Obtaining and solving systems of equations in key variables only for the small variants of AES

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Abstract

This work is devoted to attacking the small scale variants of the Advanced Encryption Standard (AES) via systems that contain only the initial key variables. To this end, we introduce a system of equations that naturally arises in the AES, and then eliminate all the intermediate variables via normal form reductions. The resulting system in key variables only is solved then. We also consider a possibility to apply our method in the meet-in-the-middle scenario especially with several plaintext/ciphertext pairs. We elaborate on the method further by looking for subsystems which contain fewer variables and are overdetermined, thus facilitating solving the large system.

Keywords: Algebraic attack, meet-in-the-middle attack, AES, Gröbner basis, normal form.

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1 Introduction

In this paper we investigate several methods for obtaining and solving key variables only equations, which appear in cryptanalysing the small scale variants of the Advanced Encryption Standard (AES). The cipher Rijndael was chosen as the AES in 2001, and was published as a FIPS 197 standard [30]. AES provides fast and simple symmetric encryptions, while maintaining high resistance to (known) attacks. Simplicity of the AES was criticized since the moment it had appeared, but no one has proposed an attack, which would, at least theoretically, break the AES. We will concentrate on the so-called algebraic attacks. They emerged in the papers of Courtois [21] and Murphy et. al. [29, 18]. The idea is to present the action of the AES block cipher as a system of algebraic equations over a finite field. Then, solving such a system would reveal a secret key. In [21] Courtois and Pieprzyk construct a system over GF(2), whereas in [29] Murphy et. al. propose to consider the system over GF(2^8). Courtois obtained his system directly from the AES, wheres Murphy et. al. proposed an embedding of the AES state space to a larger space. Different manipulations and variations of these methods were considered since their appearance. Some works in this area are [17, 16, 12, 13, 32, 29, 18, 19, 1, 2, 21, 15, 31]. So far no method presented any real threat to AES. For better understanding and in order to facilitate experimenting, small scale variants of AES were proposed [19]. We mention also that quite a few multivariate public key cryptosystems and signature schemes were attacked with algebraic methods. Some works in this area include [24, 5, 22, 25].

We elaborate on the initial proposals. The fact that the equations mentioned above have many auxiliary variables, obstructs one from considering several plaintext/ciphertext pairs. So we aim at obtaining systems that contain only variables responsible for an unknown key. We use the fact that most part of the equations above already constitutes a Gröbner basis for a suitable ordering and then apply normal form computations. The idea of using the zero-dimensional Gröbner-representation for AES was first proposed in [12] and also considered in [32]. The main difference of our approach from the former is that we work over GF(2) and we include the field equations still being able to exploit the Gröbner structure; we obtain equations in key-variables only and solve them. The latter approach is more similar to ours, but the difference is that again we work with equations over GF(2), rather than with the BES equations as in [32]. In this respect we believe that optimized data structures of PolyBoRi [8], which is the main tool in our experiments, yield an advantage. Also we provide a solid experimental material, which was not done in [32].

The contribution of this paper as we see it is the following two points:

1. *Cryptanalytic part.* The method of obtaining and solving equations in key variables only coming from the small scale variants of AES. Applying this method in a framework of the meet-in-the-middle-attack, use of several plaintext/ciphertext pairs.

2. *Symbolic computations part.* Using PolyBoRi as a tool to implement the method in (1). In particular special data structures for operating with Boolean polynomials, computing normal forms, and Gröbner bases efficiently, supposedly give an advantage against using general purpose computer algebra systems. Therefore the experimental results we present should be considered also from this point.

The paper is organized as follows. In Section 2 we recall necessary notions from computational algebra and give a brief algebraic description of the AES and the small scale variants thereof. In Section 3 we show how corresponding systems of equations over GF(2) are obtained. We note that they actually can be written in different ways. This can result in performance improvements, which have partially been presented in [9]. Then we show how to obtain systems with key variables only via normal form computations. Some experiments are discussed. We move further in Section 4 to considering the meet-in-the-middle attack. Some improvements of this attack are then presented in Section 5. We finish with the discussion of obtained results and conclusion.

An extended abstract of a preliminary version of this work is in [7].

2 Background

2.1 Algebraic basics

In this section, we recall some algebraic basics, including classical notions for the treatment of polynomial systems, as well as basic definitions and results from computational algebra. For a more detailed treatment of the subject see the book of [26] and the references therein.

Let $P = \mathrm{GF}(2)[x_1, \ldots, x_n]$ be the polynomial ring over the field GF(2). In this section we explain notions and state result in terms of $\mathrm{GF}(2)[x_1, \ldots, x_n]$, but most of the things here hold also for a polynomial ring over an arbitrary field. A *monomial ordering* on P, more precisely, on the set of monomials $\{x^\alpha = x_1^{\alpha_1} \cdot \ldots \cdot x_n^{\alpha_n} | \alpha \in \mathbb{N}^n\}$, is a well ordering "$>$" (i. e. each nonempty set has a smallest element with respect to "$>$") with the following additional property: $x^\alpha > x^\beta \Rightarrow x^{\alpha+\gamma} > x^{\beta+\gamma}$, for $\gamma \in \mathbb{N}^n$. Let $f = \sum_\alpha c_\alpha \cdot x^\alpha$ ($c_\alpha \in \mathrm{GF}(2)$) be a polynomial. If $f \neq 0$ then $\mathrm{LM}(f)$ denotes the *leading monomial* of f, the biggest monomial with respect to "$>$" occurring in f with a non-zero coefficient. Denote also by $\mathrm{LT}(f)$ the *leading term* of f, i. e. the leading monomial times the corresponding coefficient. Moreover, we set $\mathrm{tail}(f) = f - \mathrm{LT}(f)$.

If $F \subset P$ is any subset, $\mathrm{L}(F)$ denotes the *leading ideal* of F, i. e. the ideal in P generated by $\{\mathrm{LM}(f) | f \in F \backslash \{0\}\}$. A monomial m is called a *standard monomial* for an ideal I, if $m \notin \mathrm{L}(I)$.

