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► **To cite this version:**

Carlos Aguilar Melchor, Pierre-Louis Cayrel, Philippe Gaborit, Fabien Laguillaumie. A New Efficient Threshold Ring Signature Scheme Based on Coding Theory. *IEEE Transactions on Information Theory*, 2011, pp.4833-4842. 10.1007/978-3-540-88403-3\_1 . hal-01083807

**HAL Id: hal-01083807**

**<https://hal.science/hal-01083807v1>**

Submitted on 18 Nov 2014

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# A New Efficient Threshold Ring Signature Scheme based on Coding Theory

Carlos Aguilar, Pierre-Louis Cayrel, Philippe Gaborit and Fabien Laguillaumie

**Abstract**—Ring signatures were introduced by Rivest, Shamir and Tauman in 2001 [32]. These signatures allow a signer to anonymously authenticate a message on behalf of a group of his choice. This concept was then extended by Bresson, Stern and Szydlo into  $t$ -out-of- $N$  (threshold) ring signatures in 2002 [9]. We propose in this article a *generalization* of Stern’s code based identification (and signature) scheme [36] to design a practical  $t$ -out-of- $N$  threshold ring signature scheme. The size of the resulting signatures is in  $\mathcal{O}(N)$  and does *not* depend on  $t$ , contrary to most of the existing protocols. Our scheme is existentially unforgeable under a chosen message attack in the random oracle model assuming the hardness of the *minimum distance problem*, is unconditionally source hiding, has a very short public key and has an overall complexity in  $\mathcal{O}(N)$ . This protocol is the first efficient code-based ring signature scheme and the first code-based threshold ring signature scheme. Moreover it has a better complexity than number-theory based schemes which have a complexity in  $\mathcal{O}(Nt)$ . This paper is an extended version of [2] with complete proofs and definitions.

**Keywords** : Threshold ring signature, code-based cryptography, Stern’s scheme, syndrome decoding.

## I. INTRODUCTION

The constant need to electronically emulate real-life applications with strong security properties leads to the design of sophisticated identification schemes with specific properties. Ring signatures are such an identification technique, where a signer anonymously authenticates a message on behalf of a group of his own choice. The design of such special purpose signatures almost always relies on arithmetic in the ring  $\mathbb{Z}/N\mathbb{Z}$  or in groups of points of an algebraic curve equipped or not with a pairing. From the point of view of the efficiency of the computations involved in the whole cryptographic process, *error correcting codes* are a real alternative to such integral arithmetic.

1) *Code-based cryptography*: In 1978 when McEliece published his seminal work where he proposed to use the theory of error correcting codes for confidentiality purposes, he designed one of the most efficient encryption schemes, which *still* resists to cryptanalysts. His asymmetric encryption algorithm may be sum up as follows: Alice

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applies an encoding mechanism to a message and add to it a large number of errors, that can only be corrected by Bob who has information about the secret decoding mechanism. A long time after, Stern proposed in [36] a *zero-knowledge* identification protocol based on a well-known error-correcting codes problem usually referred as the *Syndrome Decoding Problem (SD)* in short).

The advantages of code-based cryptography are twofold. First code-based cryptography constitutes an alternative to classical number theory based cryptography, whose hard problems (factorization, discrete logarithm, discrete logarithm based on elliptic curve) would be broken through P. Shor’s quantum factorization algorithm, in the case a quantum computer would come to exist. Second, code-based cryptosystems are faster than classical number theory based cryptosystems ([7],[20]). Notice that cryptosystems based on hard problems potentially resistant to a quantum computer, like code-based cryptography, lattice based cryptography or multivariate cryptography have recently been gathered under the name *post-quantum cryptography*, and a special conference dedicated to these systems, *PQCrypto*, has been recently created. The main drawbacks of code-based cryptosystems is historically a large size of public key, meanwhile in recent years, propositions have been made, based on structured matrices (quasi-cyclic or dyadic) to deal with this issue [20], [4], [28]. In particular the double-circulant variation of the Stern identification scheme [20] is believed to be very hard to break, being based on the difficulty of decoding a binary code up to the Gilbert-Varshamov bound, when more scrutiny is needed for McEliece compact variations.

The Stern identification scheme (that we mainly consider in this paper) can be used as a signature scheme through the Fiat-Shamir heuristic [18]. From the two original drawbacks of the scheme : the relatively large size of key and the large length of signature (about 20 kiloBytes), only the large size of signature remains. This scheme has very good features and despite its large size of signature, it can potentially be used in many applications.

Overall code-based cryptography represents one of the few credible alternative to classical cryptography, and one attends to a rising interest in the cryptographic community for these systems, in particular practical implementation of such code-based schemes on smart cards, embedded devices or PC, have begun to be presented in conferences likes CHES or CARDIS ([17], [11], [23], [7]).

2) *Ring signature*: The concept of *ring signature*, which is the subject of this article, was introduced in 2001

by Rivest, Shamir and Tauman [32] (called RST in the following). Ring signatures are often considered as simplified group signatures without group managers. If ring signatures are related to this notion of group signatures in [13], they are indeed quite different. On one hand, group signatures have the additional feature that the anonymity of a signer can be revoked (i.e. the signer can be traced) by a designated group manager, on the other hand, ring signatures allow greater flexibility: no centralized group manager or coordination among the various users is required (indeed, users may be unaware of each other at the time they generate their public keys). Moreover, the anonymity of the signer is unconditionally guaranteed. The original motivation was to allow secrets to be leaked anonymously. For example, a high-ranking government official can sign information with respect to the ring of all similarly high-ranking officials, the information can then be verified as coming from someone reputable without exposing the actual signer.

Bresson *et al.* [9] extended the ring signature scheme into a *threshold ring signature* scheme using the concept of partitioning and combining functions. Assume that  $t$  users want to leak some secret information, so that any verifier will be convinced that  $t$  users *among a select group* held for its validity. The trivial construction consisting in producing  $t$  ring signatures clearly does not prove that the message has been signed by different signers. A *threshold ring signature* scheme effectively proves that a minimum number of users of a certain group must have actually collaborated to produce the signature, while hiding the precise membership of the subgroup (for example the ring of public keys of all members of the President’s Cabinet).

3) *Related Work:* The seminal work of Bresson *et al.* [9] suffers from a lack of efficiency since the size of the signature grows with the number of users  $N$  and the number of signers  $t$ . More precisely, the size of their  $t$ -out-of- $N$  signature is  $2^{\mathcal{O}(t)} \lceil \log_2 N \rceil \times (tl + Nl)$  where  $l$  is the security parameter. A number of  $t$  inversions are necessary to perform a signature and  $\mathcal{O}(2^t N \log_2 N)$  computations are needed in the easy direction.

