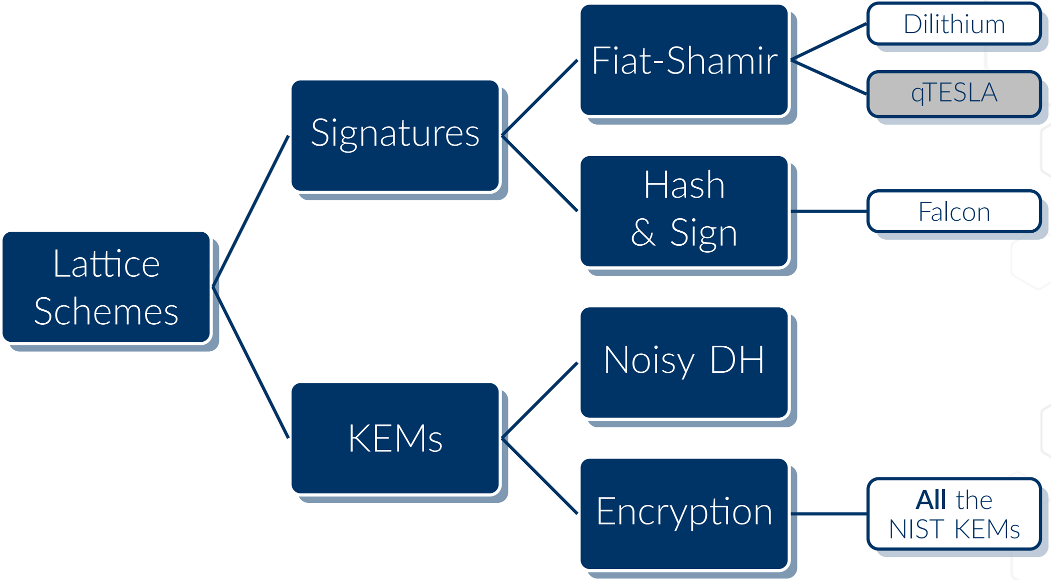
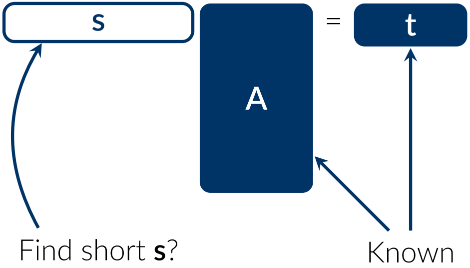
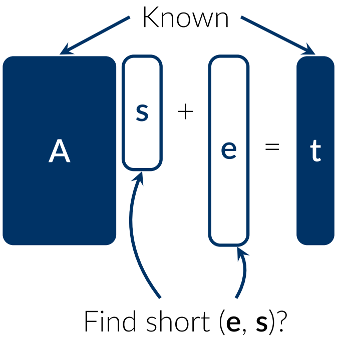
Introduction


Lattice Schemes
Signatures
KEMs
Fiat-Shamir
Hash & Sign
Noisy DH
Encryption
Dilithium
qTESLA
Falcon
All the NIST KEMs

Module-SIS



Module-LWE



NTRU

Find small f, g such that $g \cdot f^{-1} = h$ in $\mathcal{R}_q = \mathbb{Z}_q[x]/(\varphi)$

Key Encapsulation Mechanisms

Keygen($\mathbf{A} \in \mathcal{R}_q^{m\times m}$)

1. $\mathbf{S}, \mathbf{E} \leftarrow \chi_1 \times \chi_2$
2. $\mathbf{B} \leftarrow \mathbf{AS} + \mathbf{E}$
3. $\mathsf{sk} := (\mathbf{S}, \mathbf{E}), \mathsf{pk} := \mathbf{B}$

Enc($\mathtt{M}$, pk)

1. $\mathbf{R}, \mathbf{E}', \mathbf{E}'' \leftarrow \chi_3 \times \chi_4 \times \chi_5$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. $\mathbf{V} \leftarrow \mathbf{RB} + \mathbf{E}'' + \mathrm{Encode}(\mathtt{M})$
4. $\mathsf{ct} := (\mathbf{U}, \mathbf{V})$

Dec(ct, sk)

1. $\mathtt{M} \leftarrow \mathrm{Decode}(\mathbf{V} - \mathbf{US})$

Think of El Gamal, but with LWE/LWR.

Damien's excellent talk covers NTRU: https://youtu.be/yZhmKwmx48o

Keygen($\mathbf{A} \in \mathcal{R}_q^{m\times m}$)

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Enc($\mathtt{M}$, pk)

1. $\mathbf{R}, \mathbf{E}', \mathbf{E}'' \leftarrow \chi_3 \times \chi_4 \times \chi_5$
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4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V})$

Dec(ct, sk)

1. $\mathtt{M} \leftarrow \mathrm{Decode}(\mathbf{V} - \mathbf{U}\mathbf{S})$

Underlying problem/lattice

- LWE
- Module-LWE
- Ring-LWE
- (Module-)LWR
- (Module-)Integer-LWE
- and also NTRU (not here)

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4. $\mathsf{ct} := (\mathbf{U}, \mathbf{V})$

