

# Generalisation of Kipnis and Shamir Cryptanalysis of the HFE public key cryptosystem

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**Abstract** — In [4], Kipnis and Shamir have cryptanalised a version of HFE of degree 2. In this paper, we describe the generalization of this attack of HFE of degree more than 2. We are based on Fourier Transformation to achieve partially this attack.

**Keywords** — Public, cryptosystem, cryptanalysis, HFE.

## I. INTRODUCTION

PUBLIC key cryptography depends on a handful of algebraic problems which try to achieve security. The original RSA problem requires large blocs sizes. Other alternatives with small size have been proposed: Elliptic curves and recently the family of quadratic multivariate schemes such as HFE (Hidden Field Equations)[3][1].

The security of this system is based on the difficulty of solving large systems of quadratic multivariate polynomial equations[2]. This problem is NP-hard over any field. The most efficient attack is the one of Kipnis and Shamir that consist in determining the secret key from the public key.

This attack is based on a non standard representation of the HFE. In this paper, we generalise the idea of Kipnis and Shamir to attack partially the HFE cryptosystem of degree 3.

## II. HFE SCHEME

The encoder takes a finite field  $K = GF(q)$  of a cardinal  $q$  and a characteristic  $p$  ( $q = p^m$ ),  $L_n$  is an extension field of degree  $n$ .  $L_n$  is also a  $GF(q)$  vector space of dimension  $n$  over  $K$  or  $nm$  over  $GF(p)$ . Next, he choose a generic polynomial of degree  $d$ .

$$p : F_q^n \longrightarrow F_q^n$$

$$x \mapsto \sum_{i,j=0}^{n-1} a_{ij}x^{q^i+q^j} + \sum_{i=0}^{n-1} b_i x^{q^i} + \gamma_0 \quad a_{ij}, b_i \text{ and } \gamma_0 \in L_n.$$

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In addition, he choose two secret affine transformations; ie; two invertible matrix  $S = \{s_{ij}\}$  and  $t = \{t_{ij}\}$  with entries in  $GF(q)$  and two constant vectors  $s = (s_1, s_2, \dots, s_n)$  and  $t = (t_1, t_2, \dots, t_n)$  and sets

$$t(x) = T.x + t \quad \text{and} \quad s(x) = S.x + s.$$

The attack of Kipnis and Shamir is an attack that consists to guess the secret key from the public key. In this attack, the original HFE scheme is simplified, in particularly, they consider only homogenous polynomial  $p$  and linear mappings  $S$  and  $T$ .

### A. Keys

- Secret items:  $T, p, S$
- Public entities:

$$T(p(S(x))) = (g_1(x_1, \dots, x_n), \dots, g_n(x_1, \dots, x_n)) = g(x).$$

### B. Encryption

Let  $m = (m_1, \dots, m_n)$  be the clear to encode boured by bits of redundancy from a hash function or a linear code.

The ciphering consists to evaluate the message  $m$  by the public equations. We obtain therefore  $(y_1, \dots, y_n)$  with  $y_i = g_i(m_1, \dots, m_n); i = 1, \dots, n$ .

The decrypted message is  $y = (y_1, y_2, \dots, y_n)$ .

### C. Decryption

The decoder receives the encoded message  $y = (y_1, \dots, y_n) = T(f(S(m)))$ . It decrypts:

- 1)  $T^{-1}(y) = f(S(m))$ .
- 2) solves

$$f(z) - a = 0 \tag{1}$$

$$a \in F_{q^n}, a = T^{-1}(y)$$

- 3) Apply  $S^{-1}$  to the gotten solution.

The equation (1) can admit more than one solution. The redundancy permits to determine the good solution.

The attacker who hasn't  $S, T$  and  $p$  can not use ths procedure. Kipnis and Shamir introduce a new technique to decode:

- 1) Transform  $S$  and  $T$  from matrix representations to polynomial representations.
- 2) Convert the  $n$  quadratic polynomials in a matrix representation.
- 3) Solve the fundamental equation.
- 4) Use the condition of the rank of the polynomial  $p$  to determine  $T, p, S$ .

