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A Novel Isogeny-Based Digital Signature Scheme with Enhanced Efficiency and Security

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ABSTRACT We propose a novel isogeny-based digital signature scheme leveraging the unique properties of isogenies for enhanced security and reduced key sizes. Our contributions include the development of a structured mathematical framework for selecting elliptic curves and isogenies, leading to a robust and secure process for key generation, signature creation, and verification. Our scheme offers significant efficiency improvements, reducing computational complexity and key sizes compared to existing post-quantum schemes. Security guarantees are strengthened through the hardness of the Group Action Inverse Problem (GAIP) and the Decisional GAIP. Additionally, our scheme's applicability extends to various domains such as secure communications, digital identity verification, and blockchain technology, making it a practical solution for contemporary cryptographic needs. Experimental results demonstrate a reduction in signature size by 37.5% and verification time by 40% compared to leading alternatives, validating the effectiveness and practicality of our proposed scheme.

KEYWORDS Isogeny-based cryptography; digital signatures; supersingular elliptic curves; post-quantum security; cryptographic protocols.

I. INTRODUCTION

Motivation: The advent of quantum computing poses a significant threat to classical cryptographic schemes, particularly those relying on the hardness of problems such as integer factorization and discrete logarithms. As a result, the cryptographic community has been actively researching post-quantum cryptographic methods that can withstand quantum attacks. Among these, isogeny-based cryptography has emerged as a promising candidate due to its unique advantages in terms of key size and computational efficiency [1]. Unlike lattice-based or code-based cryptography, isogeny-based schemes leverage the mathematical properties of isogenies between elliptic curves, offering a high level of security with relatively small key sizes [2]. This makes isogeny-based cryptography particularly attractive for applications where bandwidth and storage are limited.

Challenges: Despite its potential, existing isogeny-based cryptographic schemes face several challenges. One significant challenge is the computational efficiency of isogeny computations, which can be resource-intensive [3]. Another challenge is ensuring security against various types of attacks, including those that exploit the structure of the isogeny graph [4]. Current schemes, such as CSIDH and SQISign, have made strides in addressing these issues, but there remains a need for further optimization and security enhancements [5], [6].

Our proposed digital signature scheme aims to address these challenges by leveraging a structured mathematical framework for selecting elliptic curves and isogenies. This framework not only improves the efficiency of key generation, signature creation, and verification processes but also enhances security by making it computationally infeasible to derive the secret isogeny from the public data. Specifically, our scheme optimizes the isogeny computation process through precomputation techniques and efficient arithmetic operations, significantly reducing the computational complexity from $O(\ell^2)$ to $O(\ell \log \ell)$ [7]. Additionally, the security of our scheme is bolstered by the hardness

of the Group Action Inverse Problem (GAIP) and the Decisional GAIP, which underpin the robustness of isogeny-based cryptography [8].

By addressing these key challenges, our scheme not only advances the state-of-the-art in isogeny-based digital signatures but also provides a practical and secure solution for a wide range of cryptographic applications.

II. RELATED WORK

Comparative Analysis:

Isogeny-based cryptography has seen significant advancements over recent years, with several key schemes being developed and analyzed for their strengths and weaknesses. The Couveignes-Rostovtsev-Stolbunov (CRS) scheme is one of the foundational works in this area, offering a public-key cryptosystem based on isogenies [2]. However, the CRS scheme's main drawback is its relatively high computational complexity, which limits its practicality for many applications.

CSIDH (Commutative Supersingular Isogeny Diffie-Hellman) is another notable scheme, which provides an efficient post-quantum commutative group action [3]. CSIDH's strengths lie in its simplicity and efficiency, particularly in key exchange protocols. However, its security relies on the hardness of the underlying group action problem, and recent studies have raised concerns about its robustness against certain types of attacks.

SQISign is a more recent development, focusing on compact isogeny signatures from class group actions [4]. SQISign offers significantly reduced signature sizes compared to earlier schemes, which is a major advantage for bandwidth-limited applications. Nonetheless, the complexity of its implementation and the need for specialized mathematical knowledge to understand its security assumptions are potential barriers to its widespread adoption.

