

Efficient unified Montgomery inversion with multibit shifting

E. Savaş, M. Naseer, A.A-A. Gutub and Ç.K. Koç

Abstract: Computation of multiplicative inverses in finite fields $GF(p)$ and $GF(2^n)$ is the most time-consuming operation in elliptic curve cryptography, especially when affine co-ordinates are used. Since the existing algorithms based on the extended Euclidean algorithm do not permit a fast software implementation, projective co-ordinates, which eliminate almost all of the inversion operations from the curve arithmetic, are preferred. In the paper, the authors demonstrate that affine co-ordinate implementation provides a comparable speed to that of projective co-ordinates with careful hardware realisation of existing algorithms for calculating inverses in both fields without utilising special moduli or irreducible polynomials. They present two inversion algorithms for binary extension and prime fields, which are slightly modified versions of the Montgomery inversion algorithm. The similarity of the two algorithms allows the design of a single unified hardware architecture that performs the computation of inversion in both fields. They also propose a hardware structure where the field elements are represented using a multi-word format. This feature allows a scalable architecture able to operate in a broad range of precision, which has certain advantages in cryptographic applications. In addition, they include statistical comparison of four inversion algorithms in order to help choose the best one amongst them for implementation onto hardware.

1 Introduction

The basic arithmetic operations (i.e. addition, multiplication and inversion) in prime and binary extension fields, $GF(p)$ and $GF(2^n)$, have several applications in cryptography, such as RSA algorithm, Diffie-Hellman key exchange algorithm [1], the US federal Digital Signature Standard [2] and also elliptic curve cryptography [3, 4]. Recently, speeding up inversion operations in both fields has been gaining attention since inversion is the most time consuming operation in elliptic curve cryptographic algorithms when affine co-ordinates are selected [5–10].

Currently, most of the elliptic curves that are employed in cryptographic applications are defined over prime $GF(p)$ and binary extension $GF(2^n)$ fields. In [11], a scalable and unified multiplier architecture for both fields is proposed and it has been shown that it is possible to design a multiplier with an insignificant increase in chip area ($\sim 2.8\%$) and no increase in time delay since the Montgomery multiplication algorithms for both fields are almost identical, except the basic addition operation of the corresponding fields.

In this paper, we give and analyse multiplicative inversion algorithms for $GF(p)$ and $GF(2^n)$, which allow very fast and area-efficient hardware implementations.

The algorithms are based on the Montgomery inversion algorithms given in [5]. Another variation of the Montgomery inversion algorithm is proposed in [7], which provides a very fast implementation of the multiplicative inverse in $GF(p)$. This algorithm takes the advantage of a multiplication unit, which already exists in most of the modern multipurpose microprocessors. Implementations of this algorithm are generally area-hungry, and incorporation of such an algorithm as part of a crypto-accelerator presents difficulties. Accordingly it is not suited to our needs.

In a recently published technical report [12], two similar algorithms for direct calculation of modular division in $GF(p)$ and $GF(2^n)$ have been proposed. Based on the binary extended Euclidean algorithm [13; Note 1] (attributed to M. Penk), [12] eliminates the correction phase of the Montgomery inversion algorithm by introducing extra add-and-shift operations in the *while* loop of the algorithm. However, performing these extra operations within the loop maintains a cost similar to performing them in Phase II. Furthermore, this approach does not run the algorithm in different modes as described in [8] in order to calculate different inverses, which prove to be useful in elliptic curve cryptography. Two algorithms proposed separately for fast calculation of inversion operations of $GF(p)$ and $GF(2^n)$ in [14, 15], respectively, do not allow a unified design.

A more recent effort [16] presents an efficient inversion algorithm that computes a direct inversion and decreases the number of additions at the expense of introducing, on average, more stand-alone [Note 2] shift operations. As far as the number of clock cycles to compute inversion is

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Note 1: Most of the binary inversion algorithms are in fact based on the binary extended Euclidean algorithm.

Note 2: Note that the shift operations following subtraction operations in the original Montgomery inversion algorithm must not be counted separately as done in [16].

concerned, shift operations are as costly as addition operations in a scalable implementation since these shift operations are performed in more than one cycle. In addition, the algorithm in [16] applies the logical OR operation on the entire bits of an integer. In cryptographic applications where the integers are large, this OR operation may have an adverse effect on the scalability and critical path delay. Therefore, we use variants of the Montgomery inversion algorithm in our work that we believe are more suitable for hardware implementation.

2 The original Montgomery inversion algorithm

The Montgomery inversion algorithm as defined in [5] computes

$$b = a^{-1}2^n \pmod{p} \quad (1)$$

given $a < p$, where p is a prime number and $n = \lceil \log_2 p \rceil$. The algorithm consists of two phases: the output of Phase I is the integer r such that $r = a^{-1}2^k \pmod{p}$, where $n \leq k \leq 2n$ and Phase II is a correction step and can be modified as shown in [8] in order to calculate a slightly different inverse that can more precisely be called *Montgomery inverse*:

$$b = \text{MonInv}(a2^n) = a^{-1}2^n \pmod{p} \quad (2)$$

This new definition is more suitable since it takes an integer in the so-called Montgomery domain and yields its multiplicative inverse, again in the Montgomery domain. Below, we give the original Montgomery inversion algorithm for completeness; however, the new algorithms in subsequent sections will compute the Montgomery inverse of an integer as defined in (2).

Algorithm A

Phase I

Input: $a \in [1, p-1]$ and p

Output: $r \in [1, p-1]$ and k , where $r = a^{-1}2^k \pmod{p}$ and $n \leq k \leq 2n$

- 1: $u := p, v := a, r := 0$, and $s := 1$
- 2: $k := 0$
- 3: while ($v > 0$)
- 4: if u is even then $u := u/2, s := 2s$
- 5: else if v is even then $v := v/2, r := 2r$
- 6: else if $u > v$ then $u := (u - v)/2, r := r + s, s := 2s$
- 7: else $v := (v - u)/2, s := s + r, r := 2r$
- 8: $k := k + 1$
- 9: if $r \geq p$ then $r := r - p$
- 10: return $r := p - r$ and k

Phase II

Input: $r \in [1, p-1]$, p , and k from Phase I

Output: $b \in [1, p-1]$, where $b = a^{-1}2^n \pmod{p}$

- 11: for $i = 1$ to $k - n$ do
- 12: if r is even then $r := r/2$
- 13: else $r := (r + p)/2$
- 14: return $b := r$

There are three important theorems about the algorithm, which have already been proven in [5].

Theorem 1: If $p > a > 0$, then the intermediate values r, s, u and v in the Montgomery inversion algorithm are always in the range $[1, 2p - 1]$.

Theorem 2: If a and p are relatively prime, p is odd, and $p > a > 0$; then the number of iterations in the first phase of Montgomery inversion algorithm is at least n and at most $2n$, where n is the number of bits in p .

Theorem 3: If p and a are relatively prime, p is odd, and $p > a > 0$, then Phase I of the Montgomery inversion algorithm returns $a^{-1}2^k \pmod{p}$.

We will include and prove analogous theorems for the Montgomery inversion algorithm for binary extension fields $\text{GF}(2^n)$ in the following Section.