Dec$(\mathbf{ct}, \mathbf{sk})$

1. $\mathtt{M} \leftarrow \mathrm{Decode}(\mathbf{V} - \mathbf{US})$

Underlying ring $\mathcal{R}_q$

- → $\mathbb{Z}_q$, q small
- → $\mathbb{Z}_q[x]/(x^n + 1)$, q prime
- → $\mathbb{Z}_q[x]/(x^n + 1)$, q power-of-2
- → $\mathbb{Z}_q[x]/(P)$, $P = x^p - x - 1$ irreducible mod q, and q prime
- → $\mathbb{Z}_q$, q huge

Keygen($\mathbf{A} \in \mathcal{R}_q^{m\times m}$)

1. $\mathbf{S}, \mathbf{E} \leftarrow \chi_1 \times \chi_2$
2. $\mathbf{B} \leftarrow \mathbf{AS} + \mathbf{E}$
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Enc($\mathtt{M}$, **pk**)

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Dec(**ct**, **sk**)

1. $\mathtt{M} \leftarrow \mathrm{Decode}(\mathbf{V} - \mathbf{US})$

Distributions χ_i

- → Binomial
- → Pseudo-Gaussian
- → Small uniform
- → Ternary (NTRU Prime, NTRU)
- → No error distribution (LWR)

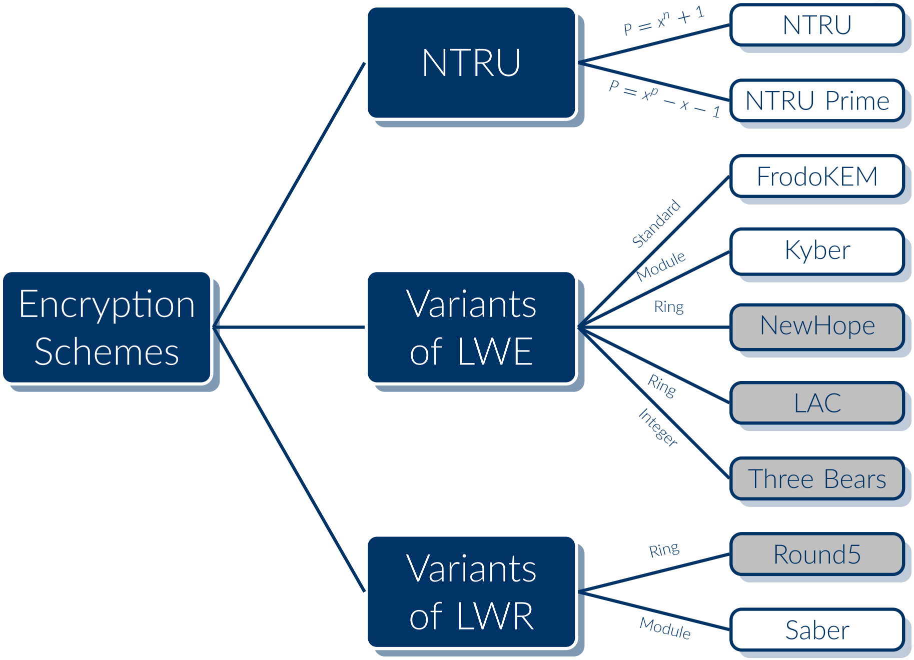
Obtaining security against active attackers

Most schemes rely on transforms in [HHK17]:

- Variants of Fujisaki-Okamoto, handle decryption failures [DRV20]
- Tight proofs in the ROM but not the QROM

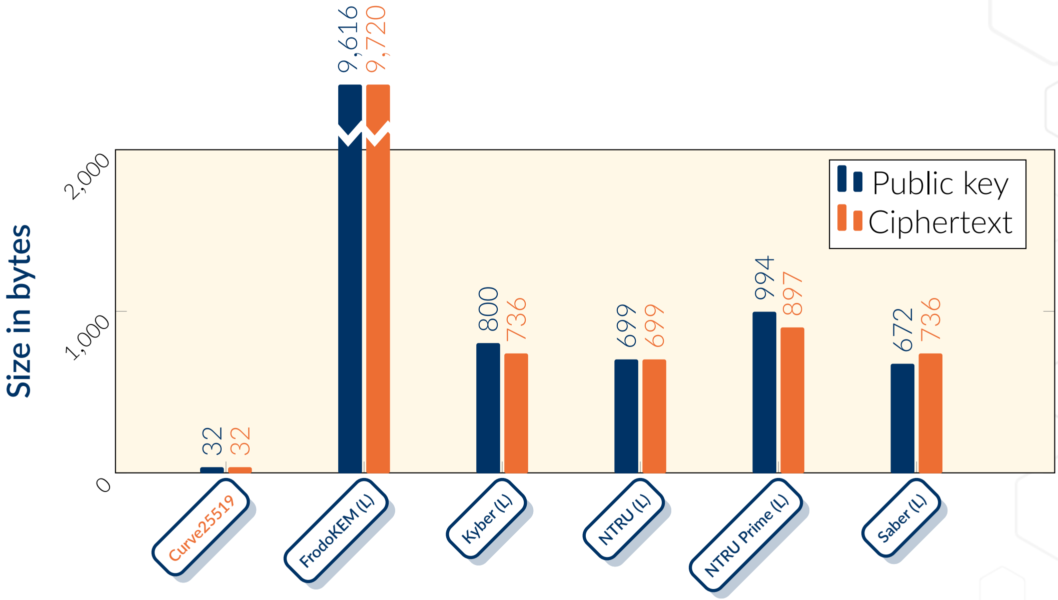
NTRU and NTRU Prime use [BP18] and [Den03] instead:

