

DEVELOPING INNOVATIVE FRAMEWORKS FOR EFFICIENT CODE-BASED SIGNATURES

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- Introduction
- A Look into the Past
- New Frameworks
- Conclusions

Part I

INTRODUCTION

In a few years time large-scale quantum computers might be reality.
But then (Shor, '94):

- RSA
- DSA
- ECC
- Diffie-Hellman key exchange
- and many others ... **not secure** !

→ NIST's Post-Quantum Cryptography Standardization Call (2017).

Main areas of research:

- Lattice-based cryptography.
- Hash-based cryptography.
- **Code-based cryptography.**
- Multivariate cryptography.
- Isogeny-based cryptography.

Code-based cryptography has been doing really well for encryption/key establishment.

3 finalists in NIST's process:

- Classic McEliece (binary Goppa)
- BIKE (QC-MDPC)
- HQC (QC Random Codes)

The same cannot be said for code-based signatures.

Only 4 NIST submissions, all either **broken or withdrawn**.

Yet, signature schemes are a crucial component in cryptography.

Can we fix this?

DECODING PROBLEMS

In general, it is hard to decode **random codes**.

PROBLEM (GENERAL DECODING)

Given: $G \in \mathbb{F}_q^{k \times n}$, $y \in \mathbb{F}_q^n$ and $w \in \mathbb{N}$.

Goal: find a word $e \in \mathbb{F}_q^n$ with $wt(e) \leq w$ such that $y - e = x \in C_G$.

Easy to see this is equivalent to the following.

PROBLEM (SYNDROME DECODING)

Given: $H \in \mathbb{F}_q^{(n-k) \times n}$, $y \in \mathbb{F}_q^{(n-k)}$ and $w \in \mathbb{N}$.

Goal: find a word $e \in \mathbb{F}_q^n$ with $wt(e) \leq w$ such that $He^T = y$.

NP-Complete (Berlekamp, McEliece and Van Tilborg, 1978; Barg, 1994).

Unique solution when w is below a certain threshold.

Very well-studied, solid security understanding (ISD).

HOW TO DO CODE-BASED CRYPTOGRAPHY?

Choose a code family with efficient decoding algorithm associated to description Δ and **hide** the structure.

To get trapdoor, need one more ingredient.

ASSUMPTION (CODE INDISTINGUISHABILITY)

It is possible to describe an error-correcting code via a matrix M which is indistinguishable from a randomly generated matrix of the same size.

Example: use **change of basis** $S \in GL(k, q)$ and **permutation** $P \in S_n$ to obtain **equivalent code**.

Hardness of assumption depends on chosen code family.

Part II

A LOOK INTO THE PAST

Use the traditional SDP-based trapdoor within **hash-and-sign** framework as in e.g. Full Domain Hash (RSA).

Given message msg , trapdoor OW function f and hash function \mathbf{H} .

Create signature $\sigma = f^{-1}(\mathbf{H}(msg))$. Verify if $f(\sigma) = \mathbf{H}(msg)$.

For CBC, trapdoor is decoding: CFS scheme.

(Courtois, Finiasz, Sendrier, 2001)

...except, domain is not “full”.

Complex sampling leads to slow signing, large keys and potential weaknesses.

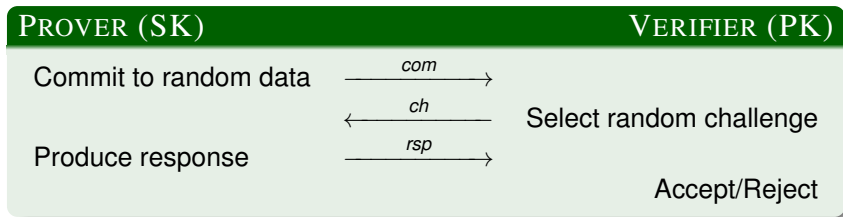
(Bleichenbacher, 2009; Faugère Gauthier-Umana, Otmani, Perret, Tillich, 2013; Landais, Sendrier, 2012; Bernstein, Chou, Schwabe, 2013)

Recent renditions still exhibit very similar features.

(Debris-Alazard, Sendrier, Tillich, 2018)

ZERO-KNOWLEDGE IDENTIFICATION SCHEMES

An interactive protocol to prove knowledge of a secret...
...without revealing anything about it.



- **Correctness**: honest prover always gets accepted.
- **Soundness**: dishonest prover (impersonator) has a bounded probability of succeeding.
- **Zero-Knowledge**: no information about the secret is leaked.

ZKIDs can be turned into signature schemes using **Fiat-Shamir** transformation.

- Replace verifier's challenge with $\mathbf{H}(com, msg)$.
 - Form signature as $\sigma = (com, rsp)$.
 - Verify as in identification protocol.
-

This method for building signatures is very promising and usually leads to efficient schemes.

(Schnorr, 1989;...)

Strong security guarantees. No trapdoor is required!

For CBC, can avoid decoding: rely **directly** on SDP.

Use **random codes** and exploit hardness of **finding low-weight words**.

(Stern, 1993)

STERN'S ZKID PROTOCOL

Select hash function \mathbf{H} .

KEY GENERATION

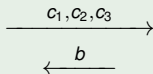
- Choose **random** binary code \mathcal{C} , given by parity-check matrix H .
- SK: $e \in \mathbb{F}_2^n$ of weight w .
- PK: the syndrome $s = He^T$.