3 The Montgomery inversion algorithm for $\text{GF}(2^n)$

Let

$$p(x) = x^n + p_{n-1}x^{n-1} + p_{n-2}x^{n-2} + \dots + p_1x + p_0$$

be an irreducible polynomial over $\text{GF}(2)$ that is used to construct the binary extension field $\text{GF}(2^n)$. An element of $\text{GF}(2^n)$ can be represented as a polynomial

$$a(x) = a_{n-1}x^{n-1} + a_{n-2}x^{n-2} + \dots + a_1x + a_0$$

whose coefficients a_i are from $\{0, 1\}$. Then arithmetic on the elements in $\text{GF}(2^n)$ is regular polynomial arithmetic where operations on coefficients are performed modulo 2.

The Montgomery inversion algorithm for $\text{GF}(2^n)$ can be given as follows:

Algorithm B

Phase I

Input: $a(x)$ and $p(x)$, where $\deg(a(x)) < \deg(p(x))$

Output: $s(x)$ and k , where $s = a(x)^{-1}x^k \pmod{p(x)}$ and $\deg(s(x)) < \deg(p(x))$ and $\deg(a(x)) + 1 \leq k \leq \deg(p(x)) + \deg(a(x)) + 1$

- 1: $u(x) := p(x), v(x) := a(x), r(x) := 0$, and $s(x) := 1$
- 2: $k := 0$
- 3: while ($u(x) \neq 0$)
- 4: if $u_0 = 0$ then $u(x) := u(x)/x, s(x) := xs(x)$
- 5: else if $v_0 = 0$ then $v(x) := v(x)/x, r(x) := xr(x)$
- 6: else if $\deg(u(x)) \geq \deg(v(x))$ then
- $u(x) := (u(x) + v(x))/x, r(x) := r(x) + s(x),$
- $s(x) := xs(x)$
- 7: else $v(x) := (v(x) + u(x))/x, s(x) := s(x) + r(x),$
- $r(x) := xr(x)$
- 8: $k := k + 1$
- 9: if $s_{n+1} = 1$ then $s(x) := s(x) + xp(x)$
- 10: if $s_n = 1$ then $s(x) := s(x) + p(x)$
- 11: return $s(x)$ and k

Phase II

Input: $s(x)$ where $\deg(s(x)) < \deg(p(x))$, $p(x)$, and k from Phase I

Output: $b(x)$ where $b(x) = a(x)^{-1}x^{2n} \pmod{p}$

- 12: for $i = 1$ to $2n - k$ do
- 13: $s(x) := xs(x) + s_{n-1}p(x)$
- 14: return $b(x) := s(x)$

Theorem 4: If $\deg(p(x)) > \deg(a(x)) > 0$ where $p(x)$ is an irreducible polynomial, then the degrees of intermediate binary polynomials $r(x), u(x)$ and $v(x)$ in the Montgomery inversion algorithm are always in the range $[0, \deg(p(x))]$, while $\deg(s(x))$ is the range of $[0, \deg(p(x)) + 1]$.

Proof: Let us assume the following terminology:

$$\begin{aligned} n &= \deg(p(x)), d_a = \deg(a(x)), d_u = \deg(u(x)), \\ d_s &= \deg(s(x)), d_v = \deg(v(x)) \text{ and } d_r = \deg(r(x)) \end{aligned}$$

The following invariants can be verified by induction:

$$\begin{aligned} p(x) &= u(x)s(x) + v(x)r(x) \\ 0 &\leq d_u \leq n \\ 0 &\leq d_s \leq n \\ d_v &\leq d_a < n \end{aligned}$$

Therefore, we have $n = \max(d_u + d_s, d_v + d_r)$ and $d_u + d_s \neq d_v + d_r$. Just before the last iteration $u(x) = v(x) = 1$ and $p(x) = s(x) + r(x)$, hence either $d_s = n$ or $d_r = n$. If $d_r = n$ then $d_s \leq n$ after the last iteration is performed while $d_s \leq n + 1$ after the last iteration when $d_s = n$ beforehand. \square

Theorem 5: If $p(x)$ is an irreducible polynomial, and $\deg(p(x)) > \deg(a(x)) > 0$, then we can find the lower and upper boundary for the number of iterations, k , in the first phase of Montgomery inversion algorithm as below:

$$n + 1 \leq k \leq \deg(a(x)) + n + 1$$

where n is the degree of the irreducible polynomial $p(x)$.

Proof: Each iteration decrements either the degree of $u(x)$ or of $v(x)$ by at least one. Initially, $\deg(u(x)) = \deg(p(x)) = n$ and $\deg(v(x)) = \deg(a(x))$. In the iteration before the very last one, we know that $u(x) = v(x) = 1$. Therefore, it can easily be shown that $k - 1 \leq \deg(a(x)) + n$. Similarly, each iteration decrements $\max\{\deg(u(x)), \deg(v(x))\}$ by at most one, hence, $k - 1 \geq n$. Consequently, we have

$$n \leq k - 1 \leq \deg(a(x)) + n$$

The lower bound is achieved when $a(x) = 1$. \square

Theorem 6: If $p(x)$ is an irreducible polynomial, and $\deg(p(x)) > \deg(a(x)) > 0$, then Phase I of the Montgomery inversion algorithm for $\text{GF}(2^n)$ returns $a(x)^{-1}x^k \pmod{p(x)}$.

Proof: Similarly to the proof in [5], the following invariants can be verified by induction:

$$\begin{aligned} a(x)r(x) &\equiv u(x)x^k \pmod{p(x)} \\ a(x)s(x) &\equiv v(x)x^k \pmod{p(x)} \end{aligned}$$

Note that there is no negative sign in the first congruence, which is natural since addition and subtraction are the same operation in $\text{GF}(2^n)$. By theorem 4, $\deg(s(x)) \leq n + 1$, it takes at most two additions by $p(x)$ to reduce the degree of $s(x)$ if it is not already reduced. By theorem 5, $k \geq n + 1$, so there are additional reduction steps to calculate the desired inverse of $a(x)$. \square

Additions and subtractions in the original algorithm are replaced with additions without carry in the $\text{GF}(2^n)$ version of the algorithm. Since it is possible to perform addition (and subtraction) with carry and addition without carry in a single arithmetic unit, this difference does not cause a change in the control unit of a possible unified hardware implementation. Step 6 of the proposed algorithm (where the degrees of $u(x)$ and $v(x)$ are compared) is different from that of the original algorithm. This necessitates a significant change to the control circuitry. To circumvent this problem we propose a slight modification in the original algorithm for $\text{GF}(p)$.

4 New variant of Montgomery inversion algorithm for $\text{GF}(p)$

Let

$$p = p_{n-1}2^{n-1} + p_{n-2}2^{n-2} + \dots + p_12 + p_0$$

be a prime number that is used to construct the prime field $\text{GF}(p)$. An element of $\text{GF}(p)$, $a < p$, can be represented as

$$a = a_{n-1}2^{n-1} + a_{n-2}2^{n-2} + \dots + a_12 + a_0$$

whose coefficients a_i are from $\{0, 1\}$. Then arithmetic on the elements in $\text{GF}(p)$ is modulo p arithmetic. The $\text{bitsize}(a)$ is defined as the number of bits in the binary representation of a . For example, the $\text{bitsize}(11)$, where $11 = (00001011)_2$ and $11 \in \text{GF}(251)$, is 4. An extended representation for an integer a ,

$$\begin{aligned} a &= \dots + a_{n+1}2^{n+1} + a_n2^n + a_{n-1}2^{n-1} + a_{n-2}2^{n-2} \\ &+ \dots + a_12 + a_0 \end{aligned}$$

is used when a also takes negative values. In case a is a negative integer excess coefficients (i.e. $\dots a_{n+1}, a_n$) are equal to 1 when two's complement representation is used for negative numbers. These coefficients are 0 when a is a positive number.

