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Parameterized Exponential Diophantine Equations for RNS-Encoded Pythagorean Triples in ECC and Embedded Control

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ABSTRACT:

This paper bridges pure number theory to cryptography/embedded systems, distinguishing it from general Diophantine equations (over 8 unknowns) yielding Pythagorean triples for RNS encoding, while bridging ECC key generation, embedded control (pole placement), and microcontroller-optimized solvers like progressive LLL. Also, focused to highlights the distinction from general Diophantine studies by emphasizing parameterization (via k, m, n for integer solutions of x, y, z, w, etc.) and practical applications in RNS-ECC and embedded optimization. Undecidability in high dimensions (>8 unknowns) limits general solvers, but parameterized forms (like your k,m,n solutions) enable practical cryptographic pipelines. It underscores the interdisciplinary novelty—distinguishing from pure number theory by practical RNS-ECC applications and embedded optimization by taking one suitable example of Diophantine equation of more than 8 unknowns.

$\alpha(X^m + Y^m)(3U^2 + V^2) = T^2(C^2 - D^2)(Z^2 - W^2)P^\beta$ **With** $\alpha > 0, \beta > 0, m > 0$ *and* $X < Y < W < Z$

Having integer design of solutions **for** $\beta > 2$ is parameterized by positive integers k, m and n, with variables defined as:

$$x = k^n, y = k^{n+1}, z = k^{n+3}, w = k^{n+2}, p = k^n,\ U = 3^n,\ V = 3^n,\ T = 2(3)^n,$$

$$\alpha = k^{(\beta+2-m)n}(1 + k^m)(k^6 - k^4)n^2, \quad \begin{Bmatrix} C = \left(\left(\frac{1+k^m}{2}\right)^2 + 1\right)n, D = \left(\left(\frac{1+k^m}{2}\right)^2 - 1\right)n, & if\ 1 + k^m\ is\ even \\ C = \left(\frac{(1+k^m)^2+1}{2}\right)n, \quad D = \left(\frac{(1+k^m)^2-1}{2}\right)n, & if\ 1 + k^m\ is\ odd \end{Bmatrix}.$$

KEYWORDS: Diophantine Equation, exponential, Pythagorean triplet, Integer design.

I. INTRODUCTION

In ECC contexts, exponential generalizations generate Pythagorean triples for RNS encoding and curve parameters, aiding LLL-reduced keys in embedded systems. These tie to elliptic curve discrete log problems rooted in Diophantine geometry.

Diophantine equations—polynomial equations with integer solutions—are a central topic in number theory. Among their many variants, **exponential Diophantine equations** involve terms where variables appear as exponents. Finding integer solutions to such equations is notably complex and has implications in mathematics, cryptography, and several scientific fields. Historical Context and Theoretical Background.

Classical Diophantine Equations: Traditionally, research started with linear and polynomial forms, such as the well-known cases of Pythagorean triples .

Exponential Generalization: The study of exponential forms expanded from these roots, posing questions that often lack general solution methods and in some cases are proven to be undecidable.

Pythagorean triples from Diophantine solutions support Residue Number System (RNS) encoding for efficient arithmetic in embedded control, linking to triples generation pipelines. The equation

$\alpha(X^m + Y^m)(3U^2 + V^2) = T^2(C^2 - D^2)(Z^2 - W^2)P^\beta$ **With** $\alpha > 0, \beta > 0, m > 0$ *and* $X < Y < W < Z$

generalizes Fermat-like forms for cryptographic primitives or curve parameters, though specific instances tie to triple-based ECC. These unify cryptography, allocation, and control in resource-limited settings.

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For microcontroller Diophantine solvers like LLL-based methods excel in real-time control, outperforming floats in integer tasks despite hardware FPUs. Progressive variants cut time for ECC-like reductions while fitting memory limits.

This paper focused on a study to find integer design of solutions Diophantine Equation $\alpha(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$ With $\alpha>0,\beta>0,m>0$ *and* $X<Y<W<Z$. Diophantine equations of higher degrees, play a meaningful role in generating special elliptic curves that are crucial for cryptography and secure communications.

II. RESULTS & DISCUSSIONS

In this paper, focused to find the general exponential integer solution of the general exponential integer solution of $(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$

With $\alpha>0,\beta>0,m>0$ is derived from fixed value of β.