- Do not require re-encryption
- Tight proofs in the QROM (under non-standard assumptions)

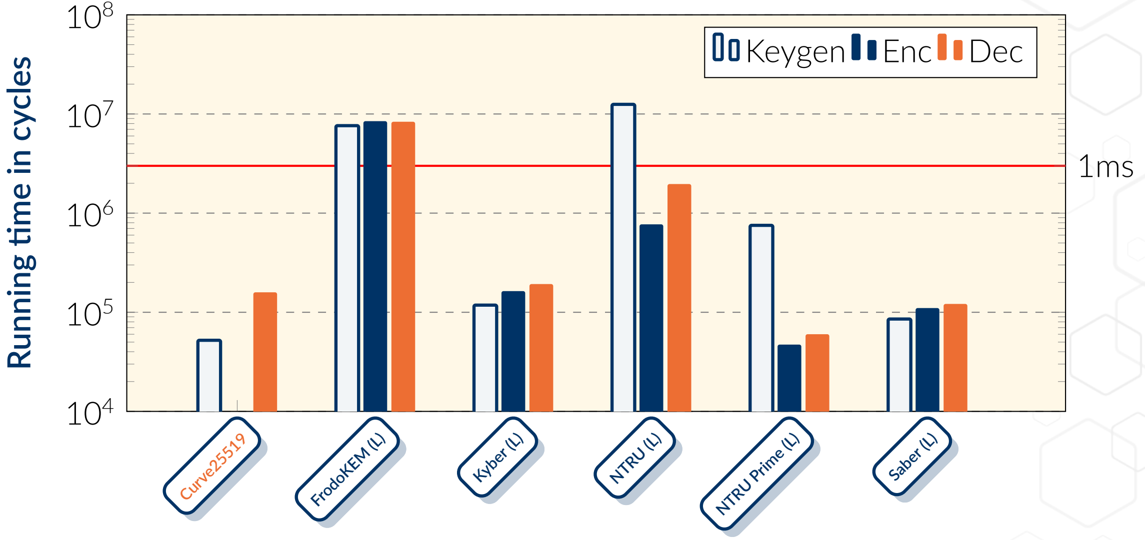


Encryption Schemes
NTRU
Variants of LWE
Variants of LWR
$P = x^n + 1$
$P = x^p - x - 1$
NTRU
NTRU Prime
Standard
Module
Ring
Ring
Integer
FrodoKEM
Kyber
NewHope
LAC
Three Bears
Ring
Module
Round5
Saber

Bandwidth cost of Level 1 KEMs

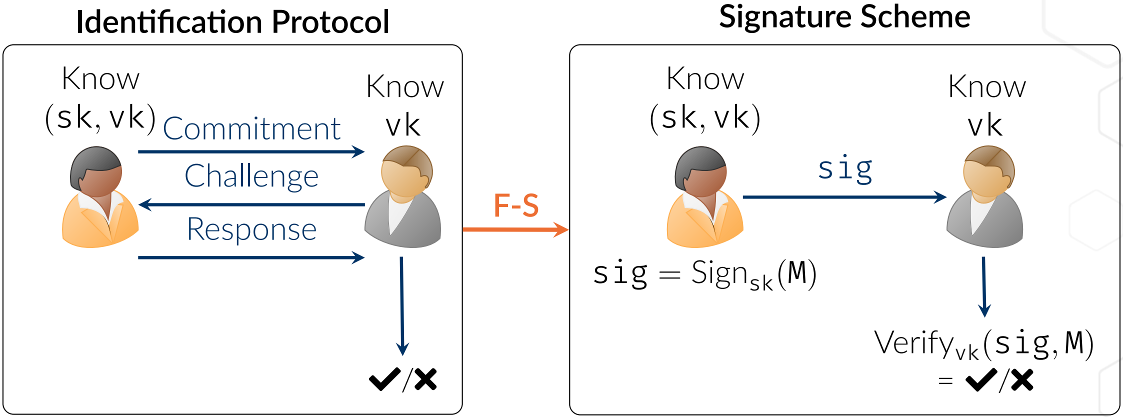


Computation Cost of Level 1 KEMs



Signatures

Fiat-Shamir Signatures



F-S refers to the Fiat-Shamir transform:

- → The challenge is now defined as $H(\text{Commitment}\|\mathtt{M})$.
- → The signature is (Commitment,Response).

