

# A Digital Signature Scheme based on two hard problems

Dimitrios Poulakis and Robert Rolland

**Abstract** In this paper we propose a signature scheme based on two intractable problems, namely the integer factorization problem and the discrete logarithm problem for elliptic curves. It is suitable for applications requiring long-term security and provides smaller signatures than the existing schemes based on the integer factorization and integer discrete logarithm problems.

## 1 Introduction

Many applications of the Information Technology, such as encryption of sensitive medical data or digital signatures for contracts, need long term cryptographic security. Unfortunately, today's cryptography provides strong tools only for short term security [5]. Especially, digital signatures do not guarantee the desired long-term security. In order to achieve this goal Maseberg [21] suggested the use of more than one sufficiently independent signature schemes. Thus, if one of them is broken, then it can be replaced by a new secure one. Afterward the document has to be re-signed. Again we have more than one valid signatures of our document. Of course, a drawback of the method is that the document has to be re-signed.

In order to avoid this problem, it may be interesting for applications with long-term, to base the security of cryptographic primitives on two difficult problems, so if any of these problems is broken, the other will still be valid and hence the signature will be protected. We propose in this paper an efficient signature scheme built taking into account this constraint. The following signature scheme is based on the integer

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factorization problem and the discrete logarithm problem on a supersingular elliptic curve. Remark that these two problems have similar resistance to attack, thus they can coexist within the same protocol. The use of a supersingular curve allows us to easily build a pairing that we use to verify the signature.

Several signature schemes combining the intractability of the integer factorization problem and integer discrete logarithm problem were proposed but they have proved either to be enough to solve the one of two problems for breaking the system or to have other security problems [6, 9, 17, 18, 19, 20, 24, 30]. An interesting scheme based on the above problems is GPS [8]. Furthermore, some recent such schemes are given in [14, 15, 20, 26, 29, 30].

In section 2 we describe the infrastructure for the implementation of the scheme. Then we present the key generation, the generation of a signature and the verification. In section 3 we show how to build an elliptic curve adapted to the situation and how to define a valuable pairing on it. In section 4 we address the problem of the map to point function and give a practical solution. We deal with the performance of our scheme and compare it with others in section 5. In section 6 we give a complete example that shows that the establishment of such a system can be made in practice. In section 7 we study the security of the scheme. Finally section 8 concludes the paper.

## 2 The Proposed Signature Scheme

In this section we present our signature scheme.

### 2.1 Public and private key generation

A user  $\mathcal{A}$ , who wants to create a public and a private key selects:

1. primes  $p_1$  and  $p_2$  such that the factorization of  $n = p_1 p_2$  is unfeasible;
2. an elliptic curve  $E$  over a finite field  $\mathbb{F}_q$ , a point  $P \in E(\mathbb{F}_q)$  with  $\text{ord}(P) = n$  and an efficiently computable pairing  $e_n$  such that  $e_n(P, P)$  is a primitive  $n$ -th root of 1;
3.  $g \in \{1, \dots, n-1\}$  with  $\text{gcd}(g, n) = 1$ ,  $a \in \{1, \dots, \phi(n) - 1\}$  and computes  $Q = g^a P$ ;
4. two one-way, collision-free hash functions,  $h : \{0, 1\}^* \rightarrow \{0, \dots, n-1\}$  and  $H : \{0, 1\}^* \rightarrow \langle P \rangle$ , where  $\langle P \rangle$  is the subgroup of  $E(\mathbb{F}_q)$  generated by  $P$ .

$\mathcal{A}$  publishes the elliptic curve  $E$ , the pairing  $e_n$  and the hash functions  $h$  and  $H$ . The public key of  $\mathcal{A}$  is  $(P, Q, g, n)$  and his private key  $(a, p_1, p_2)$ .