Proportion 1: A Study on exponential integer solution of above Diophantine Equation at

$\beta=1$ **is** $\alpha(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$

Explanation:

Let x = $k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, p=k^n, U=3^n,\ V=3^n, T=2(3)^n$

Consider $\alpha(X^m+Y^m)(3U^2+V^2)=\alpha k^{nm}(1+k^m)(2(3)^n)^2$.

Again consider $T^2(C^2-D^2)(Z^2-W^2)P^\beta=(C^2-D^2)k^{(\beta+2)n}(k^6-k^4)(2(3)^n)^2$

It follows that $\alpha(X^4+Y^4)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$ implies that

$\alpha k^{mn}(1+k^m)(2(3)^n)^2=(C^2-D^2)k^{(\beta+2)n}(k^6-k^4)(2(3)^n)^2$ implies

$\alpha(1+k^m)=k^{(\beta+2-m)n}(C^2-D^2)(k^6-k^4)$.

Solve for α, whenever $(1+k^m,D,C)$ is a Pythagorean Triplet.

From the References [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12] there is so many methods to generate Pythagorean triplet,

$$S_1=\left\{(x,y,z):\frac{z}{y}=1+\frac{2}{x^2-1}\ \text{ if } x \text{ is an odd prime number or its power}\right\}$$

$$S_2=\left\{(x,y,z):\frac{z}{y}=1+\frac{2}{\left(\frac{x}{(2p-1)^2}\right)^2-1}\ \text{ if } x \text{ is an odd composite or its Power, for some } p=1,2,3\ldots\right\}$$

$$S_3=\left\{(x,y,z):\frac{z}{y}=1+\frac{2}{\left(\frac{x}{2}\right)^2-1}\ \textit{ if } x \text{ is geometric power of 2}\right\}$$

$$S_4=\left\{(x,y,z):\frac{z}{y}=1+\frac{2}{\left(\frac{x}{2p^2}\right)^2-1},\text{otherwise (x is even composite or its power)}\right\}.$$

now I chosen one of the technique of

if r is an even number, then (r, $\left(\frac{r}{2}\right)^2-1$, $\left(\frac{r}{2}\right)^2+1$) is a Pythagorean triplet.

If r is an odd number, then (r, $\frac{r^2-1}{2}$, $\frac{r^2+1}{2}$) is a Pythagorean triplet.

It implies that $(1+k^m,D,C)$ becomes a Pythagorean Triplet depending on *whether* $1+k^m$ is odd or even.

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Case 1: **If $1+k^m$ is even**, then ($1+k^m$, $\left(\frac{1+k^m}{2}\right)^2-1$, $\left(\frac{1+k^m}{2}\right)^2+1$) is a Pythagorean triplet.

It follows that $\alpha(1+k^m)=k^{(\beta+2-m)n}(C^2-D^2)(k^6-k^4)$ and solve for α,

whenever $(1+k^m, D, C)$ becomes a Pythagorean Triplet with $C=\left(\left(\frac{1+k^m}{2}\right)^2+1\right)n$,

$D=\left(\left(\frac{1+k^m}{2}\right)^2-1\right)n$ *and* $C^2-D^2=(1+k^m)^2n^2$ and hence

$\alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2$.

Hence, **we obtain $(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P$ having integer design of solution is**

$x=k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, U=3^n,\ V=3^n, T=2(3)^n, p=k^{2n}$,

$C=\left(\left(\frac{1+k^m}{2}\right)^2+1\right)n,\ D=\left(\left(\frac{1+k^m}{2}\right)^2-1\right)n, \alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2$.

Verification:

Consider **LHS**

$\alpha(X^m+Y^m)(3U^2+V^2)=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2(k^{mn}+k^{mn+m})(2(3)^n)^2$

$=k^{\beta+2}(k^6-k^4)(1+k^m)^2n^2(2(3)^n)^2$

Consider RHS

$T^2(C^2-D^2)(Z^2-W^2)P=(2(3)^n)^2(1+k^m)^2n^2(k^{2n+6}-k^{2n+4})k^{\beta n}$

$=(2(3)^n)^2k^{\beta+2}(k^6-k^4)(1+k^m)^2n^2$.

Hence LHS = RHS.

Case 2: If $1+k^m$ is odd, then ($1+k^m$, $\frac{(1+k^m)^2-1}{2}$, $\frac{(1+k^m)^2+1}{2}$) is a Pythagorean triplet. It follows that $\alpha(1+k^m)=k^{(\beta+2-m)n}(C^2-D^2)(k^6-k^4)$ and solves for α, whenever

$(1+k^m, D, C)$ becomes a Pythagorean Triplet with $C=\left(\frac{(1+k^m)^2+1}{2}\right)n$, $D=\left(\frac{(1+k^m)^2-1}{2}\right)n$.

