

## РЕФЕРАТ

Магістерська робота містить 98 сторінок, 17 рисунків, 3 таблиці, 6 додатків та 72 джерела.

У роботі представлено аналіз перспективних симетричних шифрів, що є стандартами на державному та міжнародному рівні.

Розроблено методи побудови системи нелінійних рівнянь низького степеня від багатьох невідомих, що описують криптоалгоритми MISTY1 та ГОСТ 28147-89. Представлено характеристики алгебраїчної системи рівнянь кожного шифру та їх порівняння з аналогічними системами рівнянь для криптоалгоритмів AES, Camellia та PRESENT.

Оцінено криптографічну стійкість шифрів ГОСТ 28147-89 та MISTY1 до алгебраїчного криптоаналізу. Здійснено алгебраїчну атаку на зменшені версії криптоалгоритмів використовуючи методи SAT-solver для вирішення системи нелінійних рівнянь та відновлення ключа шифрування.

СИМЕТРИЧНІ ШИФРИ, MISTY1, ГОСТ 28147-89, АЛГЕБРАЇЧНИЙ КРИПТОАНАЛІЗ.

## РЕФЕРАТ

Магистерская работа содержит 98 страниц, 17 рисунков, 3 таблицы, 6 приложений и 72 источника.

В работе представлено анализ перспективных симметричных шифров, которые являются стандартами на государственном и международном уровне.

Разработано методы построение системы нелинейных уравнений низкой степени от многих переменных, которые описывают криптографические алгоритмы MISTY1 и ГОСТ 28147-89. Представлено характеристики алгебраической системы уравнений каждого шифра и их сравнение с аналогичными системами уравнений для криптоалгоритмов AES, Camellia, PRESENT.

Оценено криптографическую стойкость алгоритмов ГОСТ 28147-89 и MISTY1 к алгебраическому криптоанализу. Выполнено алгебраическую атаку на уменьшенные версии криптоалгоритмов, используя методы SAT-solver для решения системы нелинейных уравнений и восстановления ключа шифрования.

СИММЕТРИЧНЫЕ ШИФРЫ, MISTY1, ГОСТ 28147-89,  
АЛГЕБРАИЧЕСКИЙ КРИПТОАНАЛИЗ.

## ABSTRACT

This thesis contains 98 pages, 17 figures, 3 tables, 6 appendices and 72 references.

The work presents analysis of symmetric block ciphers that are adopted standards on country and international levels.

Methods for constructing non-linear multivariate quadratic (MQ) equations systems that define cryptoalgorithms MISTY1 and GOST 28147-89 are developed. Characteristics for each algebraic system are presented and compared to analogous systems for cryptoalgorithms AES, DES and PRESENT.

Further the strength of GOST 28147-89 and MISTY1 ciphers to algebraic cryptanalysis is researched. Algebraic attack on reduced rounds versions of the ciphers is executed using SAT-solver methods for solving non-linear equations systems and recovering the enciphering key.

SYMMETRIC CIPHERS, ALGEBRAIC CRYPTANALYSIS, MISTY1, GOST 28147-89.

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## LIST OF ABBREVIATIONS

3GPP	The third generation partnership project.
AES	Advanced Encryption Standard.
ANF	Algebraic normal form.
BR	Bit reorganization layer in ZUC stream cipher.
CBC	Cipher block chaining mode.
CFB	Cipher feedback mode.
CIS	Commonwealth of Independent States.
CNF	Conjunctive normal form.
ECB	Electronics codebook mode.
FCSR	Feedback with carry shift register.
FSM	Finite state machine.
GE	Gate equivalents.
GSM	Global System for Mobile Communications.
ISO	International Organization for Standardization.
IV	Initialization vector.
LFSR	Linear feedback shift register.
LTE	Long Term Evolution, a standard for wireless communication.
MQ	Multivariate quadratic system.
NLFSR	Non-linear feedback shift registers.
OFB	Output feedback mode.
SAT	Satisfiability (denoting boolean satisfiability problem).
SDU	System data unit.
SPN	Substitution-permutation network.
UEA	UMTS Encryption Algorithm.
UIA	UMTS Integrity Algorithm.
UMTS	Universal Mobile Telecommunications System.
XOR	Exclusive or.

## INTRODUCTION

Symmetric cryptographic transformations are known to be the only effective method of providing data confidentiality and integrity in all fields of communication technologies [1]. They need to be not only cryptographically strong, but also have high performance and low resources consumption to satisfy modern needs for securing information. Consequently, robust requirements on cryptographic security, lightweight implementation and performance are entrusted to such transformations.

Symmetric ciphers came through a long history of development and improvement from the most primitive schemes based on symbols substitution and disk encryptors to advanced mathematical algorithms following Kerckhoffs' principle [2]. A tremendous contribution to enciphering theory has been done by Claude Shannon's work [3] back in 1949. He introduced the fundamentals of information theory and made it possible to evaluate and mathematically prove cipher security. Ubiquitous computerization, mass deployment of pervasive devices and extensive Internet access caused cryptography to find comprehensive applications in information systems. Despite the advanced mathematics behind modern cryptoalgorithms, real operating security systems often have weaknesses due to incorrect usage or implementation errors.

Security of mobile communication systems fell far behind from what was state-of-the-art in modern cryptography. The A5/1 cipher used in GSM standard for over 10 years can be broken within seconds using a combined distributed rainbow table code book to decrypt GSM voice calls and text messages [4]. Communication over satellite phones has also been shown to be insecure after reverse engineering the proprietary ciphers GMR-1 and GMR-2. GMR-1 is a variant of A5/2 cipher (which is prohibited for implementation in mobile phones as of July 2007) and is vulnerable to a known ciphertext-only attack with an average case complexity of  $2^{32}$  [5]. GMR-2 is an original cipher, but its session key can be recovered with 65 bytes of keystream at a moderate computational complexity [6].

In [7] an effective attack on KASUMI cipher <sup>1)</sup> used in 3G systems is

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<sup>1)</sup>KASUMI cipher is adopted by 3GPP as A5/3 cryptographic algorithm for securing mobile communica-

presented. Key recovery for the full cipher was done in hours on low-end computer that used unoptimized cipher reference implementation. It is worth noting that KASUMI is based on MISTY cryptoalgorithm which however could not be broken by the same attack. Therefore even slight modifications to robust cipher may significantly impact the security of the algorithm.

The need of deep analysis and public evaluation of cryptographic algorithms before deploying them into real systems is obvious. Several ciphers are considered for becoming worldwide standards in the field of providing data confidentiality at the moment.

MISTY1 is a symmetric block cipher designed in 1995 which has been one of the selected algorithms in the European NESSIE project [8] and recommended for Japanese government use [9]. Though no vulnerabilities have yet been found in MISTY1 cipher, some of its successors were broken (KASUMI) or provided with a theoretical attack (Camellia) which may be feasible in future with increase of computations power [10].

GOST 28147-89 is a legacy cipher that has been a subject to cryptanalysis for more than 20 years. Despite its wide usage in Ukraine and other CIS countries since the publication in 1990, the cipher has been proposed for international standardization only in 2010, but hasn't been accepted however [11]. Therefore a detailed security evaluation and properties analysis of these ciphers are essential to validate their pervasive deployment into security systems.

Chapter 5 analyses PC users working conditions and their compliance with normative documents on safety engineering and sanitation. For retrieving and evaluating the influence of possible dangerous or harmful production factors an interaction system "Human–Machine–Environment" (HME) is developed. Safety measures are developed as the result of such system analysis.



# 1 STATE OF ART ANALYSIS AND SYNTHESIS OF SYMMETRIC CRYPTOGRAPHIC TRANSFORMATIONS

Evaluation and design rationale are essential parts of developing and deploying the considered cryptographic security system. The primary goal of cryptography is to design mathematical methods for providing security against adversary's malicious actions under any predetermined conditions.

However, as practice shows, it's unfeasible to take into account all possible attacks that may be invented in the future due to technological and scientific innovations during the development stage. Therefore, the most widespread method for analysing computationally strong cryptographic primitives is complexity evaluation of every known applicable attack.

## 1.1 Classification of attacks on symmetric ciphers

Attacks on symmetric ciphers are defined by the abilities and data that an adversary can operate with. Most of them refer actions that may be done to cipher entities such as plaintexts and ciphertexts, however a separate class of attacks that exploits cipher implementation rather than the algorithm itself exists.

A ciphertext-only attack leaves the adversary with a set of ciphertexts that she <sup>1)</sup> can use to recover the corresponding plaintext or encryption key. Such conditions are the most complex for cryptanalyst. In a known plaintext attack the adversary has a fixed set of plaintext and ciphertext pairs [12].

In chosen plaintext and chosen ciphertext attacks the adversary gets an ability to encrypt plaintexts or decrypt ciphertexts of her choice respectively. So the cipher needs to have such plaintext and ciphertext spaces that would make it infeasible for the attacker to get full dictionary of all possible plaintexts and corresponding ciphertexts [12].

Related key attacks exploits possible relations between encryption keys to break the cryptographic system [13].

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<sup>1)</sup>Following the tradition started by Shafi Goldwasser in her Lecture Notes on Cryptography, "she" is used throughout the text as referring to a subject of unknown gender.

Side channel attacks are somewhat outside of mathematical attacks scope. They use some cipher implementation peculiarities to gain information about the encryption key observing the cryptographic system during operation. So far no mathematical countermeasures exist that would guarantee the security of the transformation against these types of attacks [14].

A cipher is considered to be insecure if any type of attack exists that allows to get some information about the key with a complexity lower than a brute force.

## 1.2 Block ciphers

A block cipher is a function which maps  $n$ -bit plaintext blocks to  $n$ -bit ciphertext blocks, parameterized by a  $k$ -bit key  $K$  [12]. Here  $n$  is called the blocklength. The encryption key  $K$  has to be random. In order to always provide unique and correct decryption the mapping function defined by a chosen key must be bijective.

A straightforward usage of a block cipher to encrypt separate blocks of data may have disadvantage in many applications. Consequently, several block cipher modes of operations have been developed to satisfy various security purposes.