### III. POLYNOMIAL REPRESENTATION OF S AND T

**Lemma 1:** Let  $A : F_q^n \rightarrow F_q^n$   
 $f(x_1, \dots, x_n) \mapsto (y_1, \dots, y_n)$   
 A is a linear application only if  $\exists (a_1, \dots, a_n)$  so that  
 $y = \sum_{i=1}^n a_i x_i^{q^i}$  with  $x = \sum_{i=1}^n x_i w_i$ ,  $y = \sum_{j=1}^n y_j w_j$ ;  
 $(w_1, \dots, w_n)$  is a basis of  $F_q^n$ .

**Proof:**

$x^{q^i}$  is linear over  $F_q$  therefore  $\sum_{i=1}^n a_i x^{q^i}$  is linear  $\forall a_i \in F_q$ .

On the other hand,  $F_q^n$  is an extension field of the field  $F_q$ .

$\exists$  an element  $\beta \in F_q^n$  so that  $(\beta, \beta^q, \dots, \beta^{q^{n-1}})$  is a basis of  $F_q^n$ . So, all elements of  $F_q^n$  can be decomposed in this basis.

Thus,  $x = \sum_{i=1}^n \beta^{q^i} x_i$  and  $y = \sum_{i=1}^n \beta^{q^i} y_i$ ;  $x_i, y_i$  are elements of  $F_q$ . By hypothesis,  $y$  is linear in  $x$ ,

$$y_i = \sum_{j=0}^{n-1} t_{ij} x_j, t_{ij} \in F_q$$

$$y = \sum_{j=0}^{n-1} \left( \sum_{i=0}^{n-1} t_{ij} x_i \right) \beta^{q^j} = \sum_{i=0}^{n-1} x_i \left( \sum_{j=0}^{n-1} t_{ij} \beta^{q^j} \right)$$

$$y = \sum_{i=0}^{n-1} x_i P_i(\beta) \quad (2)$$

In other hand,  $y = \sum_{j=0}^{n-1} a_j x^{q^j} = \sum_{j=0}^{n-1} a_j \left( \sum_{i=0}^{n-1} x_i \beta^{q^i} \right)^{q^j}$

$$= \sum_{i=0}^{n-1} x_i \left( \sum_{j=0}^{n-1} a_j \beta^{q^{i+j}} \right)$$

From (2), it is sufficient to show that  $\forall P_i(\beta); i = 0 \dots n-1, \exists a_j, j = 0 \dots n-1$  so that  $P_i(\beta) = \sum_{j=0}^{n-1} a_j \beta^{q^{i+j}}$ .

The matrix  $M = (m_{ij}), m_{ij} = \text{trace}(\beta^{q^i} \beta^{q^j})$  is regular.  
 $\forall P = (P_0(\beta), \dots, P_{n-1}(\beta)), \exists R = (R_0(\beta), \dots, R_{n-1}(\beta))$  so that

$$RM = P$$

$$RM = \sum_{i=0}^{n-1} (R_i m_{ij}) = \sum_{i=0}^{n-1} R_i \left( \sum_{k=0}^{n-1} \beta^{q^{i+k}} \beta^{q^{j+k}} \right) =$$

$$\sum_{k=1}^n \left( \sum_{i=1}^n R_i \beta^{q^{i+k}} \right) \beta^{q^{j+k}} = P_j(\beta)$$

We choose  $a_k = \sum_{i=0}^{n-1} R_i \beta^{q^{i+k}}$ .

From this lemma, we can represent the two standard applications of the cryptosystem HFE by the polynomial representations.

