Tatra Mt. Math. Publ. **33** (2006), 75–81

TATRA MOUNTAINS
Mathematical Publications

A NOTE ON LÓPEZ-DAHAB COORDINATES

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ABSTRACT. López-Dahab coordinates are usually the system of choice for implementations of elliptic curves over binary fields. We give new formulas for doubling which need one squaring less and one more addition. This leads to a speed-up for binary fields in polynomial basis representation if the parameters are not fixed.

1. Introduction

Elliptic curves are studied for cryptographic applications as a group in which the *discrete logarithm problem* is believed to be hard. In a general cyclic group $G = \langle P \rangle$, for an element $Q \in G$ this is the problem of finding an integer n such that $Q = [n]P$, where $[n]P$ denotes the result of P added to itself n times. In protocols based on the discrete logarithm problem the most time consuming operation is the computation of scalar multiples. This is done by a double-and-add algorithm which may use some precomputations. Therefore, the most important parameter for the speed of the system is the time needed for doublings and additions. If windowing methods are applied, doubling is the much more frequent operation. We would like to point out right here that the negative of a point on elliptic curves is easily determined, therefore signed digit representations can be used for reducing the storage requirements.

The main reason for using elliptic curves over finite fields is that they have shorter key sizes compared to RSA and discrete logarithms in finite fields. This is mainly relevant for small embedded devices. Such systems often profit from arithmetic in binary fields, and furthermore, inversions are usually prohibitively slow. Therefore inversion-free coordinate systems have been introduced for both even and odd characteristic. We give a new formula for doubling on elliptic curves in López-Dahab coordinates, which needs 4 instead of 5 squarings. This

2000 Mathematics Subject Classification: 11T71, 11Y16, 94A60, 11G20.
Keywords: public key cryptography, elliptic curve, inversion-free systems, López-Dahab coordinates.

The work described in this paper has been supported in part by the European Commission through the IST Programme under Contract IST-2002-507932 ECRYPT.

is of interest for practical applications, as this system has already offered the best performance before.

While the formulas in [10] involve one multiplication by the curve parameter a_6, all multiplications in the new formulas involve variables. For fixed small a_6 like in the standards the old formulas are advantageous, while for random curves and for implementations which should accommodate different curves our new formulas should be preferred.

We briefly recall the definitions of elliptic curves and López-Dahab coordinates. For comparison we give the published algorithms for addition and doubling. Then we present our doubling formulas and show their correctness. We finish with a comparison between the different formulas, and show drawbacks and advantages of the new proposal.

2. Elliptic curves over finite fields

For much more material on elliptic curves we refer to [2, 6]. For background on finite fields consider [8].

An *elliptic curve E over a field* $\mathbb{K}$ denoted by $E/\mathbb{K}$ is given by the *Weierstraß equation*

$$E\colon y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6\,, \tag{1}$$

where the coefficients $a_1, a_2, a_3, a_4, a_6 \in \mathbb{K}$ are such that for each point (x_1, y_1) with coordinates in $\overline{\mathbb{K}}$ satisfying (1) the partial derivatives $2y_1 + a_1x_1 + a_3$ and $3x_1^2 + 2a_2x_1 + a_4 - a_1y_1$ do not vanish simultaneously. The last condition says that an elliptic curve is *nonsingular*. The negative of the point $P = (x_1, y_1)$ is given by $-P = (x_1, -y_1 - a_1x_1 - a_3)$. Using the projective closure which in the case of elliptic curves is simply given by

$$Y^2Z + a_1XYZ + a_3YZ^2 = X^3 + a_2X^2Z + a_4XZ^2 + a_6Z^3,$$

one sees that there is exactly one point P_∞ on the line at infinity ($Z = 0$). It has projective coordinates $(0:1:0)$, and serves as the neutral element of the group law which states now.

Addition and doubling can be defined geometrically by the chord and tangent method which gives rise to the following formulas:

$$P \oplus Q = \left(\lambda^2 + a_1\lambda - a_2 - x_1 - x_2\,,\ \lambda(x_1 - x_3) - y_1 - a_1x_3 - a_3\right), \text{ where}$$

$$\lambda = \begin{cases} \dfrac{y_2 - y_1}{x_2 - x_1} & \text{if } P \neq \pm Q\,, \\[2ex] \dfrac{3x_1^2 + 2a_2x_1 + a_4 - a_1y_1}{2y_1 + a_1x_1 + a_3} & \text{if } P = Q\,. \end{cases}$$

These formulas depend on the curve equation and it is obvious that to reach fast formulas many zero coefficients a_i are desirable.