The S-polynomial of $f, g \in P \backslash \{0\}$ with leading monomials $\mathrm{LM}(f) = x^\alpha$ and $\mathrm{LM}(g) = x^\beta$ is defined by

$$\mathrm{spoly}(f, g) = x^{\gamma-\alpha} f - x^{\gamma-\beta} g,$$

where $\gamma = (\max(\alpha_1, \beta_1), \ldots, \max(\alpha_n, \beta_n))$. Also, we recall that a finite set $G \subset P$ is called a *Gröbner basis* of an ideal $I \subset P$, if $\{\mathrm{LM}(g) | g \in G \backslash \{0\}\}$ generates $\mathrm{L}(I)$ in the ring P and the inclusion $G \subset I$ holds.

Definition 2.1 (Standard representation, reduced normal form). Let $f, g_1, \ldots g_m \in P$, and let $h_1, \ldots, h_m \in P$. Then

$$f = \sum_{i=1}^{m} h_i \cdot g_i,$$

is called a *standard representation* of f w. r. t. $g_1, \ldots, g_m$, if $h_i \cdot g_i = 0$ for all i, or $\mathrm{LM}(h_i \cdot g_i) \leq \mathrm{LM}(f)$ otherwise.

A polynomial f is said to be reduced against a generating system G, if and only if $\mathrm{supp}(f) \cap \mathrm{L}(G) = \emptyset$. A polynomial r is called the *reduced normal form* of f against G, if and only if it is reduced against G and $f - r$ has standard representation with respect to G. As the reduced normal form is unique, we may denote this by $r = \mathrm{NF}(f, G)$.

Theorem 2.2 (Buchberger's criterion, cf. e.g Theorem 1.7.3 [26]). *Let I be an ideal from* $\mathrm{GF}(2)[x_1, \ldots, x_n]$ *and* $G = \{g_1, \ldots, g_s\} \subset I$. *The following are equivalent:*

1. *G is a Gröbner basis of I.*
2. $\mathrm{NF}(f|G) = 0$ *for all* $f \in I$.
3. *Each $f \in I$ has a standard representation with respect to G.*
4. *G generates I and* $\mathrm{NF}(\mathrm{spoly}(g_i, g_j)|G) = 0$ *for* $i, j = 1, \ldots, s$.
5. *G generates I and* $\mathrm{NF}(\mathrm{spoly}(g_i, g_j)|G_{ij}) = 0$ *for a suitable subset* $G_{ij} \subset G$ *and* $i, j = 1, \ldots, s$.

The PolyBoRi framework is designed for Gröbner basis computations with the so-called *Boolean polynomials* as canonical representatives of residue classes in $\mathrm{GF}(2)[x_1, \ldots, x_n]/\langle x_1^2 + x_1, \ldots, x_n^2 + x_n\rangle$. In [10] it is described, how to apply classical Gröbner basis theory for polynomial rings to this quotient ring. On the description and principles of the PolyBoRi framework the reader is referred to [8].

Definition 2.3 (Boolean polynomial). An element $f \in \mathrm{GF}(2)[x_1, \ldots, x_n]$ is called a *Boolean polynomial*, if every variable x_i occurs with exponent 0 or 1.

The following two criteria will play a crucial role in explaining our construction in Section 3.2.

Proposition 2.4 (Product criterion, cf. e.g. p.63, [26]). *Let* $f, g \in \mathrm{GF}(2)[x_1, \ldots, x_n]$ *be polynomials such that* $\mathrm{lcm}(\mathrm{LM}(f), \mathrm{LM}(g)) = \mathrm{LM}(f) \cdot \mathrm{LM}(g)$*, then*

$$\mathrm{NF}(\mathrm{spoly}(f, g)|\{f, g\}) = 0.$$

In particular this holds if $\mathrm{LM}(f)$ *and* $\mathrm{LM}(g)$ *are coprime.*

Proposition 2.5 (Linear lead criterion, cf. [8]). *Let* $f \in \mathrm{GF}(2)[x_1, \ldots, x_n]$ *be a Boolean polynomial such that* $f = l \cdot g$, $\mathrm{LM}(l) = x_i$ *for some i and g any polynomial, then* $\mathrm{NF}(\mathrm{spoly}(f, x_i^2 + x_i)|\{f, x_1^2 + x_1, \ldots, x_n^2 + x_n\}) = 0$.

The case $g = 1$ will be of interest for us.

Definition 2.6 (Elimination orderings). Let $R = \mathrm{GF}(2)[x_1, \ldots, x_n, y_1, \ldots y_m]$. An ordering "$>$" is called an *elimination ordering* of $x_1, \ldots, x_n$, if $x_i > t$ for every monomial t in $\mathrm{GF}(2)[y_1, \ldots, y_m]$ and every $i = 1, \ldots, n$.

2.2 Description of the AES

For the full description of the AES we refer to [30]. AES in its standard form (the so-called AES-128) operates on rectangular arrays of bytes. So all operations are performed on the 4×4 arrays of bytes. As we have already mentioned, the AES is composed of relatively simple operations in order to ensure its efficient implementation. A set of initial operations that are being executed consecutively composes a *round*. AES-128 performs 10 rounds, where 9 rounds are the same, and the last 10th round differs a little. We will consider a byte either as an element of $\mathrm{GF}(2^8)$ or as a $\mathrm{GF}(2)$-vector of length 8 via $\mathrm{GF}(2^8) = \mathrm{GF}(2)[a]/\langle m(a) \rangle$, where $m(a) = a^8 + a^4 + a^3 + a + 1$ is the *Rijndael polynomial*. The specifications of such a transformation are given in [30]. The following algebraic description of one round of the AES is from [29].

The AES S-Box. The value of each byte in the array is substituted according to a table look-up. A result of this table look-up $S[\cdot]$ is the combination of three transformations.

- The input w considered as an element from $\mathrm{GF}(2^8)$ and is mapped to $x = w^{(-1)}$, where $w^{(-1)}$ is defined by

$$w^{(-1)} = w^{254} = \begin{cases} w^{-1} & w \neq 0, \\ 0 & w = 0. \end{cases}$$

  Thus "AES inversion" is identical to standard field inversion in $\mathrm{GF}(2^8)$ for non-zero field elements with $0^{(-1)} = 0$.