Before describing the new inversion algorithm, we first point out an important difference from the original Montgomery inversion algorithm. In Step 6 of the original Montgomery inversion algorithm two integers, u and v , are compared. Depending on the result of the comparison it is decided whether Step 6 or Step 7 is to be executed. We propose to modify Step 6 of the algorithm in a way that, instead of comparing u and v , the numbers of bits needed to represent them are compared. As a result of this imperfect comparison, u may become a negative integer. The fact that u might be a negative integer may lead to problems in comparisons in subsequent iterations, therefore u must be made positive again. To do that, it is sufficient to negate r . The proposed modifications can be seen in the modified algorithm given below. Note that Algorithm C is in fact a unified algorithm and it is reduced to Algorithm B provided that all addition and subtraction operations in $\text{GF}(p)$ -mode are mapped to $\text{GF}(2^n)$ addition in $\text{GF}(2^n)$ -mode. The variable $FSEL$ is used to switch between $\text{GF}(p)$ and $\text{GF}(2^n)$ modes.

Algorithm C

Phase I

Input: $a \in [1, p - 1]$ and p

Output: $s \in [1, p - 1]$ and k , where $s = a^{-1}2^k \pmod{p}$ and $n \leq k \leq 2n$

- 1: $u := p, v := a, r := 0$, and $s := 1$
- 2: $k := 0$ and $FSEL := 0 // FSEL := 1$ in $\text{GF}(2^n)$ -mode
- 3: if u is positive then
- 4: if $(\text{bitsize}(u) = 0)$ then go to Step 15
- 5: if u is even then $u := u/2, s := 2s$
- 6: else if v is even then $v := v/2, r := 2r$
- 7: else if $\text{bitsize}(u) \geq \text{bitsize}(v)$ then $u := (u - v)/2, r := r + s, s := 2s$
- 8: else $v := (v - u)/2, s := s + r, r := 2r$
- 9: Update $\text{bitsize}(u), \text{bitsize}(v)$ and sign of u
- 10: else (i.e. u is negative)
- 11: if u is even then $u := -u/2, s := 2s, r := -r$
- 12: else $v := (v + u)/2, u := -u, s := s - r, r := -2r$
- 13: $k := k + 1$
- 14: Go to Step 3
- 15: if $s_{n+2} = 1$ (i.e. s is negative)
- 16: $u := s + p$
- 17: $v := s + 2p$
- 18: if $u_{n+2} = 1$ then $s := v$
- 19: else $s := u$
- 20: $u := s - p$
- 21: $v := s - 2p$

22: if $v_{n+1} = 0$ then $s := v$
 22-a: if $s_n = 1$ and $FSEL = 1$ then $s := s - p$
 23: else if $u_n = 0$ then $s := u$
 24: else $s := s$
 25: return s and k

Phase II

Input: $s \in [1, p - 1]$, p , and k from Phase I
 Output: $b \in [1, p - 1]$, where $b = a^{-1}2^{2n} \pmod{p}$
 26: for $i = 1$ to $2n - k$ do
 27: $u := 2s - s_{n-1}p$
 28: $v := 2s - (1 + s_{n-1})p$
 29: if $v_n = 1$ then $s := u //$ i.e. if $v < 0$ in $\text{GF}(p)$ -mode
 30: else $s := v$
 31: return $b := s$

Changing the sign of both u and r simultaneously has the effect of multiplying both sides of the invariant $p = us + vr$ by -1 . Therefore, a new invariant when $r < 0$ is given as

$$-p = us + vr$$

While u and v remain to be positive integers, s and r might be positive or negative. Therefore, we need to alter the final reduction steps to bring s in the correct range, which is $[0, p)$. The range of s is $[-2p, 2p]$. As a result we need to use two more bits to represent s and r than the bitsize of the modulus.

u becomes negative as a result of $u = (u - v)/2$, when $\text{bitsize}(u) = \text{bitsize}(v)$ and $v > u$ before the operation. Since $u = (u - v)/2$ decreases the bitsize of the absolute value of u at least by one independently of whether the result is negative or positive, u will become certainly less than v after the negation operation. Therefore, if a negative u is encountered during the operation only steps 11 and 12 are executed.

Note that the variable $FSEL$ is not needed for $\text{GF}(p)$ -mode computations. Further in $\text{GF}(p)$ -mode, $FSEL = 0$ and Step 22-a is never executed. This step becomes relevant in $\text{GF}(2^n)$ -mode when $FSEL = 1$. Similarly, steps 27–30 in $\text{GF}(2^n)$ -mode become:

27: $u(x) := xs(x) + s_{n-1}p(x)$
 28: $v(x) := xs(x) + (1 \oplus s_{n-1})p(x)$
 29: if $v_n = 1$ then $s(x) := u(x)$
 30: else $s(x) := v(x)$.

Those steps are in fact equivalent to Step 13 of Algorithm B since v_n is always 1 in $\text{GF}(2^n)$ -mode.

In the following Section, we discuss the complexity of Algorithm C and provide statistical figures for the number of iterations where an iteration consists of operations from Step 3 to Step 14. The statistical figures are obtained for $\text{GF}(p)$ -mode. It is possible to obtain similar statistics for $\text{GF}(2^n)$ -mode.

5 Complexity analysis of Algorithm C and multibit shifting

In this Section, we investigate the complexity of Algorithm C in terms of the number of iterations and present a technique to improve the complexity utilising a method called *multibit shifting*. The multibit shifting was first introduced in [17]. We adopt the same multibit shifting approach for Phase I of Algorithm C, while for Phase II we propose a slightly different version that requires no precomputed values. Multibit shifting methods used for Phase I and Phase II of Algorithm C in $\text{GF}(p)$ -mode can be applied in $\text{GF}(2^n)$ -mode, and yield an overall comparable improvement, and thus the details of multibit shifting for $\text{GF}(2^n)$ -mode are deliberately omitted.

A decisive figure in determining the complexity of inversion algorithm is the number of iterations of the big

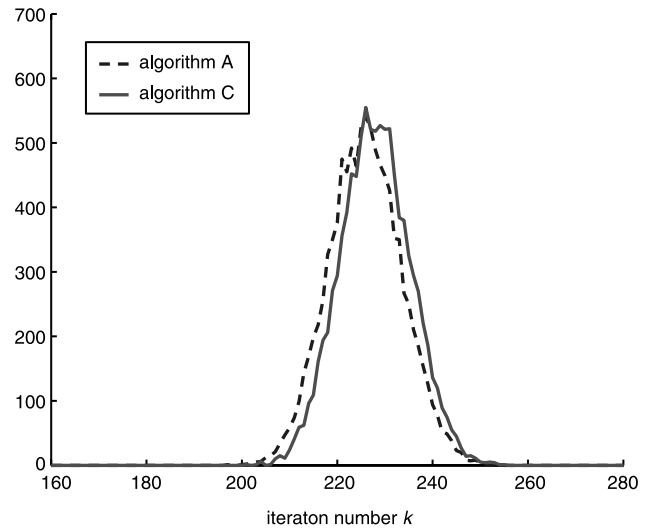


Fig. 1 Distribution of k in Algorithms A and C for 160-bit primes

Table 1: Expected values for k with primes of different sizes

n (bit length of p)	Algorithm A	Algorithm C
160	226	228
192	271	274
224	316	320
256	360	365

loop of Phase I, denoted as k . The iteration number k determines the number of operations performed such as addition, subtraction, comparison and shifting [Note 3]. The number of iterations before termination is unpredictable, but the algorithm demonstrates a regular and familiar distribution for k . Thus, we provide the result of statistical analysis on the number of iterations for both Algorithms A and C in Fig. 1.