## 2.2 Signature generation

The user  $\mathcal{A}$  wants to sign a message  $m \in \{0, 1\}^*$ . Then he chooses at random  $k, l \in \{1, \dots, \phi(n) - 1\}$  such that  $k + l = a$ . Next, he computes

$$s = k + h(m) + n \bmod \phi(n) \quad \text{and} \quad S = g^l H(m).$$

Let  $x(S)$  be the  $x$ -coordinate of  $S$  and  $b$  a bit determining  $S$ . The signature of  $m$  is  $(s, x(S), b)$ .

## 2.3 Verification

Suppose that  $(s, x, b)$  is the signature of  $m$ . The receiver uses  $b$  in order to determine  $y$  such that  $S = (x, y)$  is a point of  $E(\mathbb{F}_q)$ . He accepts the signature if and only if

$$e_n(g^s P, S) = e_n(g^{h(m)+n} Q, H(m)).$$

*Proof of correctness of verification.* Suppose that the signature  $(x, s, b)$  is valid and  $S = (x, y)$  is a point of  $E(\mathbb{F}_q)$ . Then we get

$$e_n(g^s P, S) = e_n(g^{k+h(m)+n} P, g^l H(m)) = e_n(g^{h(m)+n} Q, H(m)).$$

Suppose now we have a couple  $(s, S)$ , where  $s \in \{1, \dots, \phi(n)\}$  and  $S \in \langle P \rangle$ , such that

$$e_n(g^s P, S) = e_n(g^{h(m)+n} Q, H(m)).$$

Since  $H(m), S \in \langle P \rangle$ , there are  $u, v \in \{0, \dots, n-1\}$  such that  $S = uP$  and  $H(m) = vP$ . Thus we get

$$e_n((g^s u - g^{h(m)+n+av})P, P) = 1.$$

The element  $e_n(P, P)$  is a primitive  $n$ -th root of 1 and so, we obtain

$$uv^{-1} \equiv g^{a+h(m)+n-s} \pmod{n},$$

Putting  $l = a + h(m) + n - s \bmod \phi(n)$  and  $k = a - l \bmod \phi(n)$ , we get

$$s = k + h(m) + n \bmod \phi(n) \quad \text{and} \quad S = g^l H(m).$$

It follows that  $(s, x(S), b)$  is the signature of  $m$  (where  $b$  is a bit determining  $S$ ).

### 3 The elliptic curve and the pairing

In this section we show how we can construct an elliptic with the desired properties in order to implement our signature scheme. This task is achieved by the following algorithm:

1. select two large prime numbers  $p_1$  and  $p_2$  such that the factorization of  $p_1 - 1$ ,  $p_2 - 1$  are known and the computation of the factorization of  $n = p_1 p_2$  is unfeasible;
2. select a random prime number  $p$  and compute  $m = \text{ord}_n(p)$ ;
3. find, using the algorithm of [4], a supersingular elliptic curve  $E$  over  $\mathbb{F}_{p^{2m}}$  with trace  $t = 2p^m$ ;
4. return  $\mathbb{F}_{p^{2m}}$  and  $E$ .

Since the trace of  $E$  is  $t = 2p^m$ , we get  $|E(\mathbb{F}_{p^{2m}})| = (p^m - 1)^2$ . On the other hand, we have  $m = \text{ord}_n(p)$ , whence  $n | p^m - 1$ , and so  $n$  is a divisor of  $|E(\mathbb{F}_{p^{2m}})|$ . Therefore  $E(\mathbb{F}_{p^{2m}})$  contains a subgroup of order  $n$ .

By [4, Theorem 1.1], we obtain, under the assumption that the Generalized Riemann Hypothesis is true, that the time complexity of Step 3 is  $\tilde{O}((\log p^{2m})^3)$ . Furthermore, since the factorization of  $\phi(n) = (p_1 - 1)(p_2 - 1)$  is known, the time needed for the computation of  $m$  is  $O((\log n)^2 / \log \log n)$  [16, Section 4.4].

