Software Implementation of Genus-2 Hyperelliptic Curve Cryptosystems Over Prime Fields

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Abstract. This paper describes the system parameters and software implementation of a HECDSA cryptosystem based on genus-2 hyperelliptic curves over prime fields. We show how to reduce the computational complexity for special cases and compare the given cryptosystem with the well-known ECDSA cryptosystem based on elliptic curves.

Keywords: Hyperelliptic curve, divisor addition, efficient implementation, HECDSA.

Introduction

With the recent boost of information technology in modern society, the problem of information security becomes of special urgency. The most difficult task is to provide a secure handling and storage of critical and confidential data for government and private companies, banks and other systems. A solution to this problem is to implement systems which provide information confidentiality, integrity, authenticity and accessibility by means of cryptographic software and cryptographic hardware.

At the same time cryptanalytical methods, multiplied by the progress in capabilities of modern computers, puts high requirements on the security parameters of modern cryptosystems. Moreover, the increased data amount processed in modern information systems requires a high performance of modern cryptosystems. Hence the timing requirements to cryptographical applications have increased dramatically. I.e., prospective cryptoalgorithms must provide efficient processing of bulk data and, at the same time, a high level of security. Under this circumstances, the most urgent direction is the development of public key cryptosystems which are efficient in software and hardware and allow for setting up a PKI.

In recent decades, elliptic curve cryptosystems (ECC) have been widely exploited which can be seen by recent standardization efforts [1, 2]. However, this is not the last frontier of the research focused on algebraic curve application in cryptography. The authors of [3] have shown that elliptic curves have a worthy alternative, namely hyperelliptic curves (HEC) [4]. The standardization of ECC gave rise to intensive investigation of HEC properties. The biggest advantage of HEC over EC lies in its richer source of finite Abelian groups and the use of smaller finite fields.

Till now, however, most research has been done on several theoretical aspects of hyperelliptic curve cryptosystems (HECC), including many improvements of the underlying arithmetic on HEC. On the implementational side, improvements for specific processors and hardware platforms have been analyzed. With this contribution, we are providing a very important step towards the practical implementation of HECC by showing how to build an efficient HECDSA implementation and provide cryptographically suitable curves. Unfortunately, published results on practical implementation of HECC are rare [5, 6]. This paper is intended to provide very practical facts for the implementation of an HECDSA system with all its necessary details. There are a lot of modern articles dealing with HECC; but they describe no validated system parameters for the efficient implementation of a workable cryptosystem.

The lack of publications dedicated to exactly this topic gave us the motivation to carefully summarize all results for efficient HECC implementation, and compare HECC (HECDSA) with the existent ECC (ECDSA).

Finite Field Arithmetic

Arithmetic in the Jacobian is based on the arithmetic in a polynomial function ring over a finite field, i.e., all the transformations in the Jacobian consist of manipulation over finite field elements. In accordance with the introductory part, this paper does not focus on the finite field arithmetic and its efficient implementation. The implementation was based on results published in [7, 8, 24]. The resulting timings of arithmetic in the finite field is comparable to [8] but is worse in 3-4 times than [24] and is summarized in Table 1.

Table 1. Experimental valuations of prime base fields arithmetics timings

	$\log_2 p$	+	-	*, comb	mod	$()^2$	$()^{-1}$
1 [mks]	192	0.097	0.094	0.823	0.203	0.823	66.30
	224	0.114	0.112	1.074	0.261	1.074	88.26
	256	0.123	0.125	1.568	0.522	1.358	115.90
2 [mks]	192	0.045	0.047	0.703	0.122	0.642	43.65
	224	0.048	0.060	0.904	0.198	0.820	52.12
	256	0.058	0.073	1.207	0.582	1.184	72.19
3 [mks]	192	-	-	0.198	0.319	-	16.3
	224	-	-	0.361	0.416	-	22.3
	256			0.392	0.493		28.8

In Table 2, information about the platform, set-up and compiler can be found.

Table 2. General set-up of the implementation of the finite field arithmetic

Col #	Source	CPU	Implementation features
1	[8]	Intel, Pentium II 400 MHz	MS VC++ 6.0 (with asm)
2	authors	AMD, Athlon XP 2500+ MHz	MS VC++ 2005 (w/o asm)
3	[24]	AMD, Athlon 1 Ghz	gcc C compiler v.2.95.3, v3.1.1

All finite fields in Table 1 are taken from the recommended elliptic curve list [9].

Table 3 provides base fields for HEC. In Table 4, fields with Jacobian order for HECDSA are given.

Table 3. Experimental results of prime base field arithmetic [mks]

Field name and description	+	*, comb	mod	$()^2$	$()^{-1}$
BF1, **GF**(p_{80}): p_1=1208925819614629175095961	0.020	0.921	0.782	0.90	0.94
BF2, **GF**(p_{88}): p_2=1208925819614629174708801	0.020	0.922	0.797	0.90	11.0
BF3, **GF**(p_{81}): p_3=2417851639229258349419161	0.020	0.922	0.797	0.9	10.5
BF4, **GF**(p_{81}): p_4=4835703278458516698822641	0.020	0.922	0.781	0.9	10.5
BF5, **GF**(p_{161}): p_5=29230032746618058364073696654325660393118651805 29	0.032	2.57	2.15	2.5	34.4
BF6, **GF**(p_{84}): p_6=5000000000000000008503491	0.020	0.922	0.781	0.9	11.0

As we can see from Table 3, most of the time spent for multiplication and squaring is consumed by the modular reduction. This is related to the classical modular reduction algorithm which we applied in this case. For a speed-up, the classical algorithm will be replaced with special algorithms for Mersenne and pseudo-Mersenne primes that allow for a very efficient reduction in these fields.