Fiat-Shamir w/ discrete log

Keygen$(g \in G)$

1. $x \leftarrow \mathbb{Z}_q^\times$
2. $h \leftarrow g^x$
3. $\mathsf{sk} := x, \mathsf{pk} := h$

Sign$(\mathtt{M}, \mathbf{sk})$

1. $r \leftarrow \mathbb{Z}_q^\times$
2. $u \leftarrow g^r$
3. $c \leftarrow H(u \| \mathtt{M})$
4. $z \leftarrow r - cx$
5. $\mathtt{sig} := (c, z)$

Verify$(\mathtt{M}, \mathbf{pk})$

1. Accept if and only if $H(g^z \cdot h^c \| \mathtt{M}) = c$

3 crucial properties of ID protocol:

1. **Correctness:** *An honest prover can convince a verifier he knows* sk
2. **Soundness:** *A dishonest prover cannot convince a verifier he knows* sk
3. **(Honest Verifier) Zero-Knowledge:** *No information about* sk *is leaked*

Virtually all lattice-based Fiat-Shamir schemes transpose this blueprint to lattices, with 3 tricks:

- → Rejection sampling (a.k.a. *Fiat-Shamir with aborts*)
- → The Bai-Galbraith trick [BG14]
- → The Dilithium trick [LDK+17]

Keygen($\mathbf{A} \in \mathcal{R}_q^{k\times\ell}$)

1. $\mathbf{s}_1, \mathbf{s}_2 \leftarrow \chi_1 \times \chi_2$ (short)
2. $\mathbf{t} \leftarrow \mathbf{A}\mathbf{s}_1 + \mathbf{s}_2$
3. $\mathsf{sk} := (\mathbf{s}_1, \mathbf{s}_2), \mathsf{pk} := \mathbf{t}$

Sign($\mathtt{M}$, sk)

1. $\mathbf{r}_1, \mathbf{r}_2 \leftarrow \chi_3 \times \chi_4$ (short)
2. $\mathbf{u} \leftarrow \mathbf{A}\mathbf{r}_1 + \mathbf{r}_2$
3. $\mathbf{c} \leftarrow H(\mathbf{u} \| \mathtt{M})$ (short)
4. $\mathbf{z}_1 \leftarrow \mathbf{r}_1 - \mathbf{c}\mathbf{s}_1$
5. $\mathbf{z}_2 \leftarrow \mathbf{r}_2 - \mathbf{c}\mathbf{s}_2$
6. Rej. sampling (for HVZK)
7. $\mathtt{sig} := (\mathbf{c}, \mathbf{z}_1, \mathbf{z}_2)$

Verify($\mathtt{M}$, pk)

1. Accept iff $(\mathbf{z}_1, \mathbf{z}_2)$ is short and $H(\mathbf{A}\mathbf{z}_1 + \mathbf{z}_2 - \mathbf{t}\mathbf{c} \| \mathtt{M}) = \mathbf{c}$

$\mathsf{Keygen}(\mathbf{A} \in \mathcal{R}_q^{k\times\ell})$

1. $\mathbf{s}_1, \mathbf{s}_2 \leftarrow \chi_1 \times \chi_2$ (short)
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$\mathsf{Verify}(\mathtt{M}, \mathbf{pk})$

1. Accept iff $(\mathbf{z}_1, \mathbf{z}_2)$ is short and $H(\mathbf{A}\mathbf{z}_1 + \mathbf{z}_2 - \mathbf{t}\mathbf{c} \| \mathtt{M}) = \mathbf{c}$

Bai-Galbraith and Dilithium tricks:
Only care about most significant bits (MSB).

Bai-Galbraith trick: Discard commitment's LSBs.
$\Rightarrow$ Shorter signatures.

Keygen($\mathbf{A} \in \mathcal{R}_q^{k\times\ell}$)

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3. $\mathtt{sk} := (\mathbf{s}_1, \mathbf{s}_2), \mathtt{pk} := \mathbf{t}$

Sign($\mathtt{M}$, sk)

1. $\mathbf{r} \leftarrow \chi_3$ (short)
2. $\mathbf{u} \leftarrow \mathbf{A}\mathbf{r}$
3. $\mathbf{c} \leftarrow H(\text{MSB}(\mathbf{u}) \| \mathtt{M})$ (short)
4. $\mathbf{z} \leftarrow \mathbf{r} - \mathbf{c}\mathbf{s}_1$
5. Rej. sampling
6. $\mathtt{sig} := (\mathbf{c}, \mathbf{z})$

Verify($\mathtt{M}$, pk)

1. Accept iff $\mathbf{z}$ is short and $H(\text{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \| \mathtt{M}) = \mathbf{c}$

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3. $\mathsf{sk} := \mathbf{s}$, $\mathsf{pk} := \mathbf{t}$

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2. $\mathbf{u} \leftarrow \mathbf{A}\mathbf{r}$
3. $\mathbf{c} \leftarrow H(\mathrm{MSB}(\mathbf{u}) \| \mathtt{M})$ (short)
4. $\mathbf{z} \leftarrow \mathbf{r} - \mathbf{c}\mathbf{s}_1$
5. $\mathbf{h} \leftarrow \mathrm{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \oplus \mathrm{MSB}(\mathbf{u})$
6. Rej. sampling + check $\mathbf{h}$ short
7. $\mathtt{sig} := (\mathbf{c}, \mathbf{z}, \mathbf{h})$

Verify$(\mathtt{M}, \mathbf{pk})$

1. Accept iff $\mathbf{z}$ short, $\mathbf{h}$ short and $H(\mathrm{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \oplus \mathbf{h} \| \mathtt{M}) = \mathbf{c}$

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Dilithium trick: Discard public key's LSBs, send hint in signature to compensate error.
$\Rightarrow$ Shorter public key, slightly larger signatures.