- The intermediate value x is regarded as a $\mathrm{GF}(2)$-vector of length 8 and transformed using an (8×8) $\mathrm{GF}(2)$-matrix L_A. The transformed vector $L_A \cdot x$ is then regarded in the natural way as an element of $\mathrm{GF}(2^8)$.

- The output of the AES S-Box (substitution box) is $(L_A \cdot x) + 63$ (here 63 is the usual hexadecimal denotation of the byte 11000011), where addition is with respect to $\mathrm{GF}(2)$.

The AES linear diffusion (mixing) layer.

- Each row of the array is rotated by a certain number of byte positions.

- Each column of the array is considered to be a $\mathrm{GF}(2^8)$-vector, and a column y is transformed to the column $C \cdot y$, where C is a (4×4) $\mathrm{GF}(2^8)$-matrix.

In [29] it is shown how to transfer an affine component of an S-Box to the diffusion layer, so that S-Box is represented only by taking the inverse in GF(2^8). We use this approach in the following discussion.

The AES subkey addition. Each byte of the array is added (with respect to GF(2)) to the corresponding byte from the corresponding array of round keys.

The round key we have just mentioned are created through the so-called *key schedule*. Its specification is very similar to the main AES encryption, cf. [30].

2.3 Small scale variants

In [19] C.Cid et. al. proposed the so-called small scaled variants of the AES. The motivation for introducing this notion was that it is very hard to investigate feasibility of algebraic attacks, when one applies them directly to the original AES. So, Cid et. al. proposed to scale down the original cipher AES in terms of:

- the number of rounds n ($1 \leq n \leq 10$);
- the number of rows r in the rectangular representation ($r = 1, 2, 4$);
- the number of columns c in the rectangular representation ($c = 1, 2, 4$);
- the size e of a word in bits ($e = 4, 8$).

The notation for the scaled-down cipher is $SR(n, r, c, e)$. In this cipher all rounds are the same which is not quite true for the AES: the 10th round differs from the others. But it differs only by an affine mapping, so in principle is the same. Thus we may stick to studying ciphers $SR(n, r, c, e)$. From this prospective, the AES-128 with 10 identical rounds would be the cipher $SR(10, 4, 4, 8)$. In [19] it is written in details how to scale down the encryption operations, we refer the reader to this paper.

3 Attacking the AES via composing and solving a system in key variables only

3.1 Equations over GF(2)

One can write equations for cryptanalyzing (the small scale variants of) the AES directly bitwise over GF(2). That was an initial proposal of Courtois and Pieprzyk in [21]. There every byte of a 4×4 array is represented by 8 variables (we have 4 variables for the small scale variants with $e = 4$), each responsible for a corresponding bit in that byte. The equations can then be written in quite a straightforward way. Schematically and abusing notation we can write these equations as

$$w_0 = p + k_0, \tag{3.1}$$

$$SBOX(x_i, w_{i-1}) = 0, \quad i = 1, \dots, n, \tag{3.2}$$

$$w_i = L(x_i) + k_i, \quad i = 1, \dots, n, \tag{3.3}$$

$$SBOX_K(s_i, k_{i-1}) = 0, \quad i = 1, \dots, n, \tag{3.4}$$

$$k_i = L_K(s_i) + L'_K(k_{i-1}), \quad i = 1, \dots, n, \tag{3.5}$$

$$c = L(x_n) + k_n. \tag{3.6}$$

The field equations for all the variables are included. All identifiers are meant to refer to collections of variables (e.g. $w_0 = \{w_{0,0,0}, \dots, w_{0,0,e-1}, \dots, w_{0,rc-1,0}, \dots, w_{0,rc-1,e-1}\}$) except c and p, which are composed of elements in GF(2). Here $SBOX, SBOX_K$ are S-Box transformations for the encryption and the key schedule resp.; L, L_K are affine transformations. Note that operations in (3.2) and (3.4) are done on each separate byte, whereas in (3.1), (3.3), (3.5), and (3.6) are done on the whole rectangular array. The equations in (3.2) and (3.4) are of degree 2. The equations from $SBOX$ arise from GF(2^e)-equations $xw = 1$ translated over GF(2) via $x = \sum_{i=0}^{e-1} x_i a^i$ and $w = \sum_{i=0}^{e-1} w_i a^i$, where $m(a) = a^4 + a + 1 = 0$ for the case $e = 4$ and $m(a) = a^8 + a^4 + a^3 + a + 1 = 0$ for the case $e = 8$. So here we suppose that no 0-inversion occurs, which is true with high probability cf. [29]. The equations are listed in the Appendix A.

3.2 Writing the equations differently

The system presented in the previous subsection and also the BES-system from [29] invoked a lot of research and were a starting point for algebraic cryptanalysis of the AES. Although much effort was put in analyzing the structure of those systems, not much progress is achieved in obtaining competitive attacks. In fact, researchers were only able to cryptanalize very basic small scale variants of the AES. For example in [16] and [19] the authors could not go further $SR(10,1,1,4), SR(2,1,1,8), SR(4,2,1,4), SR(1,2,2,4)$ for BES equations and $SR(10,1,1,4), SR(2,1,1,8)$ for GF(2)-equations. Although it can be shown that one can go a bit further, that does not solve our main goal. The XSL method should also be mentioned here [21]. Initially it was believed that this method might be able to give an attack that could, at least theoretically, break AES, but some evidence afterwards show that probably estimates behind the XSL method were too optimistic ([15]).