Table 4. Experimental results for prime order fields arithmetic [mks]

Field name and description	+	*, comb	mod	$()^2$	$()^{-1}$
OF1, **GF**(p_{159}): p_7=730750818666480869498570 026461293846666412451841	0.032	1.92	1.62	1.6	26.6
OF2, **GF**(p_{171}): p_8=0x00000f9e 0x508f99f1 0x9fb43a71 0x1cd119ae 0xe6bd912d 0x2bc254b9	0.031	2.563	2.14	2.53	34.3
OF3, **GF**(p_{161}): p_9=923003274662325095624062 806971100286403110276481	0.031	2.578	2.20	2.56	32.9
OF4, **GF**(p_{162}): p_{10}=1169201309864334686834 1 5812796993850778390299668 01	0.031	2.562	2.15	2.54	32.9
OF5, **GF**(p_{320}): p_{11}=427197407184182016479 0 04215920066905783641406233172413793356 5 193825968686576267080087081984838097	0.047	7.40	6.14	7.35	107.6
OF6, **GF**(p_{164}): p_{12}=2499999999999941304386 00 999402209463966197516075699	0.031	2.578	2.17	2.547	34.4

For the purpose of comparison of HECC and ECC, we shall indicate experimental results of ECC timings.

Elliptic Curves

As experimental results of operations timings in the group of points on an elliptic curve, we used curves as listed in [9]. For the implementation, we used Jacobi projective coordinates [2]. In Table 5, SM – Scalar multiplication, DS – Digital signature.

Table 5. Experimental results of the arithmetic on elliptic curves and results from [24], [ms]

Operation		P-192	P-224	P-256	P-384	P-521
SM, Lim-Lee method		0.32	0.484	0.86	2.06	3.18
SM, left to right method, intermediate computations in Jacobi projective coordinates		2.39	3.50	6.28	15.70	25.81
	[24]	1.83	-	4.07	-	-
SM, left to right method, intermediate computations in Affine coordinates		13.73	20.68	29.43	90.75	202.9
	[24]	5.385	-	12.62	-	-
Pre-computations for the Lim-Lee SM		422	609	1172	2813	3797
DS generation, Lim-Lee method		0.47	0.47	0.93	2.03	3.12
DS verification, Lim-Lee method and left to right method		2.65	3.91	7.03	17.03	26.88

The results are to be in accordance with the results published in [7, 8]. Note, the results from [24] in Table 5 are given for reference. These are based on the high performance finite field arithmetic library and indicate how finite field arithmetic could affect the ECC and HECC's performance. This allows us to use these for a comparison to the HECC transformation.

In the next section, we will describe the HECC transformations.

Hyperelliptic Curves

We analyze the transformations in the Jacobian of genus 2 HEC in affine coordinates; this allows us to select a curve type and a transformation which provides for the least computational complexity.

Table 6. Complexity of arithmetic in the Jacobian of genus 2 HEC according to Harley's method (expressed in field operations inversion, squaring, and multiplication)

Conditions	Addition			Doubling		
	I	S	M	I	S	M
$h(x) = 0$ [12]	2		27	2		30
$h_2 = 1$ [13]	2	3	24	2	6	26
$h(x) = 0$ [16]	2		25	2		27
$h(x) = 0, f_4 = 0$ [17]	1		26	1		27
$h(x) = 0$ [18]	1		25	1		29
$f_4 = 0$ [13]	1	3	22	1	5	22

For the software implementation of the transformations in the Jacobian, we used Harley's [12] method and Lange's [13] method for HEC over prime fields. All algorithms are given in pseudo code. A detailed functional description is commented.

Divisor Addition

In the software implementation, we made suppositions that made no contradiction to [12, 13]:

- curve parameters h_2, h_1, h_0 from {0, 1};
- curve parameters $f_4, f_3, f_2, f_1, f_0 \in \mathbf{GF}(p)$, $f_5 = 1$.

The **add** divisor addition algorithm, by Harley's method and Lange's method has a complex hierarchical structure. In the nodes of this structure, there are algorithms used for addition in special cases. Such architecture provides for comfortable debugging and further support. A detailed description of transformation in Jacobian can be found in [12, 13]. During paper writing, authors have found a number of mistakes in formulae deduction and their continued and careless re-publication from paper to paper dedicated to Jacobian arithmetic. Below, in represented algorithms, there are used only both theoretically and practically proven (validated) algorithms and expressions.

In the case of divisor addition, we considered several cases: the first case occurs when the first divisor has weight 2 (**addw2wN** algorithm). The second case occurs when the first divisor has weight 1 (**addw1wN** algorithm), else - the first divisor is copied.