Later, Liu *et al.* [26] proposed another threshold ring signature based on Shamir’s secret sharing scheme. Their scheme is separable (which means that the signers are free to choose their own parameters), with a signature length *linear* in  $N$  but a *quadratic* complexity for  $t \approx N/2$  (the cost of secret sharing scheme). The notion of *mesh signature*, introduced by Boyen in [8] can also be used in that case: the signature length is also linear in  $N$  but the verification is in  $\mathcal{O}(Nt)$  bilinear pairings computations.

A variation for ring signature was introduced in [38] by Tsang, Wei, Chan, Au, Liu and Wong: the authors introduced the notion of *linkable ring signature* by which a signer can sign only once being anonymous, since a verifier can link a second signature signed by the same signer. Although this property may have interesting applications (in particular for e-vote) it does not provide full anonymity (in the sense that it cannot be repeated). Later their scheme was extended to threshold ring signature with

a complexity in  $\mathcal{O}(N)$ , but again, only a linkable ring signature which does not correspond to original required feature of [32] and [9], namely a fully anonymous scheme.

A first attempt to design ring signatures within the error correcting code setting was performed by Zheng, Li and Chen [44], but their scheme is still inefficient. After the short version of the present paper, Dallot and Vergnaud proposed a code-based threshold ring signature scheme [15], inspired by Bresson *et al.*’s construction with Courtois, Finiasz and Sendrier’s signatures [14]. Both previous schemes use [14], which makes them very difficult to use in practice.

4) *Contributions:* In this paper, we present a *generalization* of Stern’s identification and signature scheme [36] that we use to design new ring and threshold ring signature schemes. Our scheme’s performance does not depend on the number  $t$  of signers in the ring, the overall complexity and length of signatures only depend linearly in the maximum number of signers  $N$ . Our protocol also guarantees unconditional anonymity of the signers. Besides these features and its efficiency, our protocol is also the first non generic coding theory based ring signature (and threshold ring signature) protocol and may constitute an interesting alternative to number theory based protocols. Overall our protocol has a very short public key size, a signature length linear in  $N$  and the best known complexity in  $\mathcal{O}(N)$  when other number theory based threshold ring signature schemes have a complexity in  $\mathcal{O}(Nt)$ .

5) *Organization of the paper:* The rest of this paper is organized as follows. In Section II, we give a state of the art of ring signatures and threshold ring signatures. In Section III, we describe Stern’s identification and signature scheme and give some background and notation. In Section IV, we present our new *generalization* of Stern’s scheme in a threshold ring signature context. In Section V, we study the security of the proposed scheme. In Section VI we consider a variation of the protocol with double circulant matrices. In Section VII we discuss the signature cost and length. Finally, we conclude in Section VIII.

## II. OVERVIEW OF RING SIGNATURES

### A. Definition of a ring signature

Following the formalization of ring signatures proposed in [32], we review in this section some basic definitions and properties eligible to ring signature schemes.

**Definition 1 (Ring Signature)** *Let  $\lambda$  be an integer. A ring signature scheme  $RS$  consists of the following four algorithms:*

- *Setup:* is a probabilistic algorithm which takes the unary string  $1^\lambda$  as input and outputs the public parameters  $\mathcal{P}$ . The integer  $\lambda$  is the security parameter and will be an input of all algorithms.
- *KeyGen:* is a probabilistic algorithm which takes public parameters as input and outputs a pair of secret and public keys  $(sk, pk)$ .

- *Sign*: is a probabilistic algorithm which takes as input public parameters, a set  $\{pk_1, \dots, pk_N\}$  of public keys, a secret key  $sk_i$  for  $1 \leq i \leq N$ , a message  $m$ , and which outputs a ring signature  $\sigma$  on  $m$ .
- *Verify*: is a deterministic algorithm which takes as input public parameters, a set  $\{pk_1, \dots, pk_N\}$  of public keys, a putative pair message/signature  $(m, \sigma)$ , and outputs 1 if  $\sigma$  is a valid signature on  $m$  with respect to the set of public keys  $\{pk_1, \dots, pk_N\}$ , and 0 otherwise.

The crucial security property expected from a ring signature scheme (besides its unforgeability) is the *source hiding*, which is a very strong anonymity property. Indeed, it means that an attacker, even with unbounded computation capabilities, is not able to determine which member of the ring actually produced a given signature. This property is required to be unconditionally fulfilled (*i.e.* in the information theoretic sense), not only computationally. Precise definition of the security requirements will be detailed in the next section concerning *threshold* ring signatures.

From a practical point of view, most of the existing ring signature schemes have a signature length linear in  $N$ , the size of the ring. Among the many schemes appearing in the literature, one can mention the work of Bendery, Katzysz and Morselli in [3] where they present three ring signature schemes which are provably secure in the *standard model*. Recently, Shacham and Waters [34] proposed a ring signature scheme where the signature consists of  $2N + 2$  group elements and requires  $2N + 3$  pairings to be verified.

A breakthrough on the size of ring signature was obtained in [16] in which the authors proposed the first (and unique up to now) constant-size scheme based on accumulator functions and the Fiat-Shamir zero-knowledge identification scheme. However, the signature derived from the Fiat-Shamir scheme has a size of at least 160 kbits, and the security proof is conducted in the random oracle model. Another construction proposed by Chandran, Groth and Sahai ([12]) has a size in  $\mathcal{O}(\sqrt{N})$ .

Recently in [44], Zheng, Li and Chen presented a code-based ring signature scheme with a signature length of  $144 + 126N$  bits, but this scheme is based on the signature from [14] which remains very slow in comparison with other schemes.

Eventually a generalization of ring signature schemes in mesh signatures was proposed by Boyen in [8].

### B. Threshold ring signature: definition and security model

In [9], Bresson, Stern and Szydlo introduced the notion of threshold ring signature as an extension of the original concept of ring signature from Rivest *et al.* [32]. We formally define in this section the notion of threshold ring signature scheme together with the security requirements.