Everything said above is a motivation for our present work. We need some preparation. Namely, we will slightly rewrite equations from Section 3.1. In rewriting the equations we aim at the situation where we express every successive variable via its predecessors. So we rewrite equations (3.1)-(3.6) as follows.

$$w_0 = p + k_0, \tag{3.7}$$

$$x_i = sbox(w_{i-1}), \qquad i = 1, \dots, n, \tag{3.8}$$

$$w_i = L(x_i) + k_i, \qquad i = 1, \dots, n, \tag{3.9}$$

$$s_i = sbox_K(k_{i-1}), \qquad i = 1, \dots, n, \tag{3.10}$$

$$k_i = L_K(s_i) + L'_K(k_{i-1}), \qquad i = 1, \dots, n, \tag{3.11}$$

$$c = L(x_n) + k_n \tag{3.12}$$

The field equations on all the variables are added. Here $sbox, sbox_K$ are S-Box transformations for the encryption and the key schedule resp.; L, L_K are affine transformations. How do we achieve the form $x_i = sbox(w_{i-1})$? Recall that initially we have degree 2 equations $SBOX(x_i, w_{i-1}) = 0$. Now we impose a block ordering, such that $x_i > w_{i-1}$ and find a reduced Gröbner basis for these equations. We obtain exactly $x_i = sbox(w_{i-1})$ and one equation $(w_{i-1,*,0}+1)\dots(w_{i-1,*,e-1}+1) = 0$, which we can drop out by assuming that the case $w_{i-1,*,0} = 0, \dots, w_{i-1,*,e-1} = 0$ does not occur (which is true with high probability). The same is true for the key schedule. It is interesting to note that actually one can get rid of equations of the type $(w_{i-1,*,0} + 1)\dots(w_{i-1,*,e-1} + 1) = 0$ without any assumptions on non-occurrence of 0-inversion as above. Recall that an S-Box equation $SBOX(x, w) = 0$ is written with an assumption that no 0-inversion occurs. Otherwise, one must rewrite GF(2^e)-equations $x - w^{2^e-2} = 0$ over GF(2) to consider also

0-inversions. As we have checked, it turns out that if we write the equations in $SBOX$ this way, we obtain exactly the equations from *sbox* without $w_{i-1,*,0} = 0, \dots, w_{i-1,*,e-1} = 0$.

Denote now by G the set of polynomials from (3.7)-(3.11) and the complete set of field equations for every variable. We denote by the same letter an ideal generated by G. Note that G contains both polynomials responsible for encryption/key schedule and the field equations for all the variables. The following holds.

Theorem 3.1. *The set G is a Gröbner basis of a zero-dimensional ideal with respect to* `lex` *ordering induced by $k_0 < w_0 < s_1 < x_1 < k_1 < w_1 < \dots < s_n < x_n < k_n < w_n$. Variables in each of the variable-blocks $k_0, w_0, \dots, k_n, w_n$ are ordered arbitrarily.*

Proof. The claim on dimension follows easily form the fact that the field equations for all the variables are included in G. Now note that G consists of the set B of Boolean polynomials with a linear leading term (those coming from encryption/key schedule) and the set F of the field equations. The claim on the Gröbner basis follows by applying the product criterion separately to pairs from the set B and F (Proposition 2.4), and then the linear lead criterion to pairs, where one element is from B and another is from F (Proposition 2.5). □

Remark 3.2.

- Other elimination orderings can be used in Theorem 3.1, e.g a block ordering, where each variable-block constitutes one block.
- Clearly the claim that B is a Gröbner basis is trivial due to the product criterion. A distinguishing feature of Theorem above is that we actually work with the field equations included. So *a priori* it is not clear that G is a Gröbner basis. The result is guaranteed by Proposition 2.5. It is crucial for our method, since field equations are always implicitly included in PolyBoRi.

Note that when $e = 4$ *sbox* and $sbox_K$ have degree 3 and when $e = 8$ degree 7. The new equations appear more complex, but the advantage is that we can express each successive variable via its predecessors. See Appendix B for the S-Box equations for both $e = 4$. For the case $e = 8$ we have that expressions for x-variables contain resp. 118, 118, 119, 127, 119, 122, 138, 128 monomials.

Different representations for the S-Boxes were studied in the literature (cf.

[4, 17]). It is known that up to now "a change of the Rijndael polynomial should not affect the strength of the cipher". It is interesting to see if this is also true in our situation. If we take all 30 irreducible polynomials of degree 8 over GF(2), it can be seen that average number of monomials in the S-Box equations for $e = 8$ varies from 122 to 139, which is close to $256/2 = 128$, half of the number of all Boolean monomials of degree up to 7. So we see that changing Rijndael polynomial to some other irreducible polynomial does not essentially decrease the number of terms in the S-Box equations.

3.3 Gröbner basis shape. Normal forms

Now let us use the Gröbner-shape of G as per Theorem 3.1 to actually obtain equations in initial key variables k_0 only. A quite obvious corollary from Theorem 3.1 shows how to do this.

Corollary 3.3. *Denote by R the polynomials (equations) in* (3.12). *For each $f \in R, \mathrm{NF}(f, G)$ contains only initial key variables k_0.*

Note that we can obtain the same result by simply plugging in the variables successively from the beginning to the end and then plugging in in R. Similar approach was proposed for the BES in [32].

For computing a normal form with respect to a system consisting of polynomials with pairwise different linear leading terms (and the complete set of field equations), there exist fast, highly specialized algorithms in PolyBoRi. The Buchberger normal form algorithm ([11]) has the disadvantage that it uses iteration over the leading terms of intermediate results and thus its running time gets a quite direct dependency on the number of terms. The special algorithms in PolyBoRi only depend on the ZDD (zero suppressed decision diagram) structure of the involved polynomials [8]. Basically there are two variants:

1. If we have computed the reduced Gröbner basis, then all polynomials in it are tail reduced, so the computations are faster. But computing the reduced Gröbner basis is quite expensive.

2. If we work only with a Gröbner basis (not a reduced Groebner basis), the recursive normal form computation splits in more recursive branches, as the tails of the polynomials (which are used during the computation) still have to be rewritten.

Going back to Corollary 3.3 we see that it is possible to eliminate all variables except the initial key variables.

The following timings that show an application of Corollary 3.3 have been done on a AMD Dual Opteron 2.2 GHz (we have used only one CPU) with 16 GB RAM on Linux using a prerelease version of PolyBoRi 0.5 ([8]). Solving the final system with the key variables is done with the symmgbGF2 algorithm [10] (an advanced version of SlimGB: [6]) implemented in PolyBoRi. We give the cumulative time for the whole process: normal form reduction and solving.