By a change of variables $x \mapsto u^2x + r = x'$ and $y \mapsto u^3y + u^2sx + t = y'$ with $(u, r, s, t) \in \mathbb{K}^* \times \mathbb{K}^3$, the curve is transformed to an *isomorphic* one.

In this paper we are concerned with elliptic curves over binary fields $\mathbb{F}_{2^d}$. Supersingular curves over $\mathbb{F}_{2^d}$ can be characterized by the fact that they have no point of order 2 over the algebraic closure $\bar{\mathbb{F}}_2$, and these are exactly those curves for which $a_1 = 0$. Supersingular curves have been shown to lead to significantly weaker DL systems [5, 11].

Hence we concentrate on $a_1 \neq 0$. One can transform the curve using

$$y \mapsto a_1^3 y + \frac{a_3^2 + a_1^2 a_4}{a_1^3}, \quad x \mapsto a_1^2 x + \frac{a_3}{a_1},$$

followed by a division by a_1^6 to an isomorphic curve given by

$$y^2 + xy = x^3 + a_2' x^2 + a_6',$$

which is nonsingular whenever $a_6' \neq 0$.

This equation can be simplified even further if d is odd, which is the case in most applications. Then we have $\mathrm{Tr}(1) = 1$. We now use the additivity of the trace $\mathrm{Tr}(a + b) = \mathrm{Tr}(a) + \mathrm{Tr}(b)$, and consider two cases:

If $\mathrm{Tr}(a_2') = 0$, then $w^2 + w + a_2'$ has a solution $a \in \mathbb{F}_{2^d}$ by the additive version of the Hilbert 90 theorem, and thus the transformation $y \mapsto y + ax$ leads to $y^2 + xy = x^3 + a_6'$.

Otherwise $w^2 + w + a_2' + 1$ has a solution $a \in \mathbb{F}_{2^d}$ by the additive version of the Hilbert 90 theorem as $\mathrm{Tr}(a_2' + 1) = \mathrm{Tr}(a_2') + \mathrm{Tr}(1) = 0$. In this case the transformation $y \mapsto y + ax$ leads to $y^2 + xy = x^3 + x^2 + a_6'$.

For the operation count we will always assume that $a_2 \in \{0, 1\}$, but to allow applicability of the formulas also for even d we use the general equation

$$y^2 + xy = x^3 + a_2 x^2 + a_6, \qquad \text{for } a_2 \in \mathbb{F}_{2^d},\ a_6 \in \mathbb{F}_{2^d}^*.$$

3. Coordinate systems

So far we have stated the curve in affine coordinates and briefly mentioned projective coordinates. As projective coordinates are unique up to multiplication by scalars, one easily sees that addition and doubling can be described without using inversions. As a drawback much more multiplications are introduced. This effect punishes additions harder, as the coordinates need to be multiplied there with the respective other Z-coordinates to reach common denominators.

If the operations steam from a scalar multiplication and the input were in affine coordinates, one can use the correspondence $(x_1, y_1) \sim (x_1 : y_1 : 1)$ assigning projective coordinates to a point in affine ones. An operation involving two types of input coordinates, and also allowing a different type of output coordinates is called a *mixed operation*. If one input is in affine coordinates, mixed additions are usually much faster. This can be used in a left-to-right scalar multiplication algorithm if also the precomputed points are given in affine coordinates.

Starting from the idea of projective coordinates other inversion-free systems were introduced in which the correspondence to affine coordinates assigns weights to the coordinates. We concentrate on *López-Dahab* coordinates. Here for $Z \neq 0$ the point $(X : Y : Z)$ corresponds to the affine point $(X/Z, Y/Z^2)$, and the neutral element is given by $(1 : 0 : 0)$. The points satisfy the equation

$$Y^2 + XYZ = X^3Z + a_2X^2Z^2 + a_6Z^4. \tag{2}$$

Starting from the formulas given in [10] both addition and mixed addition were improved.