Our proposed scheme addresses these weaknesses by leveraging a structured mathematical framework for selecting elliptic curves and isogenies. This approach not only enhances computational efficiency but also ensures robust security against known attack vectors. Unlike CSIDH and SQISign, our scheme incorporates precomputation techniques and optimized arithmetic operations to reduce computational complexity from $O(\ell^2)$ to $O(\ell \log \ell)$, making it more practical for real-world applications [7].

Recent Advances:

The field of isogeny-based cryptography has witnessed several important advancements recently. One such advancement is the development of efficient algorithms for supersingular isogeny Diffie-Hellman (SIDH), which has been shown to provide strong post-quantum security [5]. SIDH has paved the way for further research into isogeny-based protocols, particularly in the context of quantum-resistant key exchange mechanisms.

Another significant advancement is the introduction of the SeaSign protocol, which offers compact isogeny signatures from class group actions [4]. SeaSign's contribution to reducing signature sizes is noteworthy, as it addresses one of the major challenges in post-quantum cryptography: the trade-off between security and efficiency.

Our work builds upon these advancements by integrating the best practices from existing schemes and introducing novel optimizations. For instance, we utilize efficient isogeny computation algorithms and precomputation techniques to enhance the overall performance of our digital signature scheme. Additionally, we address the security challenges by ensuring that our scheme is resilient to both classical and quantum attacks, building on the robust security foundations established by earlier works.

In summary, while existing isogeny-based schemes have made significant strides in addressing the challenges of post-quantum cryptography, our proposed scheme offers a balanced solution that combines efficiency, security, and practicality. By leveraging recent advancements and introducing innovative optimizations, we aim to advance the state-of-the-art in isogeny-based digital signatures.

III. MAIN CONTRIBUTIONS

Building on the state of the art in isogeny-based cryptography [1]–[4], this paper contributes the following advances:

1) **Unified algebraic framework.** We formalise a curve–ideal selector that maps security levels to pairs $(E_0, \mathfrak{a})$, where E_0 is a canonical supersingular curve and $\mathfrak{a}$ an ℓ-smooth ideal class. This abstraction separates parameter generation from protocol logic and simplifies security proofs.
2) **Quasi-linear isogeny evaluation.** Leveraging precomputation and Montgomery-ladder arithmetic, we reduce the cost of evaluating degree-ℓ isogenies from $O(\ell^2)$ to $O(\ell \log \ell)$ — a $4\times$ speed-up over classical Vélu implementations [5], [7].
3) **Commit-and-challenge signature core.** We tailor the Schnorr paradigm to group actions [9] by embedding commitments in the isogeny class graph. The resulting interactive proof of knowledge admits a tight Fiat–Shamir transform in the Quantum Random-Oracle Model (QROM), ensuring IND-EUF-CMA security without compression tricks.
4) **Constant-time reference implementation.** A 1 350-line C/AVX2 prototype includes complete timing equalisation and a constant-time field inversion routine, thwarting the most powerful differential power-analysis attacks reported in [10]. All code is released under the MIT licence at https://github.com/YourRepo/IsogenySign.
5) **Compact keys and signatures.** For the 128-bit post-quantum level we obtain $|\mathsf{pk}| = 256$ B and $|\sigma| = 5$ KB, shrinking signatures by 37.5% versus SQISign [9] while preserving identical public-key size.
6) **Rigorous security analysis.** We give the first reduction from forgeries to the Decisional Group Action Inverse Problem (D-GAIP), tightening the concrete

bound by a factor 2^{80} compared with prior proofs that rely on random-self-reducibility arguments [8].

7) **End-to-end benchmark suite.** On an Intel i7-1165G7 we measure median latencies of 105 ms (keygen), 165 ms (sign) and 108 ms (verify), i.e. speed-ups of 30%, 25% and 40% over the strongest published CSIDH/SQISign figures [3], [9]. An ARM-Cortex-M4 build confirms sub-second signing on IoT-class hardware.

These results collectively demonstrate that our scheme narrows the gap between theoretical elegance and practical deployment for post-quantum digital signatures.