### 1.2.1 Algebraic representation

A symmetric block cipher may be represented as an algebraic system [15]

$$\Sigma_A = \langle X, K, Y, E, D \rangle \quad , \quad (1.1)$$

where  $X$  is a plaintext space defined over finite alphabet  $Q_X$ ,  
 $K$  — a key set (usually defined by fixed length strings over  $Q_X$ ),  
 $Y$  — ciphertext space defined over finite alphabet  $Q_Y$ ,  
 $E : X \times K \rightarrow Y$  — a set of enciphering rules based on parametrized maps  $e_k(x) = y$  for which  $k \in K$ ,  $x \in X$ ,  $y \in Y$ .  
Mappings  $e_k(\cdot)$  and  $d_k(\cdot)$  for any  $k \in K$  are bijective and ensure satisfaction of both conditions  $d_k(e_k(x)) = x$  and  $e_k(d_k(y)) = y$ . Plaintext and ciphertext

spaces of all widespread modern symmetric ciphers coincide ( $Q_X = Q_Y$ ), so such ciphers are therefore endomorphic, that is  $X = Y$ . For cryptographically secure ciphers the sets of encrypting and decrypting rules must have random mapping properties, and  $e_k(\cdot)$ ,  $d_k(\cdot)$  must be random permutations.

### 1.2.2 Modes of operation

Simple encryption of data chunks block-by-block is called an electronics codebook mode (ECB). As seen from figure 1.1 each plaintext is encrypted independently. Error propagation is limited within one block, but this mode is insecure for enciphering large correlated data [12].

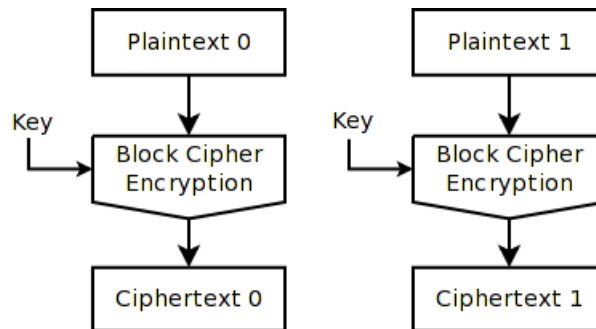


Figure 1.1 — ECB mode of operation

Cipher block chaining mode (CBC) is represented on figure 1.2. In CBC mode two identical plaintext do not encrypt to the same ciphertext as the encryption depend on the initialization vector (IV) and two previous blocks instead. This causes error propagation in ciphertext expand to two blocks, but modifications to plaintext influence all subsequent blocks and make correct decryption impossible. Such encryption mode is also more secure for enciphering correlated data [12].

Cipher feedback mode (CFB) shown on figure 1.3 turns a block cipher into self-synchronizing (see section 1.3.1) stream cipher.

Output feedback mode (OFB) is similar to CFB (figure 1.4) and differs only by a feedback connection. The main advantages of this mode is absence of error propagation (since keystream generation doesn't depend on the plaintext) and parallel processing capability.

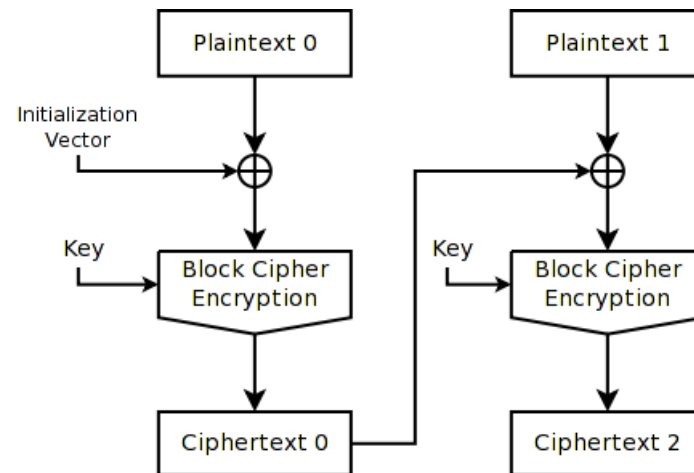


Figure 1.2 — CBC mode of operation

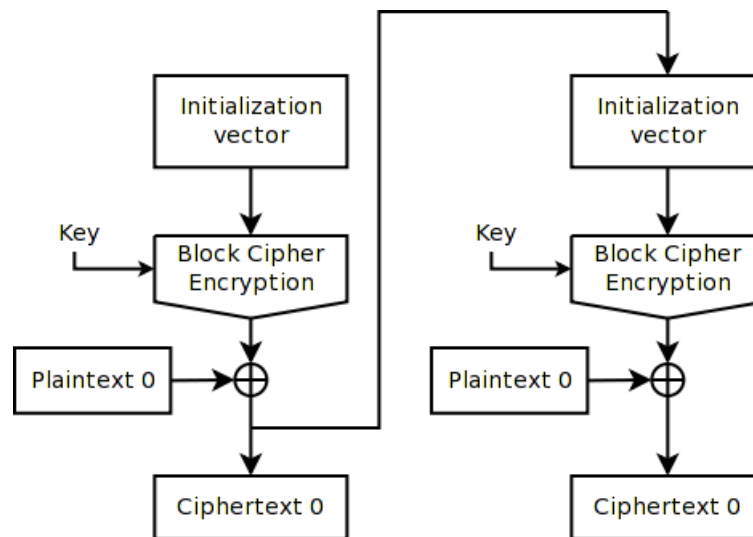


Figure 1.3 — CFB mode of operation

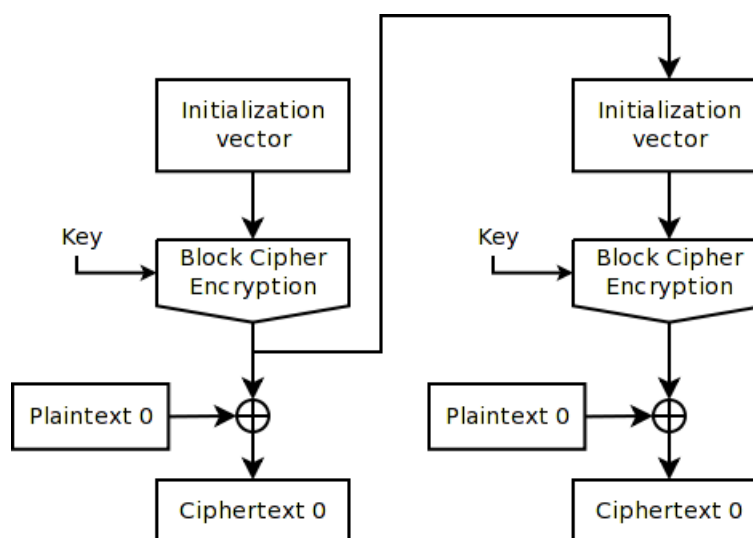


Figure 1.4 — OFB mode of operation

### 1.3 Stream ciphers

The distinct difference between stream ciphers and block ciphers was for the first time defined by Rainer Rueppel [16]:

“Block ciphers operate with a fixed transformation on large blocks of plaintext data; stream ciphers operate with a time-varying transformation on individual plaintext digits”.

Stream ciphers gained great progress since Shannon’s analysis of the Vernam cipher where he proved it to be theoretically unbreakable [3]. However such cryptosystems were complex and unprofitable to implement because of the need of secret channel to exchange key material which was the size of the message itself.

Trying to overcome disadvantages of the Vernam cryptosystem, stream ciphers inherit its idea, but use short key instead to generate a pseudo-random sequence of needed length. That is, plaintext is encrypted into ciphertext with pseudo-random sequence, called the keystream, which is produced by a finite state automaton whose initial state is determined by a secret key. Therefore stream ciphers require high structural secrecy in order to be cryptographically strong.

Stream ciphers are fast and well suited for hardware though some cryptoalgorithms designed for efficient software implementation exist. They are generally used in cases of continuous or unknown amount of data to be encrypted and strict buffering constraints.

#### 1.3.1 Classification

Depending on the choice of how the next state of cryptosystem is generated from the current state, two types of stream ciphers are distinguished: synchronous and self-synchronizing (or asynchronous) [12].

In synchronous stream ciphers the next state of the automaton is independent of plaintext and ciphertext. Such ciphers have no error-propagation and consequently don’t detect errors during decryption. This fact allows an attacker to inconspicuously alter ciphertext which will be successfully de-

encrypted to a different plaintext. Another significance consists in the fact that encrypting and decrypting devices must constantly stay synchronized. Otherwise the decryption will fail.

Asynchronous stream ciphers are able to resume correct decryption in case transmitter and receiver fall unsynchronized. Error-propagation is limited to the state bits that depend on previously generated ciphertexts. Such ciphers are difficult for analysis because the keystream depends on input message. They are also vulnerable to playback attack: if an attacker repeats some previously recorded ciphertext, the receiver will successfully decrypt it (after synchronization) and consider the message to be valid unless time markers are used.

### 1.3.2 Design principles

Rainer Rueppel distinguished four approaches to stream cipher construction [17]:

- a) system-theoretic approach; use fundamental design principles to create difficult and unknown problem for the cryptanalyst;
- b) information-theoretic approach; try to keep the cryptanalyst in the dark about the plaintext; she will never get a unique solution;
- c) complexity-theoretic approach; make the cryptosystem equivalent to some known and difficult problem (factorization, solving discrete logarithms);
- d) randomized approach; generate unsolvable problem by forcing the cryptanalyst to examine lots of useless data.

Engineering and analysing of numerous stream ciphers resulted in essential design criteria [18]:

- a) long period;
- b) linear complexity;
- c) statistical criteria (randomness, correlation, etc.);
- d) confusion — every keystream bit must be a complex transformation of all the key bits;
- e) diffusion — redundancies in substructures must be dissipated into long-range statistics;
- f) nonlinearity criteria for Boolean functions.

However it is impossible to prove such cryptosystems are secure enough. A cipher might satisfy all criteria and still be weak to some cryptanalysis techniques.

### 1.3.2.1 Feedback shift registers

Any feedback shift register consists of a shift register and a feedback function [17]. The shift register itself is a sequence of bits. New pseudo-random bit is generated by shifting the sequence one bit to the right. The new input bit of the register is computed as a function of some bits already in register.

Linear feedback shift register (LFSR) is widely used in stream ciphers. Its feedback function is XOR of some bits in register (figure 1.5). The list of such bits is called a tap sequence. Such type of LFSR is called a Fibonacci configuration. A  $n$ -bit LFSR is able to produce a pseudo-random sequence of period  $2^n - 1$  bits. In order to get a maximal-period linear sequence ( $m$ -sequence), the tap sequence must be formed by a primitive polynomial modulo 2. Even though using sparse polynomials leads to more efficient software implementation, dense polynomials are better for cryptographic applications. The only secret parameter of LFSR should be the initial state derived from the master key. Another type of LFSR is called a Galois configuration. It

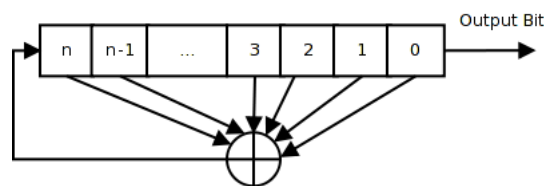


Figure 1.5 — Linear feedback shift register (Fibonacci configuration)

has the same properties, but the feedback scheme is different: each bit in the tap sequence is XORed with the output bit and replaced; the output bit then becomes the new left-most bit (figure 1.6). A sequence generated by LFSR is linear by itself and therefore useless for cryptography. It is possible to recover the LFSR structure from intercepting only  $2n$  bits of the generator using Berlekamp-Massey algorithm [19].