The distribution of k in Fig. 1 is obtained using 100 different 160-bit prime numbers and 100 different inversion calculations for each prime. Algorithms A and C demonstrate almost identical statistical behaviour (or more precisely an unimportant degradation in Algorithm C). The expected values of k are 226 and 228 for Algorithms A and C, respectively, which is about 1.4 times the bit length of the prime modulus p . The latter observation is confirmed by statistical analysis for $\text{GF}(p)$ with larger moduli. The results for these larger moduli are shown in Table 1.

In the original Montgomery inversion algorithm (i.e. Algorithm A), the expected behaviour of Phase I is that steps 4, 5, 6 and 7 are executed almost the same number of times. Consequently the k loop performs shift operations half of the time (steps 4 and 5) and addition/subtraction operations (steps 6 and 7) in the other half. In Table 1, for instance, for 160 bit prime, one can conclude that 113 iterations out of 226 in Algorithm A are spent on shift operations. For future reference, we use the term *shift operations* for the former and *addition operations* for the latter, respectively. For example, in Algorithm C, steps 5, 6 and 11 performs *shift operations*, while steps 7, 8 and 12

Note 3: Note that multiplication and division by 2 is just one bit shift operation to the left and right, respectively.

Table 2: Reduction in number of shifts and total number of iterations

n , bits	No. of shifts in Phase I			No. of iterations in Phase II			
	Alg. A	Alg. C	Reduction in shifts, %	Alg. A	Alg. C	Reduction in Phase II, %	Reduction in total number of iterations, %
160	113	66	42	92	67	27	22
192	135	78	42	111	78	30	23
224	158	91	42	128	91	29	23
256	180	104	42	147	103	30	23

perform *addition operations*. The number of addition and shift operations are different in Algorithm C.

For the binary extension field $GF(2^n)$, where n is chosen in the same range as in Table 1, the ratio of the expected number of iterations over n is found to be ~ 1.7 while the distribution function has exactly the same form and features a close resemblance to that of the so-called *almost inverse algorithm* in [6]. We must note that the higher expected number of iterations increases the complexity of Phase I of both algorithms. However, it decreases the number of iterations in Phase II. Therefore, a larger k does not necessarily mean a higher complexity in our setting when both phases are taken into consideration. In the following Section, we show how the number of iterations is reduced using a multibit shifting method.

5.1 Multibit shifting for Phase I

Multibit shifting requires that the three least significant bits of u or v be inspected instead of just making an evenness check. At times it is possible to shift the integer more than one bit to the right. For instance, when the least significant three bits of u are all zero (i.e. $u_2u_1u_0 = 000$) it is possible to shift u to the right by three bits. While this check increases the hardware negligibly, the net effect of this technique on the complexity is not obvious and requires statistical analysis. Our experiment with the precision range given in Table 1 (i.e. [160, 256]) shows that there is about 42% [Note 4] reduction in the number of shift operations when three-bit shifting is applied. It has also been observed that three-bit shifting provides the optimum performance improvement. The exact number of shift operations when multibit shifting is applied is tabulated at the end of this Section along with the overall effect of the multibit shifting on the complexity.

5.2 Multibit shifting for Phase II

The loop in Phase II of Algorithm C executes $2n - k$ times after k is determined as the output of Phase I. Each iteration involves a subtraction operation and left shift operation by one bit. As in the case of Phase I shifting, it is also possible to shift s more than one bit in an iteration depending on the *most significant bits* of u . For instance, it is possible to shift s to the left by three bits when $s_{n-1}s_{n-2}s_{n-3} = 000$. The result may be greater than p , and hence it must be brought back to the range of $[1, p - 1]$. The algorithm for Phase II of Algorithm C with three-bit shifting, which provides the maximum reduction in the number of iterations with an insignificant cost in hardware, is given below.

Phase II with three-bit shifting

Input: $s \in [1, p - 1], p$, and k from Phase I

Output: $b \in [1, p - 1]$, where $b = a^{-1}2^{2n} \pmod{p}$

```

26:   $i := 1$ 
27:   $t := s_{n-1}s_{n-2}s_{n-3}$ 
28:  if  $i < 2n - k$  then
29:    if  $t = 0$  then
29-a:    $u := 8s$ 
29-b:    $v := 8s - p$ 
29-c:    $i := i + 3$ 
30:  else if  $t = 1$  then
30-a:    $u := 4s$ 
30-b:    $v := 4s - p$ 
30-c:    $i := i + 2$ 
31:  else if  $t = 2$  OR  $t = 3$  then
31-a:    $u := 2s$ 
31-b:    $v := 2s - p$ 
31-c:    $i := i + 1$ 
32:  else
32-a:    $u := 2s$ 
32-b:    $v := 2(s - p)$ 
32-c:    $i := i + 1$ 
33:  if  $(v < 0)$  then  $s := u$ 
34:  else  $s := v$ 
35:  return  $b := s$ 

```

Note that since $2n - k$ is not always a multiple of 3, a slight modification to the above algorithm is necessary. The algorithm given above must be adapted for the unified case. The sign check on v can be done in the same manner by checking whether v_n is 0 or 1 since $v_n = 1$ implies that v is negative. Our experiments for Phase II with three-bit shifting are found to be the optimum choice, providing $\sim 30\%$ reduction in the number of iterations.

5.3 Overall effect of multibit shifting on number of iterations

We conducted some experiments in which we used 100 different prime numbers of varying precisions, namely 160, 192, 224 and 256 bits. For every prime number, we computed the Montgomery inverse of 100 different integers, totalling 10 000 inverse computations. The results are shown in Table 2.

In Table 2, the total number of iterations is defined as: number of *addition operations* in Phase I + number of *shift operations* in Phase I + number of iterations in Phase II. We have mentioned previously that half of the values of Algorithm A in Table 1 are *addition operations* and the other half *shift operations*. Reduction in total number of iterations, as reported in the last column of Table 2, is percentage decrease in total number of iterations for Algorithm C compared to Algorithm A.

6 Comparison with other inversion algorithms

The paucity of hardware architectures implementing inversion algorithms hinders a fair comparison of different inversion algorithms from the perspective of hardware implementation. Many inversion algorithms are designed to

Note 4: The reduction in percentage is obtained by subtracting the number of shift operations after multibit shifting is applied from the number of shift operations without multibit shifting and then dividing it by the latter.