Cipher	time, sec.	memory, MB
SR(10,2,2,4)	1205	170
SR(10,1,1,4)	0.02	75
SR(10,1,2,4)	0.2	79
SR(10,1,1,8)	2	183

Note that the reduction step takes the lion's share of the computation, whereas time for the final solving is quite negligible. We could not perform necessary reductions with F4 implementation in Magma, [23, 14]. We tried `NormalForm`, `Reduce`, `ReduceGroebnerBasis` both with and without field equations. The reduction was done with respect to `lex` ordering. PolyBoRi- and Magma-examples together with the running scripts can be downloaded from `http://www.mathematik.uni-kl.de/~bulygin/en/files.html`.

We tried solving systems with Magma and Singular [27] as per (3.1)-(3.6). We could attack only the full 10 rounds of $SR(10,1,1,4)$ and 3-4 rounds of some 8-bit ciphers. See also results in [19, 16].

We would like to mention an attack based on MRHS linear equations ([31]). In [31] the author was able to break $SR(10,1,1,8)$ in 0.32 sec., which is better than above. Note, however that for key sizes larger than 8, the method of MRHS linear equations needs some bits of a key to be guessed. For instance for $SR(10,2,1,8)$ one needs 8 bits out of 16 to be guessed. Our method does not have such a limitation. It is also notable that for 8 bits known in advance in $SR(10,2,1,8)$ our method needs 4 sec. to execute.

For $SR(10,2,2,4)$ we have 16 equations of degree 16 in 16 key variables with approx. 32000 terms per equation. Note that the equations we obtain are actually reduced with respect to field equations for the key variables. In general with this approach for $SR(10,r,c,e)$, taking an assumption that the small scale variants of AES have the "best possible" diffusion layer, at the end we will have a system of rce equations in rce unknowns of degree rce with the number of terms approx. 2^{rce-1} per equation. So solving such a system for "large" parameters r, c, e is a big challenge. One further point is that PolyBoRi can represent structured polynomials of huge size in a compact way. In this way we can handle carry bits of adders blocks in integrated circuits very efficiently (number of terms $2^N - 1$, memory consumption: $3 \cdot N - 1 \cdot C$ for some constant C). For more background about the verification of integrated circuits with computational algebra we refer to [10]. Unfortunately we did not observe such a nice behavior when studying SR-ciphers. In general, we consider block ciphers vulnerable to such a attack, if one of the following conditions, comes true.

1. Some of the equations purely in the key variables are small (in the number of terms and degree).
2. Some of the equations purely in the key variables are structured.

4 Meet-in-the-middle attack

The idea of the meet-in-the-middle attack is not new in cryptanalysis. The ideas of "meet-in-the-middle" were employed already for attacking DES. The main feature of such attacks is to move from both sides: plaintext and ciphertext in the "middle" of a cipher, and there find some binding relations. In algebraic cryptanalysis the technique of "meet-in-the-middle" is studied in [19, 16] in context of the small scale variants of AES. There the authors propose to divide equations for n rounds into two subsystems: one consisting of equations for rounds $1, \ldots, n/2$ (here n is assumed to be even), and the one consisting of equations for rounds $n/2+1, \ldots, n$. By computing Gröbner bases with respect to `lex` ordering the authors get rid of variables that do not appear in rounds $n/2$ and $n/2+1$. So at the end one deals with a smaller system with the variables from rounds $n/2$ and $n/2+1$ only. Using also equations from the key schedule it is possible to recover the key. We also mention the use of the meet-in-the-middle principle in [1, 2].

In our approach the meet-in-the-middle attack as described in [19, 16] can be realized in quite a straightforward way. One just has to do "usual" reductions in rounds $1, \ldots, n/2$, and then "reverse" reductions in rounds $n/2+1, \ldots, n$. One then gets equations in k_0 and k_n from the equations describing encryption plus some key-variables-only equations from the key schedule. In this section our aim will be to illustrate this idea and to see how far can we go in parameters r, c, and e when attacks on two rounds of $SR(2, r, c, e)$ are considered. Note that here we will essentially use equations obtained from several pairs to make our systems more overdetermined. This is possible, since reduction complexity is not an issue here, see below for the results.

Recall the equations from Section 3.2. Let us write them down again explicitly for the case $n = 2$ and then discuss how to "invert" the second round to make the meet-in-the-middle attack possible.

Encryption		Key Schedule	
$w_0 = p + k_0$	(E1)	$s_1 = sbox_K(k_0)$	(K1)
$x_1 = sbox(w_0)$	(E2)	$k_1 = L_K(s_1) + L'_K(k_0)$	(K2)
$w_1 = L(x_1) + k_1$	(E3)	$s_2 = sbox_K(k_1)$	(K3)
$x_1 = sbox(w_0)$	(E4)	$k_2 = L_K(s_1) + L'_K(k_1)$	(K4)
$c = L(x_1) + k_2$	(E5)		

The field equations are assumed to be included. Now doing "usual" reduction in (E1)-(E3) we get equation of the form w_1 ="something in k_0", and in (K1)-(K2) of the form k_1 ="someting in k_0". Now we need to "invert" equations (E4),(E5),(K3), and (K4) to meet these reduced equations in the middle. The former three equations are easily invertible, namely (E4) inverts as $w_1 = sbox^{-1}(x_2) = sbox(x_2)$, considering that in all $SR(n, r, c, e)$ holds $sbox = sbox^{-1}$. Similarly (K3) inverts as $k_1 = sbox_K^{-1}(s_2) = sbox_K(s_2)$. Then (E5) inverts as $x_2 = L^{-1}(k_2 + c)$, where L^{-1} is the inverse of the invertible affine transformation L.