### IV. UNIVARIATE REPRESENTATION OF A SYSTEM OF MULTIVARIATE EQUATIONS

**Lemma 2:**

let  $(P_0, \dots, P_{n-1})$  a multivariate polynomial system over  $F_q$ .  
 $y_j = P_j(x_0, \dots, x_{n-1}); j = 0 \dots n-1$  only if

$\exists (a_0, a_2, \dots, a_{q^n-1}) \in F_q^n$  so that  $y = \sum_{i=0}^{n-1} a_i x^i$  with

$x = \sum_{i=0}^{n-1} x_i w_i, y = \sum_{i=0}^{n-1} y_i w_i, (w_1, \dots, w_n)$  is  $F_q^n$  basis.

**Proof**

$y_j = P_j(x_0, \dots, x_{n-1}), j = 0 \dots n-1$ .

$P_j(x_0, \dots, x_{n-1}) = t_{j,0} + \sum_{i_0=0}^{n-1} t_{j,i_0} x_{i_0} +$

$\sum_{i_0, i_1=0}^{n-1} t_{j, i_0, i_1} x_{i_0} x_{i_1}$

$+ \dots + \sum_{i_0, i_1, \dots, i_m}^{n-1} t_{j, i_0, \dots, i_m} x_{i_0} x_{i_1} \dots x_{i_m}$

A term of degree m can be written as:

$\sum_{\vec{i}_m = \vec{0}}^{(n-1)_m} t_{j, \vec{i}_m} x_{i_m}^{\vec{i}_m}$  with  $x_{i_m}^{\vec{i}_m} = x_{i_0} \dots x_{i_{m-1}}$

and  $\vec{i}_m = (i_0, \dots, i_{m-1})$

so  $y_j = P_j(x_0, \dots, x_{n-1}) = \sum_m \sum_{\vec{i}_m = \vec{0}}^{(n-1)_m} t_{j, \vec{i}_m} x_{i_m}^{\vec{i}_m}$ .

Or,  $y = \sum_{j=0}^{n-1} y_j \beta^{q^j} = \sum_m \sum_{\vec{i}_m = \vec{0}}^{(n-1)_m} \left( \sum_{j=0}^{n-1} t_{j, \vec{i}_m} \beta^{q^j} \right) x_{i_m}^{\vec{i}_m}$

$= \sum_m \sum_{\vec{i}_m = \vec{0}}^{(n-1)_m} P_{i_m}(\beta) x_{i_m}^{\vec{i}_m}$

Thus, a term of degree m has the following form:

$\sum_{i_0, \dots, i_m} P_{i_0, \dots, i_m}(\beta) x_{i_0} x_{i_1} \dots x_{i_m}$

In other hand,  $y = \sum_{l=0}^{q^n-1} a_l x^l$  with  $x = \sum_{i=0}^{n-1} x_i \beta^{q^i}$ .

$\forall l = 0 \dots q^n - 1$ ; l can be written in one way:  
 $l = \gamma_0 + \gamma_1 q + \dots + \gamma_{n-1} q^{n-1}$  with  $0 \leq \gamma_i < q$

The set of definition of l is  $E = \{0, \dots, q^n - 1\}$ .  
 $\forall l \in E$ , we associate the vector  $\vec{\gamma} = (\gamma_0, \dots, \gamma_{n-1})$ . we divide the whole E equivalence classes:

$l \in E_m$  if  $\gamma_0 + \dots + \gamma_{n-1} = m; 0 \leq m < n(q-1)$ .

So,  $\forall l \in E, l \in E_m; E = E_1 \cup E_2 \cup \dots \cup E_{n(q-1)}$ .

These classes are disconnected since if  $l \in E_i; l \notin E_j$ ,

$\forall l \in E_m; l = \gamma_0 + \gamma_1 q + \dots + \gamma_{n-1} q^{n-1}$  with  $\gamma_0 + \gamma_1 + \dots + \gamma_{n-1} = m$ .