**Definition 2 (Threshold Ring Signature)** Let  $\lambda, t$  and  $N$  be three integers. A  $(t, N)$ -threshold ring signature scheme  $TRS$  consists of the following four algorithms:

- *Setup*: is a probabilistic algorithm which takes the unary string  $1^\lambda$  as input and outputs the public parameters  $\mathcal{P}$ .
- *KeyGen*: is a probabilistic algorithm which takes public parameters as input and outputs a pair of secret and public keys  $(sk, pk)$ .
- *Sign*: is a probabilistic interactive protocol between  $t$  users, involving public parameters, a set  $\{pk_1, \dots, pk_N\}$  of public keys, a set of  $t$  secret keys  $\{sk_{i_1}, \dots, sk_{i_t}\}$ , a message  $m$ , and which outputs a  $(t, N)$ -threshold ring signature  $\sigma$  on  $m$ .
- *Verify*: is a deterministic algorithm which takes as input public parameters, a threshold value  $t$ , a set  $\{pk_1, \dots, pk_N\}$  of public keys, a putative pair message/signature  $(m, \sigma)$ , and outputs 1 if  $\sigma$  is a valid signature on  $m$  with respect to the set of public keys  $\{pk_1, \dots, pk_N\}$ , and 0 otherwise.

The scheme  $TRS$  must be *correct*, which means that for all  $(\lambda, N, t) \in \mathbb{N}^3$ , for all  $m \in \{0, 1\}^*$ , for all  $\mathcal{P} \leftarrow TRS.Setup(1^\lambda)$ ,  $TRS.Verify(\mathcal{P}, t, \{pk_1, \dots, pk_N\}, (m, \sigma)) = 1$  as long as  $(sk_i, pk_i) \leftarrow TRS.KeyGen(\mathcal{P}) \forall 1 \leq i \leq N$ , and  $\sigma \leftarrow TRS.Sign(\mathcal{P}, \{pk_1, \dots, pk_N\}, \{sk_{i_1}, \dots, sk_{i_t}\}, m)$  with  $\{sk_{i_1}, \dots, sk_{i_t}\} \subset \{sk_1, \dots, sk_N\}$ .

Let us now discuss the security criteria which must be fulfilled by a threshold ring signature scheme.

1) *Unforgeability*: The conventional notion of security for signatures was introduced by Goldwasser, Micali and Rivest in [21]. A signature scheme is said to be secure if it is indeed *existentially unforgeable* under a *chosen message attack*. We formally describe by the following game between an existential forger  $\mathcal{F}$  and its challenger  $\mathcal{C}$ , the similar notion of security for a threshold ring signature scheme.

**Definition 3** A threshold ring signature scheme is said to be *existentially unforgeable* under a *chosen message attack* if no PPT adversary  $\mathcal{F}$  has a non-negligible advantage in the following game.

- 1) The challenger  $\mathcal{C}$  chooses a security parameter  $\lambda$  and executes  $\mathcal{P} \leftarrow TRS.Setup(1^\lambda)$  and  $(sk_i, pk_i) \leftarrow TRS.KeyGen(\mathcal{P})$  for  $1 \leq i \leq N$ . It gives all  $pk_i$ 's to the forger  $\mathcal{F}$  and keeps the corresponding secret keys to itself.
- 2) The forger  $\mathcal{F}$  can issue the following queries:
  - a) a signing query for some message  $m$ ; the challenger  $\mathcal{C}$  executes  $\sigma \leftarrow TRS.Sign(\mathcal{P}, \{pk_1, \dots, pk_N\}, \{sk_{i_1}, \dots, sk_{i_t}\}, m)$  and hands  $\sigma$  to  $\mathcal{F}$ ;
  - b) a corrupt query for some  $pk_i \in \{pk_1, \dots, pk_N\}$ :  $\mathcal{C}$  gives  $\mathcal{F}$  the corresponding secret key  $sk_i$ .
- 3)  $\mathcal{F}$  outputs a  $(t, N)$ -threshold ring signature  $\tilde{\sigma}^*$  for a new message  $m^*$ .

The adversary  $\mathcal{F}$  succeeds if  $TRS.Verify(\mathcal{P}, t, \{pk_1, \dots, pk_N\}, (m^*, \tilde{\sigma}^*)) = 1$ ,  $m^*$  has not been asked by  $\mathcal{F}$  in a signing query in step 1 of the game and the number of corrupt queries is strictly

less than  $t$ . An attacker  $\mathcal{F}$  is said to  $(\tau, q_s, q_c, \varepsilon)$ -break the unforgeability of the TRS scheme if he succeeds in the game within running time  $\tau$  and with probability  $\varepsilon$  after having made  $q_s$  signing queries and  $q_c$  corrupt queries.

2) *Anonymity of signers*: The essential notion of security for ring signatures is an anonymity property, called *source hiding*. Roughly speaking, a  $(t, N)$ -threshold signature scheme is *source hiding* (or has perfect anonymity) if a signature on a message  $m$  produced by a set of signers  $S_0$  of a given ring  $R$  looks exactly the same as a signature on the message  $m$  produced by another set  $S_1$  of signers of the ring  $R$ . More formally, this notion is extended to the threshold setting in the following definition.

**Definition 4 (Source hiding)** *Let  $t$  and  $N$  be two integers. A  $(t, N)$ -threshold ring signature scheme TRS is said to be unconditionally source hiding if there exists a probabilistic polynomial time algorithm Fake taking as inputs some public parameters, a set  $\{pk_1, \dots, pk_N\}$  of public keys, a set of  $t$  secret keys  $\{sk_{i_1}, \dots, sk_{i_t}\}$  and a message  $m$ , which outputs a bit string such that*

$$\begin{aligned} & \text{TRS.SignKey}(\mathcal{P}, \{pk_1, \dots, pk_N\}, \{sk_{i_1}, \dots, sk_{i_t}\}, m) = \\ & \text{Fake}(\mathcal{P}, \{pk_1, \dots, pk_N\}, \{sk_{j_1}, \dots, sk_{j_t}\}, m) \\ & \text{with } \#\{sk_{i_1}, \dots, sk_{i_t}\} \cap \{sk_{j_1}, \dots, sk_{j_t}\} < t, \text{ for all} \\ & m \in \{0, 1\}^*, \text{ for all } \mathcal{P} \leftarrow \text{TRS.Setup}(1^\lambda) \text{ and } (sk_i, pk_i) \leftarrow \\ & \text{TRS.KeyGen}(\mathcal{P}) \quad \forall 1 \leq i \leq N. \end{aligned}$$

### C. Fiat-Shamir Heuristic

Fiat and Shamir proposed in [18] a general paradigm for designing a secure signature scheme from a secure identification scheme. The idea is to start from a secure 3-round public coin identification scheme (with a commitment  $\alpha$  from the prover, a random challenge  $\beta$  from the verifier and the response  $\gamma$  from the prover), and then to turn into a digital signature scheme with the help of a random oracle  $\mathcal{H}$ . Indeed, to sign a message  $m$ , the signer (who knows the secret) produces a valid transcript  $(\alpha, \beta, \gamma)$  of the interactive identification protocol where  $\beta = \mathcal{H}(\alpha, m)$ . Its efficiency and ease of design make the Fiat-Shamir protocol very popular. As indicated by Pointcheval and Stern in [31], an honest-verifier zero-knowledge protocol leads to a secure signature scheme in the random oracle model. This framework will be used to obtain our ring signature scheme from our generalized Stern's identification protocol.