Hence $C^2-D^2=(1+k^m)^2n^2$ and hence $\alpha=k^{(\beta+2-m)n}(C^2-D^2)(k^6-k^4)$.

Hence, $(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P$ **having integer design of solution is**

$x=k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, U=3^n,\ V=3^n, T=2(3)^n, p=k^{2n}$,

$C=\left(\frac{(1+k^m)^2+1}{2}\right)n, D=\left(\frac{(1+k^m)^2-1}{2}\right)n,\ \alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2$.

Verification:

Consider **LHS**

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$\alpha(X^m+Y^m)(3U^2+V^2)=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2(k^{mn}+k^{mn+m})(2(3)^n)^2$

$=k^{\beta+2}(k^6-k^4)(1+k^m)^2n^2(2(3)^n)^2$

Consider RHS

$T^2(C^2-D^2)(Z^2-W^2)P=(2(3)^n)^2(1+k^m)^2n^2(k^{2n+6}-k^{2n+4})k^\beta$

$=(2(3)^n)^2k^{\beta+2}(k^6-k^4)(1+k^m)^2n^2.$

Hence LHS $= RHS.$

III. ALGORITHM FOR ELLIPTIC CURVE CRYPTOGRAPHY

From the References [13],[14],[15],[16],[17],[18],[19],[20],[21],[22],[23],[24]

(I) *Ep* (X, Y, Z, W, U, V, T): $(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$

is the equation for an elliptic curve, where *Ep* is an elliptic curve defined over the finite field *Ep* for $x=k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, p=k^n,\ U=3^n,\ V=3^n, T=2(3)^n$.

(II) **Key Generating**: The message will be encrypted by the sender using the recipient's public key and the recipient will use his private key to decrypt it.

(i) Let "M" be the point on the elliptic curve.

(ii) Select "M" as the point from*Ep* (X, Y, U, V,).

(iii) Choose generator point β in *Ep* (X, Y, Z, W, U, V, T).

(iv) Select a private key n from the interval $1\le n\le p-1$ and utilize it to compute β the public key.

(v) Choose a number M that falls LHS of elliptic curve. $M=(X^m+Y^m)(3U^2+V^2)$.

(III) **Encryption**:

Let α cipher texts that will be generated. $\alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2$

(IV) **Decryption**:

The original point that we have sent, point "M", needs to be decrypted using the formula

$M=T^2(C^2-D^2)(Z^2-W^2)P$, as it was sent to the recipient.

IV. CONTROL APPLICATIONS

From the References [25],[26],[27],[28],[29],[30],[31],[32],[33],[34],[35],[36]

Known attacks on crypto using exponential Diophantine problems primarily exploit lattice-based methods and partial key recovery, as these schemes remain experimental and underexplored compared to RSA or ECC. Weighted LLL (Lenstra-Lenstra-Lovász) variants break Diophantine-based encryption by reconstructing ideals in polynomial rings like F_p[x,y,z,t], especially for parameters targeting 128-bit security; experiments show insecurity even for moderate dimensions. Progressive LLL, as in your paper's microcontroller solvers, counters this by optimizing for embedded constraints but remains vulnerable if lattice dimensions exceed hardware limits. Continued fraction expansions recover private exponents in multi-exponent setups (e.g., RSA variants with shared moduli), extending to exponential forms via Legendre's equation when gcd conditions hold on convergent like e1/e3 ≈ d3k1/d1k3. Coppersmith's method finds small roots of modular exponential polynomials, enabling partial key exposure attacks. Parameterized forms (>8 unknowns yielding Pythagorean triples) resist general solvers due to undecidability but face hybrid threats combining lattices with RNS decoding; embedded pole-placement integration adds timing side-channels.

- Pole Placement: Diophantine solutions from Ep parameters solve characteristic equations for discrete-time stabilizers.

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- RNS Encoding: Pythagorean triples derived from curve points accelerate modular ops in resource-constrained feedback.
- Unified Pipeline: ECC secure comms + LLL solver optimizations create end-to-end crypto-control for embedded systems.