Algorithm add. Divisor addition. **Input**: divisors d1 and d2 **Output**: divisor res	**Algorithms addw2wN**. Divisor addition with first divisor weight equal 2. **Input**: divisors d1 and d2, where weight(d1) = 2 **Output**: divisor res
1. if(weight(d1) = 2) then res = addw2wN(d1, d2) 2. else if(weight(d1) = 1) then res = addw1wN(d1, d2) 3. else res = d2 return (res)	1. if(weight(d2) = 2) then res = addw2w2(d1, d2) 2. else if (weight(d2) =1) then res = addw1w2(d2, d1) 3. else res = d1 return (res)

The algorithm for weight 2 divisor addition is **addw2w2**. This algorithm is called most frequently. In different cases for the addition, the **addw2wN** algorithm considers the second divisor of weight 2, 1 or 0.

We will consider the case of both divisors having weight 2, which is the most frequent case.

Algorithm addw2w2.Addition weight 2 divisors.
Input: divisors d1 and d2, where weight(d1) = weight(d2) = 2. ad1, ad2, ad3, ad4, ad5 – temporary divisors.
Output: divisor res

```
1. if (d1.u0 = d2.u0) and (d1.u1 = d2.u1) and (d1.u2 = d2.u2) then
        1.1 if(d1.v0 = d2.v0) and (d1.v1 = d2.v1) then
```

```
            1.1.1. res = dualw2(d1)
            return (res)
    1.2. if (d1.v0 = -d2.v0) and (d1.v1 = -d2.v1) then
            1.2.1 res = O
            return (res)
    1.3. else
            1.3.1. ad1.u0 = (d2.v0 - d1.v0) * (d2.v1 - d1.v1)^-1
            1.3.2. ad1.u1 = 1; ad1.u2 = 0
            1.3.3. ad1.v0 = d1.v0 - d1.u0 * d1.v1; ad1.v1 = 0
            1.3.4. res =dualw1rw2(ad1)
            return (res)
2. else
    2.1. z1 = d1.u1 - d2.u1
    2.2. z2 = d2.u0 - d1.u0
    2.3. z3 = d1.u1 * z1 + z2
    2.5. r = z2 * z3 + z1^2 * d1.u0
    2.6. if(r <> 0) then
            2.6.1. res = addw2w2_i(d1, d2)
            return (res)
    2.7. else
            2.7.1. xP1 = (d1.u0 - d2.u0) * (d1.u1 - d2.u1)^-1
            2.7.2. yP1 = xP1 * d1.v1 + d1.v0
            2.7.3. z2 = xP1 * d2.v1 + d2.v0
            2.7.4. ad1.u2 = 0; ad1.u1 = 1; ad1.u0 = -xP1
            2.7.5. ad1.v1 = 0; ad1.v0 = yP1
            2.7.6. ad3.u2 = 0; ad3.u1 = 1; ad3.u0 = d1.u1 - xP1
            2.7.7. ad3.v1 = 0; ad3.v0 = d1.v0 - ad3.u0 * d1.v1
            2.7.8. ad5.u2 = 0; ad5.u1 = 1; ad5.u0 = d2.u1 - xP1
            2.7.9. ad5.v1 = 0; ad5.v0 = d1.v0 - ad5.u0 * d1.v1
            2.7.10. if(yP1 = z2) then
                    2.7.10.1. ad2 = dualw1rw2(ad1)
                    2.7.10.2. ad4 = addw1w2(ad3, ad2)
                    2.7.10.3. res = addw1w2(ad4, ad5)
            2.7.11. else res = addw1w1(ad3, ad5)
return (res)
```

We will consider the case of the first divisor having weight 1. Further branching is done as per second divisor weight. We will now consider the case of the first divisor having weight 1 and the second divisor having weight 2.

Algorithm addw1wN. Addition weight 1 divisor and divisor with unknown weight
Input: divisors d1 and d2, where weight(d1) = 1
Output: divisor res

```
1. if (weight(d2) = 2) then
        res = addw1w2(d1, d2,)
2. else if (weight(d2) = 1) then
        res =addw1w1(d1, d2)
```

Algorithm addw1w2. Addition weight 1 and weight 2 divisors
Input: Divisors d1 and d2, where weight(d1) = 1, weight(d2) = 2
Output: divisor res

```
1. r = d2.u0 – (d2.u1 - d1.u0) * d1.u0
2. if(r = 0) then
        res = addw1w2Cmn(d1, d2)
3. else
```

```
3. else res = d1;                                   res = addw1w2_i(d1, d2)
return (res)                                    return (res)
```

Now, the most common case is considered when adding divisors with weight 1 and 2. In this case the second divisor support has either point P_1 or point $-P_1$ of the first divisor support.