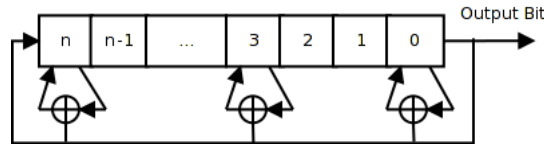


Figure 1.6 — Linear feedback shift register (Galois configuration)

Feedback with carry shift registers (FCSR) are similar to LFSRs but instead of XORing the tapping sequence bits are added to the carry register. The result reduced modulo 2 becomes the feedback bit of the register and the result divided by 2 becomes the new value of the carry register.

The carry register has to be at least  $\log_2 t$ , where  $t$  is the number of taps. Thus, before the carry register is filled there are some states of FCSR that never repeat. The maximum period of FCSR differs from the one of LFSR. It equals to  $q - 1$ , where  $q$  is the connection integer and defined as  $q = 2q_1 + 2^2q_2 + 2^4q_4 + \dots + 2^nq_n - 1$ ;  $q$  has to be a prime for which 2 is a primitive root. In fact not every initial state guarantees maximum period of the register. That means the all pseudo-random sequence generators based on FCSR will have a set of weak keys [17].

Non-linear feedback shift registers (NLFSR) use non-linear feedback function. Such stream ciphers as Grain and Trivium are based on NLFSRs. The idea both behind NLFSRs and FCSRs is to ensure high non-linearity of the output sequence. However such non-linear behavior makes the analysis of such registers almost impossible. The described registers are unpredictable — they don't guarantee maximal-period sequence, which also depends on the initial state of the register, output sequences may have biases of zeroes and ones or contain long bit series. Hereby, the advantage of these registers may at the same time lead to critical flaw. Consequently, NLFSRs and FCSRs should be used with utmost caution.

### 1.3.2.2 Clock control

Clock control is one of several ways to introduce high nonlinearity in pseudo-random sequence generated by linear feedback shift registers. The rate of register clocking varies either depending on several LFSRs or on certain bits of the register state [20]. As will be shown further, the combination of clock



control, combination and filter generators allow to form a pseudo-random sequence satisfying all statistic requirements and yet resistant to known attacks.

### 1.3.2.3 Generators

The use of feedback shift registers for cryptographic applications is possible by combining several registers into a single generator.

The technique of combining outputs of several registers by a Boolean function is called *combination generator* (figure 1.7). The output sequence  $s_t$  of a combination generator composed on  $n$  LFSRs is given by

$$s_t = f(u_1, u_2, \dots, u_n), \quad \forall t \leq 0, \quad (1.2)$$

where  $u_i$  denotes the sequence generated by the  $i$ -th LFSR and  $f$  is a function of  $n$  variables [21]. The output of the  $f$  function must be uniformly

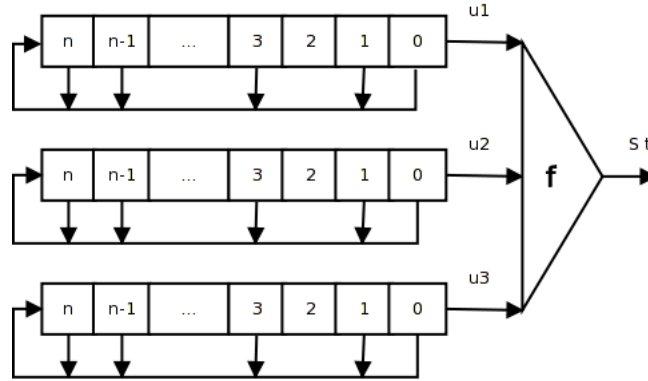


Figure 1.7 — Combination generator

distributed and balanced in order to produce pseudo-random sequences.

Linear complexity of the keystream generated by a combination generator composed of  $n$  LFSRs with primitive feedback polynomials combined by a Boolean function  $f$  equals to

$$f(L_1, L_2, \dots, L_n), \quad (1.3)$$

where the algebraic normal form of  $f$  is evaluated over integers and all lengths  $L_1, \dots, L_n$  are distinct and greater than 2. High linear complexity of the generator is required to ensure that Berlekamp-Massey algorithm is computationally infeasible.

Combination generators are vulnerable to correlation attacks based on recovering the initial states of all LFSRs from the knowledge of some sequence produced by the generator (known plaintext attack). In order to protect generators from this kind of attacks, the LFSR feedback polynomials should not be sparse to ensure a high correlation-immunity order of the combining function. However the correlation-immunity of a balanced Boolean function of  $n$  variables is limited with  $n - 1 - \deg(f)$  [21]. Tradeoffs between high algebraic degree, high nonlinearity and high correlation-immunity may be outwitted replacing the combining function by a finite state automaton with memory.

*Filter generators*, in distinction of combination generators, consist of single LFSR and its state is filtered by a nonlinear function (figure 1.8). The output of the function is a pseudo-random sequence formed by the generator. Just like in combination generators the filtering function must be uniformly distributed and balanced.

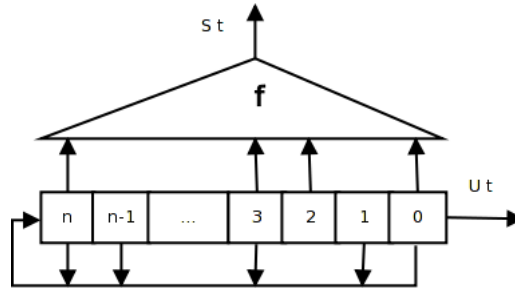


Figure 1.8 — Filter generator

Any filter generator can be represented by a corresponding combination generator consisting of  $n$  copies of the LFSR with shifted initial states when the combining function complies the filtering function.

Filter generators are vulnerable to fast correlation and generalized inversion attacks [22]. Filtering function should be highly nonlinear in order to resist the fast correlation attack. The inversion attack depends on the largest spacing between two taps of the LFSR which conflicts with the statement that LFSRs should use dense polynomials. Also the greatest common divisor of all spaces between taps should be equal to 1 or else the inversion attack could be simplified [21].

Algebraic attacks are also applicable to filter generators since a keystream bit can be represented by a function of  $L$  initial bits of the LFSR. Therefore,

knowing  $N$  keystream bits allows to form an algebraic system of  $N$  equations of  $L$  variables. Usage of Gröbner bases (which may be viewed as nonlinear generalization of Gaussian elimination for linear systems) enables an attacker to lower the degree of equations until the recovery of LFSR initial state is possible by solving the algebraic system even with filtering function of high degree.

Some designs of LFSR-based generators that promise to be secure are considered further.

*Alternating stop-and-go generator* uses three LFSRs of different length. LFSR-1 controls clocking of the other two. If output of LFSR-1 is 0, LFSR-3 is clocked, if its output is 1, LFSR-2 is clocked. The output of the generator is the XOR of LFSR-2 and LFSR-3. A correlation attack on LFSR-1 exists, but it does not threaten the generator's security [17].

*Bilateral stop-and-go generator* uses two LFSRs of length  $n$  and its output bit equals to XOR of the outputs of each LFSR. The functioning of the generator is described by algorithm 1.1. So far no critical attacks on

```

if Output of (LFSR-2 at time  $t - 1$ ) == 0 and
    Output of (LFSR-2 at time  $t - 2$ ) == 1
then
    | Block (LFSR-2 at time  $t$ )
end

if Output of (LFSR-1 at time  $t - 1$ ) == 0 and
    Output of (LFSR-1 at time  $t - 2$ ) == 1 and
    LFSR-1 clocked at time  $t$ 
then
    | Block (LFSR-2 at time  $t$ )
end

```

Algorithm 1.1 — Bilateral stop-and-go generator functioning

this generator have been presented. Another alternative is filter generator that consists in forming cryptographically strong pseudo-random sequence as some nonlinear function of a state of the single register [16].

The idea behind the *shrinking generator* is simple and uses two LFSRs. Both of them are clocked each time: if the output of LFSR-1 is 1, then the

generator outputs bit from LFSR-2, otherwise both bits are discarded and the LFSRs are clocked again. The generator is said to be secure if no sparse polynomials are used in LFSRs, but the downside is irregular output rate. This problem can be solved by buffering though it complicates implementation.

*Self-shrinking generator* is similar to shrinking generator but uses pairs of bits from a single LFSR. After clocking the register twice output bits are analysed: if the first bit is 1, the output is the second bit; if the first bit is 0, bits are discarded and the register is clocked again. This generator is slower but requires less memory. However its properties are hard to analyse.

#### 1.3.2.4 T-functions

A new building block for symmetric ciphers called T-function was introduced by Klimov and Shamir in 2003 [23]. T-function is a class of invertible mappings that mix arithmetic and boolean operations and process full machine words.

Consider a construction where each input variable has  $n$  bits, and  $m$  input variables are placed in  $m$  rows of  $m \times n$  bit matrix. Then a T-function is defined by mapping

$$f : \mathbb{B}^{m \times n} \rightarrow \mathbb{B}^{k \times n} , \quad (1.4)$$

where  $\mathbb{B} = \{0, 1\}$  and each  $k$ -th column of the output depends only on the first  $k$  columns of the input. In general, in order to compute the  $k$ -th output bit only input bits  $0, 1, \dots, k$  must be known. Most machine instructions are T-functions: negation, addition, subtraction, multiplication, left shift, which is identical to multiplication by 2. Any combination of T-functions is also a T-function.

The name of such transformation refers to the triangular dependence of the following form [24]:

$$\begin{pmatrix} [f(x)]_0 \\ [f(x)]_1 \\ [f(x)]_2 \\ \vdots \\ [f(x)]_{n-1} \end{pmatrix} = \begin{pmatrix} f_0([x]_0) \\ f_1([x]_0, [x]_1) \\ f_2([x]_0, [x]_1, [x]_2) \\ \vdots \\ f_{n-1}([x]_0, \dots, [x]_{n-2}, [x]_{n-1}) \end{pmatrix} , \quad (1.5)$$

where  $[f(x)]_k$  is the  $k$ -th output column and  $[x]k-1, \dots, [x]_0$  — first  $k$  input columns.