## III. NOTATIONS AND BACKGROUND ON CODING THEORY AND STERN'S IDENTIFICATION PROTOCOL

### A. Permutation notation

We first introduce two notions of *block permutation* that we will use in our protocol. Consider  $n$  and  $N$  two integers.

**Definition 5** *A constant  $n$ -block permutation  $\Sigma$  on  $N$  blocks is a permutation by block which permutes together  $N$  blocks of length  $n$  block by block. Each block is treated as a unique position as for usual permutations.*

A more general type of permutation is the  $n$ -block permutation  $\Sigma$  on  $N$  blocks

**Definition 6** *A  $n$ -block permutation  $\Sigma$  on  $N$  blocks is a permutation which satisfies that the permutation of a block of length  $n$  among  $N$  blocks is exactly included in a block of length  $n$ .*

A constant  $n$ -block permutation is a particular  $n$ -block permutation in which the blocks are permuted as such. For instance the permutation  $(6, 5, 4, 3, 2, 1)$  is a 2-block permutation on 3 blocks and the permutation  $(3, 4, 5, 6, 1, 2)$  is a constant 2-block permutation on 3 blocks since the order on each block  $((1, 2), (3, 4)$  and  $(5, 6))$  is preserved in the block permutation.

The notion of product permutation is then straightforward. Let us define  $\sigma$ , a family of  $N$  permutations  $(\sigma_1, \dots, \sigma_N)$  of  $\{1, \dots, n\}$  on  $n$  positions and  $\Sigma$  a constant  $n$ -block permutation on  $N$  blocks defined on  $\{1, \dots, N\}$ . We consider a vector  $v$  of size  $nN$  of the form :

$$v = (v_1, v_2, \dots, v_n, v_{n+1}, \dots, v_{n+n}, v_{2n+1}, \dots, v_{nN}),$$

we denote  $V_1$  the first  $n$  coordinates of  $v$  and  $V_2$  the  $n$  following coordinates and so on, to obtain:  $v = (V_1, V_2, \dots, V_N)$ . We can then define a  $n$ -block permutation on  $N$  blocks,  $\Pi = \Sigma \circ \sigma$  as

$$\Pi(v) = \Sigma \circ \sigma(v) =$$

$$(\sigma_1(V_{\Sigma(1)}), \dots, \sigma_N(V_{\Sigma(N)})) = \Sigma(\sigma_1(V_1), \dots, \sigma_N(V_N)).$$

### B. Difficult problems in coding theory

Let us recall that a linear binary code  $C$  of length  $n$  and dimension  $k$ , is a vector subspace of dimension  $k$  of  $\mathbb{F}_2^n$ . The *weight* of an element  $x$  of  $\mathbb{F}_2^n$  is the number of non zero coordinates of  $x$ . The minimum distance of a linear code is the minimum weight of any non-zero vector of the code. One define the scalar product between  $x$  and  $y$  from  $\mathbb{F}_2^n$  as  $x \cdot y = \sum_{i=1}^n x_i y_i$ . A generator matrix  $G$  of a code is a generator basis of a code, the dual of a code  $C$  is defined by  $C^\perp = \{y \in \mathbb{F}_2^n \mid x \cdot y = 0, \forall x \in C\}$ . Usually a generator matrix of the dual of a code  $C$  is denoted by  $H$ . Remark that  $x \in C \iff Hx^t = 0$ . For  $x \in \mathbb{F}_2^n$ , the value  $Hx^t$  is called the syndrome of  $x$  for  $H$ .

The usual hard problem considered in coding theory is the following *syndrome decoding (SD) problem*, proven to be NP-complete in [5] in 1978.

**Problem: (SD)** Syndrome decoding of a random code

**Instance:** A  $(n - k) \times n$  random matrix  $H$  over  $\mathbb{F}_2$ , a non null target vector  $y \in \mathbb{F}_2^{(n-k)}$  and an integer  $\omega > 0$ .

**Question:** Is there  $x \in \mathbb{F}_2^n$  of weight  $\leq \omega$ , such that  $Hx^t = y^t$  ?

This problem was used by Stern to design his identification protocol [36], but in fact a few years later a variation on this problem called the *minimum distance (MD) problem* was also proven to be NP-complete in [39]:

**Problem: (MD)** Minimum Distance

**Instance:** A binary  $(n-k) \times n$  matrix  $H$  and an integer  $\omega > 0$ .

**Question:** Is there a non zero  $x \in \mathbb{F}_2^n$  of weight  $\leq \omega$ , such that  $Hx^t = 0$  ?

It was remarked in [20] that this problem could also be used with Stern's scheme, the proof works exactly the same. Notice that the practical difficulty of both SD and MD problems are the same: the difficulty of finding a word of small weight in a random code. The associated intractable assumptions associated to these problems are denoted by **SD assumption** and **MD assumption**, see [37] for a precise formal definition of the SD assumption related to the SD problem.

### C. Stern's Identification Protocol

This scheme was developed in 1993 (see [36]). It provides a zero-knowledge identification protocol, not based on number theory problems. Let  $h$  be a hash function. Given a public random matrix  $H$  of size  $(n-k) \times n$  over  $\mathbb{F}_2$ . Each user  $L$  receives a secret key  $s_L$  of  $n$  bits and of weight  $\omega$ . A user's public identifier is the secret key's syndrome  $i_L = Hs_L^t$ . It is calculated once in the lifetime of  $H$ . It can thus be used by several future identifications. Let us suppose that  $L$  wants to prove to  $V$  that he is indeed the person corresponding to the public identifier  $i_L$ .  $L$  has his own private key  $s_L$  such that the public identifier satisfies  $i_L = Hs_L^t$ . The two protagonists run the protocol depicted in Fig. 1.