PROVER

Choose $y \in \mathbb{F}_2^n$ and permutation π .

Set $c_1 = \mathbf{H}(\pi, Hy^T)$, $c_2 = \mathbf{H}(\pi(y))$

$c_3 = \mathbf{H}(\pi(y + e))$



If $b = 0$ set $rsp = (y, \pi)$

If $b = 1$ set $rsp = (y + e, \pi) \xrightarrow{rsp}$

If $b = 2$ set $rsp = (\pi(y), \pi(e))$

VERIFIER

Select random $b \in \{0, 1, 2\}$.

Verify c_1, c_2 .

Verify c_1, c_3 .

Verify c_2, c_3
and $wt(\pi(e)) = w$.

High **soundness error** implies that adversary has non-trivial **cheating probability**; for Stern's scheme, soundness error is $2/3$.

This means several **repetitions** are necessary to amplify error and reach target authentication level.

Transmitting the entire transcript produces a **very long** signature (e.g. ≥ 100 kB).

Several variants proposed over the years:

- Stern, 1993.
- Véron, 1996.
- Gaborit, Girault, 2007.
- Cayrel, Véron, El Yousfi, 2010.
- Aguilar, Gaborit, Schrek, 2011.
- ...

Goal: decreasing soundness error. For example, CVE scheme achieves $\frac{q}{2(q-1)} \approx 1/2$. Efficient for large finite fields.

Part III

NEW FRAMEWORKS

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We can use this in CBC! For example, apply this to CVE setting.

(Gueron, P., Santini, 2020)

GPS PROTOCOL

KeyGen: as in CVE, usual syndrome s , matrix H .

HELPER

- Generate random $y, \tilde{e} \in \mathbb{F}_q^n$, with \tilde{e} of weight w , from **seed**.
- Compute $aux = \{\mathbf{Com}(y + c\tilde{e})\}_{c \in \mathbb{F}_q}$.
- Send seed to prover and aux to verifier.

PROVER

Regenerate y, \tilde{e} from seed.

Determine μ s.t. $e = \mu(\tilde{e})$

$$\alpha = \mathbf{Com}(\mu, H(\mu(y))^T) \xrightarrow{\alpha}$$

$$\xleftarrow{c}$$

Select random $c \in \mathbb{F}_q$.

$$z = y + c\tilde{e} \xrightarrow{z}$$

Verify $\alpha = \mathbf{Com}(\mu, H(\mu(z))^T - cs)$.

Verify $\mathbf{Com}(z)$ with corresponding value from aux .

VERIFIER

Here the soundness error is $1/q$.

Use “cut-and-choose” technique to remove preprocessing.

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GPS scheme parameters ($\lambda = 128$, sizes in kB):

M	τ	q	n	k	w	PK	Sig
512	23	128	220	101	90	0.10	27.06
1024	19	256	207	93	90	0.11	23.98
2048	16	512	196	92	84	0.11	21.22
4096	14	1024	187	90	80	0.12	19.76

PROVING HAMMING WEIGHT VIA POLYNOMIALS

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Then $\deg(Q) = w$ and $wt(e) \leq w$ is equivalent to

$$Q \cdot S - P \cdot F = 0$$

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where $F = \prod_{i=1}^n (X - \gamma_i)$ and $\deg(P) \leq w - 1$.

This transforms SDP into a **polynomial problem** and completely avoids the need for an isometry.

(Feneuil, Joux, Rivain, 2022)

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This is done directly on shares $Q^{(j)}(r_l)$, $S^{(j)}(r_l)$ and $(P \cdot F)^{(j)}(r_l)$, via standard MPC techniques to verify **multiplication triple**.

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Optimized implementation underway.

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Group action structure allows to achieve **advanced functionalities** (e.g. identity-based, ring signatures). (Barengi, Biasse, Ngo, P., Santini, 2022)

LESS ZK IDENTIFICATION SCHEME

Public data: hash function \mathbf{H} , code \mathcal{C} with generator G

KEY GENERATION

- SK: invertible matrix S and monomial matrix Q .
- PK: matrix $G' = SGQ$ (can be systematic form).

PROVER'S COMPUTATION

- Choose random monomial matrix \tilde{Q} .
- Set $\tilde{G} = \text{SystForm}(G\tilde{Q})$ and $h = \mathbf{H}(\tilde{G})$.
(After receiving challenge bit b).
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- Set $\tilde{G} = \text{SystForm}(G\tilde{Q})$ and $h = \mathbf{H}(\tilde{G})$.
(After receiving challenge bit b).
- If $b = 0$ respond with $\tau = \tilde{Q}$.
- If $b = 1$ respond with $\tau = Q^{-1}\tilde{Q}$.

LESS ZK IDENTIFICATION SCHEME

Public data: hash function \mathbf{H} , code \mathcal{C} with generator G

KEY GENERATION

- SK: invertible matrix S and monomial matrix Q .
- PK: matrix $G' = SGQ$ (can be systematic form).

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VERIFIER'S COMPUTATION

- If $b = 0$ verify that $\mathbf{H}(\text{SystForm}(G\tau)) = h$.
- If $b = 1$ verify that $\mathbf{H}(\text{SystForm}(G'\tau)) = h$.

Part IV

CONCLUSIONS

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Explore the connection between codes and other post-quantum areas; isometry-based crypto?

Grazie, Danke, Merci, Grazcha, Thank you
and Congratulations to Joachim!