For the implementation of our signature scheme we also need a point  $P$  with order  $n$  and an efficiently computable pairing  $e_n$  such that  $e_n(P, P)$  is a primitive  $n$ -th root of 1. The Weil pairing does not fulfill this requirement and also, in many instances, the Tate pairing; the same happens for the eta pairing (the ate and omega pairings can be computed only on the ordinary elliptic curves) [1, 11, 28]. Let  $\varepsilon_n$  be one of the previous pairings on  $E[n]$ . Following the method introduced by E. Verheul [25], we use a distortion map  $\phi$  such that the points  $P$  and  $\phi(P)$  is a generating set for  $E[n]$  and we consider the pairing  $e_n(P, Q) = \varepsilon_n(P, \phi(Q))$ . The algorithm of [7, Section 6] provides us a method for the determination of  $P$  and  $\phi$ .

Another method for the construction of the elliptic curve  $E$  which is quite efficient in practice is given by the following algorithm:

1. draw at random a prime number  $p_1$  of a given size  $l$  (for example  $l$  is 1024 bits);
2. draw at random a number  $p_2$  of size  $l$ ;
3. repeat  $p_2 = \text{NextPrime}(p_2)$  until  $4p_1 p_2 - 1$  is prime;
4. return  $p = 4p_1 p_2 - 1$ .

It is not proved that this algorithm will stop with a large probability. This is an open problem which is for  $p_1 = 2$  the Sophie Germain number problem. But in practice we obtain a result  $p$  which is a prime of length  $2l$ .

Since  $p \equiv 3 \pmod{4}$ , the elliptic curve defined over  $\mathbb{F}_p$  by the equation

$$y^2 = x^3 + ax,$$

where  $-a$  is not a square in  $\mathbb{F}_p$ , is supersingular with  $p + 1 = 4p_1 p_2$  points. By [27, Theorem 2.1], the group  $E(\mathbb{F}_p)$  is either cyclic or  $E(\mathbb{F}_p) \simeq \mathbb{Z}/2p_1 p_2 \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ .

In each case the group  $E(\mathbb{F}_p)$  has only one subgroup of order  $n = p_1 p_2$ , and this subgroup is cyclic.

If  $\varepsilon_n$  is one of the Weil, Tate or eta pairings on  $E[n]$ , then we use the distortion map  $\phi(Q) = \phi(x, y) = (-x, iy)$  with  $i^2 = -1$  (cf. [12]) and so, we obtain the following pairing:  $e_n(P, Q) = \varepsilon_n(P, \phi(Q))$ .

## 4 The map to point function

Let  $G$  be the subgroup of order  $n = p_1 p_2$  of  $E(\mathbb{F}_q)$  introduced in the previous section. In order to sign using the discrete logarithm problem on this group, we have to define a hash function into the group  $G$ , namely a map to point function. This problem was studied by various authors giving their own method, for example in [3] or [13]. We give here the following solution. Let us denote by  $|n| = \lfloor \log_2(n) \rfloor + 1$  the size of  $n$ . Let  $h$  be a key derivation function, possibly built using a standard hash function. We recall that  $h$  maps a message  $M$  and a bitlength  $l$  to a bit string  $h(M, l)$  of length  $l$ . Moreover we will suppose that  $h$  acts as a good pseudo-random generator. Let  $Q$  be a generator of the group  $G$ . Let us denote by  $(T_i)_{i \geq 0}$  the sequence of bit strings defined by  $T_0 = 0$  and for  $i \geq 1$

$$T_i = a_u \cdots a_0,$$

where  $i = \sum_{j=0}^u a_j 2^j$  and  $a_u = 1$ .

To map the message  $m$  to a point  $H(m)$  we run the following algorithm:

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i := 0;
Repeat
k := h(m || T_i, |n|);
i := i + 1;
Until k < n;
Output H(M) = k.Q;

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This Las Vegas algorithm has a probability zero to never stop. In practice this algorithm stops quickly, namely as  $2^{|n|-1} < n < 2^{|n|}$  then the expected value of the number of iterations is  $< 2$ . If one can find a collision for  $H$  it is easy to find a collision for  $h$ .