Addition

We give the addition formulas as stated in [7]. Let $P = (X_1 : Y_1 : Z_1)$, $Q = (X_2 : Y_2 : Z_2)$ such that $P \neq \pm Q$, then $P \oplus Q = (X_3 : Y_3 : Z_3)$ is given by

$$\begin{aligned}
&A_1 = X_1Z_2\,,\ A_2 = X_2Z_1\,,\ C = A_1 + A_2\,,\\
&B_1 = A_1^2\,,\ B_2 = A_2^2\,,\ D = B_1 + B_2\,,\\
&E_1 = Y_1Z_2^2\,,\ E_2 = Y_2Z_1^2\,,\ F = E_1 + E_2\,,\\
&G = CF,\ Z_3 = Z_1Z_2D,\ X_3 = A_1(E_2 + B_2) + A_2(E_1 + B_1)\,,\\
&Y_3 = (A_1G + E_1D)D + (G + Z_3)X_3\,.
\end{aligned}$$

A general addition in this coordinate system takes $13M + 4S + 9A$, where M denotes a multiplication, S means a squaring and A an addition. In the original formulas one more multiplication by a_2 was used which could be neglected in our case. The savings of [7] over [10] consist in 2 squarings less on the cost of one addition, which is worthwhile in the setting we consider here.

Mixed addition

Mixed addition is much faster needing only $8M+5S+8A$ and one multiplication by a_2 as shown in [1].

Let $P = (X_1 : Y_1 : 1)$, $Q = (X_2 : Y_2 : Z_2)$ such that $P \neq \pm Q$, then $P \oplus Q = (X_3 : Y_3 : Z_3)$ is given by

$$\begin{aligned}
&U = Z_2^2Y_1 + Y_2\,,\ S = Z_2X_1 + X_2\,,\ T = Z_2S,\ Z_3 = T^2\,,\\
&V = Z_3X_1\,,\ C = X_1 + Y_1\,,\ X_3 = U^2 + T(U + S^2 + a_2T)\,,\\
&Y_3 = (V + X_3)(TU + Z_3) + Z_3^2C\,.
\end{aligned}$$

Doubling

If $P = (X_1 : Y_1 : Z_1)$, then $[2]P = (X_3 : Y_3 : Z_3)$ is given by

$$S = X_1^2\,,\ T = Z_1^2\,,\ Z_3 = ST\,,\ T = a_6T^2, \tag{3}$$
$$X_3 = S^2 + T\,,\ Y_3 = (Y_1^2 + a_2Z_3 + T)X_3 + TZ_3\,,$$

requiring $4M + 5S + 4A$ and one multiplication by a_2.

For fixed a_2 and a_6 it is also possible to use less additions if $\sqrt{a_6}$ can be precomputed. E.g., for $a_2 = 1$ one can use

$$S = X_1^2\,,\ T = \sqrt{a_6}Z_1^2\,,\ U = X_1Z_1,\ Z_3 = U^2\,, \tag{4}$$
$$X_3 = (S+T)^2,\ Y_3 = \big(US + (Y_1 + T)(S+T)\big)^2\,,$$

requiring $4M + 5S + 3A$ including one multiplication by $\sqrt{a_6}$ [9].

For fixed $a_2 = 0$ one uses

$$S = X_1^2,\ T = \sqrt{a_6}Z_1^2,\ S = S + T\,,\ U = X_1Z_1\,,\ Z_3 = U^2, \tag{5}$$
$$X_3 = S^2,\ Y_3 = (UT + (Y_1 + T)S)^2, \tag{6}$$

which also requires $4M + 5S + 3A$ including one multiplication by $\sqrt{a_6}$ [3].

4. Improved doubling formulas

Now we show how to save one squaring in the doubling step. We first state the doubling formulas, and then show their correctness by giving the relation to (3).

Doubling

If $P = (X_1 : Y_1 : Z_1)$, then $[2]P = (X_3 : Y_3 : Z_3)$ is given by

$$S = X_1^2,\ U = S + Y_1\,,\ T = X_1Z_1\,,\ Z_3 = T^2,\ T = UT, \tag{7}$$
$$X_3 = U^2 + T + a_2Z_3\,,\ Y_3 = (Z_3 + T)X_3 + S^2Z_3\,,$$

requiring $4M + 4S + 5A$ and one multiplication by a_2.