The primary advantage of T-functions is computation efficiency both in hardware and software implementation on modern processors. Despite of having desirable cryptographic properties, some functions revealed weaknesses to correlation, algebraic and distinguishing attacks [25] with a complexity of  $2^{32}$ . Even though usage of T-functions is highly attractive, reasonable security of such transformations should be proved first.

#### 1.4 Formulation of the problem

In spite of advances in mathematic methods of modern cryptography, real world security system often end up using vulnerable ciphers due to insufficient preliminary analysis. By the time the security cryptoalgorithm is properly studied, the cipher itself is already deployed in global system – switching is expensive and hard technologically.

In order to prevent such situations methods for efficient cryptographic security analysis of ciphers need to be propagated and best practices for cryptographic primitives design and evaluation provided. Most widely used cryptanalytic methods (linear and differential cryptanalysis, etc.) are based on statistical approach and require tremendous amount of data for sane evaluation. Even with exponential growth of computational power it most probably will be impossible neither in the near future nor any given time in future to apply these statistical methods to modern full-scale ciphers.

To make statistical cryptanalytic methods somewhat applicable to ciphers used in modern security systems the concept of baby-ciphers has been introduced. The concept implied proportional shrinking of all transformations of the cipher in order to get a baby-version – still similar to the original cipher but its full statistical analysis is computationally feasible. However the correspondence of such statistical evaluation to the full-scale original cipher hasn't yet been proved.

Nonetheless algebraic analysis of cryptoalgorithms and recent advances in computational algebra allow to obtain systems of multivariate equations that mathematically describe the behaviour of full-scale ciphers and require

only few pairs of plaintext/ciphertext for valid analysis. Most equations systems for modern ciphers are still hard to compute, but the complexity gap for solving full-scale system of equations is times smaller than for statistical methods to analyze full-scale cipher.

Though the algebraic analysis method is promising, it is not yet widely used and has been applied to only few ciphers. In order to perform algebraic analysis of any cryptoalgorithm it first must be defined by a system of multivariate non-linear equations. Therefore to make the algebraic cryptanalysis technique commonly used by cryptologists some patterns and best practices in constructing polynomial equations for modern ciphers must be made available to the public. Not only the theoretical part is important for valid evaluation. The ready to use reference software implementation with examples is the key wide applicability of algebraic analysis methods.

In order to solve the described issues and enable algebraic analysis efficiently applicable for modern symmetric cipher following solutions need to be provided:

- a) develop guide lines for constructing system of non-linear equations for modern ciphers as well as for individual transformations commonly used in modern ciphers;
- b) describe the most efficient methods and provide best practices for solving algebraic equations systems;
- c) use provided methods for applying algebraic attack to actual ciphers;
- d) describe needed software tools and provide reference implementation for all steps of algebraic attack for easy reproduce and application to other ciphers.

## 2 ALGEBRAIC ANALYSIS OF SYMMETRIC BLOCK CIPHERS

Being a fairly new technique, algebraic cryptanalysis is one of the most promissory and powerful methods for analysing cryptographic algorithms [26]. It implies modeling a cryptographic algorithm by a set of algebraic equations that form multivariate polynomial equations system over finite field. The lower degree such system has the easier it is to solve, so it is a rule of thumb in algebraic analysis to construct algebraic systems that contain only quadratic multivariate (MQ<sup>1</sup>) equations.

The essence of algebraic cryptanalysis is an assumption made by Claude Shannon in [3] that binds cipher security to the difficulty of solving the corresponding algebraic equations set: “Breaking a good cipher should require as much work as solving a system of simultaneous equations in a large number of unknowns of a complex type”.

The main advantage of algebraic cryptanalysis over other methods is the need for only few pairs of plaintexts and ciphertexts. Breaking Keeloq cipher is a good example of successful algebraic attack on full scale cryptoalgorithm [27]. The attack allows to recover the encryption key in  $2^{14.77}$  times faster than a brute force search.

An Advanced Encryption Standard (AES) that is also widely used outside of the USA is potentially vulnerable to XSL attack (a type of algebraic cryptanalysis). The attack is claimed to significantly weaken the cipher. Even though the practical applicability of the attack hasn’t yet been proven, the algebraic structure of AES that is efficiently described with algebraic equations system may be compliant to such analysis as mentioned in [28]:

“We have one criticism of AES: we don’t quite trust the security. What concerns us the most about AES is its simple algebraic structure. No other block cipher we know of has such a simple algebraic representation. We have no idea whether this leads to an attack or not, but not knowing is reason enough to be skeptical about the use of AES.” (*Bruce Schneier, Niels Ferguson*).

Given an equations system that completely describes the cryptographic

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<sup>1</sup>It also became a widespread practice to denote the problem of solving multivariate quadratic equation systems as MQ for short.

algorithm one gets a powerful tool for researching its hidden properties. However such systems are hard to solve for full scale ciphers. Complexity of polynomial systems is usually described by the number of equations, their degree and number of variables they have [27].

It is shown in [29] that solving multivariate quadratic equations systems over  $GF(2)$  (MQ) and finding satisfying solutions for boolean expressions in several variables (SAT) are NP-hard problems. But their complexity significantly drops if the system becomes overdefined, i.e. there are much more equations than unknowns [30].

## 2.1 Construction of algebraic equations for cryptographic primitives

Generally an algebraic attack is executed in two steps:

- a) An analyzed cipher is described by multivariate equations system;
- b) For given plaintext and ciphertext pairs the equation is solved for recovering the key bits.

Therefore to complete the first step, every transformation of the cipher has to be defined by polynomial equations. If all input variables are replaced by given bits and the rest of variables obtain output and intermediate values equal to those of original transformation, then the equations are correct.

Most of cryptographic algorithms consist of the following operations:

- bit permutations;
- modular addition (XOR is equivalent to modulo 2 addition);
- logical operations (AND, OR, Negation);
- substitution (S-boxes);

As will be shown further, these transformations may be completely defined by polynomial equations systems in algebraic normal form (ANF), that is expressed using operations *Exclusive Or* (XOR) and *conjunction* (logical AND).



### 2.1.1 Logical operations

Algebraic normal form consists of two operations: AND, XOR, so these are trivial to describe. Negation may be expressed by applying XOR with constant 1. Logical OR operation may be expressed in ANF as follows:

$$x \vee y = (x \wedge y) \oplus x \oplus y . \quad (2.1)$$

Correctness of the proposed equation may be verified by constructing a truth table for both expressions (figure 2.1).

$x$	$y$	$x \vee y$
T	T	T
T	F	T
F	T	T
F	F	F

(a) Logical OR in CNF

$x$	$y$	$x \underline{\vee} y \underline{\vee} (x \wedge y)$
T	T	T
T	F	T
F	T	T
F	F	F

(b) Logical OR in ANF

Figure 2.1 — Truth tables for logical OR

### 2.1.2 Bit permutations

Consider simple 4-bit permutation that needs to be defined by equations system (figure 2.2). After matching each bit to certain variable one could obtain the corresponding equations system.

$$\begin{cases} y_0 = x_3; \\ y_1 = x_2; \\ y_2 = x_1; \\ y_3 = x_0. \end{cases} \quad (2.2)$$

Then equations (2.2) could be transformed to implicit form to obtain the final polynomials:

$$\begin{cases} y_0 \oplus x_3 = 0; \\ y_1 \oplus x_2 = 0; \\ y_2 \oplus x_1 = 0; \\ y_3 \oplus x_0 = 0. \end{cases} \quad (2.3)$$

So the given 4-bit permutation has been defined by 4 equations in 8 variables. Such solution is simple but unfortunately introduces more variables than equations which may lead to underdefined and therefore unsolvable system. However more efficient approach exists. Since there is no multiplication in this transformation that could increase equations degree and the variables are only renamed, they may be just reordered for the following transformation to receive correct values. That way no additional equations or variables are introduced at all.

Any cyclic bit shift is just a special case of ordered permutation and is defined similarly.

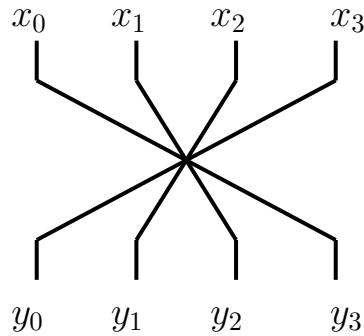


Figure 2.2 — 4-bit permutation

### 2.1.3 Modular addition

During the Ukrainian national public cryptographic competition the following method for defining modular addition with equations system has been proposed by the author of *Labyrinth* block cipher.

Modular addition  $R = X + Y$  of two  $n$ -bit numbers is defined as

$$X = (x_0, \dots, x_{n-1}), Y = (y_0, \dots, y_{n-1}), R = (r_0, \dots, r_{n-1}), \quad (2.4)$$

where  $i$  — is a bit number, so  $x_i$  represents  $i$ -th bit of number  $X$ . Then the addition on a bit level is defined as follows:

$$r_i = x_i \oplus y_i \oplus c_{i-1} \quad , \quad (2.5)$$

where  $c_i$  is a carry bit variable and is defined by (2.6).

$$c_i = r_{i+1} \oplus x_{i+1} \oplus y_{i+1} \quad . \quad (2.6)$$

The goal is to get null space equations for every addition bit without explicitly using the carry variable. It turns out that for addition bits  $0 < i < (n - 1)$  three implicit equations may be defined:

$$\begin{cases} (x_i \oplus r_i)(x_i \oplus c_i) = 0; \\ (y_i \oplus r_i)(y_i \oplus c_i) = 0; \\ (x_i \oplus y_i) \cdot r_i \oplus x_i y_i \oplus x_i \oplus y_i \oplus c_i = 0. \end{cases} \quad (2.7)$$

The final equation system that defines every addition bit may be extracted from (2.7) by substituting every  $c_i$  variable according to 2.6:

$$\begin{cases} x_i \oplus x_i r_i \oplus x_i r_{i+1} \oplus x_i x_{i+1} \oplus x_i y_{i+1} \oplus r_i r_{i+1} \oplus r_i x_{i+1} \oplus r_i y_{i+1} = 0; \\ y_i \oplus y_i r_i \oplus y_i r_{i+1} \oplus y_i x_{i+1} \oplus y_i y_{i+1} \oplus r_i r_{i+1} \oplus r_i x_{i+1} \oplus r_i y_{i+1} = 0; \\ x_i r_i \oplus y_i r_i \oplus x_i y_i \oplus x_i \oplus y_i \oplus r_{i+1} \oplus x_{i+1} \oplus y_{i+1} = 0. \end{cases} \quad (2.8)$$

Thereby a single addition bit is defined by three equations of degree 2 each containing 12 quadratic terms. Even though the equations in (2.8) fully describe  $n$ -bit modular addition, adding a redundant equation  $r_0 = x_0 + y_0$  for the very first bit was found to give crucial increase on system solving performance.