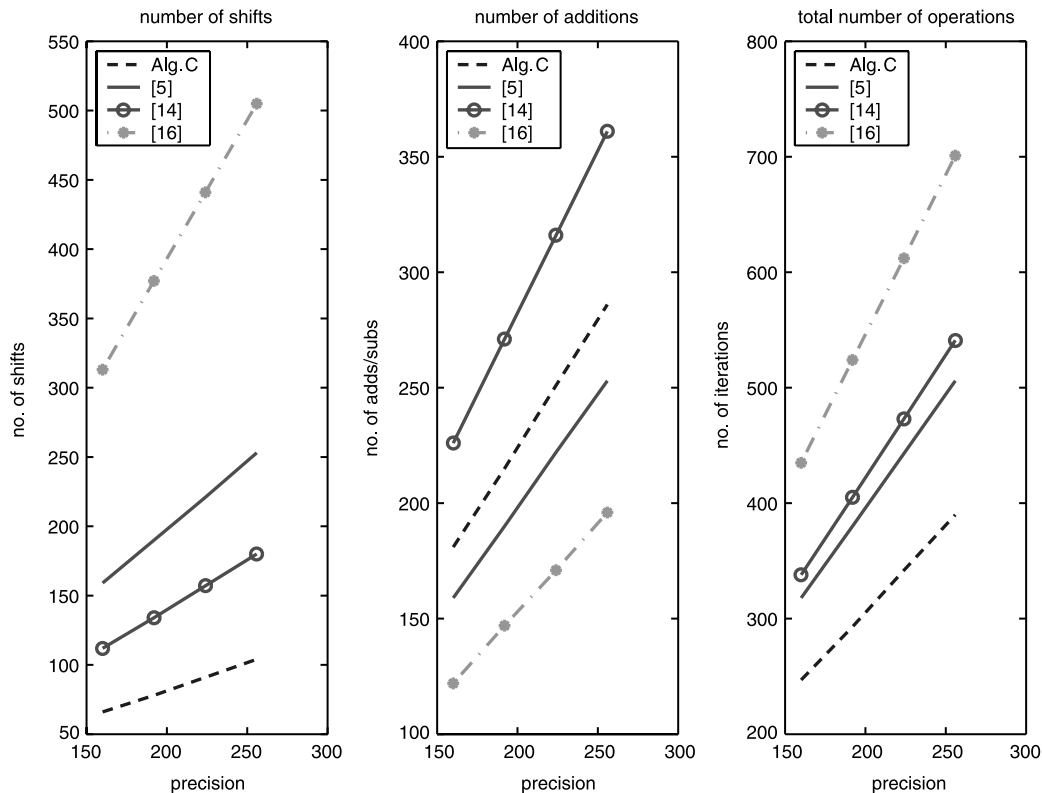


Fig. 2 Comparison of four algorithms in terms of number of operations

be implemented in software on general-purpose processors. It is difficult to predict how efficiently hardware implementations of these algorithms will perform. In this Section, we try to address this issue and determine the factors that are decisive in the performance of a hardware implementation. Finally, using these factors we compare Algorithm C against three other inversion algorithms.

As mentioned before, many inversion algorithms are binary variants of an extended Euclidean algorithm. Typically, these algorithms consist of a main loop executing a number of times. The number of iterations before termination demonstrates a familiar distribution whose statistics are shown in Fig. 1. Each iteration incorporates different combinations of iterations such as addition operations, shift operations, addition operations followed by shift operations, etc. Which combination is executed in a particular iteration is determined using certain conditional check operations such as parity check (e.g. Steps 4 and 5 of Algorithm A), integer or degree comparison (e.g. Step 6 of Algorithm B), etc. The expected number of these operations and/or certain combinations of these operations determines the complexity of the algorithm from the perspective of hardware implementation.

To compare different inversion algorithms, we classified the operations as follows: (i) *standalone shift* operations that cannot be executed along with an addition or subtraction operation simultaneously; and (ii) addition operations that are basically addition or subtraction operations. For example, Steps 5 or 6 of Algorithm C are standalone shift operations, while $(u - v)/2$ in Step 7 of the same algorithm is considered as an addition operation. Although the latter also has a shift following the subtraction, it is considered as an addition operation since this shift can be incorporated into an adder while designing the hardware. Also assuming that we can employ as many adders or shifters as we need, we consider operations that can be executed simultaneously by different units working in parallel, as only one operation.

In case addition and shift operations are executed in the same iteration in parallel, we count it as a single addition operation [Note 5]. For example, Step 7 of Algorithm C is counted as a single addition operation.

Under these assumptions, we compared four algorithms: Algorithm A in [5], Algorithm C proposed in this paper, the inversion algorithms proposed by Brown *et al.* in [14] and by Lorenz in [16]. Algorithms A and C are proposed for Montgomery arithmetic, and Algorithm C is basically a variant of Algorithm A optimised for hardware implementation. Note that Phase II of Algorithm A is modified according to the new definition of Montgomery inverse. On the other hand, algorithms in [14, 16] do not use Montgomery arithmetic. Excluding the conditional checks such as parity check or integer comparison, we counted the number of standalone shift operations and additions by running these four algorithms 10 000 times (with 100 different integers whose inverses are to be calculated for 100 different primes). In Fig. 2, the statistics obtained from this experiment are displayed. As can be observed in Fig. 2, the number of shift operations in Algorithm C is much fewer than those in the other three algorithms owing to the multibit shifting technique. Lorenz's algorithm in [16] has the fewest addition operations. In terms of total number of operations, Algorithm C compares favourably with others.

As shown in the following Section, where the details of our hardware architecture are discussed, shift and addition operations are of equal cost in terms of number of clock cycles because of the scalable nature of the architecture. Therefore, Algorithm C, which has the fewest expected

Note 5: Note that we assume that adders and shifters are inexpensive and that including up to four adders or shifters brings about no significant overhead in design area. In our scalable design, these units are inexpensive compared to memory and control logic. With other design approaches such as ones requiring very long full-precision adders, this assumption does not hold.

number of operations in total is the best choice for our design. For other architectures taking different approaches the best choice may be different. For example, Lorenz's algorithm in [16] may perform better where the shift operations are much less expensive than additions.

7 Hardware architecture

Algorithm C presented in Section 4, which is reduced to Algorithm B in $GF(2^n)$ -mode is suitable for scalable and unified design. Before discussing the details of the design issues involved we give definitions of scalable and unified architectures for arithmetic operations.

Scalability: An arithmetic unit is called scalable if it can be reused or replicated in order to generate long-precision results independent of the data path precision for which the unit was originally designed.

Scalability of the arithmetic modules is important in the cryptographic context since it allows an increase in the key length when the need for more security arises without having to modify or re-design the cryptographic unit. The scalability of the inverter unit can easily be achieved by using shifter and adder units, which handle only certain numbers of bits at a time. One addition (or shift) operation, therefore, in the corresponding field takes more than one clock cycle since the operands can be represented in multiprecision format. The number of bits that the unit operates on is referred to as *word* and the length of the word is yet to be determined. The word length cannot be too small since this increases the clock cycle count, leading to a slow execution of the whole operation. On the other hand, using long word units leads to other complications such as longer latency and higher gate count during hardware realisation. 16-, 32- and 64-bit block adders and shifters provide reasonable latency and gate counts. The length of a word can be determined or adjusted with respect to given area, speed or latency requirements.