- 1) **Commitment Step:**  $L$  randomly chooses  $y \in \mathbb{F}_2^n$  and a permutation  $\sigma$  of  $\{1, 2, \dots, n\}$ . Then  $L$  sends to  $V$  the commitments  $c_1, c_2$  and  $c_3$  such that :
 
$$c_1 = h(\sigma | Hy^t); \quad c_2 = h(\sigma(y)); \quad c_3 = h(\sigma(y \oplus s))$$
 where  $h(a|b)$  denotes a hash value of the concatenation of the sequences  $a$  and  $b$ .
- 2) **Challenge Step:**  $V$  sends  $b \in \{0, 1, 2\}$  to  $L$ .
- 3) **Answer Step:**
  - if  $b = 0$  :  $L$  reveals  $y$  and  $\sigma$ .
  - if  $b = 1$  :  $L$  reveals  $(y \oplus s)$  and  $\sigma$ .
  - if  $b = 2$  :  $L$  reveals  $\sigma(y)$  and  $\sigma(s)$ .
- 4) **Verification Step:**
  - if  $b = 0$  :  $V$  verifies that  $c_1, c_2$  have been honestly calculated.
  - if  $b = 1$  :  $V$  verifies that  $c_1, c_3$  have been honestly calculated.
  - if  $b = 2$  :  $V$  verifies that  $c_2, c_3$  have been honestly calculated, and that the weight of  $\sigma(s)$  is  $\omega$ .
- 5) Iterate the steps 1,2,3,4 until the expected security level is reached.

Fig. 1. Stern's protocol

*Remark:* During the fourth step, when  $b$  equals 1, it can be noticed that  $Hy_L^t$  derives directly from  $H(y \oplus s_L)^t$  since

we have:

$$Hy^t = H(y \oplus s_L)^t \oplus i_L = H(y \oplus s_L)^t \oplus Hs_L^t .$$

■

It is proven in [36] that this scheme is a zero-knowledge Fiat-Shamir like scheme with a probability of cheating in  $2/3$  (rather than in  $1/2$  for Fiat-Shamir).

*Remark:* In [20] the authors propose a variation on the scheme by taking the secret key to be a small word of the code associated to  $H$ . This results is exactly the same protocol except that, as the secret key is a codeword, the public key (*i.e.* the secret key's syndrome) is not the matrix  $H$  together with the syndrome but only the matrix  $H$ . The protocol remains zero-knowledge with the same feature. The problem of finding a small weight codeword in a code has the same type of complexity that the syndrome decoding problem (and is also NP-complete). The only drawback of this point of view is that it relates the secret key with the matrix  $H$  but in our case we will be able to take advantage of that. ■

## IV. OUR THRESHOLD RING SIGNATURE SCHEME

In this section, we describe a new efficient threshold ring identification scheme based on coding theory. This scheme is a *generalization* of Stern's scheme. Furthermore, by applying the Fiat-Shamir heuristic [18] to our threshold ring identification scheme, we immediately get a  $t$ -out-of- $N$  threshold ring signature scheme with signature's size in  $\mathcal{O}(N)$ .

### A. A Code-Based Construction of Threshold Ring Signature

Consider a ring of  $N$  members  $(P_1, \dots, P_N)$  and among them  $t$  users who want to prove that they have been cooperating to produce a ring signature. Each user  $P_i$  computes a public matrix  $H_i$  of  $(n-k) \times n$  bits. A user's public key consists of the public matrix  $H_i$  and an integer  $w$  (common to all public keys). The associated secret key is  $s_i$  a word of weight  $w$  of the code  $C_i$  associated to the dual of  $H_i$ .

The general idea of our protocol is that each of the  $t$  signers performs by himself an instance of Stern's scheme using matrix  $H_i$  and a null syndrome as parameters (as in the scheme's variation proposed in [20]). The results are collected by a leader  $L$  among the signers in order to form, with the addition of the simulation of the  $N-t$  non-signers, a new interactive protocol with the verifier  $V$ . The master public matrix  $H$  is created as the direct sum of the ring members' public matrices. Eventually, the prover  $P$ , formed by the set of  $t$  signers among  $N$  (see Fig 2), proves (by a slightly modified Stern's scheme - one adds a condition on the form of the permutation) to the verifier  $V$  that he knows a codeword  $s$  of weight  $t\omega$  with a particular structure:  $s$  has a null syndrome for  $H$  and a special form on its  $N$  blocks of length  $n$ : each block of length  $n$  has weight 0 or  $\omega$ . In fact this particular type of word can only

be obtained by a cooperation process between  $t$  members of the ring. Eventually the complexity is hence the cost of  $N$  times the cost of a Stern identification for a single prover (the multiplication factor obtained on the length of the matrix  $H$  used in the protocol) and this for *any value of  $t$* .

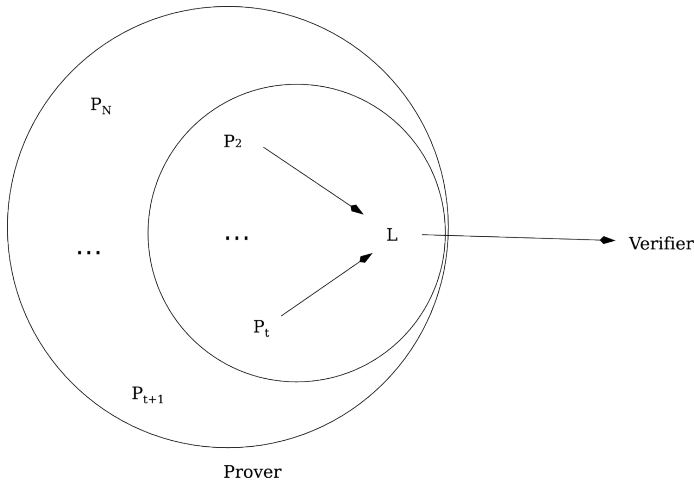


Fig. 2. Threshold ring signature scheme in the case where the  $t$  signers are  $P_1, \dots, P_t$  and the leader  $L = P_1$ , for a group of  $N$  members.

Besides the combination of two Stern protocols (one done individually by each signer  $P_i$  with the leader, and one slightly modified done by the leader with the verifier), our scheme relies on the three following main ideas:

- 1) The master public key  $H$  is obtained as the direct sum of all the public matrices  $H_i$  of each of the  $N$  users.
- 2) Indistinguishability among the members of the ring is obtained first, by taking a common syndrome value for all the members of the ring: the null syndrome, and second, by taking secret keys  $s_i$  with the same weight  $\omega$  (public value) associated to public matrices  $H_i$ .
- 3) Permutation constraint: a constraint is added in Stern's scheme on the type of permutation used: instead of using a permutation of size  $Nn$  we use a  $n$ -block permutation on  $N$  blocks, which guarantees that the prover knows a word with a special structure, which can only be obtained by the interaction of  $t$  signers.