Algorithms addw1w2Cmn. Addition weight 1 and weight 2 divisors in common case.
Input: divisors d1 and d2, where weight(d1) = 1 and weight(d2) = 2
Output: divisor res

```
1. r = d2.u0 – (d2.u1 - d1.u0) * d1.u0
2. if (r <> 0) then
        2.1. res = addw1w2_i(d1, d2)
        return (res)
3. if ((d2.v0 - d1.u0 * d2.v1) = d1.v0) then
        3.1. res.u2 = 0; res.u1 = 1; res.u0 = d2.u1 - d1.u0
        3.2. res.v0 = d2.v0 - res.u0 * d2.v1; res.v1 = 0
4. else
        4.1. if (d2.u1 = 2 * d1.u0) then
                4.1.1. ad2 = dualw2_i(d2)
                4.1.2. ad1 = -d1
                4.1.3. res = addw1w2(ad1, ad2)
        4.2. else
                4.2.1. ad1 = dualw1rw2(d1)
                4.2.2. ad2.u2 = 0; ad2.u1 = 1; ad2.u0 = d2.u1 - d1.u0
                4.2.3. ad2.v1 = 0; ad2.v0 = d2.v0 – (ad2.u0 * d2.v1)
                4.2.4. res = addw1w2_i(ad2, ad1)
return (res)
```

We consider the case of a divisor addition having weight 1 in algorithm **addw1w1** while we consider algorithm **addw1w2_i** of divisor addition with weight 1 and 2 in the most frequent case.

We consider the **addw2w2_i** algorithm of divisor addition having weight 2 in the most frequent case [13].

Algorithm addw1w1. Weight 1 divisor addition **Input**: weight 1 divisors d1 and d2 **Output**: res	**Addition addw1w2_i**. Weight 1 divisor and weight 2 divisor addition in most frequent case **Input**: weight 1 divisor d1 and weight 2 divisor d2 **Output**: res

1. if (d1.u0 = d2.u0) then
    1.1. if(d1.v0 = d2.v0) then
        res = dualw1rw2(d1)
    1.3. if(d1.v0 = -d2.v0) res = O
2. else
	1. r = d2.u0 - (d2.u1 - d1.u0) * d1.u0
	2. inv = $(r)^{-1}$
	3. s0 = inv*(d2.v1*d1.u0 + d1.v0 - d2.v0)
	4. l1 = s0 * d2.u1; l0 = s0 * d2.u0
	5. k2 = curve.f4 - d2.u1

2.1. top = (d1.u0 - d2.u0)$^{-1}$
2.2. res.v1 = d2.v0 - d1.v0
2.3. res.v1 = res.v1 * top
2.4. top1 = d2.v0 * d1.u0
2.5. top2 = d1.v0 * d2.u0
2.6. res.v0 = top1 - top2
2.7. res.v0 = res.v0 * top
2.8. res.u2 = 1;
2.9. res.u1 = -(d1.u0 + d2.u0)
2.10. res.u0 = d1.u0 * d2.u0
return (res)
6. k1 = curve.f3 - k2 * d2.u1 - d2.u0
7. res.u2 = 1
8. res.u1 = (k2 - s0^2) - d1.u0
9. k2 = res.u1 * d1.u0
10. res.u0 = k1 – (2 * d2.v1 + l1) * s0- k2
11. top = s0 * res.u1
12. res.v1 = top – (l1 + d2.v1)
13. res.v0 = s0 * res.u0 – (l0 - d2.v0)
return (res)

Algorithm addw2w2_i. Weight 2 divisor addition in most frequent case
Input: Weight 2 divisors d1 and d2
Output: res

1. z1 = d1.u1 - d2.u1
2. z2 = d2.u0 - d1.u0
3. z3 = d1.u1 * z1 + z2
4. r = z2 * z3 + z1^2 * d1.u0
5. inv1 = z1; inv0 = z3
6. w1 = d1.v0 - d2.v0
7. w2 = d1.v1 - d2.v1
8. w3 = inv0 * w1; w4 = inv1 * w2
9. s1s = inv1 + inv0
10. w1 = w1 + w2
11. s1s= s1s * w1 - w3 - w4- w4 * d1.u1
12. s0s = w3 - w4 * d1.u0
13. if(s1s = 0) then
13.1. s0 = s0s * (r)$^{-1}$
13.2. res.u0 = curve.f4 - d2.u1
13.3. res.u0 = res.u0 - d1.u1
13.4. res.u0 = res.u0 - s0^2
13.5 res.u1 = 1; res.u2 = 0
13.6. w1=(d2.u1 + res.u0) * s0
13.7. w1 = w1 + d2.v1
13.11. w2 = s0 + d2.v0
13.12. res.v0 = res.u0 * w1
Continued in the next column

continuation
13.13. res.v0 = res.v0 - w2
13.14. res.v1 = 0
return (res)
14. w1 = (r * s1s)$^{-1}$; w2 = w1 * r
15. w3= s1s^2 * w1; w4 = r * w2
16. w5 = w4^2; s0ss = s0s * w2
17. l2s = s0ss + d2.u1
18. l1s = s0ss * d2.u1 + d2.u0
19. l0s = s0ss * d2.u0
20. inv0 = s0ss - d1.u1
21. res.u0=(l2s- d1.u1) * inv0 - d1.u0+ l1s
22. res.u0 = res.u0 + 2 * d2.v1 * w4
23. top = (d1.u1 + d2.u1 - curve.f4) * w5
24. res.u0 = res.u0 + top
25. res.u1 = (s0ss + l2s) - d1.u1 - w5
26. res.u2 = 1
27. w1 = l2s - res.u1
28. w2 = res.u1 * w1 + res.u0 - l1s
29. res.v1 = w3 * w2 - d2.v1
30. w4 = res.u0 * w1 - l0s
31. res.v0 = w3 * w4 - d2.v0
return (res)

Furthermore, we will describe a **dual** divisor doubling algorithm. In this algorithm, the branching is depending on the weight of the doubled divisor. Algorithm **dualw1** is called when a divisor with weight 1 is doubled.