Keygen($\mathbf{A} \in \mathcal{R}_q^{k \times \ell}$)

1. $\mathbf{s}_1, \mathbf{s}_2 \leftarrow \chi_1 \times \chi_2$ (short)
2. $\mathbf{t} \leftarrow \mathsf{MSB}(\mathbf{A}\mathbf{s}_1 + \mathbf{s}_2)$
3. $\mathsf{sk} := \mathbf{s}, \mathsf{pk} := \mathbf{t}$

Sign($\mathtt{M}$, sk)

1. $\mathbf{r} \leftarrow \chi_3$ (short)
2. $\mathbf{u} \leftarrow \mathbf{A}\mathbf{r}$
3. $\mathbf{c} \leftarrow H(\mathsf{MSB}(\mathbf{u}) \| \mathtt{M})$ (short)
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7. $\mathtt{sig} := (\mathbf{c}, \mathbf{z}, \mathbf{h})$

Verify($\mathtt{M}$, pk)

1. Accept iff $\mathbf{z}$ short, $\mathbf{h}$ short and $H(\mathsf{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \oplus \mathbf{h} \| \mathtt{M}) = \mathbf{c}$

Bai-Galbraith and Dilithium tricks:
Only care about most significant bits (MSB).

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6. Rej. sampling + check $\mathbf{h}$ short
7. $\mathtt{sig} := (\mathbf{c}, \mathbf{z}, \mathbf{h})$

Verify($\mathtt{M}$, pk)

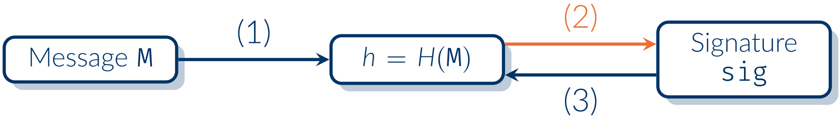
1. Accept iff $\mathbf{z}$ short, $\mathbf{h}$ short and $H(\mathsf{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \oplus \mathbf{h} \|\mathtt{M}) = \mathbf{c}$

In the Dilithium trick, it is **vital** to control the norm and Hamming weight of $\mathbf{h}$. Otherwise forgery is simple:

1. Sample random $\mathbf{z}$ and $\mathbf{u}$
2. $\mathbf{c} \leftarrow H(\mathsf{MSB}(\mathbf{u})\|\mathtt{M})$
3. $\mathbf{h} \leftarrow \mathsf{MSB}(\mathbf{A}\mathbf{z} - \mathbf{t}\mathbf{c}) \oplus \mathsf{MSB}(\mathbf{u})$

See qTESLA-*-s [BAA+19].

Signatures based on *Hash-then-Sign*



- **The signer** computes (1), then (2) using the signing key sk.
- **The verifier** computes (1), then (3) using the verification key pk, and checks that the results match.

In RSA signatures, (2) + (3) define a trapdoor permutation, but lattices rely on weaker notions: TPSF and average TPSF.

Trapdoor permutation $\Rightarrow$ TPSF $\Rightarrow$ Average TPSF

GPV signatures (2008)

Falcon instantiates this blueprint.

Keygen(1^λ)

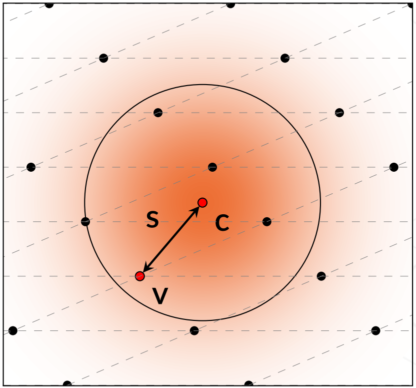
1. Gen. matrices $\mathbf{A}, \mathbf{B}$ s.t.:
   - $\mathbf{B} \cdot \mathbf{A} = 0$
   - $\mathbf{B}$ has small coefficients
2. $\mathsf{pk} := \mathbf{A}, \mathsf{sk} := \mathbf{B}$

Sign$(\mathtt{M}, \mathbf{sk} = \mathrm{B})$

1. Compute $\mathbf{c}$ such that $\mathbf{c} \cdot \mathbf{A} = H(\mathtt{M})$
2. $\mathbf{v} \leftarrow$ vector in $\mathcal{L}(\mathbf{B})$, close to $\mathbf{c}$
3. $\mathtt{sig} := \mathbf{s} = (\mathbf{c} - \mathbf{v})$

Verify$(\mathtt{M}, \mathbf{pk} = \mathrm{A}, \mathbf{\mathtt{sig}} = \mathrm{s})$

Check ($\mathbf{s}$ short) & ($\mathbf{s} \cdot \mathbf{A} = H(\mathtt{M})$)



How to compute efficiently a close vector (the second algorithm assumes we precomputed the Gram-Schmidt orthogonalization $\mathbf{B} = \mathbf{L} \cdot \tilde{\mathbf{B}}$).