The overall scheme is described by the following algorithms.

1) *TRS.Setup*: Given a security parameter  $\lambda$ , *TRS.Setup* outputs a length  $n$ , a dimension  $k$ , an integer (the weight)  $\omega$  and the threshold value  $t$ .

2) *TRS.KeyGen*: Given the public parameters  $\{\lambda, n, k, \omega, t\}$ , *TRS.KeyGen* outputs a pair of keys where the public key consists of a  $(n - k) \times n$  parity check matrix  $H$  and the secret key of a single codeword of weight  $\omega$  from the code  $C$  with parity check matrix  $H$ .

3) *TRS.Sign*: The signing algorithm will be composed of the following sub-procedures

- *Lead*: this phase consists in agreeing on a leader.
- *Make-RPK*: a group public key is defined as the direct sum of the  $N$  public keys  $pk_i = H_i$ , for  $1 \leq i \leq N$ . The matrix  $H$  is then a  $N(n - k) \times Nn$  matrix such that  $H = \bigoplus_{i=1}^N H_i$ .
- *NIZKPK*: this phase consists in the combination of  $t$  zero-knowledge proofs of the knowledge of the secret keys. The paradigm of Fiat-Shamir is applied to this global proof to obtain a  $(t, N)$ -threshold ring signature  $\sigma$  on  $m$ .

4) *TRS.Verify*: Given the public parameters, the threshold value,  $N$  public keys  $\{pk_i\}_{1 \leq i \leq N}$  and a putative pair message/signature  $(m, \sigma)$ , this phase consists in recovering the group public-key and checking the validity of the Fiat-Shamir signature on  $m$ .

## B. TRS.Setup

With  $1^\lambda$  as input, where  $\lambda$  is the security parameter, the *Setup* algorithm is run to obtain the values of the parameters  $n, k, t, w$ . The integers  $n$  and  $n - k$  are the matrix parameters,  $\omega$  is the weight of the secret key  $s_i$  and  $t$  is the number of signers (the threshold). This algorithm also creates a public database  $pk_1, \dots, pk_N$ , (which are indeed matrices  $H_i$ ). Note that the parameters  $n, k$  and  $\omega$  are set once for all, and that any new user knowing these public parameters can join the ring. The parameter  $t$  has to be defined at the beginning of the protocol.

The matrices  $H_i$  are constructed in the following way: choose  $s_i$  a random vector of weight  $\omega$ , generate  $k - 1$  random vectors and consider the code  $C_i$  obtained by these  $k$  words (the operation can be reiterated until the dimension is exactly  $k$ ). The matrix  $H_i$  is then a  $(n - k) \times n$  generator matrix of the dual code of  $C_i$ . Remark that this construction leads to a rather large public matrix  $H_i$ , we will consider in Section VI, an interesting variation of the construction.

## C. Make-RPK

Each user owns a  $(n - k) \times n$ -matrix  $H_i$  (public) and a  $n$ -vector  $s_i$  (secret) of small weight  $\omega$  (public) such that  $H_i s_i^t = 0$ . The problem of finding a codeword  $s$  of weight  $\omega$  is a MD problem as defined earlier. The  $t$  signers choose a leader  $L$  among them which sends a set of public matrices  $H_1, \dots, H_N$ .

*Remark:* In order to simplify the description of the protocol (and to avoid double indexes), we consider in the following that the  $t$  signers correspond to the first  $t$  matrices  $H_i$  ( $1 \leq i \leq t$ ) (although more generally their order can be considered random in  $\{1, \dots, N\}$  since the order depends of the order of the  $N$  matrices sent by the leader). ■

The RPK (Ring Public Key) is then constructed as follows:

$$H = \begin{pmatrix} H_1 & 0 & 0 & \cdots & 0 \\ 0 & H_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & H_N \end{pmatrix}.$$

#### D. TRS.Sign and TRS.Verify

We now describe the core of our identification protocol in Fig. 3. The TRS.Sign and TRS.Verify are obtained by applying the Fiat-Shamir paradigm on this protocol.

The leader  $L$  collects the commitments given from the  $t-1$  other signers ( $L$  is also a signer), simulates the  $N-t$  non-signers and chooses a random constant  $n$ -block permutation  $\Sigma$  on  $N$  blocks. From all these commitments  $L$  creates the master commitments  $C_1, C_2$  and  $C_3$  which are sent to the verifier  $V$ , who answers by giving a challenge  $b$  in  $\{0, 1, 2\}$ . Then  $L$  sends the challenge to each of the other  $t-1$  signers and collects their answers to create a global answer for  $V$ . Upon reception of the global answer,  $V$  verifies that it is correct by checking the commitments as in the regular Stern's scheme.

Recall that in the description of the protocol, in order to avoid disturbing double indexes, we consider that the  $t$  signers correspond to the first  $t$  matrices  $H_i$ .

In the figure 3,  $h(a_1 | \cdots | a_j)$  denotes the hash of the concatenation of the sequence formed by  $a_1, \dots, a_j$ .

### V. SECURITY

#### A. Security of Our Scheme

We first prove that our scheme is HVZK with a probability of cheating of  $2/3$ . We begin by a simple lemma.