P r o o f . We first expand the expressions in (3) and (7), and then show their equality.

For X_3 we have by (3): $X_3 = X_1^4 + a_6Z_1^4$, which should be equal to $X_3 = (X_1^2 + Y_1)^2 + (X_1^2 + Y_1)X_1Z_1 + a_2X_1^2Z_1^2$ obtained by (7). In fact one has that

$$\begin{aligned} X_3 &= X_1^4 + a_6Z_1^4 = X_1^4 + Y_1^2 + X_1^3Z_1 + X_1Y_1Z_1 + a_2X_1^2Z_1^2 \\ &= (X_1^2 + Y_1)^2 + (X_1^2 + Y_1)X_1Z_1 + a_2X_1^2Z_1^2, \end{aligned}$$

where the second equality follows from the curve equation (2).

The expressions for $Z_3 = X_1^2 Z_1^2$ coincide obviously.

For Y_3 we have from (3)

$$\begin{aligned} Y_3 &= a_6 Z_1^4 Z_3 + (Y_1^2 + a_2 Z_3 + a_6 Z_1^4) X_3 \\ &= (X_3 + X_1^4) Z_3 + (Y_1^2 + a_2 Z_3 + a_6 Z_1^4) X_3 \\ &= (Z_3 + X_1^3 Z_1 + X_1 Y_1 Z_1) X_3 + X_1^4 Z_3 \\ &= (Z_3 + (X_1^2 + Y_1) X_1 Z_1) X_3 + (X_1^2)^2 Z_3 \,, \end{aligned}$$

and the final equation equals the formula in (7). □

5. Comparison

From the operation count we see that the number of multiplications remains unchanged, while the number of squarings is decreased by 1, and one more addition is needed if one uses the new doubling formula. Furthermore, the coefficient a_6 no longer appears in the formulas.

If the field $\mathbb{F}_{2^d}$ is represented with respect to a normal basis, then a squaring is *less* expensive than an addition, hence the known formulas are more efficient in this case.

The same conclusion is to be drawn for hardware implementations for which the curve is fixed, and thus multiplications by the constant coefficient a_6 or $\sqrt{a_6}$ can be hard-coded in the design of the chip, as the new system has 4 general multiplications, whereas the old system had one multiplication by a_6 or by $\sqrt{a_6}$. Additionally for fixed curves the special formulas depending on a_2 can be applied saving one further addition.

The curves selected in the standards all use a small a_6 such that multiplications involving a_6 are about as cheap as an addition. For them the usual doubling formulas (3) are fastest, as multiplications by a_6 are cheaper than those by $\sqrt{a_6}$. Also precomputed tables facilitate the multiplication by curve constants.

In all other situations, i.e., in the usual polynomial basis representation and for varying curves, the new doubling formulas are advantageous as one squaring is more time consuming than an addition, and $\sqrt{a_6}$ cannot be assumed to be precomputed. Namely the squaring consists of the cheap step of squaring the representing polynomial by inserting zeros in the representation and of the reduction modulo the irreducible polynomial. As this polynomial is at least a trinomial, one needs at least 2 additions per squaring, and more for less sparse irreducible polynomials like pentanomials. In this context we would like to mention the recent preprint [4] showing that one can use a *redundant polynomial*

representation by a trinomial of slightly larger degree if no irreducible trinomial is available.

To sum up, depending on the application the new doubling formulas can offer advantages over the standard ones. The distinction depends on whether multiplications by the constant a_6 or $\sqrt{a_6}$ are cheaper than a general multiplication and also on whether $\sqrt{a_6}$ is provided as a curve parameter. Our formulas (7) are faster for general curves, while (3) or the fixed formulas for $a_2 = 1$ or $a_2 = 0$ should be chosen for the standardized curves, and likely also for fixed curves in general.

Acknowledgment. The author would like to thank the organizers of WARTACRYPT '04 for the invitation and for compiling an interesting program.

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Received September 24, 2004

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