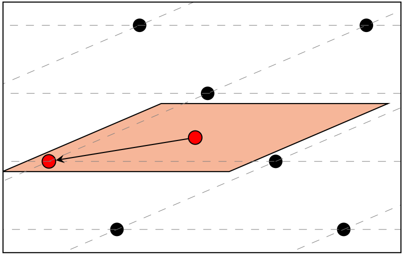
RoundOff(B, c)

1. $\mathbf{t} \leftarrow \mathbf{c} \cdot \mathbf{B}^{-1}$
2. For $j \in \{n, \ldots, 1\}$:
   1. $z_j \leftarrow \lfloor t_j \rceil$
3. Return $\mathbf{v} := \mathbf{z} \cdot \mathbf{B}$

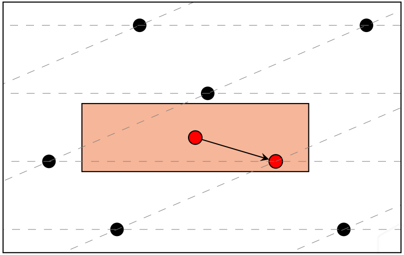
NearestPlane(B, L, c)

1. $\mathbf{t} \leftarrow \mathbf{c} \cdot \mathbf{B}^{-1}$
2. For $j \in \{n, \ldots, 1\}$:
   1. $z_j \leftarrow \lfloor t_j + \sum_{i>j} (t_1 - z_i) L_{i,j} \rceil$
3. Return $\mathbf{v} := \mathbf{z} \cdot \mathbf{B}$

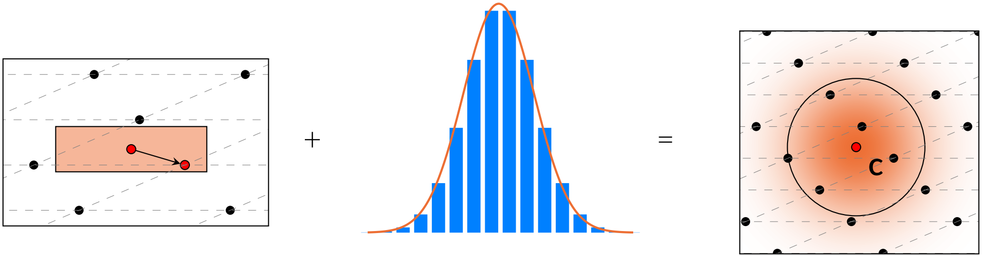
$\Downarrow$

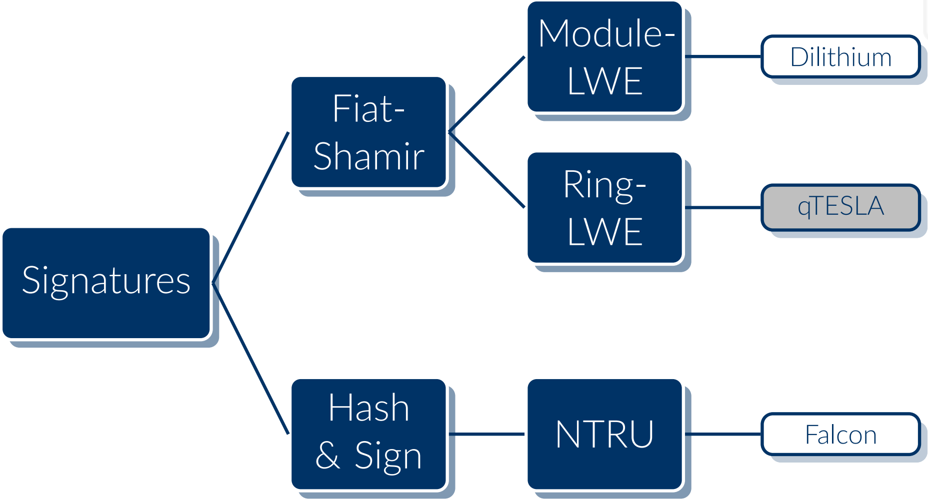


$\Downarrow$



- **Problem:** When used for signing, the algorithms RoundOff and NearestPlane leak the shape of the private key **B**, leading to attacks.
- **Solution:** Replace rounding with (Gaussian) randomized rounding.