**Lemma 1** *Finding a vector  $v$  of length  $nN$  such that the global weight of  $v$  is  $tw$ , the weight of  $v$  for each of the  $N$  blocks of length  $n$  is 0 or  $\omega$  and such that  $v$  has a null syndrome for  $H$ , is hard under the MD assumption.*

*Proof:* The particular structure of  $H$  (direct sum of the  $H_i$  of same length  $n$ ) implies that finding such a  $n$ -block vector of length  $nN$  is exactly equivalent to finding a solution for the local hard problem of finding  $s_i$  of weight  $\omega$  such that  $H_i s_i^t = 0$ , which is not possible under our assumption.  $\square$

**Theorem 2** *Our scheme is an honest verifier proof of knowledge, with a probability of cheating  $2/3$ , that the group of signers  $P$  knows a vector  $v$  of length  $nN$  such that the global weight of  $v$  is  $tw$ , the weight of  $v$  for each of the  $N$  blocks of length  $n$  is 0 or  $\omega$  and such that  $v$  has a null syndrome for  $H$ . The scheme is secure under the MD assumption in the random oracle model.*

*Proof:* We need to prove the usual three properties of completeness, soundness and zero-knowledge. The property of completeness is straightforward since for

#### 1) Commitment Step:

- Each of the signers chooses  $y_i \in \mathbb{F}_2^n$  randomly and a random permutation  $\sigma_i$  of  $\{1, 2, \dots, n\}$  and sends to  $L$  the commitments  $c_{1,i}, c_{2,i}$  and  $c_{3,i}$  such that :

$$c_{1,i} = h(\sigma_i | H_i y_i^t); \quad c_{2,i} = h(\sigma_i(y_i)); \\ c_{3,i} = h(\sigma_i(y_i \oplus s_i))$$

- $L$  sets the secret  $s_i$  of the  $N-t$  missing users at 0 and computes the  $N-t$  corresponding commitments by choosing random  $y_i$  and  $\sigma_i$  ( $t+1 \leq i \leq N$ ).
- $L$  chooses a random constant  $n$ -block permutation  $\Sigma$  on  $N$  blocks  $\{1, \dots, N\}$  in order to obtain the *master commitments*:

$$C_1 = h(\Sigma | c_{1,1} | \dots | c_{1,N}), \quad C_2 = h(\Sigma(c_{2,1}, \dots, c_{2,N})), \\ C_3 = h(\Sigma(c_{3,1}, \dots, c_{3,N})).$$

- $L$  sends  $C_1, C_2$  and  $C_3$  to  $V$ .
- #### 2) Challenge Step:
- $V$  sends a challenge  $b \in \{0, 1, 2\}$  to  $L$  which sends  $b$  to the  $t$  signers.
- #### 3) Answer Step:
- Let  $P_i$  be one of the  $t$  signers. The first part of the step is between each signer and  $L$ .
- Three possibilities :
    - if  $b = 0$  :  $P_i$  reveals  $y_i$  and  $\sigma_i$ .
    - if  $b = 1$  :  $P_i$  reveals  $(y_i \oplus s_i)$  (denoted by  $(y \oplus s)_i$ ) and  $\sigma_i$ .
    - if  $b = 2$  :  $P_i$  reveals  $\sigma_i(y_i)$  (denoted by  $(\sigma(y))_i$ ) and  $\sigma_i(s_i)$  (denoted by  $(\sigma(s))_i$ ).
  - $L$  simulates the  $N-t$  others Stern's protocol with  $s_i = 0$  and  $t+1 \leq i \leq N$  and sets  $s = (s_1, \dots, s_N)$ .
  - $L$  computes the answer for  $V$  (and sends it) :
    - if  $b = 0$  :  $L$  constructs  $y = (y_1, \dots, y_N)$  and  $\Pi = \Sigma \circ \sigma$  (for  $\sigma = (\sigma_1, \dots, \sigma_N)$ ) and reveals  $y$  and  $\Pi$ .
    - if  $b = 1$  :  $L$  constructs  $y \oplus s = ((y \oplus s)_1, \dots, (y \oplus s)_N)$  and reveals  $y \oplus s$  and  $\Pi = \Sigma \circ \sigma$ .
    - if  $b = 2$  :  $L$  constructs and reveals  $\Pi(y)$  and  $\Pi(s)$ .
- #### 4) Verification Step:
- if  $b = 0$  :  $V$  verifies that  $\Pi(s)$  is a  $n$ -block permutation and that  $C_1, C_2$  have been honestly calculated.
  - if  $b = 1$  :  $V$  verifies that  $\Pi(s)$  is a  $n$ -block permutation and that  $C_1, C_3$  have been honestly calculated.
  - if  $b = 2$  :  $V$  verifies that  $C_2, C_3$  have been honestly calculated, and that the weight of  $\Pi(s)$  is  $tw$  and that  $\Pi(s)$  is formed of  $N$  blocks of length  $n$  and of weight  $\omega$  or 0.
- #### 5) Iterate the steps 1,2,3,4 until the expected security level is reached.

Fig. 3. Generalized Stern's protocol



instance for  $b = 0$ , the knowledge of  $y$  and  $\Pi$  permits to recover  $\Sigma$ ,  $\sigma_i$  and the  $y_i$  so that it is possible for the verifier to recover all the  $c_i$  and hence the master commitment  $C_1$ , the same for  $C_2$ . The cases  $b = 1$  and  $b = 2$  works the same. The proof for the soundness and zero-knowledge follow the original proof of Stern in [37] for the problem defined in the previous lemma, by remarking that the structure of our generalized protocol is copied on the original structure of the protocol with  $\Sigma$  in Fig.3 as  $\sigma$  in Fig.1, and with the fact that one checks in the answers  $b = 0$  and  $b = 1$  in the protocol that the permutation  $\Pi$  is an  $n$ -block permutation on  $N$  blocks.  $\square$

This result naturally leads to the following theorem:

**Corollary 3** *The resulting threshold ring signature scheme obtained from the application of the Fiat-Shamir heuristic on our generalized Stern's protocol is existentially unforgeable under a chosen message attack in the random oracle model assuming the hardness of the MD problem.*

*Remark:* It is also not possible to have information leaked between signers during the protocol since each signer only gives information to  $L$  (for instance) as in a regular Stern's scheme which is zero-knowledge. ■

Now we consider the anonymity provided to the signers by our protocol. Formally we obtain:

**Theorem 4** *Our threshold ring signature scheme is unconditionally source hiding.*

Our protocol generalizes Gaborit and Girault's flavour of Stern's protocol [20] in the sense that the small weight secret codeword in their protocol is "expanded" into a vector where blocks of secret non-zero vectors (the secret key of user  $i$ ) correspond to 1 in the small secret (at the  $i$ th position), whereas the blocks of zeros correspond to 0 in the small secret. The source hiding essentially comes from the fact that this Gaborit and Girault's variant of Stern's original protocol perfectly hides the position of 1s and 0s in the secret. Then, any subset of  $t$  users can produce a given ring signature with equal probability.