Algorithm dual. General case of divisor doubling
Input: divisor d
Output: divisor res

Algorithm dualw1. Weight 2 divisor doubling.
Input: weight 1 divisor d
Output: divisor res

1. if (weight(d) = 2) then
    res = dualw2(d)
2. else if (weight(d) = 1) then
    res = dualw1(d)
3. else res = O
return (res)

1. if (d.v0 = 0) then
    res = O
2. else
    res = dualw1rw2(d)
return (res)

Algorithm dualw1rw2. Weight 1 divisor doubling and resulting divisor has weight 2
Input: weight 1 divisor d
Output: weight 2 divisor res

1. u10 = d.u0
2. res.u2 = 1; res.u1 = 2 * u10
3. res.u0 = u10^2
4. ft0 = 3 * curve.f3 - 4 * curve.f4 * u10
5. ft0 = ft0 + 5 * res.u0
6. ft0 = ft0 * res.u0
7. ft0 = ft0 - 2 * curve.f2 * u10 + curve.f1
8. res.v1 = ft0 * (2 * d.v0)$^{-1}$
9. res.v0 = d.v0 + res.v1 * u10
return (res)

Algorithm dualw2. Weight 2 divisor doubling in general case
Input: weight 2 divisor d
Output: weight 2 divisor res

1. if(d.v0 =0) and (d.v1 = 0) then
    res = O
    return (res)
2. vt1 = 2 * d.v1; vt0 = 2* d.v0
3. w0 = d.v1^2; w1 = d.u1^2
4. w2 = vt1^2; w3 = d.u1 * vt1
5. r = d.u0 * w2 + (vt0 - w3) * vt0
6. if(r = 0) then
    6.1. xP2=d.v1 * (d.v0)$^{-1}$- d.u1
    6.2. yP2 = xP2 * d.v1 + d.v0
    6.3. ad1.u0 = -xP2
    6.4. ad1.u1 = 1; ad1.u2 = 0
    6.5. ad1.v0 = yP2; ad1.v1 = 0
    6.6. res = dualw1rw2(ad1)
7. else res = dualw2_i(d)
return (res)

Algorithm **dualw2** is called when a divisor with weight 2 is doubled. The **dualw1rw2** algorithm is worth for a separate consideration since it doubles divisors with weight 1 and produces the resulting divisor with weight 2 [12].

Let us describe algorithm **dualw2_i** for doubling weight 2 divisors which is the most frequent case [13].

Algorithm dualw2_i. Weight 2 divisor doubling in most frequent case.
Input: weight 2 divisor d
Output: divisor res

1. vt1 = 2 * d.v1; vt0 = 2 * d.v0
2. w0 = d.v1^2; w1 = d.u1^2
3. w2 = vt1^2; w3= d.u1 * vt1
4. inv0 = vt0 - w3; inv1 = -vt1
5. r = d.u0 * w2 + inv0 * vt0

continuation
    14.5. res.v0 = res.u0 * w1 - w2
    14.6. res.v1 = 0
    14.7. res.u1 = 1; res.u2 = 0
    return (res)

```
6. w3 = w1 + curve.f3
7. w4 = 2 * d.u0
8. top = curve.f4 * d.u1
9. k1 = 2 * (w1 – top) + w3 – w4
10. k0 = (2* w4 + top – w3) * d.u1 + curve.f2 - w0 - 2 * curve.f4 * d.u0
11. w0 = k0 * inv0; w1 = k1 * inv1
12. s1s = (k1 + k0) * (inv1 + inv0) – w0 - (d.u1 + 1) * w1
13. s0s = w0 - w1 * d.u0
14. if (s1s = 0) then
        14.1. s0 = s0s * (r)^-1
        14.2 w2 = s0 * d.u0 + d.v0
        14.3.res.u0=curv.f4-s0^2-2*d.u1
        14.4. w1=s0*(d.u1-res.u0)+ d.v1
continued in the next column
15. w1 = (r * s1s)-1; w2 = r * w1
16. w3 = s1s^2 * w1; w4 = r * w2
17.; w5 = w4^2; s0ss = s0s * w2
18. l2s = d.u1 + s0ss
19. l1s = d.u1 * s0ss + d.u0
20. l0s = d.u0 * s0ss
21. res.u0=s0ss^2+(2*d.u1-curve.f4)* w5
22. res.u0 = res.u0 + 2 * d.v1 * w4
23. res.u1 = 2 * s0ss - w5; res.u2 = 1
24. w1 = l2s - res.u1
25. w2 = res.u1 * w1 + res.u0 - l1s
26. res.v1 = w2 - w3 - d.v1
27. w4 = res.u0 * w1 - l0s
28. res.v0 = w4 * w3 - d.v0
return (res)
```

Complexity Analysis

In this section, we will provide an analysis of the complexity of the transformations of divisor addition considering different input data given in Table 7. For the sake of a compact representation, in Table 7 the input divisors were given without point at infinity P_∞. As we stated above, this work is based on the transformation described at [12, 13], however we have made several improvements in the cases other than the most frequent cases in comparison to [13, 16].