Unified architecture: Even though prime and binary extension fields, $GF(p)$ and $GF(2^n)$, respectively, have dissimilar properties, the elements of both fields are represented using almost the same data structures in digital systems. In addition, the algorithms for basic arithmetic operations in both fields have structural similarities allowing a unified module design methodology. Therefore, a scalable arithmetic module which is versatile in the sense that it can be adjusted to operate in both fields is feasible, provided that this extra functionality does not lead to an excessive increase in area and dramatic decrease in speed. In addition, designing such a module must require only a small amount of extra effort and no major modification in control logic of the circuit.

Algorithm C can be implemented in a unified hardware architecture provided that a dual-field adder/subtractor (DFA/S) that operates in both fields is available. For the inverter unit to be scalable, the DFA/S is designed to operate on words at a clock cycle rather than the whole operand. Hence, it is referred to as word-DFA/S (or W DFA/S). In addition to W DFA/S, a bidirectional shifter, which is able to shift one word to the left or right at a clock cycle, is needed to perform the shift operations.

Since there is no negative number in $GF(2^n)$, the steps 10–12 and 15–19 will never be executed in $GF(2^n)$ -mode. Algorithm C, when executed in $GF(p)$ -mode, replaces the integer comparison operation of the original algorithm with just one bitsize comparison. In exchange for that, u takes negative integer values because of this imperfect comparison. Therefore, the variables u and r may have to change sign if the subtraction operation in Step 7 produces a

negative result. Performing these two negation operations immediately after Step 7 would necessitate extra clock cycles which may be more expensive than the integer comparison operation. Therefore, these two negation operations (i.e. taking two's complements of u and r) are performed in the next iteration of Algorithm C (Step 11 or 12). To perform the negation operations concurrently with two addition/subtraction operations in the next iteration, besides two W DFA/Ss we need two negators, which can be implemented as a relatively less complicated word adder. By having two extra negators, which may have a limited impact on the area as demonstrated by our implementation results, no extra clock cycles are spent on comparison operations. In a similar implementation presented in [17], the comparison is done utilizing a full subtraction. In [17], to avoid extra clock cycles due to this subtraction operation three extra full-length registers are employed, leading to a substantial increase in chip area. In the implementation in [17], both $(u - v)$ and $(v - u)$ are computed and the negatives of the results are discarded. For example, if $(u - v)$ is negative then $u < v$, hence the operation that must be performed is actually $(v - u)/2$. However, some extra clock cycles are still needed to perform two subsequent shift operations. On the other hand, our proposed algorithm eliminates the need for these extra clock cycles as well as three extra registers of full precision. The only extra cost for the comparison is two negators. Therefore, our implementation calculates inversion faster and requires less chip space than the one in [17].

The sign of the integer u is positive initially. The operation $u = (u - v)/2$ is completed at most in $e = \lceil n/w \rceil$ clock cycles. In the $(e + 1)$ st cycle, all control information, the sign of u , bitsize of u and v become available, and hence next iteration can start in the $(e + 2)$ nd clock cycle. This basically means that one iteration takes $(e + 1)$ clock cycles to finish. Note that the operation $r + s$ may need the $(e + 1)$ st clock cycle to complete since s may get two bits longer than the modulus.

The W DFA/S, performing operation $(u - v)/2$ (or $(v - u)/2$) on a word-by-word basis, also calculates the bitsize of the result in the same manner. When operation $(u - v)/2$ starts, the bitsize of the result is initially set to zero. When the first word of the result is generated its bitsize is stored in a temporary register without disturbing the bitsize of the result on which subsequent word computations depend. After e clock cycles the bitsize of the result is fully calculated, and hence it is updated from the temporary register. In the $(e + 1)$ st cycle after operation $(u - v)/2$ started, this information is used to determine how to proceed with the calculations. In the same clock cycle, the bitsize of the result is also checked to determine whether it is zero. A result with zero bitsize indicates the termination of the computations (step 4 of Algorithm C). Note that the bitsize of a negative u is meaningless and the algorithm terminates after u becomes 1. Therefore, a negative result only indicates that the computations must carry on.

In Table 3, an example for the calculation of $u := (u - v)/2$ is given for 160-bit operands. The operands u and v can be expressed as five-word multiprecision numbers, where each word is 32-bit (e.g. $u = (u^{(4)}u^{(3)}u^{(2)}u^{(1)}u^{(0)})$). As can be observed in steps 5, 6, 7, 8, 11, 12 of Algorithm C, one of the six different operations may update the values of u , v , r and s in each clock cycle. These operations are distinguished by an operation code (*opcode* for short) and the opcode must be determined in the preceding clock cycle before an operation starts. In clock cycle 1, the operation $(u^{(0)} - v^{(0)})/2$ is performed assuming that the opcode is known. The result of this operation is the least significant

Table 3: Execution steps of $(u-v)/2$ with operands of five words where world length is 32

Clock cycle	Operation	Output of adder	Result available in register file
1	$(u^{(0)} - v^{(0)})/2$	$(u^{(0)} - v^{(0)})/2[30 : 0]$	-
2	$(u^{(1)} - v^{(1)})/2$	$(u^{(1)} - v^{(1)})/2[30 : 0] \parallel (u^{(0)} - v^{(0)})/2[31]$	$(u^{(0)} - v^{(0)})/2[31 : 0]$
3	$(u^{(2)} - v^{(2)})/2$	$(u^{(2)} - v^{(2)})/2[30 : 0] \parallel (u^{(1)} - v^{(1)})/2[31]$	$(u^{(1)} - v^{(1)})/2[31 : 0]$
4	$(u^{(3)} - v^{(3)})/2$	$(u^{(3)} - v^{(3)})/2[30 : 0] \parallel (u^{(2)} - v^{(2)})/2[31]$	$(u^{(2)} - v^{(2)})/2[31 : 0]$
5	$(u^{(4)} - v^{(4)})/2$	$(u^{(4)} - v^{(4)})/2[30 : 0] \parallel (u^{(3)} - v^{(3)})/2[31]$	$(u^{(3)} - v^{(3)})/2[31 : 0]$
6	opcode for the next iteration is calculated	-	$(u^{(4)} - v^{(4)})/2[31 : 0]$