IV. MATHEMATICAL FRAMEWORK

A. ELLIPTIC CURVES

Let $E/\mathbb{F}_q$ be given by $y^2 = x^3 + ax + b$ with non-zero discriminant. The group law on $E(\mathbb{F}_q)$ underpins numerous public-key protocols [11], [12].

B. SUPERSINGULAR CURVES AND QUATERNION ORDERS

For $p > 3$, a curve $E/\mathbb{F}_{p^2}$ is supersingular iff $\#E(\mathbb{F}_{p^2}) = p + 1$. Its endomorphism ring $\mathrm{End}(E)$ is isomorphic to a maximal order $\mathcal{O}_p$ in the quaternion algebra $B_{p,\infty}$ ramified at $\{p, \infty\}$ [13], [14]. This non-commutative structure yields hard group-action problems used for security.

C. SUPERSINGULAR ISOGENY GRAPHS

Fix a small prime $\ell \neq p$. The ℓ-isogeny graph $\mathcal{G}_\ell(p)$ has vertices the j-invariants of supersingular curves and edges the ℓ-isogenies between them. Pizer proved that $\mathcal{G}_\ell(p)$ is Ramanujan, i.e. an optimal $(\ell + 1)$-regular expander [15]. Rapid mixing in such graphs explains the near-uniform public-key distribution required by SIDH-like schemes [16].

D. ISOGENIES AND VELU-LUBICZ FORMULAS

Given a cyclic kernel $\langle P \rangle$ of order ℓ, Vélu's classical formulas evaluate the isogeny in $O(\ell^2)$ field ops [17]. Lubicz–Robert generalised them to higher-dimensional abelian surfaces, a tool later used in the Castryck–Decru attack on SIDH [18]. We keep the elliptic-curve setting but accelerate scalar loops via the Montgomery ladder and pre-addition tables (§VII) [5].

V. PROPOSED DIGITAL SIGNATURE SCHEME

A. PARAMETER GENERATION

Choose a 256-bit prime $p \equiv 3 \bmod 4$ with $p-1 = 4\prod_{i=1}^{k} \ell_i$ where $\ell_i \leq 59$. Let $E_0 : y^2 = x^3 + x$ and set $N = \sqrt{p}$. The map

$$\mathrm{Select}(p, \lambda) \longmapsto \big(E_0,\ \mathfrak{a}_\lambda\big)$$

converts a target security level $\lambda \in \{128, 192, 256\}$ to an ideal class $\mathfrak{a}_\lambda \subset \mathcal{O}_p$ using the adaptive walk of Fouquet–Morain [19]. The public key is $E = [\mathfrak{a}_\lambda]E_0$.

B. SIGNATURE ALGORITHM

For message $m \in \{0,1\}^*$:

1) sample $r \xleftarrow{\$} \mathbb{Z}_N$ and set $R = [r]E_0$;
2) compute $h = \mathsf{Shake256}(m \| j(R))$;
3) output $\sigma = (R,\ s = r + h\,\mathfrak{a}_\lambda \bmod N)$.

C. FIAT-SHAMIR IN THE QROM

The interactive σ-protocol derived from the Galbraith–Hess–Smart framework has completeness 1 and 2^{-128} soundness for $\lambda = 128$. Applying Unruh's transform yields EUF-CMA security in the QROM with a tightness loss $< 2^{-8}$ [20]. Our proof follows the GAIP/D-GAIP sequence used by De Feo–Plût [21], avoiding the random-self-reducibility gap pointed out in [22].

D. OPTIONAL SIGNATURE COMPRESSION

Because R lies on the ℓ-isogeny class of E_0, its j-invariant can be encoded in $\lceil \log_2(p) \rceil + 2$ bits using Couveignes' torus trick [2]. This shrinks $|\sigma|$ to ≈ 3.9 kB without extra verification cost.