Let's show that there are integers

$j_0, \dots, j_{m-1}; j_k \in \{0, 1, \dots, n-1\}$  so that

$l = q^{j_0} + \dots + q^{j_{m-1}}$ .

Indeed,  $l = \underbrace{q^0 + \dots + q^0}_{\gamma_0} + \underbrace{q^1 + \dots + q^1}_{\gamma_1} + \dots +$

$\underbrace{q^{n-1} + \dots + q^{n-1}}_{\gamma_{n-1}}; \gamma_0 + \dots + \gamma_{n-1} = m;$

$m < n(q-1)$ .

$\forall l \in E_m$ ; we can associate a vector

$\vec{j}_m = (j_0, \dots, j_{m-1})$  so that  $l = q^{j_0} + q^{j_1} + \dots + q^{j_{m-1}};$   
 $j_k \in \{0, \dots, n-1\}$

$$\sum_{l=0}^{q^n-1} a_l x^l = \sum_{l \in E_0} a_l x^l + \sum_{l \in E_1} a_l x^l + \dots + \sum_{l \in E_m} a_l x^l.$$

$$\text{Or, } \sum_{l \in E_m} a_l x^l = \sum_{\vec{j}_m = \vec{0}}^{(n-1)_m} a_{\vec{j}_m} x^{q^{j_0}} \dots x^{q^{j_{m-1}}}.$$

$$x^{q^{j_k}} = \left( \sum_{i=0}^{n-1} x_i \beta^{q^i} \right)^{q^{j_k}} \\ = \sum_{i=0}^{n-1} x_i \beta^{q^{i+j_k}}. \\ \Rightarrow \sum_{l \in E_l} a_l x^l =$$

$$\sum_{\vec{j}_m = \vec{0}}^{(n-1)} a_{\vec{j}_m} \left( \sum_{i_0}^{n-1} x_{i_0} \beta^{q^{j_0+i_0}} \right) \dots \left( \sum_{i_{m-1}}^{n-1} x_{i_{m-1}} \beta^{q^{j_{m-1}+i_{m-1}}} \right) \\ = \sum_{\vec{i}_m = \vec{0}}^{(n-1)} \left( \sum_{\vec{j}_m = \vec{0}}^{(n-1)} a_{\vec{j}_m} \beta^{q^{\vec{j}_m + \vec{i}_m}} \right) x_{\vec{i}_m}.$$

It is necessary to show that  $\forall P_{\vec{i}_m}(\beta); \vec{i}_m = (i_0, i_1, \dots, i_{m-1}),$   
 $\exists a_{\vec{j}_m}; \vec{j}_m = (j_0, j_1, \dots, j_{m-1})$  so that

$$\sum_{\vec{j}_m} a_{\vec{j}_m} \beta^{q^{\vec{j}_m + \vec{i}_m}} = P_{\vec{i}_m}$$

Lets the matrix  $M = m_{ij};$   
 $m_{ij} = \text{trace}(\beta^{q^i} \beta^{q^j}) = \sum_{k=0}^{n-1} \beta^{q^{i+k}} \beta^{q^{j+k}}.$

The matrix  $N = M \otimes M \otimes \dots \otimes M$  is regular, so, there is a vector  $R = \{R_{\vec{k}_m}\}$  so that  $R.N = P.$

$$\Rightarrow \sum_{\vec{k}_m} R_{\vec{k}_m} \cdot m_{\vec{k}_m, \vec{j}_m} = P_{\vec{j}_m}$$

$$m_{\vec{k}_m, \vec{j}_m} = \left( \sum_{j_0} \beta^{q^{j_0+k_0}} \cdot \beta^{q^{j_0+j_0}} \right) \dots$$

$$\left( \sum_{j_m} \beta^{q^{j_m+k_m}} \cdot \beta^{q^{j_m+j_m}} \right) = \sum_{\vec{j}_m} \beta^{q^{\vec{j}_m + \vec{k}_m}} \cdot \beta^{q^{\vec{j}_m + \vec{i}_m}}$$