*Proof:*

The distributions of the signatures produced by any subset of  $t$  users are actually the same. The Fake algorithm to exhibit is just the Sign algorithm used with any set of  $t$  secret keys. Using adequate random coins, a given signature can be produced by any set of  $t$  users. Indeed, each commitment produced by a signer involving its secret corresponds to a one-time pad of the secret, which means that the distribution of this commitment is perfectly indistinguishable from a random one, as well as a distribution coming from any other secret. Therefore, the whole protocol perfectly hides the signers. The probability for an attacker to guess one of the original signers is no more than  $t/n$ , a random guess (and the probability that the attacker recover the whole group is no more

than  $1/\binom{n}{t}$ ). Finally this discussion does not rely on any computational assumption.  $\square$

### B. Practical Security of Stern's Scheme from [36]

The security of Stern's Scheme relies on three properties of random linear codes:

- 1) Random linear codes satisfy a Gilbert-Varshamov type lower bound [27],
- 2) For large  $n$  almost all linear codes lie over the Gilbert-Varshamov bound [30],
- 3) Solving the syndrome decoding problem for random codes is NP-complete [5].

In practice Stern proposed in [36] to use rate  $1/2$  codes and  $\omega$  just below the Gilbert-Varshamov bound associated to the code. For such code the exponential cost of the best known attack [10] (or the more recent [6]) can be lower bounded by an approximation in  $O(n) \frac{\binom{n}{\omega}}{\binom{n-k}{\omega}}$ , which gives a code with today security ( $2^{80}$ ) of  $n = 634$  and rate  $1/2$  and  $\omega = 69$ .

## VI. AN INTERESTING VARIATION OF THE SCHEME BASED ON DOUBLE-CIRCULANT MATRICES

In Section IV we described a way to create the public matrices  $H_i$ , this method as in the original Stern's paper, leads to a large size of the public keys  $H_i$  in  $n^2/2$  bits. It was recently proposed in [20], to use double-circulant random matrices rather than pure random matrix for such matrices. A double circulant matrix is a matrix of the form  $H_i = (I|C)$  for  $C$  a random  $n/2 \times n/2$  cyclic matrix and  $I$  the identity matrix. Following this idea one can construct the matrices  $H_i$  as follows: consider  $s_i = (a|b)$  where  $a$  and  $b$  are random vectors of length  $n/2$  and weight  $\approx \omega/2$ , then consider the matrix  $(A|B)$  obtained for  $A$  and  $B$  square  $(n/2 \times n/2)$  matrices obtained by the  $n/2$  cyclic shifts of  $a$  and  $b$  (each row of  $A$  is a shift of the previous row, beginning with first row  $a$  or  $b$ ).

Now consider the code  $G_i$  generated by the matrix  $(A|B)$ , the matrix  $H_i$  can then be taken as  $H_i = (I|C)$  such that  $H_i$  is a dual matrix of  $G_i$  and  $C$  is cyclic since  $A$  and  $B$  are cyclic, and hence can be described with only its first row. It is explained in [20] that this construction does not decrease the difficulty of the decoding but clearly decrease dramatically the size of the description of  $H_i$ :  $n/2$  bits against  $n^2/2$ .

It is then possible to define a new problem:

**Problem:** (MD-DC) Minimum Distance of Double circulant Codes:

**Instance:** A binary  $n/2 \times n$  double circulant matrix  $H$  and an integer  $\omega > 0$ .

**Question:** Is there a non zero  $x \in \mathbb{F}_2^n$  of weight  $\leq \omega$ , such that  $Hx^t = 0$  ?

It is not known whether this problem is NP-complete or not (although the problem of decoding quasi-cyclic code

in general, has been proven NP-complete in [4]), but the problem is probably as hard as the MD problem, and on practical point of view (see [20] for details) the practical security is almost the same for best known attack that the MD problem. Practically the author of [20] propose  $n = 347$ .

Now all the proof of security we considered in this paper can also be adapted to the MD-DC problem, since for the generalized Stern protocol we introduced we can take any kind of  $H_i$  with the same type of problem: knowing a small weight vector associated to  $H_i$  (in fact only the problem assumption changes).

## VII. LENGTH AND COMPLEXITY

In this section we examine the complexity of our protocol and compare it to other protocols.

### A. The case $t = 1$

This case corresponds to the case of classical ring signature schemes. Our proposal is then not so attractive in term of signature length since we are in  $\mathcal{O}(N)$ , or more precisely 20 kiloBytes  $\times N$  (where 20 kiloBytes is the cost of one Stern signature). On the other hand, since Stern's protocol is fast in terms of speed, our protocol is faster than all others protocols for small values of  $N$  ( $N = 2$  or  $3$ ) which may have some applications. In particular, the case  $N = 2$  corresponds to a designated verifier signature scheme [24].

### B. The general case

#### Signature length.

It is straightforward to see that the signature length of our protocol is in  $\mathcal{O}(N)$ , more precisely around 20 kiloBytes  $\times N$ , for 20 kiloBytes the length of one signature by the Fiat-Shamir paradigm applied to the Stern scheme (a security of  $2^{-80}$  is obtained by 140 repetitions of the protocol). For instance consider a particular example with  $N = 100$  and  $t = 50$ , we obtain a 2 MegaBytes signature length, which is quite large, but still tractable. Of course other number theory based protocols like [8] or [26] have shorter signature lengths (in 8 kiloBytes or 25 kiloBytes) but are slower.

#### Public key size.

If we use the double-circulant construction described in Section VI, we obtain, a public key size in  $347N$  which has a factor 2 or 3 better than [26] and of same order than [8].

#### Complexity of the protocol.

The cost of the protocol is  $N$  times the cost of one Stern signature protocol hence in  $\mathcal{O}(N)$ , (more precisely in  $140n^2N$  operations) and this for any  $t$ . When all other fully anonymous threshold ring signature protocol have a complexity in  $\mathcal{O}(tN)$  operations (multiplications or modular exponentiations in large integer rings, or pairings). Hence on that particular point our algorithm is faster than other protocols.

## VIII. CONCLUSION

In this paper we presented a new (fully anonymous)  $t$ -out-of- $N$  threshold ring signature scheme based on coding theory. Our protocol is a very natural generalization of the Stern identification scheme and our proof is based on the original proof of Stern. We showed that the notion of weight of vector particularly went well in the context of ring signature since the notion of ad hoc group corresponds well to the notion of direct sum of generator matrices and is compatible with the notion of sum of vectors of small weight. Eventually we obtain a unconditionally source hiding protocol. Our protocol is the first non-generic protocol based on coding theory and (as usual for code based protocol) is very fast compared to other number theory based protocols

Moreover the protocol we described can also be easily generalized to the case of general access scenario. Eventually the fact that our construction is not based on number theory but on coding theory may represent an interesting alternative. We hope this work will enhance the potential of coding theory in public key cryptography.

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