The question remains only with (K4): $k_2 = L_K(s_1) + L'_K(k_1)$. Let us represent this linear system in matrix form:

$$(E_{rce} \quad | \quad M \quad | \quad N),$$

where E_{rce} is a unity matrix $rce \times rce$, and $M \in Mat(\mathrm{GF}(2), rce, re), N \in Mat(\mathrm{GF}(2), rce, rce)$ are full-rank matrices. Obviously, E_{rce} corresponds to k_2-variables, M to s_1-, and N to k_1-variables. Now if we perform Gaussian elimination so that matrix M is brought to the diagonal form, we obtain:

$$\left(\begin{array}{c|c|c} T' & E_{re} & N' \\ \hline T'' & 0 & N'' \end{array}\right).$$

Here $T', N' \in Mat(\mathrm{GF}(2), re, rce), T'', N'' \in Mat(\mathrm{GF}(2), rce{-}re, rce)$. Therefore it is possible to get the following linear equations: $s_2 = A_1(k_1, k_2), A_2(k_1, k_2) =$

0, where A_1 is given by matrices T' and N', and A_2 is given by T'' and N''. The block $s_2 = A_1(k_1, k_2)$ has re equations (the number of components in s-variables) and the block $A_2(k_1, k_2) = 0$ has $rce - re$ equations. So inverting equations in this way we get:

Encryption		Key Schedule	
$w_0 = p + k_0$	(E1)	$s_1 = sbox_K(k_0)$	(K1)
$x_1 = sbox(w_0)$	(E2)	$k_1 = L_K(s_1) + L'_K(k_0)$	(K2)
$w_1 = L(x_1) + k_1$	(E3)	$k_1 = sbox_K(s_2)$	(K3')
$w_1 = sbox(x_2)$	(E4')	$s_2 = A_1(k_1, k_2)$	(K4')
$x_2 = L^{-1}(k_2 + c)$	(E5')	$A_2(k_1, k_2) = 0$	(K4")

Now obviously equations (E3) and (E4') match through w_1-variables which yields rce equations in k_0 and k_2 of total degree $e - 1$ from the encryption part. From the key schedule we get rce equations in k_0 and k_1 of total degree $e - 1$ from (K2), re equations in k_2 and k_1 of total degree $e - 1$ from (K3') and $rce - re$ linear equations in k_1 and k_2 from (K4"). Now note that if we want to use P plaintext/ciphertext pairs for our attack, then the equations from the key schedule will be the same for all the pairs and the equations from the encryption part will be different. Summarizing we have that using P pairs we get $Prce + rce + re$ equations of degree $e - 1$ and $rce - re$ linear equations. All these equations are composed of $3rce$ variables, namely coming from k_0, k_1, and k_2.

In order to show how different the meet-in-the-middle representation is from the one we have in Section 3.2, let us compare some important parameters of obtained systems, using $SR(2, 2, 2, 4)$ as an example. As is mentioned above, the system in the initial key variables only from Section 3.2 obtained via Corollary 3.3 includes only k_0 variables, whereas the one constructed using the meet-in-the-middle principle includes k_0, k_1, and k_2. The following table gives the comparison of some parameters (field equations are not considered):

method	# vars	# eqs	highest deg.	av. # of terms
"normal" 1 pair	16	16	9	≈ 2,500
"normal" 10 pairs	16	160	9	≈ 2,500
"m-i-m" 1 pair	48	48	3	10
"m-i-m" 10 pairs	48	192	3	22

As we can see, although the extent to which the systems are overdetermined is better in the "normal" systems, we gain much in degree and the number of terms by applying the meet-in-the-middle principle.

We mention here one trick we used in order to reduce size of polynomials in key variables after reductions in the encryption part. Let $f_{i,j}$ denote a polynomial in key-variables only obtained via equating (E3) and (E4') for the i-th bit and j-th pair. It turns out that any sum $f_{i,j'} + f_{i,j''}$ had approximately twice as few terms as any of $f_{i,j}$ (which all have approximately the same size). So what we do is we replace for every $i = 1, \dots, rce$ each $f_{i,j}$ in our system by $f_{i,j} + f_{i,j+1}$ for $j = 1, \dots, P-1$ and $f_{i,P}$ by $f_{i,P} + f_{i,1}$. Thus we obtain an equivalent system where the polynomials responsible for the encryption are reduced in size by a factor of 1.5-4. Note that if $f_{i,j}$'s were completely random one would get that any sum $f_{i,j'} + f_{i,j''}$ has essentially the same size as $f_{i,j'}$ or $f_{i,j''}$. This observation shows that $f_{i,j}$'s are not quite random. But note also that by taking 4-,8-,16-,... sums (i.e. the sums obtained by adding some 4,8,16,.. equations for a given bit position i) we get the same size as by 2-sums, which one would expect from random polynomials. Also taking 3-sums yields the same size as summands. This phenomenon is to be studied further.

Let us now present some experimental results that were obtained using PolyBoRi. The timings have been done on a AMD Dual Opteron Processor 242 GB 1.6 GHz (we have used only one CPU) with 8 GB RAM on Linux. The same machine has been used for Magma experiments.

Cipher	Key size, bit	P	t_{red}, sec.	t_{tred}, sec.	t_{solve}, sec.	mem., MB
SR(2,2,4,4)	32	8	0.1	0.8	1.3	35
SR(2,4,2,4)	32	8	0.2	1.6	1.4	37
SR(2,4,4,4)	64	8	0.3	2.4	3.7	61
SR(2,2,2,8)	32	64	4.0	256	≈3,300	1,214
SR(2,1,4,8)	32	64	0.4	25.6	≈950	353

Here t_{red} is time to obtain key-variables-only equations from one pair via normal form reductions as described above, t_{tred} is the total time for reductions of all pairs, and t_{solve} is time to solve the final key-variables-only system. "mem." means the peak of memory consumption. Note that for $e = 4$ fast dense linear algebra implemented in libm4ri by Gregory Bard and Martin Albrecht was used [28]. For $e = 8$, the system reduction was done using ZDDs (which consume less memory in this case). Note that results for $SR(2, 4, 4, 4)$ are quite interesting. They imply that we are able to break with only 8 pairs a 64-bit cipher (although a very simple one) in basically 4 sec. if we do the

eight reductions in parallel, and 6 sec. without parallelization.
Let us now present some results obtained with MAGMA 2.14-15.

Cipher	Key size, bit	P	t_{red}, sec.	t_{tred}, sec.	t_{solve}, sec.	mem., MB
SR(2,2,4,4)	32	8	0.1	0.8	2.5	43
SR(2,4,2,4)	32	8	0.6	4.8	7.8	190
SR(2,4,4,4)	64	8	2.9	23.2	64.8	667

We were unable to get any reasonable results for$SR(2,2,2,8)$ and $SR(2,1,4,8)$. Namely it is quite impossible to make reductions as we need. We tried `NormalForm`, `Reduce`, `ReduceGroebnerBasis` both with and without field equations. Only with
`ReduceGroebnerBasis` and field equations included could we perform reductions for just one pair's encryption part in 163 seconds.