Table 7. Complexity of divisor addition algorithms in relation to input divisors

Input data	$D_2=(P_1)$		$D_2=(2P_1)$		$D_2=(P_1+P_2)$	
$D_1=(P_1)$	7A,1S,5M,1I	1	31A,5S,22M,3I	2	28A,2S,17M,2I	3
$D_1=(-P_1)$	1A	4	5A,3M	5	5A,3M	5
$D_1=(P_2)$	6A,5M,1I	6	18A,1S,10M,1I	7	28A,2S,17M,2I	3
$D_1=(2P_1)$	31A,5S,22M,3I	2	25A,4S,17M,1I/ 23A,7S,17M,1I	8	58A,4S,33M,4I	9
$D_1=(P_1+P_2)$	28A,2S,17M,2I	3	58A,4S,33M,4I	9	25A,4S,17M,1I/ 23A,7S,17M,1I	8
$D_1=(-P_1+P_2)$	5A,3M	5	16A,6S,13M,2I	10	12A,1S,7M,2I	11
$D_1=(P_1+P_3)$	28A,2S,17M,2I	3	58A,4S,33M,4I	9	58A,4S,33M,4I	9
$D_1=(-P_1+P_3)$	5A,3M	5	16A,6S,13M,2I	10	16A,6S,13M,2I	10
$D_1=(P_3+P_4)$	18A,1S,10M,1I	7	34A,5S,25M,1I/ 22A,5S,14M,1I	12	34A,5S,25M,1I/ 22A,5S,14M,1I	12

The entries of this table show the complexity of the algorithms according to the input values at the respective column and row. Furthermore, the entries are enumerated with an ID and entries of similar computational complexity are assigned the same ID.

The second term after the slash sign provides the complexity of weight 2 divisor addition algorithms which are given for the case of the resulting divisor of weight 1.

We will now compare the results given in Table 7 and the results given in Table 8 obtained from [16]. (Formulas from [13] are more efficient than [16], but, unfortunately, [13] does not contain summarized results as in Tables 7, 8.) With these tables, we get a more exact picture of complexity of the algorithms than before. Furthermore, these exact values are characterized by the decreased complexity for the most frequent cases. Authors propose optimized execution ways for the general case divisor addition which allows for an increase in Jacobian arithmetic performance.

Table 8. Divisor addition algorithms complexity in relation to input divisors obtained from [16]

Input data	D_2=P_1		D_2=2P_1		D_2=P_1+P_2	
D_1=P_1	1I+5M	1	1I+11M	2	2I+17I	3
D_1= -P_1	0	4	3M	5	3M	5
D_1=P_2	1I+3M	6	1I+10M	7	2I+17M	3
D_1=2P_1	1I+11M	2	2I+25M	8	4I+33M	9
D_1=P_1+P_2	2I+17M	3	4I+33M	9	2I+25M	8
D_1= -P_1+P_2	5A+3M	5	2I+13M	10	2I+7M	11
D_1=P_1+P_3	2I+17M	3	4I+33M	9	4I+33M	9
D_1= -P_1+P_3	3M	5	2I+13M	10	2I+13M	10
D_1=P_3+P_4	1I+10M	7	2I+23M	12	2I+23M	12

Experimental Results

To be able to provide practical results, we executed the experimental evaluation of Jacobian arithmetic and direct cryptographic transformations. In Table 9, we provide the respective parameters. All the experiments were executed in accordance to the conditions described in Table 1, column 2.

Table 9. List of parameters that have been evaluated in the experimental timing evaluation while operations were executed in the Jacobian of genus 2 HEC in affine representation

#	Operation
1	Weight 2 divisor addition, D_1=(P_1+P_2), D_2=(P_3+P_4), different points in support
2	Weight 1 divisor addition, D_1=(P_1), D_2=(P_2), different points in divisors support
3	Weight 2 divisor doubling, D_1=(P_1+P_2), different points in divisors support
4	Weight 1 divisor doubling, D_1=(P_1), different points in divisors support
5	Pre-computations for Lim-Lee SM of weight 2 divisor, D_1=(P_1+P_2)
6	Weight 2 divisor SM, D_1=(P_1+P_2), Lim-Lee method
7	Weight 2 divisor SM, D_1=(P_1+P_2), left to right (l-to-r) method
8	Pre-computations for Lim-Lee SM of weight 1 divisor, D_1=(P_1)
9	Weight 1 divisor SM, D_1=(P_1), Lim-Lee method
10	Weight 1 divisor SM, D_1=(P_1), left to right method

The performance estimation for HECDSA was executed for curves from different sources. For each curve, the prime group order and base divisors of different weight are specified. Table 10 could be used for building a workable cryptosystem. It summarizes all required system parameters from the latest publications dedicated to system parameters generation. These base divisors are generated using authors' Jacobian arithmetic library.