#### 2.1.4 S-boxes

An arbitrary S-box is fully defined by equations of degree 2 that can be obtained by finding null space equations as described in [31].

Consider the S-box  $(7, 6, 0, 4, 2, 5, 1, 3)$  for example. To find corresponding null space equations the following matrix  $8 \times 22$  is constructed. Each row contains the values of all possible 22 monomials for each of 8 possible inputs

for variables  $\{x_0, x_1, x_2, x_3\}$ .

$$\begin{pmatrix}
 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & x_0 \\
 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & x_1 \\
 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & x_2 \\
 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & y_0 \\
 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & y_1 \\
 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & y_2 \\
 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & x_0x_1 \\
 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & x_0x_2 \\
 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & x_0y_0 \\
 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & x_0y_1 \\
 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & x_0y_2 \\
 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & x_1x_2 \\
 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & x_1y_0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & x_1y_1 \\
 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & x_1y_2 \\
 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & x_2y_0 \\
 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & x_2y_1 \\
 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & x_2y_2 \\
 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & y_0y_1 \\
 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & y_0y_2 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & y_1y_2
 \end{pmatrix} \tag{2.9}$$

The null space equations are then obtained by applying Gaussian elimination to the matrix.

$$\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_1 + x_2 + y_0 + y_1 + 1 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_0 + x_1 + y_2 + 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_0 + y_0 + 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_0 + x_2 + y_1 + y_2 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & x_0y_0 + x_0 + x_1 + x_2 + y_0 + y_1 + y_2 + 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & x_0y_0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & x_0y_0 + x_2 + y_0 + y_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & x_0y_0 + x_1 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0x_2 + x_1 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0x_1 + x_1 + x_2 + y_0 + y_1 + y_2 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_1 + x_0 + x_2 + y_0 + y_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_0y_2 + x_1 + x_2 + y_0 + y_1 + y_2 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_1x_2 + x_0 + x_1 + x_2 + y_2 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_1y_0 + x_0 + x_2 + y_1 + y_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_1y_1 + x_1 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_1y_2 + x_1 + x_2 + y_0 + y_1 + y_2 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_0y_0 + x_2y_0 + x_1 + x_2 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_2y_1 + x_0 + y_1 + y_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_2y_2 + x_1 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & y_0y_1 + x_0 + x_2 + y_0 + y_1 + y_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & y_0y_2 + x_1 + x_2 + y_0 + y_1 + 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & y_1y_2 + x_2 + y_0
\end{pmatrix} \quad (2.10)$$

This yields to 14 equations that fully describe the S-box transformations.

### 2.1.5 Feistel network

Using the described methods of constructing algebraic equations for widely used cryptographic transformations it is straightforward to define generic Feistel network with polynomial equations system.

Consider a Feistel network on figure 2.3. All input and output bits of the Feistel network are considered to be unknown and therefore are replaced with variables. Then going through each transformation those variables are

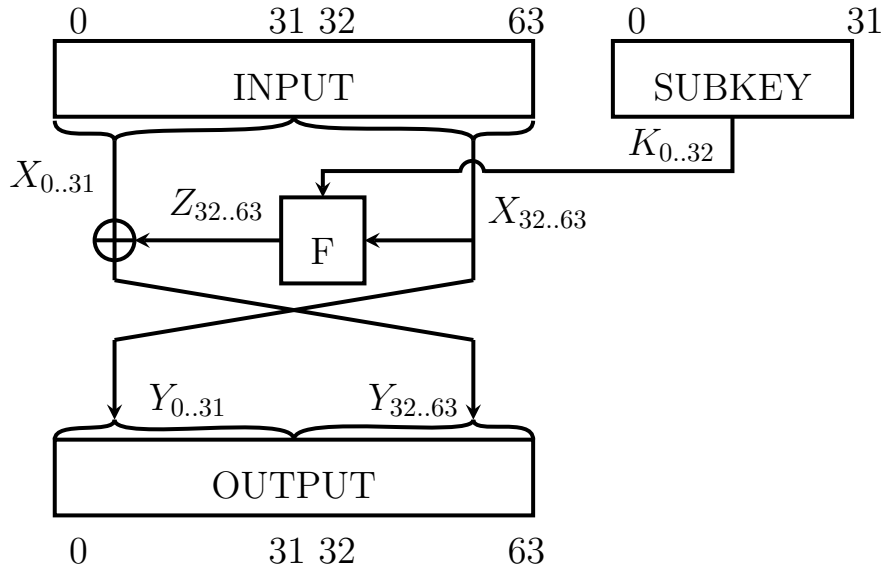


Figure 2.3 — Feistel network

used for equations construction that are further assigned to next variables for the following transformation. This example on figure 2.3 demonstrates such process for single round of Feistel network. The resulting number of equations and variables depends on transformations used in  $F$  function. For full-scale Feistel networks the internal variables for each round must be distinct. This may be achieved by prefixing variables names with current round number. However the output variables of round  $n$  are equal to input variables of adjacent round  $n + 1$  and therefore are common.

Some transformations (like modular addition and S-boxes) increase the degree of monomials. There are two possible ways of preventing the equations degree growth: with preprocessing or post-processing. The preprocessing implies introducing new variables before each transformation that contains multiplication. Post-processing however decreases the degree of already constructed equations until they become quadratic by applying the following operation repeatedly:

$$\{m = wxyz\} \Rightarrow \{a = wx; b = yz; m = ab\} . \quad (2.11)$$

Many ciphers based on Feistel networks (including the studied ones) use the key that is larger than the block size. Therefore a single known plaintext and ciphertext pair may not introduce enough information for recovering all the key bits. In this case several systems of equations should be joined

together. Such systems share only the key variables (and variables for sub-keys and key scheduling if any) while the rest of variables are distinct. Then the plaintext and ciphertext pairs obtained on the same key must be injected into the extended system. The number of introduced known values for plaintext/ciphertext variables must be equal to the unicity distance of the cipher.

## 2.2 Methods for solving algebraic equation systems

### 2.2.1 Gröbner basis

Finding a Gröbner basis is equivalent to solving various problems concerning polynomial systems [27]. As Gaussian elimination method solves linear equation systems, the Gröbner basis is designed to do the same for non-linear polynomial systems.

In [32] the Gröbner basis is defined as following.

For a fixed monomial order a finite subset  $G = \{g_0, \dots, g_{m-1}\}$  of an ideal  $\mathbb{I}$  is said to be a Gröbner basis if

$$\langle LT(g_0), \dots, LT(g_{m-1}) \rangle = \langle LT(I) \rangle, \quad (2.12)$$

where  $LT$  denotes the leading term of a polynomial.

Notably the leading term of every polynomial from  $\mathbb{I}$  is divisible by the leading term of at least one polynomial from  $\mathbb{G}$ .

Gröbner basis has been successfully applied for attacking several ciphers, including FLURRY and CURRY [33] and even showed to be more efficient than SAT solvers in algebraic attack on Bivium [34].

Even though in most cases Gröbner basis method is not efficient enough for attacking full-scale ciphers it is useful for exhausting more linearly independent equations by applying it to some transformations (like S-boxes).

### 2.2.2 SAT solvers

Another approach to solving MQ problem is SAT<sup>2)</sup> solvers that are used for determining a set of variables that would satisfy a given boolean formula.

An efficient method of converting equation systems from the algebraic normal form (ANF) to the conjunctive normal form (CNF) was proposed in [35]. After conversion the resulting system is solved by a SAT solver of cryptanalyst's choice. SAT solvers also require less memory and make it possible to solve problems infeasible for Gröbner basis algorithms.

SAT solvers gained lots of attention lately since the problem of finding solutions satisfying a given system of boolean equations is NP-complete so developing a SAT solving algorithm running in polynomial time would help to experimentally show equality of P and NP. So proving (or disproving) the equivalence of these two complexity classes would affect not only asymmetric ciphers based on factorization problem as was thought before, but any cipher that may be efficiently described by an algebraic equations system.

## 2.3 Summary

In this chapter the methods for defining most widely used cryptographic primitives with system of non-linear equations are described. The techniques of obtaining equations for bit permutations, modular addition, some logical operations and S-boxes should allow to construct full-scale non-linear equations systems for most modern symmetric ciphers.

Also some most efficient methods for solving the constructed system of equations are described. The software tools for computational algebra that provide needed functionality are described in section 4. Reference implementation for defining individual transformations with non-linear equations and constructing full-scale system of equations is provided in appendices A-D.

A computational power of low-end computer will not make it possible to perform an algebraic attack on full-scale cipher but will allow to research algebraic properties of individual transformations and parts of the cryptalgorithm to make some predictions for cipher security.

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<sup>2)</sup>SAT is an abbreviation denoting boolean satisfiability problem.



### 3 ALGEBRAIC ATTACK ON GOST 28147-89 AND MISTY1

#### 3.1 Description of GOST 28147-89 cipher

Officially adopted in 1989 the GOST 28147 cipher has been developed in former USSR and is now the encryption standard in most CIS countries. For more than 20 years of cryptanalysis no efficient attack that would significantly reduce the cipher security had been found.

GOST 28147-89 is a symmetric block cipher with a key length of 256 bits. It's represented by a Feistel network of 32 rounds. The round function consists of key addition modulo  $2^{32}$ , substitution layer represented by eight 4-bit S-boxes, and a cyclic left shift by 11 bits (figure 3.1). S-boxes are not defined in the original standard [36]. For some time they were considered to be another secret parameter, but such approach caused more problems than gained additional security. Use of different S-boxes set caused some cipher implementations to be incompatible. Later all possible benefits of secret substitution layer were scattered by introducing a method to recover all unknown S-boxes in  $2^{32}$  encryptions [37]. The 256-bit key is split into

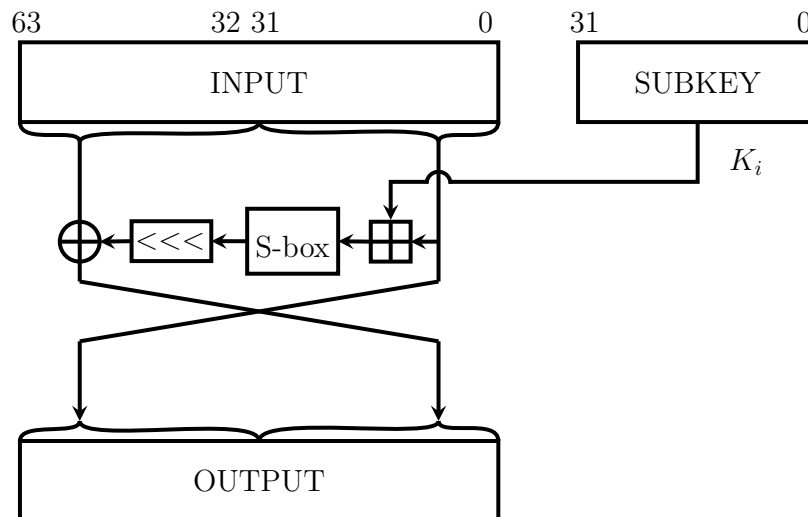


Figure 3.1 — GOST 28147-89 round function

8 32-bit subkeys that are used sequentially throughout the Feistel network. During the last 8 rounds subkeys are fed in reverse order. Half blocks are not switched after the last round in order to make encryption and decryption procedures similar.