Remark 4.1.

- In principle it is possible to apply the method for two rounds to the case of three rounds almost with no changes: one just has to do "forward" reductions in rounds 1-2 and "reverse" reductions in the third round. We could not break even 32-bit ciphers for $e = 4$ in any reasonable time with this approach. See the next section on more advanced techniques to tackle the problem.
- The trick on reducing size of polynomials in the encryption part gives a win in efficiency up to 50% for POLYBORI. Interestingly enough, this tricks considerably slowed down the MAGMA-computation. So for the table presented above for MAGMA we did not implement the trick.
- Special data structures employed in POLYBORI are particularly useful for normal form reductions that we need for obtaining key-variables-only equations. It seems that general purpose computer algebra systems like MAGMA and SINGULAR are not well suited for the purpose of our approach.

5 Using weak diffusion and guessing some bits

5.1 Overdetermined polynomial systems

It is well known (see e.g. [3]), that it is usually easier to compute the Gröbner bases of strongly overdetermined systems. Applying the techniques presented in the previous sections to obtain systems in the key variables only, it is possible to get such systems. The relation between variables and equations can be improved by considering more pairs of ciphertext and plaintext. However the number of variables is still quite large.

5.2 Subsets in less variables

The equation systems obtained in Section 4 seem to have more structure than those in Section 3 (at least for a small number of rounds). However most Gröbner bases implementations (even if they are optimized for the Boolean case) are quite unaware of this structure. Assuming, that we have have a subsystem, which involves much less variables (which is for certain a result of the weak diffusion layer when working with small number of rounds like 2 or 3), the usual Buchberger's algorithm would mix them quite strongly with the polynomials that are not included in the considered subsystem, so that their combination would involve more variables. Since more variables usually make computations harder, such an effect is not desirable. So it seems quite appropriate to treat these subsystems in less variables separately to preserve their structure. However, they could describe a complex zero set, whose knowledge might not solve our problem (usually we assume that the complete system has exactly one solution). Actually it is possible in our experiments to overdetermine these subsystems by increasing the number of pairs, so that they will also have only one solution in practice. In this way, solving them will yield the solution for every variable involved in the subsystem. Using these values, it will be much easier to solve the complete system by computing a Gröbner basis or applying the same trick again. Of course clustering subsystems of polynomials doesn't seem to be obvious in general.

Finding a good (not necessarily the best) solution for identifying such subsystems in polynomial time seems to be related to optimization techniques. In our case, we just used a very simple solution: we considered the variable sets of each of the Boolean polynomials that constitute the system. Let $f_i, i = 1, \ldots, N$ for some N be polynomials in the key variables only system. For each $i = 1, \ldots, N$ we examine which variables occur in f_i. Denote this set of variables by $Var(f_i)$. Then we collect all the polynomials from the system that contain only variables from $Var(f_i)$ and no others. Denote the subsystem so obtained by $SubSys(f_i)$. Then among all $SubSys(f_i), i = 1, \ldots, N$ we look only for overdetermined ones. Among these overdetermined ones we collect those with the least number of variables occurring, i.e. with the smallest $|Var(f_i)|$. Then for uniqueness of choice we choose the one subsystem that has among those the most polynomials, i.e. the one with maximal $|SubSys(f_i)|$. This makes the clustering very fast. Of course, the performance of our computations strongly depends on finding a subsystem in as few variables as possible and also as much overdetermined as possible. While the practical experiments show that the background is quite promising, our method here is quite basic and should be optimized for more complex ciphers to give better results (easier equation systems) to be processed by our solving algorithms.

5.3 Guessing of key bits

Another aspect often applied in cryptanalysis is the guessing of bits in the key. This can be combined quite well with the idea introduced in the previous subsection. Having found a subsystem in less number of variables, we consider small subsets of these variable (preferably some variables out of the initial key k_0). Plugging in trial values for these variables, can yield a system, which is much easier to solve via Gröbner basis computation for each possible value of a trial. This means, that in the presented timings, we really try each combination of these small sets of bits we guess, so no knowledge of them is required for the attack in advance. For example for $SR(2,2,2,8)$ and 64 pairs plugging in just two bits simplified the systems dramatically, such that it was easier to solve four of these systems via the Buchberger's algorithm, than just one of these systems. While plugging in values provides some speed up, Gröbner basis computations can be seen as a good supplement to these search techniques. This is the area, where still much research needs to be done, in a much wider scope: touching both the field of computational algebra as well as the very optimized toolset of SAT-solvers. An initial (quite theoretical) publication on these aspects was done in [20].

We don't have a special selection strategy for the bits at the moment. We tried just taking the first bits of the k_0 variables in the subsystem, as well as a random selection, but it didn't make much difference. Finding a more sophisticated method here could yield further improvements of results. The only thing, we can say at this time point of time, that it is seems reasonable to guess bits of k_i only for one i.

5.4 Recursion

After having found bits of the key using the techniques in 5.3 and 5.2, we can simplify our key variables only system. This easier system can be analyzed and treated again with the same techniques. In this way, in each step of recursion more bits values will be found. While in this way, a large number of bits might be guessed, the Gröbner bases calculation on the subsystems of equations make sure, that we will only continue our search on a specific configuration of guessed bits, if a solution exists.

We next present some results obtained with the method of this section.

Cipher	Key size, bit	P	t_{red}, sec.	t_{tred}, sec.	t_{solve}, sec.	# b.g.
SR(3,2,4,4)	32	256	0.01	2.56	657	7
SR(2,2,2,8)	32	64	2.7	172.8	356	2
SR(2,2,4,8)	64	256	5.5	1,408	1,131	10

Here "# b.g." means the number of bits guessed during the computations.