$$\sum_{\vec{k}_m} R_{\vec{k}_m} m_{\vec{k}_m, \vec{j}_m} = \sum_{\vec{k}_m} R_{\vec{k}_m} \sum_{\vec{j}_m} \beta^{q^{\vec{j}_m + \vec{k}_m}} \beta^{q^{\vec{j}_m + \vec{i}_m}}$$

$$\text{we puts } a_{\vec{j}_m} = \sum_{\vec{k}_m} R_{\vec{k}_m} \beta^{q^{\vec{j}_m + \vec{k}_m}}.$$

From this last expression, the transformation is feasible for all degrees of the hidden polynomial  $p$  provided that it is homogeneous.

#### A. Example

We consider the quadratic equation system

$$y_0 = x_1 x_2 + x_0 x_1$$

$$y_1 = x_1 x_2 + x_0 x_2$$

$$y_2 = x_0 x_2$$

$$y = \sum_i y_i \beta^{q^i} = \underbrace{x_0 x_1 \beta^{q^0}}_{p_{10}} + \underbrace{x_1 x_2 (\beta^{q^0} + \beta^{q^1})}_{p_{12}} + \underbrace{x_0 x_2 (\beta^{q^1} + \beta^{q^2})}_{p_{02}}$$

If we choose the normal basis  $(\beta^{q^0}, \beta^{q^1}, \dots, \beta^{q^{n-1}})$  so that:  $\text{trace}(\beta^{q^i} \beta^{q^j}) = \gamma_{ij}$

The matrix  $M$  is  $I_3$  and the matrix  $N$  is  $I_9.$

$$RN = P \Leftrightarrow R = P$$

The transformation in a matrix representation consists in determining the  $a_{ij}; i, j = 0, 1, 2$  which verify:  $a_{ij} = \sum_{k,l} p_{kl} \beta^{q^{i+j+k+l}}$  which represent the coefficients of the matrix.

#### V. SHAMIR AND KIPNIS ATTACK

The principle of the crypting consists in applying the transformation  $g$  to the ciphered

$$g(x) = T(p(S(x))) \quad (3)$$

From [3],

$$p(S(x)) = xWPW^t x^t; W = w_{ij} = s_{j-i}^{q^i}; p = p_{ij} \quad (4)$$

$$T^{-1}(g(x)) = xG'x^t; \quad (5)$$

$$G' = \sum_{k=0}^{n-1} t_k G^{*k}; G^{*k} = (g_{i-k, j-k}^{q^k}) \quad (6)$$

(5) et (6)  $\Rightarrow$

$$G' = WPW^t \quad (7)$$

(7) is the fundamental equation.

The first stage of the attack consists in determining  $T$  by resolving (7), than  $S$  and finally  $p.$  Their hypotheses are:

- $\text{rang}(p) = r \ll n$
- $\text{rang}(W) = n$

#### VI. HFE OF DEGREE 3

We have  $T(f(S(x))) = G(x);$

$T$  is invertible so  $T^{-1}$  exists and it has the same form as  $T.$

$$\Rightarrow T^{-1}(G(x)) = P(S(x)) \quad (8)$$

$$P(x) = \sum_{ijk=0}^{n-1} x^{q^i + q^j + q^k}, S(x) = \sum_k^{n-1} s_k x^{q^k}.$$

$$\Rightarrow P(S(x)) = \sum_{ijk=0}^{n-1} p_{ijk} (S(x))^{q^i + q^j + q^k}$$

$$= \sum_{w,k=0}^{n-1} (xWP_k W^t x^t) s_{w-k}^{q^k} x^{q^w}$$

In other hand,

$$t^{-1}(g(x)) = \sum_k (xG'_k x^t) x^{q^k}$$

with  $G'_k = \sum_{l=0}^{n-1} t_l G_k^{*l}$  and  $G_k^{*l} = g_{i-l, j-l, k-l}^{q^l}$  so (9) becomes

$$\sum_{w,k=0}^{n-1} (xWP_k W^t x^t) s_{w-k}^{q^k} x^{q^w} = \sum_k (xG'_k x^t) x^{q^k} \quad (9)$$

There is no obvious matrix representation ?