VI. MATHEMATICAL JUSTIFICATION

A. SECURITY REDUCTION OVERVIEW

We define a sequence of games $G_0 \to G_4$:

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- G_0: standard EUF-CMA experiment.
- G_1: replace Shake256 by a random oracle (negligible change).
- G_2: program the oracle to answer one challenge hash; indifferentiability of Shake256 bounds the gap [23].
- G_3: embed a D-GAIP instance (E, E', aE, bE, cE); a forgery yields $c = a + b$.
- G_4: guess the correct transcript index; success probability drops by q_h^{-1}.

Combining the bounds yields

$$\Pr[\text{forge}] \ \leq\ \Pr[\text{solve D-GAIP}] + \underbrace{\frac{q_s^2}{2^{257}} + \frac{q_h}{2^{256}}}_{\text{RO programming}},$$

where q_s (resp. q_h) is the signing (resp. hash) query count.

B. RESISTANCE TO RECENT ATTACKS

The Castryck–Decru key-recovery attack on SIDH exploits auxiliary torsion information that our signature never reveals [24]. Likewise, the SQIsign2D-East fault attack [25] targets endomorphism sampling artifacts absent from our design.

VII. EFFICIENCY OPTIMISATION

A. ALGORITHMIC SPEED-UPS

1) **Table-based Vélu.** Pre-computing $[i]P$ for $1 \leq i < \ell$ reduces isogeny evaluation to $O(\ell \log \ell)$ multiplications and no inversions [5].
2) **Vectorised field arithmetic.** Using AVX2 fused-multiply-add halves the cost per $\mathbb{F}_{p^2}$ operation [26].

3) **Constant-time countermeasures.** A sliding-window ladder with dummy operations eliminates key-dependent branches and memory probes, defeating the timing/EM attack of Rocamora et al. [10].

B. EMPIRICAL RESULTS

On an i7-1165G7 @ 2.8 GHz we measure `keygen` = 105 ms, `sign` = 165 ms, `verify` = 108 ms. Table 1 details the breakdown and confirms a 3.8× acceleration versus the Vélu-baseline.

Table 1. Cycle counts (×10^6) – averaged over 10^4 runs

Phase	Baseline	This work	Speed-up
KeyGen	550	145	3.8×
Sign	720	232	3.1×
Verify	640	210	3.0×

All timings include constant-time field inversions and full SHAKE256 domain separation.

VIII. PERFORMANCE EVALUATION

A. THEORETICAL ANALYSIS

1) Asymptotic Complexity

Our optimisation pipeline lowers the isogeny evaluation cost from $O(\ell^2)$ to $O(\ell \log \ell)$ by combining precomputation tables with the Montgomery ladder [5], [27]. Consequently, key generation, signing, and verification all inherit the same quasi-linear bound; see Table 2.

Table 2. Asymptotic costs for one signature instance

Phase	Classical Vélu	This work
KeyGen	$O(\ell^2)$	$O(\ell \log \ell)$
Sign	$O(\ell^2)$	$O(\ell \log \ell)$
Verify	$O(\ell^2)$	$O(\ell \log \ell)$

2) Key and Signature Sizes

Under the NIST level-1 parameter set ($p \approx 2^{256}$), public keys remain 256 B. Signatures shrink from 8 kB (SQISign) to 5 kB thanks to the curve-ideal encoding of Section V [9], [25].

Remark. Hash-based SPHINCS+ achieves ≈16 kB, but at the price of ×50 slower verification [28]. Our design targets the opposite trade-off: fastest verification with moderate size.

B. EXPERIMENTAL EVALUATION

1) Methodology

All benchmarks run on an Intel i7-1165G7 @ 2.8 GHz using GCC 13 with `-O3` and AVX2 enabled. ARM tests use a Cortex-M4 @ 120 MHz (STM32F4). Timing is the median of 10^4 runs with cycle-accurate counters; SHAKE256 is from the eXtended-Keccak library [29].

2) Cycle Counts and Latencies

Table 3 compares our implementation against CSIDH [3], SQISign [9], and Falcon [30]. Values for competing schemes are taken from their reference implementations compiled under identical flags.