However some recent works [38, 39] claim the fastest attack on GOST has complexity  $2^{224}$  and requires  $2^{32}$  known plaintexts.

### 3.2 Construction of equations system for GOST 28147-89

Using methods described in section 2.1 system of algebraic equations for GOST 28147-89 is defined as follows.

Consider variable format  $X_{r,b}$ , where  $r$  denotes round for which the variable is defined and  $b$  is a bit number of the block. Then defining one round of GOST cipher requires 4 sets of variables:

- a)  $X_{r,0...63}$  for input block,
- b)  $K_{r\%8,0...31}$  for a subkey (where  $\%$  denotes modulo reduction),
- c)  $Y_{r,0...31}$  for the result of key addition,
- d)  $Z_{r,0...31}$  for the result of S-box substitution.

Input to a key addition modulo  $2^{32}$  are variables  $X_{r,31...63}$  of the right input half-block and  $K_{r\%8,0...31}$  of the subkey. The result of key injection is assigned to variables  $Y_{r,0...31}$ . GOST 28147-89 key injection transformation can be described with 93 equations. Obtaining the equations for modular addition is described in section 2.1.3.

During this research the S-boxes used in GOST cipher implementation are those proposed in [40] and given in appendix E. Every such S-box is defined by 21 equations each containing up to 14 monomials, so the total number of equations for S-box layer is 168. Input variables  $Y_{r,0...31}$  are passed to substitution layer which generates 32 output variables  $Z_{r,0...31}$ .

Cyclic shift is equivalent to renaming variables  $Z_{r,0...31}$  to  $Z_{r,\{21...31,0...20\}}$ . Equations for XORing round function output with the left input half-block and switching the half-blocks are trivial. The resulting polynomials of a single Feistel network round are then assigned to the next round variables  $X_{r+1,0...63}$ .

Obtaining equations for modular addition described in details in section 2.1.3.

The chosen approach of constructing polynomial system for GOST 28147-89 cipher allows to define a single cipher round with 325 quadratic equations. An algebraic equation system describing full GOST 28147-89 cipher contains 10432 polynomials in 4416 variables. In case of using the subkeys in straight

order (without reversing during last 8 rounds) the number of polynomials and variables in the system stays the same. That means the reversing the subkeys during last 8 rounds does not strengthen the cipher from algebraic point of view, but only complicates its implementation.

### 3.3 Key recovery for 6 rounds of GOST 28147-89

In order to solve the equation system some chosen plaintext and the corresponding ciphertext are injected into the system (by substituting variables of the first and the last block to their corresponding values). Since GOST 28147-89 cipher has the key length of 256 bits, having an equation system for a single pair of plaintext and ciphertext doesn't allow to recover the encryption key. The solution combines several equation systems for distinct plaintexts and ciphertexts in order to inject more information into the resulting polynomial system. Considering the 64-bit input block it is evident that a successful 256-bit key recovery should be possible using an equation system for at least 4 plaintext/ciphertext pairs.

Using a premier SAT solver [41] 6 rounds of GOST 28147-89 cipher had been broken and a complete list of the used subkeys completely recovered. After observations during the research two factors were found to influence the equation system solving complexity. The more zeroes encryption key contains, the easier the polynomial system is for solving since modular addition of zero does not generate carries. Also the chosen plaintexts should have maximum hamming distance in order to introduce enough information to the system.

Finding solution for more rounds of GOST 28147-89 polynomial system requires much larger time gap on an ordinary laptop. However the memory requirements are small so taking into account the simplicity and uniformity of the cipher structure it is rational to assume that a more powerful computer would allow to break more rounds of the cipher.

### 3.4 Description of MISTY1 cipher

MISTY1 is a symmetric block cipher with a 128-bit key, a 64-bit block and a variable number of rounds that inherits Feistel structure [42]. The algorithm was designed to be robust against linear and differential cryptanalysis and sustain efficiency on any platform. Therefore the operations used in the cipher do not exploit software instructions specific for certain processor architecture.

The cipher is also described in RFC 2994. It has recursive structure of nested Feistel networks – the outer level Feistel network uses round function  $FO$  which itself represents another smaller Feistel network  $FI$  (figure 3.2).

The nested Feistel round functions  $FO$  and  $FI$  are presented on figures 3.3a and 3.3b respectively.

Key schedule is performed by iterative applying of  $FI$  function to each 16-bit chunk of the key (figure 3.3c). Hereby 128 additional subkey bits are generated. Both the key and the subkey bits are used during enciphering.

The key injecting function includes conjunction and disjunction operations and is presented on figure 3.4.

S-boxes in MISTY1 are constructed algebraically. S-Box  $S_7$  has degree 2 and  $s_9$  is of degree 3. Equations for each S-box are defined in (3.1, 3.2).

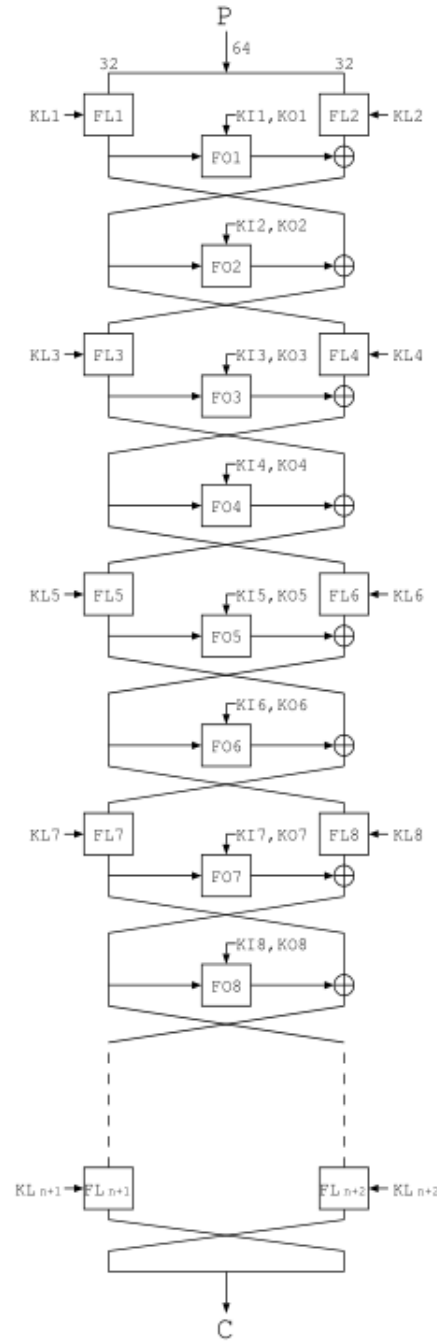


Figure 3.2 — MISTY1 cipher structure

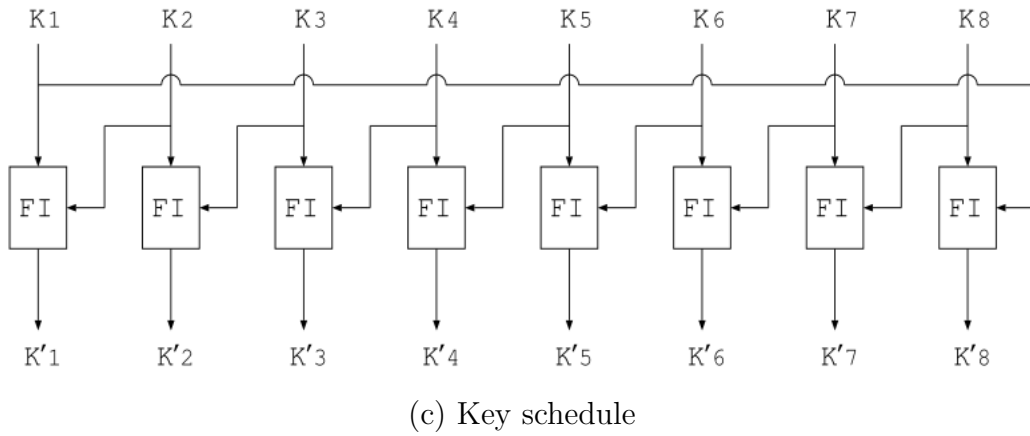
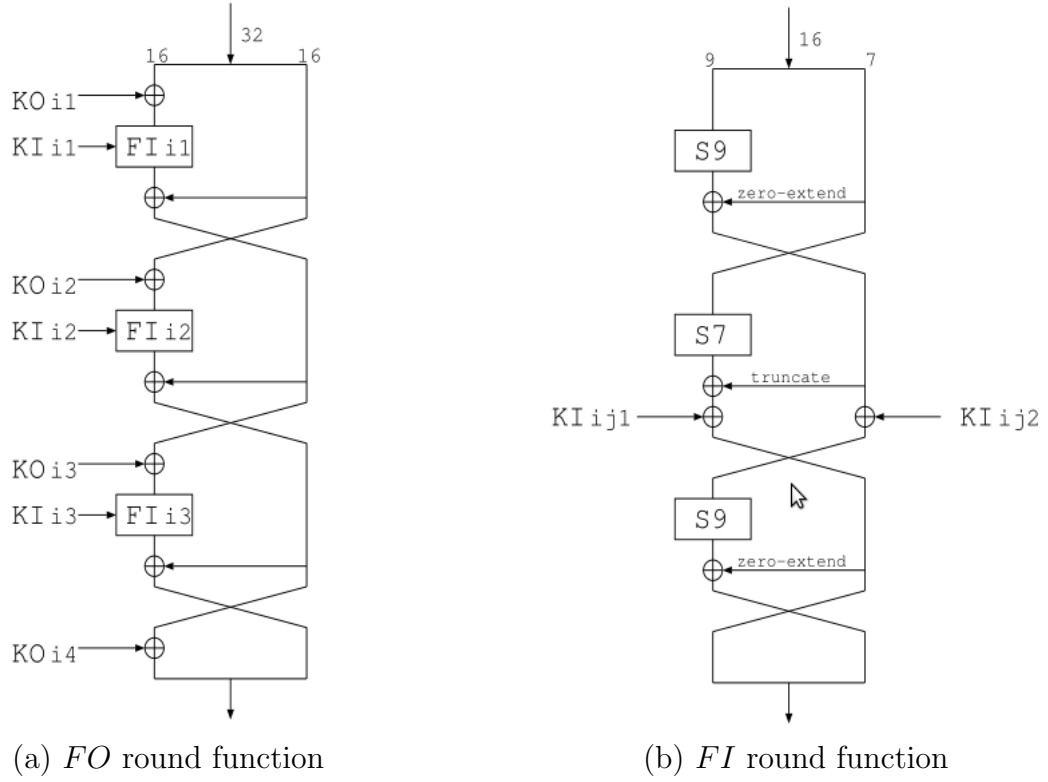
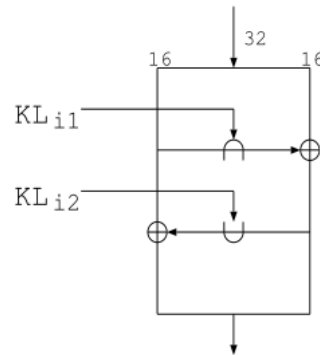