Table 10. Curves used in the experiments

	Curve and Jacobian description
K1	**Curve**: $y^2 = x^5 + 3x$, [19]. **Base field**: BF2. **Base divisor order**: OF2. **Cofactor**: 2. **#J**: 2*191561942 608242456073498418 252108663 615312031 512 914 969. **Base divisor weight 2** (different points in support): u_0=0x00007cc9 0x4c35d2c6 0xe53c9f13; u_1=0x0000a263 0xe5badea0 0x63324a19; u_2=1; v_0=0x00006147 0x46c02932 0xdb6db227; v_1=0x0000082e 0x403d1170 0x8401e93f. **Base divisor weight 1**: u_0=0x0000c525 0xe1e33bf9 0x1d5c9e4b; u_1=1; u_2=0; v_0=0x00003a36 0x0e120f58 0x9e493e65; v_1=0.
K2	**Curve**: $y^2 = x^5$ + 147 402 359 165 232 802 427 861 608 x^5 + 410 568 485 776 723 560 558 900 263 x^3 + 182 918 789 828 164 278 158 149 944 x^2 + 21 629 125 395 450 339 743 039 380 x +164 765 300 788 381 420 683 697 803, [20] **Base field**: BF3. **Base divisor order**: OF3. **Cofactor**: 32. **#J**: 186 993390967282535841815985 746 607 893 082 760 172 058 351392. **Base divisor weight 2** (different points in support): u_0=0x00b42349 0x0dafd9fb 0xfdc4ffff; u_1=0x00365670 0xba8ff7c4 0xd78b1122; u_2=1; v_0=0x0002a0d8 0x1292bb51 0x18bde044; v_1=0x010a095d 0x83e512f5 0xa5d601de. **Base divisor weight 1**: u_0=0x00c3c62f 0x7575fbf8 0x33f26e98; u_1=1; u_2=0; v_0=0x006f0262 0x92330815 0xe95f2a1f; v_1=0.
K3	**Curve**: $y^2 = x^5$ +16807 x, [21]. **Base field**: BF4. **Base divisor order**: OF4. **Cofactor**: 2. **#J**: 584 600 654 932 465 019 124 8125 613 942 200 572 806 220 552 962. **Base divisor weight 2** (different points in support): u_0=0x0001659c 0x5ba76be1 0x8af27c0a; u_1=0x00017609 0xf7c36463 0x73b67d70; u_2=1; v_0=0x00005856 0x10c73f7d 0xcd44faa0; v_1=0x0000f61a 0xa0e690e6 0x8c039702. **Base divisor weight 1**: u_0=0x00013157 0xf9304487 0xfe61a03e; u_1=1; u_2=0; v_0=0x0000efc8 0x0aeb6ba2 0xd53d517f; v_1=0.
K4	**Curve**: $y^2 = x^5$ +243 x, [21]. **Base field**: BF5. **Base divisor order**: OF5. **Cofactor**: 2. **#J**: 23 384 026 197 286 693 734 683 162 559 398 770 155 678 059 933 602. **Base divisor weight 2** (different points in support): u_0=0x000353e6 0xdbf41c47 0xc36b70c0; u_1=0x0002feb4 0x900ecb40 0x0f9e9749; u_2=1; v_0=0x0003470d 0x58c98d55 0x7250290f; v_1=0x00017bee 0x333ebe25 0x9d608242. **Base divisor weight 1**: u_0=0x0003ddfa 0xe82dd75f 0xfdbb6c76; u_1=1; u_2=0; v_0=0x0001243a 0x5fba40fb 0xe0a0628a; v_1=0.
K5	**Curve**: $y^2 = x^5$ +371293 x, [21]. **Base field**: BF6. **Base divisor order**: OF6. **Cofactor**: 2. **#J**: 8543 948 143 683 640 329 580 084 318 401 338 115 672 828 124 663 448

	275 867 130 387 651 937 273 152 534 160 174 163 969 676 194. **Base divisor weight 2** (different points in support): u_0=0x00000000 0x0a666ced 0x9e3224f6 0x94fdac4a 0xa1694f53 0x4e67b73a; u_1=0x00000001 0xfc7689a3 0xf3f58c91 0xf7d4367f 0xf8a69ba3 0xf8ac347e; u_2=1; v_0=0x00000000 0x9348b4a9 0x15fbaea2 0x100be54d 0x90a91887 0x71600c09; v_1=0x00000000 0x1427f768 0x2888c86a 0x5aaf4273 0xd9bf0b9e 0x336ccd43. **Base divisor weight 1:** u_0=0x00000001 0xf11030ad 0xfab1afdf 0xdad8b1bd 0xf716f596 0x31eea096; u_1=1; u_2=0; v_0=0x00000000 0x186e086c 0xa0f1d327 0x6fbced02 0x1e77e117 0x412efc16; v_1=0.
K6	**Curve**: $y^2 = x^5$+ 2682810822839355644900736x^3 + 226591355295 993102902 116x^2+2547674715952929717899918x+4797309959708489673059 350, [22]. **Base field**: BF7. **Base divisor order**: OF6. **Cofactor**: 1. **#J**: 24 999 999 999 994 130 438 600 999 402 209 463 966 197 516 075 699. **Base divisor weight 2** (different points in support): u_0=0x0001f086 0x14077642 0x85553ac5; u_1=0x0001f031 0x4761f58d 0xa0c1db51; u_2=1; v_0=0x0000af4b 0x71adc1da 0x67827fe6; v_1=0x0000304c 0x013ba45f 0xc74e75ca. **Base divisor weight 1**: u_0=0x0000eae9 0xd24b61c0 0x776e2f95; u_1=1; u_2=0; v_0=0x0003860b 0x36744576 0xb26dd538; v_1=0.