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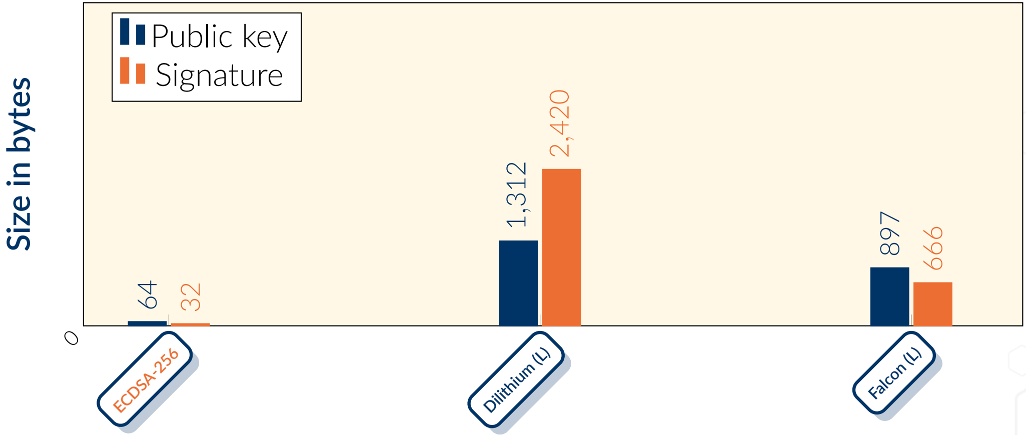
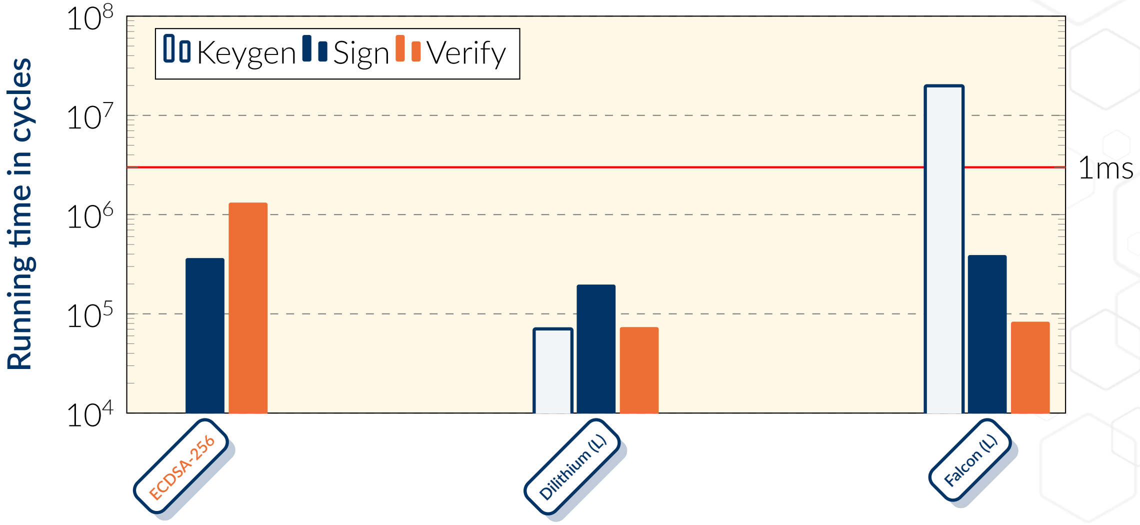
Bandwidth cost of Level 1 Signatures



Computation Cost of Level 1 Signatures



Ninja Tricks

Figure 1: Broadcast

Figure 2: Group Messaging

In LWE/LWR proposals, **U** does almost not depend on the public key.

- → Use the same **A** for all public keys.
- → Use the same **U** when encrypting **the same M** to several recipients.

$\mathsf{Enc}(\mathtt{M}, \mathbf{pk} = (\mathbf{A}, \mathbf{B}))$

1. $\mathbf{R}, \mathbf{E}', \mathbf{E}'' \leftarrow \chi_3 \times \chi_4 \times \chi_5$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. $\mathbf{V} \leftarrow \mathbf{RB} + \mathbf{E}'' + \mathsf{Encode}(\mathtt{M})$
4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V})$

In LWE/LWR proposals, **U** does almost not depend on the public key.

- → Use the same **A** for all public keys.
- → Use the same **U** when encrypting **the same** $\mathtt{M}$ to several recipients.

Enc($\mathtt{M}$, **pk** = (**A**, **B**))

1. $\mathbf{R}, \mathbf{E}', \mathbf{E}'' \leftarrow \chi_3 \times \chi_4 \times \chi_5$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. $\mathbf{V} \leftarrow \mathbf{RB} + \mathbf{E}'' + \mathrm{Encode}(\mathtt{M})$
4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V})$

$\Longrightarrow$

MultiEnc($\mathtt{M}$, $\mathbf{pk}_1, \ldots, \mathbf{pk}_k$)

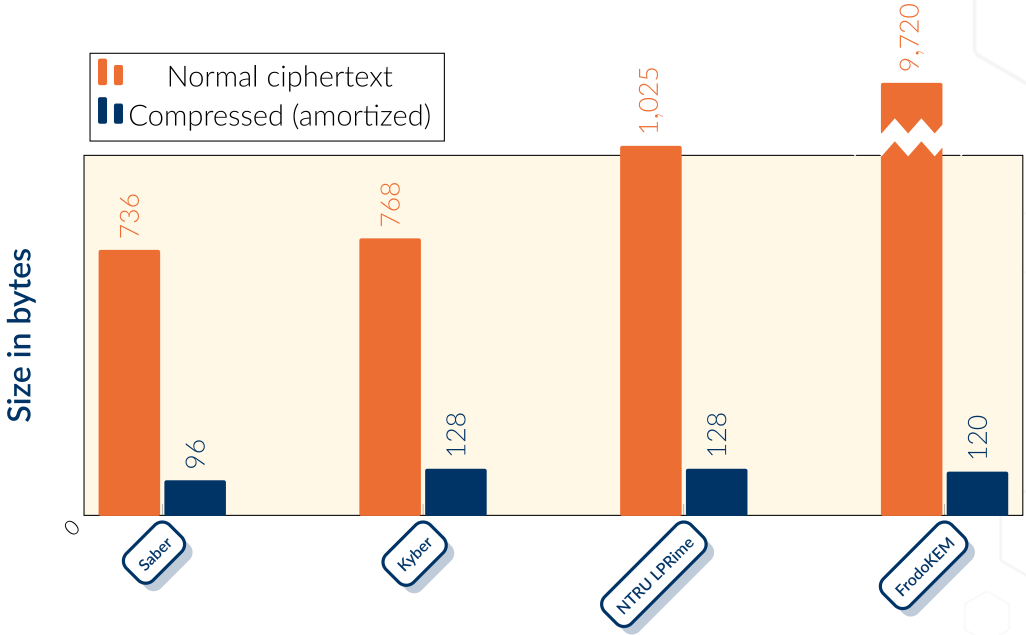
1. $\mathbf{R}, \mathbf{E}' \leftarrow \chi_3 \times \chi_4$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. For $i = 1, \ldots, k$:
   1. $\mathbf{E}''_i \leftarrow \chi_5$
   2. $\mathbf{V}_i \leftarrow \mathbf{RB}_i + \mathbf{E}''_i + \mathrm{Encode}(\mathtt{M})$
4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V}_1, \ldots, \mathbf{V}_k)$

This improves amortized costs by **factors up to 169**.