E.g. 1: Suppose k = 2, m = 4, $\boldsymbol{\beta = 1}$ then $1 + k^m = 1 + k^4 = 17$, is odd; Having an integer design of solution is

x = $2^n, y = 2^{n+1}, z = 2^{n+3}, w = 2^{n+2}, p = 2^{2n}$, $\boldsymbol{U = 3^n,\ V = 3^n\ , T = 2(3)^n}$,

$C = \left(\frac{(1+2^4)^2+1}{2})\right)n = 145n,\ D = \left(\frac{(1+2^4)^2-1}{2}\right) = 144n$

$C^2 - D^2 = (1+2^4)^2 n^2,\ \alpha = (1+2^4)(2^6 - 2^4)n^2.$

Suppose n = 1; then x = $2, y = 4, z = 16, w = 8, p = 4$,U = 3 , V = 3 , T = 6

$C = \left(\frac{(1+2^4)^2+1}{2})\right) = 145,\ D = \left(\frac{(1+2^4)^2-1}{2}\right) = 144$

$C^2 - D^2 = (1+2^4)^2 = 289,\ \alpha = (1+2^4)(2^6 - 2^4) = 816.$

Consider **LHS=** $\boldsymbol{\alpha(X^4 + Y^4)(3U^2 + V^2)}$ **=816**$\boldsymbol{(2^4 + 4^4)(36) = 7990272.}$

RHS $\boldsymbol{= T^2(C^2 - D^2)(Z^2 - W^2)P = 36 * 289 * (16^2 - 8^2) * 4 = 7990272.}$

E.g. 2: Suppose k = 3, m = 4, $\boldsymbol{\beta = 1}$ then $1 + k^4 = 82$, is even; Having an integer design of solution is

x = $3^n, y = 3^{n+1}, z = 3^{n+3}, w = 3^{n+2}, p = 3^{2n}$, $\boldsymbol{U = 3^n,\ V = 3^n\ , T = 2(3)^n}$,,

$C = \left(\left(\frac{1+3^4}{2}\right)^2 + 1\right)n = 1681n,\ D = \left(\left(\frac{1+3^4}{2}\right)^2 - 1\right)n = 1600n$

$C^2 - D^2 = (1+3^4)^2 n^2 = 6724n,\ \alpha = (1+3^4)(3^6 - 3^4)n^2 = 53136n^2.$

Suppose n = 1; then x = $3, y = 9, z = 81, w = 27, p = 9$, U = 3 , V = 3 , T = 6, $C^2 - D^2 = 6724,\ \alpha = 53136$

Consider **LHS=** $\boldsymbol{\alpha(X^4 + Y^4)(3U^2 + V^2)}$ **=53136**$\boldsymbol{* (3^4 + 9^4) * 36 = 352929312 * 36 = 12705455232.}$

RHS $\boldsymbol{= T^2\ (C^2 - D^2)(Z^2 - W^2)P = 36 * 6724 * (81^2 - 27^2) * 9 = 12705455232.}$

V. CONCLUSION

In summary, this research paper contributes to the ongoing efforts to explore novel mathematical constructs in the design of secure and efficient cryptographic systems. By harnessing the properties of Diophantine triples and special polynomial sequences, it's possible to develop elliptic curves that offer robust security features for modern cryptographic applications. It distinguishes from classical Diophantine studies by highlighting exponential forms, high dimensionality, and applications like elliptic curve cryptography primitives, Fermat-like generalizations, and integer-based real-time solvers outperforming FPUs. In this paper, focused given Diophantine equation with more than 8 unknowns

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$\alpha(X^m+Y^m)(3U^2+V^2)=T^2(C^2-D^2)(Z^2-W^2)P^\beta$ **With** $\alpha>0,\beta>0,m>0$ *and* $X<Y<W<Z$

Having integer design of solutions **for** $\beta>2$ is parameterized by positive integers k, m and n, with variables defined as:

$$x=k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, p=k^n,\ U=3^n,\ V=3^n, T=2(3)^n,$$

$$\alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2,\quad \begin{Bmatrix} C=\left(\left(\frac{1+k^m}{2}\right)^2+1\right)n, D=\left(\left(\frac{1+k^m}{2}\right)^2-1\right)n, & if\ 1+k^m\ is\ even \\ C=\left(\frac{(1+k^m)^2+1}{2}\right)n, D=\left(\frac{(1+k^m)^2-1}{2}\right)n, & if\ 1+k^m\ is\ odd \end{Bmatrix}$$

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