6 Conclusions and future research

In this paper we presented several methods of obtaining and solving systems of equations coming from algebraic cryptanalysis of small scale variants of AES. The peculiarity of our method in comparison with numerous other attempts is that we aim at a situation where only key variables are present in the systems. After showing the method on some small scale variants for 10 rounds we showed how meet-in-the-middle idea can be used in our framework. Here also the use of several plaintext/ciphertext pairs facilitated by our method is illustrated. With this approach we could break 2 rounds of e.g. $SR(2,4,4,4)$ with only 8 pairs in negligible time. Then we used the fact that diffusion is very weak when the number of rounds is small and also employed the idea of bit-guessing and subsystem finding to move further and break 3 rounds of $SR(3,2,4,4)$ and 2 rounds of $SR(2,2,4,8)$. Note that these results actually show that we can beat the exhaustive search for these cases. Although other conventional statistical methods probably can break these instances faster, we believe that these results provide a significant advance for algebraic attacks. We see quite a lot of room for improving heuristics used in our approach, therefore further research may yield better results for the small scale variants of AES as well as for other ciphers.

We also would like to mention that application of the described method became possible by using specialized data structures and algorithms implemented in PolyBoRi. Examples considered in this paper could be an illustration that quite large problems leading to dense systems of equations can still be feasible if optimizations on all levels are made:

- model/problem (combining the equations for several pairs of plaintext/ciphertext);
- algorithmic (problem specific solving strategies);
- implementation (the PolyBoRi framework).

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Appendix A: Writing equations as in Section 3.1

Here by (w_i) and (x_i) we understand the bits coming in and out of an S-Box.
S-Box equations for $e = 4$:

$$\begin{aligned}
&x_2w_3 + x_1w_3 + x_3w_2 + x_2w_2 + x_3w_1 + x_0w_0 + 1 = 0,\\
&x_3w_3 + x_1w_3 + x_2w_2 + x_3w_1 + x_0w_1 + x_1w_0 = 0,\\
&x_1w_3 + x_2w_2 + x_0w_2 + x_3w_1 + x_1w_1 + x_2w_0 = 0,\\
&x_1w_3 + x_0w_3 + x_2w_2 + x_1w_2 + x_3w_1 + x_2w_1 + x_3w_0 = 0.
\end{aligned}$$

S-Box equations for $e = 8$:

$$\begin{aligned}
&x_7w_7 + x_6w_7 + x_3w_7 + x_2w_7 + x_1w_7 + x_7w_6 + x_4w_6 + x_3w_6 + x_2w_6 + x_5w_5+\\
&+x_4w_5 + x_3w_5 + x_6w_4 + x_5w_4 + x_4w_4 + x_7w_3 + x_6w_3 + x_5w_3 + x_7w_2 + x_6w_2+\\
&+x_7w_1 + x_0w_0 + 1 = 0,\\
&x_6w_7 + x_4w_7 + x_1w_7 + x_7w_6 + x_5w_6 + x_2w_6 + x_6w_5 + x_3w_5 + x_7w_4 + x_4w_4+\\
&+x_5w_3 + x_6w_2 + x_7w_1 + x_0w_1 + x_1w_0 = 0,\\
&x_7w_7 + x_5w_7 + x_2w_7 + x_6w_6 + x_3w_6 + x_7w_5 + x_4w_5 + x_5w_4 + x_6w_3 + x_7w_2+\\
&+x_0w_2 + x_1w_1 + x_2w_0 = 0,\\
&x_7w_7 + x_2w_7 + x_1w_7 + x_3w_6 + x_2w_6 + x_4w_5 + x_3w_5 + x_5w_4 + x_4w_4 + x_6w_3+\\
&+x_5w_3 + x_0w_3 + x_7w_2 + x_6w_2 + x_1w_2 + x_7w_1 + x_2w_1 + x_3w_0 = 0,\\
&x_7w_7 + x_6w_7 + x_1w_7 + x_7w_6 + x_2w_6 + x_3w_5 + x_4w_4 + x_0w_4 + x_5w_3 + x_1w_3+\\
&+x_6w_2 + x_2w_2 + x_7w_1 + x_3w_1 + x_4w_0 = 0,\\
&x_6w_7 + x_3w_7 + x_1w_7 + x_7w_6 + x_4w_6 + x_2w_6 + x_5w_5 + x_3w_5 + x_0w_5+\\
&+x_6w_4 + x_4w_4 + x_1w_4 + x_7w_3 + x_5w_3 + x_2w_3 + x_6w_2 + x_3w_2 + x_7w_1+\\
&+x_4w_1 + x_5w_0 = 0,\\
&x_7w_7 + x_4w_7 + x_2w_7 + x_5w_6 + x_3w_6 + x_0w_6 + x_6w_5 + x_4w_5 + x_1w_5 + x_7w_4+\\
&+x_5w_4 + x_2w_4 + x_6w_3 + x_3w_3 + x_7w_2 + x_4w_2 + x_5w_1 + x_6w_0 = 0,\\
&x_7w_7 + x_6w_7 + x_5w_7 + x_2w_7 + x_1w_7 + x_0w_7 + x_7w_6 + x_6w_6 + x_3w_6 + x_2w_6+\\
&+x_1w_6 + x_7w_5 + x_4w_5 + x_3w_5 + x_2w_5 + x_5w_4 + x_4w_4 + x_3w_4 + x_6w_3 + x_5w_3+\\
&+x_4w_3 + x_7w_2 + x_6w_2 + x_5w_2 + x_7w_1 + x_6w_1 + x_7w_0 = 0.
\end{aligned}$$

Appendix B: Writing equations as in Section 3.2

S-Box equations for $e = 4$:

$$\begin{aligned}
x_0 &= w_3w_2w_1 + w_2w_1w_0 + w_2w_1 + w_2w_0 + w_3 + w_2 + w_1 + w_0,\\
x_1 &= w_3w_1w_0 + w_3w_1 + w_2w_1 + w_2w_0 + w_1w_0 + w_3,\\
x_2 &= w_3w_2w_0 + w_3w_0 + w_2w_0 + w_1w_0 + w_3 + w_2,\\
x_3 &= w_3w_2w_1 + w_3w_2 + w_3w_1 + w_3w_0 + w_3 + w_2 + w_1.
\end{aligned}$$

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