- → Faster encryption
- → Smaller ciphertexts

See [KKPP20].

Impact on Potential NIST Standards (Level I)

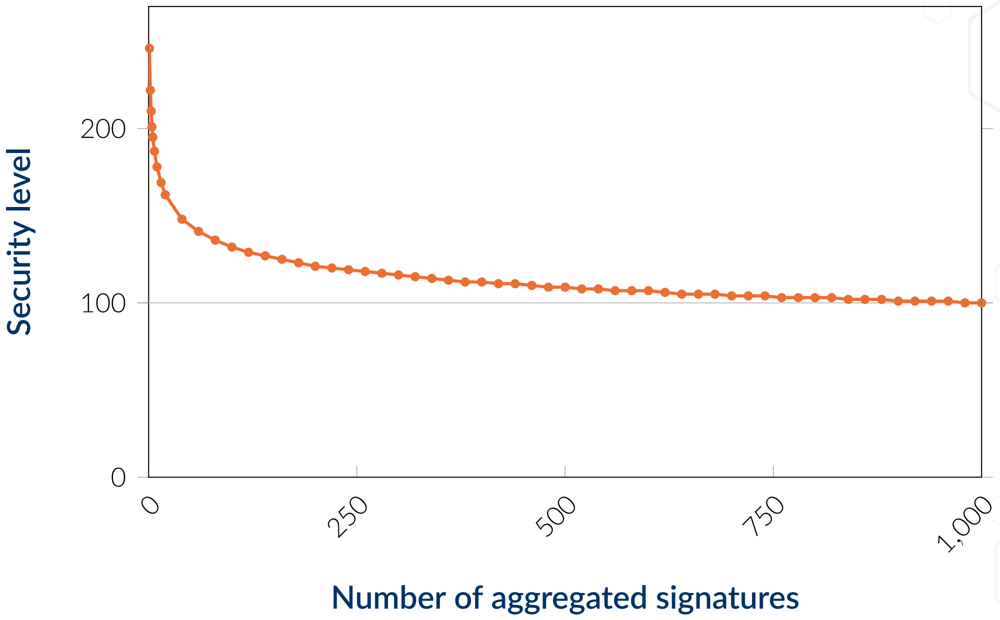


A cute property of GPV signatures

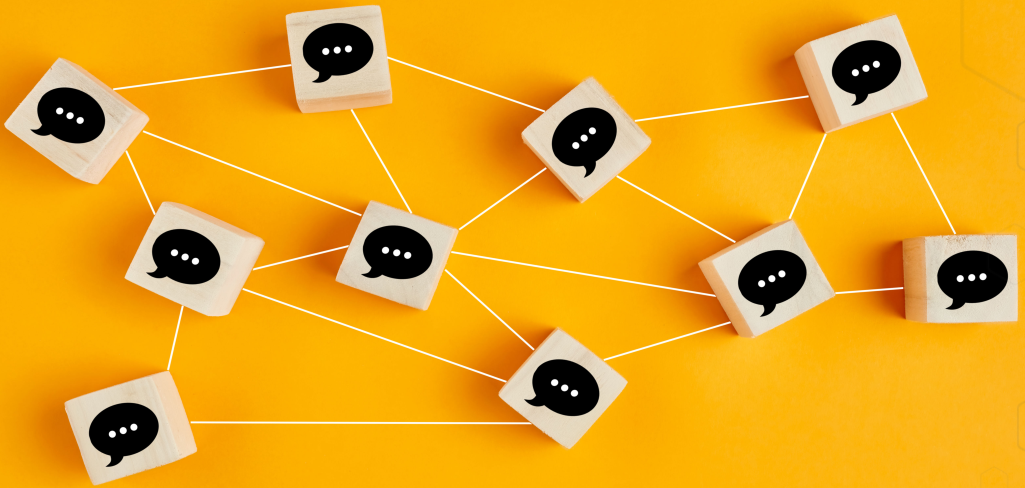
Like all GPV signatures, Falcon supports *single-signer* signature aggregation.

$$\left.\begin{aligned} \mathbf{s}_1 \cdot \mathbf{A} &= H(\mathtt{M}_1) \\ &\vdots \\ \mathbf{s}_k \cdot \mathbf{A} &= H(\mathtt{M}_k) \end{aligned}\right\} \Longrightarrow \left(\sum_i \mathbf{s}_i\right) \cdot \mathbf{A} = \sum_i H(\mathtt{M}_i)$$

For up to **1000 signatures**, aggregate signature size **< 3kB**.



Security level
200
100
0
0
250
500
750
1,000
Number of aggregated signatures



Questions?

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