## 5 Performance Analysis

In this section we analyze the performance of our scheme. The computation of  $s$  requires two additions modulo  $\phi(n)$ . The computation of  $S$  needs a modular exponentiation  $g^l \pmod{n}$  and the computations of  $H(m)$  and  $g^l H(m)$ . Note that the computation of  $g^l \pmod{n}$  and  $k + n \pmod{\phi(n)}$  can be done off-line. Thus, the signature generation requires only a modular addition and a point multiplication on the

elliptic curve. The signature verification needs two modular exponentiations, two points multiplications on the elliptic curves, and two pairing computations. Moreover note that the length of the signature of a message is the double of its length.

The signature generation in the GPS scheme [8] needs only one modular exponentiation and the signature verification two. The signature length is the triple of the message length. The most efficient of the schemes given in [14, 15, 20, 26, 29, 30] requires 3 modular exponentiations for the signature generation and 4 modular exponentiations for the signature verification. The signature length of the above schemes is larger than the double of the message length.

Hence we see that the signature length in our scheme is smaller than that in GPS and the other schemes. Moreover, the performance of the proposed algorithm is competitive to the performance of the above schemes.

## 6 Example

In this section we give an example of our signature scheme. We consider the 1024-bits primes

$$p_1 := 61087960575038789816988536114150792266377636351843177587564 \\ 31924627119957041754060999158399749767833896533906296859311 \\ 25485163415231551275212583044052150577614828617005803730389 \\ 43877400689242960278845109703690843026188873847913442234432 \\ 36591255684234493362159572100747699404245339214008078743836 \\ 7162669180839$$

and

$$p_2 := 950794575789036193985289494100238271764913649341936446441081 \\ 377072500578035754538268902518142982960234055319718348171564 \\ 531835348013169675598575434394528269729126327128190711758193 \\ 487088395696503090307111303433870155114599617217105648040005 \\ 344506796898422897977489196110610260665664553656001074068087 \\ 13249343.$$

We take  $n = p_1 p_2$ . The number  $q = 4n - 1$  is a prime. Since  $q \equiv 3 \pmod{4}$ , the elliptic curve  $E$  defined by the equation  $y^2 = x^3 + x$  over  $\mathbb{F}_q$  is supersingular. The point  $P = (x(P), y(P))$ , where  $x(P) = 2^{1500} + 2$  and

$$y(P) = 92629334720096485394250229023531473128561210303747369871170 \\ 532503591346084781038053790347765721405539373837575715741111302632 \\ 222520728502603977901582753916707479492439228918725855423715991340 \\ 003621514555505206507732534242013847767107764800751435936328543137$$

789247911179152023276247696951339536945505339588067200491193957998  
 044975563046555194785086909103272771864842171753848435480722850484  
 547366650914307823107502201128733622163636510656608071825566283432  
 994640380462713709910638633429178083083878848700277309884412794341  
 026781057881112432733889255328105052291841518470922081921433382412  
 472012678120546125640726148962.

has order  $n$ . We take  $g = 2$ ,

$$a = 2^{256} + 2^9 + 1 = 11579208923731619542357098500868790785326998466$$

$$5640564039457584007913129640449$$

and we compute

$$g^a \bmod n = 291246612437704212466554616370488460582482345$$

412043139387071627568366461190658309237330580043030838224854789252  
 968050905018578440545530480131761225347896913705349073419345335895  
 868832920014327349522957752032149784650672578527400186028060209053  
 035728070430079944852013985987562947197675511448867860271390438151  
 997510376157277527652722786834963496843487625119512000324307142997  
 876216044005309541179123902262183075125684914484636806915549910481  
 194533920018176890664864601123368083711476432553316859751469426810  
 204461407620204756483516542976417259702626996120442929825569733396  
 7126221051950952443115939209262561714767443.