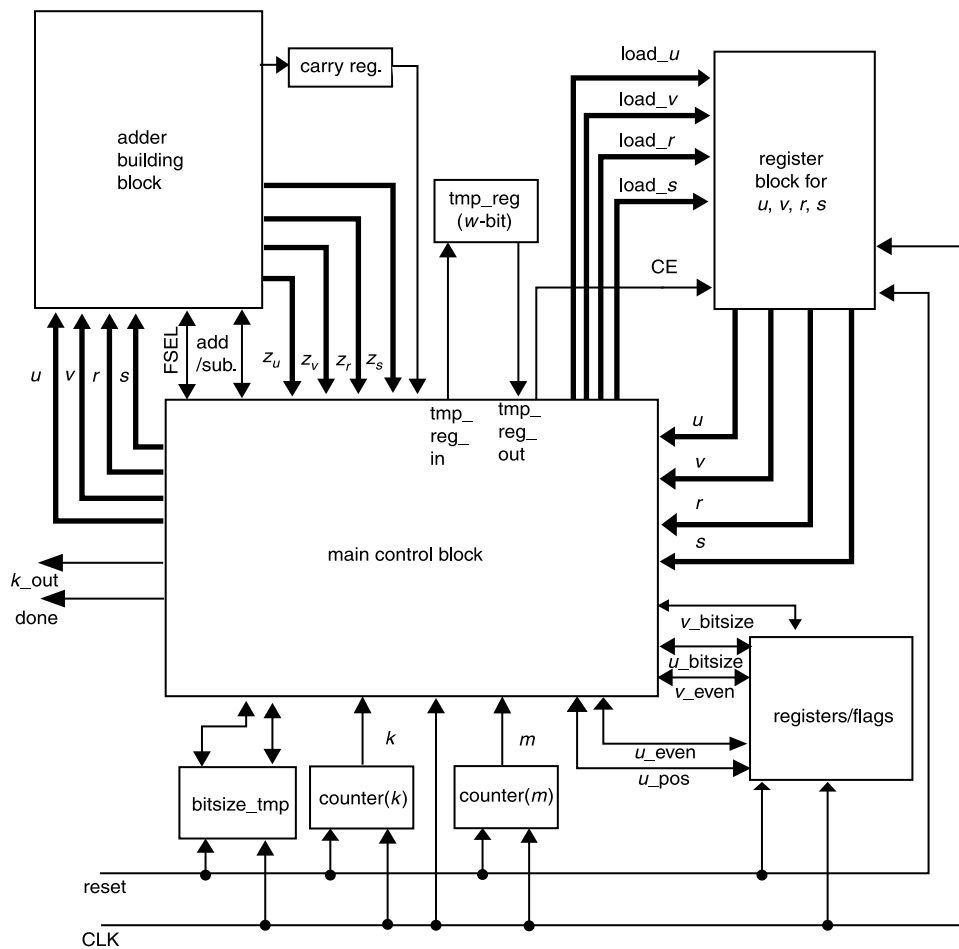


Fig. 3 Block diagram of module implementing Phase I

31 bits of $(u^{(0)} - v^{(0)})/2$ and the most significant bit is yet to be computed in the next clock cycle. Thus, the result is not considered to be ready and in the next cycle the result is written to the register. In other words, the result of $(u^{(0)} - v^{(0)})/2$ is available in the register file in clock cycle 2. This calculation continues until all the words of u and v are exhausted in clock cycle 5. In the following cycle (i.e. clock cycle 6), the complete result of $(u - v)/2$ operations becomes available in the register and the opcode is calculated for the next iteration.

In Fig. 3, the block diagram for Phase I of the inversion module is illustrated. *Adder Building Block* contains two WDFAs/Ss and two negators, while *Register Block* contains registers for four intermediate variables, u , v , r and s . *Main Control Block* is responsible for generating the opcode and selecting which part of the register block is used and updated in each clock cycle. The information the control block uses to determine the opcode, such as the bitsize, the parity of u and v , and the sign of u is kept in the block named

Registers/Flags. Before an iteration starts, the control block updates some of these values and subsequently uses them for generating the opcode for the next iteration. Note that the opcode remains unchanged for e clock cycles after it is set, where e is the number of words in the operands. To keep track of this, a counter is introduced in the design (*counter(m)*). When u becomes 0, the control block activates the *done* signal, indicating that the computation is terminated and the results are available in register s and at the output k_{out} of the control block.

tmp_reg is used to store words of operands during shift operations, while the carry register holds the carry as a result of addition or subtraction of two words. *bitsize_tmp* register keeps the intermediate values of bitsize of u and v , while the current value is kept in *Registers/Flags*. These new values are used to update *Registers/Flags* in the last clock cycle of the current iteration. The main control block takes a word of u , v , r and s from the register block each clock cycle and supplies them to the adder block. Each of the four adders

produces the results in outputs z_u, z_v, z_r and z_s . The control block decides how to update the register block with these values.

Note that the module in Fig. 3 implements Steps 1–14 of Algorithm C (Steps 1–8 of Algorithm B) and the rest of its Phase I is implemented along with Phase II using a different control logic which is not shown here, and is referred from now on as *Phase II control logic*. Phase II control logic is less complicated than the main control block shown in Fig. 3 and uses the same register and adder blocks. We only report the area requirements of the Phase II control logic in the following Section since its critical path delay does not increase the overall critical path.

8 Implementation results

In this Section, we present some implementation results of the inversion unit capable of operating in both $GF(p)$ and $GF(2^n)$. We synthesised the unit using Synopsys tools with 0.18 μm CMOS technology [18]. During the synthesis, no optimisation method is applied; hence the figures presented here can be further optimised using standard optimisation options of Synopsys tools.

Implementation results consist of three categories: (i) area requirements; (ii) maximum applicable clock frequency

Table 4: Time and area costs of block adder with $w = 16$, $w = 32$ and $w = 64$

World length, w	Propagation time, ns	Area (in NAND gates)	Total area (in NAND gates)
16	1.65	198	792
32	1.93	451	1804
64	2.31	989	3956

Table 5: Area cost of register block with various precisions

Bitsize	Area (in NAND gates)
1	30
160	4800
192	5760
224	6720
256	7680

Table 6: Time and area costs of control blocks

Word length w	Main control		Phase II control	
	Time delay, ns	Area (NAND gates)	Time delay, ns	Area (NAND gates)
16	4.00	3474	1.87	779
32	4.40	6369	2.01	1970

Table 7: Area and time requirements for a 160-bit inverter with $w = 32$

	Adder (32-bit)	Register	Main control	Phase II control	Overall
Area (in NAND gates)	1804	4800	5867	1970	14441
Time delay, ns	1.93	Negligible	4.34	2.01	4.34

(critical path delay); (iii) number of clock cycles to compute an inversion operation. Time and area requirements of main blocks in our design are reported separately. This facilitates accurate estimation of these requirements for inverters with different precisions and word lengths, etc. For instance, doubling the word length immediately results in an almost two-fold increase in area of adder and control blocks, while causing a relatively small increase in critical path delay of these blocks. Similarly, there is a linear relation between the register block size and the precision of the operands.

As noted before, the adder block should normally contain two adders and two negators operating on the words of the operands. In our implementation, however, we use four W DFA/Ss in the adder block in order to make the design more regular. Table 4 shows time and area costs of a single W DFA/S and total cost of adder block for different precisions that can be used for cryptographic applications. Similarly, we give the area cost of the register block for various operand precisions as in Table 5.

We also implemented the control blocks for two word lengths, $w = 16$ and $w = 32$, and give the results in Table 6. We did not implement the control blocks for $w = 64$; however, we estimate a two-fold increase in the area and $< 10\%$ increase in the critical path delay.

Based on the figures in Tables 4–6, area and time requirements for a 160-bit inverter with $w = 32$ are reported in Table 7. Note that these figures are comparable to those in [17]. We avoid a direct comparison because of the different technologies used. Also such comparison may be misleading since the main focus of the work in [17] is to compare the scalable implementation against fixed-precision implementation.