In Table 11, we provide the experimental timing estimates of group operations for the curves from Table 9 and the parameters from Table 8.

From Table 11, one can see that the time of addition and doubling for weight 1 divisors is about 2 times less than for weight 2 divisors. The time for doubling is 2 times larger than the addition time of weight 2 and weight 1 divisors.

Co-factors with large Hamming weight obviously reflect on the pre-computation time for curves K1 and K2.

Table 11. Experimental results of operations in the Jacobian of genus 2 HEC in affine representation

	1 [ms]	2 [ms]	3 [ms]	4 [ms]	5 [ms]	6 [ms]	7 [ms]	8 [ms]	9 [ms]	10 [ms]
K1	0,036	0.0156	0.0469	0.0218	1656	0.86	9.65	1625	0.625	2.891
K2	0,035	0.0171	0.0484	0.0219	2015	1.062	9.844	2000	0.657	2.875
K3	0,0359	0.0156	0.0469	0.0219	1984	1.031	9.563	1950	0.73	2.891
K4	0.0375	0.0156	0.0468	0.0219	1984	1.031	9.594	1969	0.73	2.906
K5	0.103	0.0469	0.1328	0.0641	10266	5.64	55.35	10219	2.719	8.297
K6	0.0359	0.0172	0.0468	0.0203	1984	1.063	10.56	1969	1.11	9.57

Unlike in Table 12, let’s demonstrate the results published in [24]. Unfortunately, [24] does not describe the HECs used.

Table 12. Experimental results of SM in the Jacobian of genus 2 HEC in affine and projective representation for the specified bit length of base field [24]

	160 [ms]	192 [ms]	256 [ms]	320 [ms]	512 [ms]
Affine	2.23	2.71	5.79	11.11	41.69
Projective	2.2	2.35	4.89	9.45	33.23

The time required for a scalar multiplication is essentially affected by the non-optimized finite field arithmetic and is implementation. As we can see, in Table 12, there is used a highly efficient base field arithmetic implementation [24].

The next step is the estimate of performance of an HECDSA implementation. In Table 13, we show the parameters which are of particular interest, SM – Scalar multiplication, DS – Digital signature.

Weight 1 divisors are the most interesting ones since they allow to decrease the computational complexity. This result was presented in [23]. Furthermore, we will emphasize the optimized transformation implementation based on weight 1 base divisors.

Table 13. Parameters for the timing analysis of operations in the Jacobian of genus 2 HEC in affine representation

#	Operation
1	Pre-computations for the weight 2 divisor SM by Lim-Lee method, $D_1=(P_1+P_2)$
2	DS generation, weight 2 base divisor, $D_1=(P_1+P_2)$, Lim-Lee method
3	DS verification, weight 2 base divisor, $D_1=(P_1+P_2)$, Lim-Lee and l-to-r methods
4	Pre-computations for the weight 1 divisor SM by Lim-Lee method, $D_1=(P_1)$
5	DS generation, weight 1 base divisor, $D_1=(P_1)$, Lim-Lee method
6	DS verification, weight 1 base divisor, $D_1=(P_1)$, Lim-Lee and l-to-r methods

Table 14. Experimental timings for HECDSA cryptographic transformations in the Jacobian of genus 2 HEC in affine divisor representation for curves listed in Table 9

Curve	1, ms	2, ms	3, ms	4, ms	5, ms	6, ms
K1	1656	0.922	11.09	1625	0.903	11.125
K2	2015	1.125	12.359	2000	1.109	12.204
K3	1984	1.106	11.531	1950	1.094	11.438
K4	1984	1.109	11.734	1969	1.094	11.687
K5	10266	5.843	65.000	10219	5.828	66.023
K6	1984	1.094	11.843	1969	1.11	11.687

Digital signature verification time is much influenced by operations in the field of prime group order module. In this case, specialized algorithms using pseudo-Mersenne and Mersenne primes are not applicable.

Summary

In this work, the results of the efficient HECDSA implementation on genus 2 HEC over prime fields are demonstrated. The obtained results indicate the commensurable performances when generating and verifying digital signatures over elliptic and hyperelliptic curves under the DSA scheme, see Tables 5 and 14. Despite of extended further HECC optimizations, we can speak boldly of HEC as a practical alternative to EC in modern cryptosystems.

This contribution does provide detailed information of algorithms, curves, and underlying arithmetic algorithms for the implementation of HECC in applications. With this paper, we hope to bring HECC a major step towards practical applications.

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