Figure 3.3 — MISTY1 internal functions

Figure 3.4 — Key injection *FL* function

$$\begin{aligned}
y_0 &= x_0 + x_1x_3 + x_0x_3x_4 + x_1x_5 + x_0x_2x_5 + x_4x_5 + \\
&\quad + x_0x_1x_6 + x_2x_6 + x_0x_5x_6 + x_3x_5x_6 + 1 \\
y_1 &= x_0x_2 + x_0x_4 + x_3x_4 + x_1x_5 + x_2x_4x_5 + x_6 + \\
&\quad + x_0x_6 + x_3x_6 + x_2x_3x_6 + x_1x_4x_6 + x_0x_5x_6 + 1 \\
y_2 &= x_1x_2 + x_0x_2x_3 + x_4 + x_1x_4 + x_0x_1x_4 + x_0x_5 + x_0x_4x_5 + \\
&\quad + x_3x_4x_5 + x_1x_6 + x_3x_6 + x_0x_3x_6 + x_4x_6 + x_2x_4x_6 \\
y_3 &= x_0 + x_1 + x_0x_1x_2 + x_0x_3 + x_2x_4 + x_1x_4x_5 + \\
&\quad + x_2x_6 + x_1x_3x_6 + x_0x_4x_6 + x_5x_6 + 1 \\
y_4 &= x_2x_3 + x_0x_4 + x_1x_3x_4 + x_5 + x_2x_5 + x_1x_2x_5 + \\
&\quad + x_0x_3x_5 + x_1x_6 + x_1x_5x_6 + x_4x_5x_6 + 1 \\
y_5 &= x_0 + x_1 + x_2 + x_0x_1x_2 + x_0x_3 + x_1x_2x_3 + x_1x_4 + \\
&\quad + x_0x_2x_4 + x_0x_5 + x_0x_1x_5 + x_3x_5 + x_0x_6 + x_2x_5x_6 \\
y_6 &= x_0x_1 + x_3 + x_0x_3 + x_2x_3x_4 + x_0x_5 + x_2x_5 + \\
&\quad + x_3x_5 + x_1x_3x_5 + x_1x_6 + x_1x_2x_6 + x_0x_3x_6 + x_4x_6 + x_2x_5x_6
\end{aligned} \tag{3.1}$$

$$\begin{aligned}
y_0 &= x_0x_4 + x_0x_5 + x_1x_5 + x_1x_6 + x_2x_6 + x_2x_7 + \\
&\quad + x_3x_7 + x_3x_8 + x_4x_8 + 1 \\
y_1 &= x_0x_2 + x_3 + x_1x_3 + x_2x_3 + x_3x_4 + x_4x_5 + x_0x_6 + \\
&\quad + x_2x_6 + x_7 + x_0x_8 + x_3x_8 + x_5x_8 + 1 \\
y_2 &= x_0x_1 + x_1x_3 + x_4 + x_0x_4 + x_2x_4 + x_3x_4 + x_4x_5 + \\
&\quad + x_0x_6 + x_5x_6 + x_1x_7 + x_3x_7 + x_8 \\
y_3 &= x_0 + x_1x_2 + x_2x_4 + x_5 + x_1x_5 + x_3x_5 + x_4x_5 + \\
&\quad + x_5x_6 + x_1x_7 + x_6x_7 + x_2x_8 + x_4x_8 \\
y_4 &= x_1 + x_0x_3 + x_2x_3 + x_0x_5 + x_3x_5 + x_6 + x_2x_6 + \\
&\quad + x_4x_6 + x_5x_6 + x_6x_7 + x_2x_8 + x_7x_8 \\
y_5 &= x_2 + x_0x_3 + x_1x_4 + x_3x_4 + x_1x_6 + x_4x_6 + x_7 + \\
&\quad + x_3x_7 + x_5x_7 + x_6x_7 + x_0x_8 + x_7x_8 \\
y_6 &= x_0x_1 + x_3 + x_1x_4 + x_2x_5 + x_4x_5 + x_2x_7 + x_5x_7 + \\
&\quad + x_8 + x_0x_8 + x_4x_8 + x_6x_8 + x_7x_8 + 1 \\
y_7 &= x_1 + x_0x_1 + x_1x_2 + x_2x_3 + x_0x_4 + x_5 + x_1x_6 + \\
&\quad + x_3x_6 + x_0x_7 + x_4x_7 + x_6x_7 + x_1x_8 + 1 \\
y_8 &= x_0 + x_0x_1 + x_1x_2 + x_4 + x_0x_5 + x_2x_5 + x_3x_6 + \\
&\quad + x_5x_6 + x_0x_7 + x_0x_8 + x_3x_8 + x_6x_8 + 1
\end{aligned} \tag{3.2}$$

### 3.5 Construction of equations system for MISTY1

MISTY1 is a 64-bit Feistel network similar to GOST 28147-89 and doesn't use any additional operations that are not described in 2.1, therefore construction of equations is performed similarly.

There are few differences however. Even though the transformations used in MISTY1 are resembling those of GOST 28147-89 its structure is much more complicated due to nested Feistel networks. Initially equations for each function are constructed and tested for correctness so that definition of each Feistel network is self-contained. Afterwards those equations are chained into single system as usually.

Since MISTY1 uses key scheduling, equations for this transformation also must be explicitly defined.

Nested structure of MISTY1 results in big number of variables so they must be named carefully to avoid confusion. The following format was used for MISTY1 variables:  $R_{<n>\_<func>\_<op>\_<bit>}$ , where  $n$  denotes number of current round,  $func$  stands for function to which variable belongs,  $op$  is some operation inside the function,  $bit$  is the number of bit in a block. For example variable  $R_{5\_F0\_K02\_15}$  denotes number of current round,  $func$  stands for function to which variable belongs,  $op$  is some operation inside the function,  $bit$  is the number of bit in a block. For example variable  $R_{5\_F0\_K02\_15}$  stands for round 5, function  $FO$ , operation of injecting subkey  $KO_{i2}$ , precisely bit 15 of the subkey.

Using the described method the full-scale system of equations for MISTY1 has been constructed and shown to have 3488 equations in 3680 variables. Because of nested structure too many variables are introduced and the system becomes underdefined and therefore unsolvable. To overcome such problem it is possible to apply Gröbner basis (described in 2.2.1) to some transformation for obtaining more equations and possibly eliminating some of the variables. It has been decided to post-process equations for S-box  $S_7$  by computing the corresponding Gröbner basis. The resulting system has 8448 equations in 3680 variables, so usage of Gröbner basis introduced another 5000 equations.



### 3.5.1 Key recovery for 2 rounds of MISTY1

For the attack 4 systems of equations for distinct plaintext/ciphertext pairs have been combined in order for the number of known values to reach the unicity distance.

With the use of **CryptoMiniSat** solver on a low-end computer an equations system for two MISTY1 rounds have successfully been solved and the used subkeys recovered. For the system of 4 rounds equivalent keys can be obtained for a given plaintext/ciphertext pair.

Further combinations of Gröbner basis technique with SAT-solvers and usage of powerful computers may refine the efficiency of the attack and provide more capabilities for analyzing properties of the cryptoalgorithm.

## 3.6 Summary

The chapter provides description of constructing systems of non-linear equations for cryptoalgorithms GOST 28147-89 and MISTY1 that are based on Feistel network and some approaches for solving the obtained equations set.

Gröbner basis method generally is not efficient enough for solving full-scale equations system but is useful for obtaining exhaustive list of linearly independent equations for given transformation. It is especially beneficial for S-box equations.

With advance of SAT-solver algorithms they become efficient enough for solving large equations sets and with the help of powerful computers it might be possible to solve system of equations for some full-scale cipher. The downside of such algorithms is their nondetermination and therefore no guarantee of average run time for given instance. This exaggerates complexity evaluation of solving given equations set and one can only predict the overall complexity of the problem based on preliminary characteristics of equations set (degree, number of equations and variables, etc.) and estimate the possibility of its solving but cannot bind these factors to some certain time complexity of the attack.

Using the proposed methods for defining symmetric ciphers with equations set, polynomial system for MISTY1 has 8448 equations in 3680 variables and the system for GOST 28147-89 has 10432 equations in 4416 variables. For comparison, the polynomial system for the PRESENT cipher that is designed for lightweight cryptography purposes contains 11067 quadratic equations in 4216 variables [43]. Even though PRESENT has very simple structure, its equations system is larger. But also PRESENT has much smaller key space and requires more space for hardware implementation. It is claimed that AES cipher can be described with an algebraic system of 8000 quadratic equations in 1600 unknowns [44] which is significantly smaller than the GOST 28147-89 or MISTY1 equations system. An equations set for symmetric block cipher Camellia contains 6224 equations in 3584 variables [45].

## 4 DESCRIPTION OF DEVELOPED METHODS FOR SOFTWARE IMPLEMENTATION

### 4.1 Tools and software used for computations

All computations in this thesis are performed using only free open source software. The computer algebra system used for algorithm implementations and experiments is “SAGE: Software for Algebra and Geometry Experimentation” which is provided under the terms of the GNU General Public License [46]. SAGE is described as a “free and open software that supports research and teaching in algebra, geometry, number theory, cryptography, etc.” [47].

For this thesis the most used components of SAGE were Singular computer algebra system [48], PolyBoRi C++ library for efficient reduced Gröbner basis computation [49], and `crypto` module for cryptography related routines.