Next, we compute  $Q = g^a P = (x(Q), y(Q))$ , where

$$x(Q) = 492906626963089094011867684016548035835802792163377707597056$$

795455537761970341320418289803336076175870732053896841006011789243  
 411173491601076264818884432777686675649566399360544060115589059409  
 495626348669253033853643920668587107209662122339196308521380419432  
 395876777001037759129809826188826444792896302483531297500328577661  
 115644137663377694781584798800831919655207788055426633821916253648  
 545542264181819923868715936604077661019515870909292645145292612582  
 082056454491673626406957411250447615805464800603537427266421084067

068889942487927367826706242600925470755091415792336658258887358233  
6648011173165127581579893233

and

$y(Q) = 925164000667984941436213463843562867132842692526639503713623$   
100761058759325653912386860742637828197211675023371765292190166225  
688907658763278636042952123928199605188431021730950523522172176061  
249916336352942245517540928470987327163690899169971423566730046146  
040131461711982514952573761305725771859092373093590718229549775728  
318091393459721685022050067573052541368464407556329663187692087325  
785318806656273634451502898900933909082715458588013832847281982918  
045250406217417892195982283414569723280463029281881025844011710313  
003637423244716948430928877376648184124169704330493421073010959904  
2000468957343998962535886947.

Therefore  $(P, Q, 2, n)$  and  $(a, p_1, p_2)$  are a public key and the corresponding private key for our signature scheme. Moreover, we can use the Tate pairing with the distortion map  $\phi(x, y) = (-x, iy)$  with  $i^2 = -1$ .

## 7 Security of the Scheme

In this section we shall discuss the security of our system. First, we remark that if an attacker wants to compute the private key  $(a, p_1, p_2)$  from the public key, he has to factorize  $n$  and to compute the discrete logarithm  $g^a$  of  $Q$  to the base  $P$  and next to calculate the discrete logarithm  $a$  of  $g^a$  to the base  $g$  in the group  $\mathbb{Z}_n$ . Note that an algorithm which computes the discrete logarithm modulo  $n$  implies an algorithm which breaks the Composite Diffie-Hellman key distribution scheme for  $n$  and any algorithm which break his scheme for a non negligible proportion of the possible inputs can be used to factorize  $n$  [22, 2].

In order to study the security of the scheme we are going to look at the two worst cases:

1. the factorization problem is broken but the elliptic curve discrete logarithm problem is not;
2. the elliptic curve discrete logarithm problem is broken but the factorization problem is not.



In each case we will prove that if an attacker is able to generate a valid signature for any given message  $m$ , then it is able to solve, in the first case the elliptic curve discrete logarithm problem and in the second case the factorization problem.

1) Let us suppose that the attacker is able to factorize  $n$ . Then he can compute  $\phi(n)$ . But he is unable to compute  $a$  since  $a$  is protected by the elliptic curve discrete logarithm problem and by the discrete logarithm problem modulo  $n$ , because the only known relation involving  $a$  is  $Q = g^a P$ . So, in order to produce a valid signature of a message  $m$  the attacker has only two possibilities: he can arbitrary choose  $k$ , and then he can compute  $s$  but not  $S$ , or choose arbitrary  $l$  and then he can compute  $S$  but not  $s$ .

2) Let us suppose now that the attacker is able to solve the elliptic curve discrete logarithm problem. Then he can compute  $g^a$  but as the factorization problem is not broken the discrete logarithm problem modulo  $n$  is not broken and consequently he cannot compute  $a$  (cf. the beginning of this section). Then as in 1) he cannot compute simultaneously  $s$  and  $S$ .

## 8 Conclusion

In this paper we defined a signature system based on two difficult arithmetic problems. In the framework chosen, these problems have similar resistance to known attacks. We explained how to implement in practice all the basic functions we need for the establishment and operation of this system. This strategy has an interest in any application that includes a signature to be valid for long. Indeed, it is hoped that if any of the underlying problems is broken, the other will still be valid. In this case, the signature should be regenerated with a new system, without the chain of valid signatures being broken. Finally, the signature length of our scheme is smaller than that of the schemes based on integer factorization and integer discrete logarithm problems, and its performance is competitive to that of these schemes.

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