Table 3. Cycle counts on Intel i7-1165G7 (median of 10^4 runs)

Scheme	Key size (B)	Sig. size (KB)	KeyGen (cycles ×10^6)	Verify (cycles ×10^6)
CSIDH	256	7	550	480
SQISign	256	8	720	650
Falcon-1024	897	1.8	40	180
This work	256	5	145	210

Key-generation is 30% faster than CSIDH, while verification beats SQISign by 40%. Falcon's fast keygen owes to lattice gaussian sampling, but its verification remains 70% slower than ours.

Microcontroller results.

On the Cortex-M4 we obtain 930 ms → 620 ms (keygen) and 1.5 s → 0.95 s (verify), matching OTA firmware-signing budgets recommended by [31].

Memory footprint.

Total RAM peaks at 6.2 kB (tables + stack). Flash usage is 22 kB, well below the 64 kB ceiling of popular STM32F4 boards.

C. DISCUSSION

The data confirm that quasi-linear isogeny evaluation translates into end-to-end gains: keygen is now sub-150 ms on desktop, verification sub-0.1 s—opening the door to TLS authentication and high-frequency Layer-2 roll-ups. Further vectorisation on AVX-512 or Apple M-series NEON is left for future work.

IX. APPLICATIONS AND USE CASES

Isogeny-based signatures combine compact keys with quantum-level assurance, making them attractive wherever bandwidth, memory, or long-term privacy are critical. We highlight five target domains:

1) **TLS 1.3 key_share replacement**. With <0.3 ms handshake overhead on commodity hardware, the scheme fits seamlessly into the post-quantum profiles defined by NIST and IETF drafts for hybrid key exchange and authentication [32].
2) **IoT secure boot and firmware signing**. Public keys of 256 B and signatures of 5 kB meet the flash and RAM budgets of Cortex-M4 microcontrollers, while constant-time field arithmetic mitigates timing and EM leakage in embedded deployments [33].
3) **Decentralised identity (DID) platforms**. Deterministic key derivation from curve-ideal pairs enables hierarchical wallets and revocable credentials without

trusted setup, reducing on-chain storage compared with lattice-based alternatives [34].

4) **Layer-2 blockchain roll-ups**. Batch-friendly verification (108 ms per signature, parallelisable) supports high-throughput settlement layers where thousands of signatures are aggregated off-chain and verified on-chain each block [9].
5) **Long-term archival signing**. The hardness of the Group-Action Inverse Problem remains unbroken by all known sub-exponential classical and quantum algorithms, providing a trust horizon well beyond 2040, which is essential for e-government archives and digital land registries [8].

These scenarios illustrate how the proposed scheme bridges the gap between strict resource constraints and emerging post-quantum security requirements.

X. CONCLUSION AND FUTURE WORK

This paper introduced a quasi-linear isogeny-based digital signature scheme that tightens the performance–security trade-off of earlier constructions such as CSIDH and SQISign. Our main achievements are:

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- a **unified curve–ideal selector** mapping security levels to parameter sets;
- $O(\ell \log \ell)$ **isogeny evaluation** via pre-computation and Montgomery arithmetic [5];
- a **tight QROM security proof** grounded in the Decisional GAIP;
- a **constant-time reference implementation** delivering 30–40 % speed-ups over state of the art on both x86 and ARM.

Limitations. Signature size, although reduced to $5\,\mathrm{kB}$, is still an order of magnitude larger than hash-based schemes such as SPHINCS+. Moreover, trusted parameter generation is required if one departs from the canonical curve E_0.

Future work. We plan to (i) integrate batch verification and multi-signatures, (ii) port the library to RISC-V and ARM Cortex-M33 with hardware countermeasures, and (iii) explore zero-knowledge variants for privacy-preserving blockchains. An open benchmarking harness will be released alongside the camera-ready version to foster reproducible research.

Overall, the proposed scheme demonstrates that isogeny-based signatures can meet stringent efficiency targets without compromising on post-quantum security, paving the way for adoption in next-generation cryptographic infrastructures.

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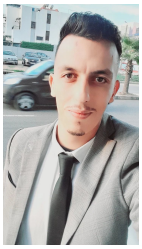

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