Besides time and area, the number of clock cycles to complete an inversion operation is also important in assessing the efficiency of an inversion module. We provide expected values for the number of clocks for certain precisions based on the figures in Tables 1 and 2. As pointed out earlier, an iteration of the loops in Phases I and II takes exactly $e + 1$ clock cycles to finish, where $e = \lceil n/w \rceil$. In addition to these steps, some intermediate steps are necessary to bring s in the correct range (i.e. steps 9 to 14 of Algorithm B and steps 15 to 25 of Algorithm C). These steps take an additional $2(e + 1)$ clock cycles. Taking into account the initialisation steps, which take $e + 1$ clock cycles, we need to add $3(e + 1)$ extra clock cycles to clock cycles spent on the main loops of Phases I and II.

As an example, based on the figures in Tables 1 and 2 and considering the additional clock cycles mentioned above, we calculated expected execution time in terms of number of

Table 8: Estimated clock cycle counts for inversion and ratio to multiplication operation

n (bits)	Inversion			Total number of clocks	Multiplication	Ratio
	Phase I + Phase II	After multibit shifting	Extra clock cycles			
160	1920	1498	18	1516	327	4.6
192	2688	2070	21	2091	398	5.25
224	3584	2760	24	2784	469	5.94
256	4608	3548	27	3575	526	6.80

clock cycles for an inversion operation using word length 32. The results are summarised in Table 8. Table 8 also includes the clock cycle count estimates for the modular multiplication operation for the same precisions, which is assumed to be performed using unified and scalar Montgomery modular multiplication unit proposed in [11] with 7 pipeline stages and a 32-bit word size. The ratio of inversion time to multiplication time, which is important in the decision about whether affine or projective co-ordinates are to be employed in elliptic curve cryptography, is also included in the Table. It is argued in [19] that for binary extension fields, $GF(2^n)$ projective co-ordinates, which do not entail fast execution of inversion operation, perform better than the affine co-ordinates when the inversion operation is more than 7 times slower than the multiplication operation. Similarly, our calculations show that this ratio is about 9 for prime field $GF(p)$. As can be observed in Table 8, the ratio stays lower than 7 for the precision of interest to the elliptic curve cryptography. The ratios achieved here are better than the previous work of [10], which employs similar inversion algorithms. Note that, unlike the current work, [10] does not report on the time complexity of Phase II of the algorithm. The improvement is largely due to the multibit shifting techniques used in the two phases of the algorithm.

However, one must also consider that the maximum critical path delay of the inverter can be greater than that of a multiplier because of the more complicated control logic of the inverter. Therefore, in case a multiplier that utilises a faster clock is employed, the ratios in Table 8 are subject to changes depending on the difference in the clock rates.

9 Conclusion

We presented two multiplicative inversion algorithms for $GF(p)$ and $GF(2^n)$ which are suitable for scalable and unified hardware implementations. The hardware implementation of these algorithms is easy, fast and area efficient. We presented experimental results and estimated values to show the practicality of the new algorithms. We also reported on the time and area complexity of the inversion unit using our implementation results. It turns out that the two new algorithms presented in this paper can enable hardware implementations that calculate inversions at such a speed that the usage of projective co-ordinates in elliptic curve cryptography no longer offers a significant advantage over affine co-ordinates. While projective co-ordinates [20] do not necessitate an inversion unit, they require considerably more temporary storage space than

affine co-ordinates. Therefore, the extra design space used to implement an inversion unit may no be significant.

10 References

- Diffie, W., and Hellman, M.E.: 'New directions in cryptography', *IEEE Trans. Inf. Theory*, 1976, **22**, pp. 644–654
- National Institute for Standards and Technology, "Digital signature standard (DSS)", Federal Register, Aug 1991, Vol. 56, p. 169
- Koblitz, N.: 'Elliptic curve cryptosystems', *Math. Comput.*, 1987, **48**, (177), pp. 203–209
- Menezes, A.J.: 'Elliptic curve public key cryptosystems' (Kluwer Academic Publishers, Boston, MA, 1993)
- Kaliski, B.S., Jr.: 'The Montgomery inverse and its applications', *IEEE Trans. Comput.*, 1995, **44**, (8), pp. 1064–1065
- Schroepel, R., Orman, H., O'Malley, S., and Spatscheck, O.: 'Fast key exchange with elliptic curve systems', in Coppersmith, D. (Ed.): 'Advances in cryptography – CRYPTO 95', *Lect. Notes Comput. Sci.*, No. 973, 1995, pp. 43–56
- Kobayashi, T., and Morita, H.: 'Fast modular inversion algorithm to match any operand unit', *IEICE Trans. Fundam.*, 1999, **E82-A**, (5), pp. 733–740
- Savaş, E., and Koç, Ç.K.: 'The Montgomery modular inverse – revisited', *IEEE Trans. Comput.*, 2000, **49**, (7), pp. 763–766
- Hasan, M.A.: 'Efficient computation of multiplicative inverses for cryptographic applications', Technical Report CORR 2001–03, Centre for Applied Cryptographic Research, 2001
- Savaş, E., and Koç, Ç.K.: 'Architecture for unified field inversion with applications in elliptic curve cryptography'. Proc. 9th IEEE Int. Conf. on Electronics, Circuits and Systems – ICECS, Dubrovnik, Croatia, Sept. 2002, Vol. 3, pp. 1155–1158
- Savaş, E., Tenca, A.F., and Koç, Ç.K.: 'A scalable and unified multiplier architecture for finite fields $GF(p)$ and $GF(2^m)$ '. in 'Cryptographic Hardware and Embedded Systems, Workshop on Cryptographic Hardware and Embedded Systems' (Springer-Verlag, Berlin, 2000), pp. 277–292
- Shantz, S.C.: 'From Euclid's GCD to Montgomery multiplication to the great divide', Technical Report SMLI TR–2001–95, Sun Microsystems Laboratory Technical Report, June 2001
- Knuth, D.E.: 'The art of computer programming', Vol. 2, (Addison-Wesley, Reading, MA, 1981, 2nd edn.)
- Brown, M., Hankerson, D., Lopez, J., and Menezes, A.: 'Software implementation of the NIST curves over prime fields'. Technical Report CORR 2000–56, Centre for Applied Cryptographic Research, 2000
- Hankerson, D., Lopez, J., and Menezes, A.: 'Software implementation of elliptic curve cryptography over binary fields'. Technical Report CORR 2000–42, Centre for Applied Cryptographic Research, 2000
- Lórenz, R.: 'New algorithm for classical modular inverse', in Kaliski, B.S., Jr., Koc, C.K., and Paar, C. (Eds.): 'Cryptographic Hardware and Embedded Systems', LNCS (Springer-Verlag, Berlin, 2002), pp. 57–70
- Gutub, A.A.-A., Tenca, A.F., Savaş, E., and Koç, Ç.K.: 'Scalable and unified hardware to compute montgomery inverse in $GF(p)$ and $GF(2^m)$ ', in Kaliski, B.S., Jr., Koç, Ç.K., and Paar, C. (Eds.): 'Cryptographic Hardware and Embedded Systems', LNCS (Springer-Verlag, Berlin, 2002), pp. 485–500
- UMC 0.18 μ m CMOS process family. <http://www.umc.com/english/process/d.asp>
- Lopez, J., and Dahab, R.: 'Fast multiplication on elliptic curves over $GF(2^m)$ without precomputation', in 'Cryptographic Hardware and Embedded Systems, Workshop on Cryptographic Hardware and Embedded Systems' (Springer-Verlag, Berlin, 1999), pp. 316–325
- IEEE. P1363: Standard specifications for public-key cryptography, 2000