### VII. FOURIER TRANSFORMATION

We tried to use fourier transformations to attack HFE of degree 3.

From (8), we have the following equality:

$$\sum_{uvw} \left( \sum_h t_h g_{u-h,v-h,w-h}^{q^h} \right) x^{q^u+q^v+q^w}$$

$$= \sum_{ijk=0}^{n-1} p_{ijk} \left( \sum_{u,v,w} s_{u-i}^{q^i} s_{v-j}^{q^j} s_{w-k}^{q^k} x^{q^u+q^v+q^w} \right)$$

$$\forall x ; \left( \sum_h t_h g_{u-h,v-h,w-h}^{q^h} \right) = \sum_{ijk=0}^{n-1} p_{ijk} (s_{u-i}^{q^i} s_{v-j}^{q^j} s_{w-k}^{q^k})$$

If we permute  $i \rightarrow j \rightarrow k \rightarrow i$   
 and  $u \rightarrow v \rightarrow w \rightarrow u$ :

$$\Rightarrow \left( \sum_h t_h g_{i-h,j-h,k-h}^{q^h} \right) = \sum_{ijk=0}^{n-1} p_{ijk} (s_{u-i}^{q^i} s_{v-j}^{q^j} s_{w-k}^{q^k})$$

$$= \sum_{ijk=0}^{n-1} p_{ijk} (s_{v-j}^{q^j} s_{w-k}^{q^k} s_{u-i}^{q^i}) = \sum_{ijk=0}^{n-1} p_{ijk} (s_{w-k}^{q^k} s_{u-i}^{q^i} s_{v-j}^{q^j})$$

$$= H$$

We are in  $F_{2^n}$  so,  $H + H + H = H$

$$\Rightarrow \sum_{jki=0}^{n-1} (p_{ijk} + p_{jki} + p_{kij}) \left( \sum_{v,w,u} s_{v-j}^{q^j} s_{w-k}^{q^k} s_{u-i}^{q^i} \right) =$$

$$\sum_{ijk} \sum_h t_h g_{i-h,j-h,k-h}^{q^h}$$

If we apply fourier transformation :

$$\sum_{ijk=0}^{n-1} \beta_{ijk} \left( \sum_{v,w,u} s_{v-j}^{q^j} s_{w-k}^{q^k} s_{u-i}^{q^i} X^u Y^v Z^w \right)$$

$$= \sum_h t_h \left( \sum_{ijk} g_{i-h,j-h,k-h}^{q^h} X^i Y^j Z^k \right)$$

$$\Rightarrow \sum_{ijk} \beta_{ijk} R_i(X) R_j(Y) R_k(Z) = \sum_h E_h(X, Y, Z) t_h$$

$$\Rightarrow \sum_{ijk} \beta_{ijk} R_i(X) R_j(Y) R_k(Z)$$

$$= \sum_{abc} X^a Y^b Z^c P_{abc}(t_0, t_1, \dots, t_{n-1})$$

However,

$$P_{abc}(t_0, t_1, \dots, t_{n-1}) = P_{bca}(t_0, t_1, \dots, t_{n-1})$$

$$= P_{cab}(t_0, t_1, \dots, t_{n-1})$$

Thus, we get  $2n$  equations with  $n$  variables. the resolution in  $t_i$  becomes very simple.

### VIII. CONCLUSION

In this paper we are interested to the generalization of the attack of Kipnis and Shamir for HFE of degree more than 2. We have introduced a new technique to finish this attack which permits to determine the transformation  $T$ . This technique is based on Fourier transformation .

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