The implementation architecture of GOST 28147-89 cipher and its equation system generator is inspired by CTC cipher algebraic cryptanalysis description in [32].

Computation of solutions for multivariate algebraic systems of equations is performed by CryptoMiniSat [41], a SAT Race 2010 [50] winning SAT solver licensed under GNU Lesser General Public License.

Conversion of the polynomial system from ANF to CNF format and parsing the results of CryptoMiniSat computations is done by `anf2cnf.py` script [51].

### 4.2 Usage of implemented functionality

#### 4.2.1 GOST 28147-89 implementation

The `Gost` class implements GOST 28147-89 cryptographic algorithm and its multivariate quadratic equation system generator. The implementation is not efficient since it treats every bit as a boolean polynomial ring element, so

it is useful for researching purposes only.

One can customize GOST 28147-89 parameters (like input block size, number of rounds, key addition mode and subkeys ordering) to get small scale cipher. A cipher instance compliant with the specification defined in the standard may be constructed as shown in listing 4.1:

Listing 4.1: Creating GOST instance

```

1 sage: gost = Gost(block_size=64, rounds=32, key_add='mod', key_order='
    frwrev')
2 sage: print Gost()
3 GOST cipher (Block Size = 64, Rounds = 32, Key Addition = mod, Key Order
    = frwrev)

```

Those parameters are default and so may be omitted. To create the small scale version of GOST 28147-89 one can specify smaller values for parameters (listing 4.2):

Listing 4.2: Small scale GOST

```

1 sage: gost = Gost(block_size=8, rounds=3, key_add='mod', key_order='frw'
    )
2 sage: print gost.ring
3 Boolean PolynomialRing in K00, K01, K02, K03, Y00, Y01, Y02, Y03, Z00,
    Z01, Z02, Z03, K10, K11, K12, K13, Y10, Y11, Y12, Y13, Z10, Z11, Z12,
    Z13, K20, K21, K22, K23, Y20, Y21, Y22, Y23, Z20, Z21, Z22, Z23, X00
    , X01, X02, X03, X04, X05, X06, X07, X10, X11, X12, X13, X14, X15,
    X16, X17, X20, X21, X22, X23, X24, X25, X26, X27, X30, X31, X32, X33,
    X34, X35, X36, X37

```

Cipher variables are defined over boolean polynomial ring. The used notation is described in section 2.1.3. In SAGE implementation left digits of the variable index identify round number and right digits specify the number of bit defined by the variable. For instance, variable K0325 defines 25-th bit of a subkey for round 3. It is worth noting that for small block sizes the cyclic shift value is proportionally decreased from 11 bits to  $\text{ceil}(\text{block\_length}/3)$ , where  $\text{ceil}(x)$  stands for the smallest integer not less than  $x$ . The minimum block size is 8 bits since the cipher becomes degenerated with smaller input blocks. There are two possible modes for key addition: **mod** for a standard modular addition and **xor** for simple XORing. Also two subkey orderings are supported: **frwrev** is for the default ordering when subkeys are reversed on the last 8 rounds and **frw** for no reversing. Default S-boxes used in the cipher are those proposed in GOST R 31.11-94 [40] and given in appendix E.

Obtaining polynomial system for the cipher is shown in listing 4.3:

Listing 4.3: Obtaining polynomial system

```

1 sage: gost = Gost()
2 sage: gost.polynomial_system()
3 Polynomial Sequence with 10432 Polynomials in 4416 Variables

```

## 4.2.2 MISTY1 implementation

The `Misty` class implements MISTY1 cryptographic algorithm and its multivariate equations system generator. Its interface is similar to that one of GOST 28147-89. The implementation is not efficient since it treats every bit as a boolean polynomial ring element, so it is useful for researching purposes only.

A required parameter is the number of rounds for the cipher which should be multiple of 4 according to the specification. An optional argument is a prefix that will be prepended to the names of variables for the equations system. This is used when combining several systems.

An instance of MISTY1 polynomial system generator may be created as shown in listing 4.4.

Listing 4.4: Creating MISTY1 instance

```

1 sage: m = Misty(8)
2 sage: m.polynomial_system()
3 Polynomial Sequence with 8448 Polynomials in 3680 Variables

```

A decorator `@groebner_basis` for post-processing the equations via Gröbner basis is implemented and should decorate every function, for which equations the Gröbner basis should be computed as show on listing 4.5).

Listing 4.5: Misty Gröbner basis

```

1 @groebner_basis
2 def s7(self, x, r=None):
3     y = [0] * len(x)
4     ...

```

### 4.2.3 Solving polynomial systems

Obtaining an equation system for the cipher is not enough for recovering an encryption key. Information about plaintext and ciphertext has to be injected into equation system by substituting corresponding variables. Also a single equation system for the specified plaintext and ciphertext does not allow to get a solution for the key variables, so an ability to combine several equation systems with different plaintext and ciphertext pairs is needed.

Injecting variable values is implemented by adding new `inject` method to a standard `PolynomialSequence_generic` class and is shown in listing 4.6.

Listing 4.6: Injecting variable values into equation system

```

1  sage: gost = Gost(block_size=64, rounds=5, key_add='mod', key_order='frw
    ')
2  sage: plaintext = gost.random_block()
3  sage: key = gost.random_key()
4  sage: ciphertext = gost.encrypt(plaintext, key)
5  sage: f = gost.polynomial_system()
6  sage: print f
7  Polynomial Sequence with 1630 Polynomials in 864 Variables
8  sage: f2 = f.inject(gost.gen_vars(gost.var_names['block'], 0), plaintext
    )
9  sage: f2 = f2.inject(gost.gen_vars(gost.var_names['block'], 5),
    ciphertext)
10 sage: print f2
11 Polynomial Sequence with 1630 Polynomials in 736 Variables

```

For combining several equation systems one should use `join_systems` function (listing 4.7) which accepts a list of polynomial systems with injected known variables and a list of cipher instances for which the systems were constructed. The function will construct a new boolean polynomial ring that would include variables from all systems and have the same variables for encryption subkeys. Consequently, the joined equation systems must contain ciphertexts obtained on the same key, otherwise combining such systems would not help to find the solution. In order to distinct variables from different equation systems one should add a `prefix` string when constructing a cipher object as shown in listing 4.7.

Listing 4.7: Combining several equation systems

```

1  sage: gost1 = Gost(block_size=64, rounds=3, key_add='mod', key_order='
    frw', prefix='a')

```

```

2  sage: gost2 = Gost(block_size=64, rounds=3, key_add='mod', key_order='
    frw', prefix='b')
3  sage: plaintext1 = gost1.random_block()
4  sage: plaintext2 = gost1.random_block()
5  sage: key = gost1.random_key()
6  sage: ciphertext1 = gost1.encrypt(plaintext1, key)
7  sage: ciphertext2 = gost2.encrypt(plaintext2, key)
8  sage: f1 = gost1.polynomial_system()
9  sage: f2 = gost2.polynomial_system()
10 sage: f1 = f1.inject(gost1.gen_vars(gost1.var_names['block'], 0),
    plaintext1)
11 sage: f1 = f1.inject(gost1.gen_vars(gost1.var_names['block'], 5),
    ciphertext1)
12 sage: f2 = f2.inject(gost2.gen_vars(gost2.var_names['block'], 0),
    plaintext2)
13 sage: f2 = f2.inject(gost2.gen_vars(gost2.var_names['block'], 5),
    ciphertext2)
14 sage: f = join_systems([f1, f2], [gost1, gost2])
15 sage: print f1
16 Polynomial Sequence with 978 Polynomials in 416 Variables
17 sage: print f2
18 Polynomial Sequence with 978 Polynomials in 416 Variables
19 sage: f1 == f2
20 False
21 sage: f = join_systems([f1, f2], [gost1, gost2])
22 sage: print f
23 Polynomial Sequence with 1956 Polynomials in 736 Variables

```

All functionality for solving the GOST 28147-89 and MISTY1 polynomial systems is now implemented. Two approaches are used for solving equation systems: using reduced Gröbner basis and using SAT solver.

In listing 4.8 computing the reduced Gröbner basis for polynomial system is demonstrated. Since all equations in the resulting list equal 0 it is possible to extract the values of the key bits. In this case the method allowed to recover only 91 out of 96 subkeys bits for a 3 round GOST polynomial system.

Listing 4.8: Solving equation system using reduced Gröbner basis

```

1  sage: ideal = f.ideal()
2  sage: basis = ideal.interreduced_basis()
3  sage: print basis
4  Polynomial Sequence with 735 Polynomials in 736 Variables
5  sage: key = [i for i in sorted(basis) if str(i).startswith(gost1.
    var_names['key'])]
6  sage: print key
7  [K0229, K0228, K0221, K0220, K0223 + 1, K0222, K0225, K0224, K0227 + 1,
    K0226, K0131, K0130, K0001, K0000 + 1, K0003, K0002, K0005 + 1, K0004
    , K0007, K0006, K0009 + bY0009, K0008, K0230 + 1, K0231 + 1, K0126 +
    1, K0127 + 1, K0124 + 1, K0125, K0122, K0123, K0120 + bY0009, K0121 +
    bY0009 + 1, K0128, K0129 + 1, K0012 + 1, K0013, K0010 + 1, K0011 +
    1, K0016, K0017, K0014 + 1, K0015, K0018, K0019 + 1, K0203 + 1, K0202
    + 1, K0201 + 1, K0200 + 1, K0207 + 1, K0206, K0205 + 1, K0204 + 1,
    K0209 + 1, K0208 + bY0009 + 1, K0119 + bY0009, K0118, K0117, K0116,
    K0115 + 1, K0114, K0113, K0112, K0111 + 1, K0110 + 1, K0029 + 1,
    K0028, K0023 + 1, K0022, K0021 + 1, K0020, K0027, K0026 + 1, K0025 +

```

```
1, K0024, K0218 + 1, K0219 + 1, K0214, K0215, K0216 + 1, K0217, K0210
, K0211, K0212 + 1, K0213 + 1, K0108, K0109 + 1, K0100 + 1, K0101 +
1, K0102, K0103, K0104, K0105 + 1, K0106, K0107, K0030, K0031]
```

For solving an equation system  $f$  with CryptoMiniSat solver via SAGE one needs to install CryptoMiniSat available at [41] first. Then use `anf2cnf.py` script provided at [51] for converting the polynomial system to DIMACS CNF format, call CryptoMiniSat for solving the system and parse the result back into SAGE as shown in listing 4.9. In the example the  $s$  variable will store a solution dictionary and  $t$  will be initialized by the time needed for computation.

Listing 4.9: Solving equation system using SAT solver

```
1 sage: solver = ANFSatSolver(f.ring())
2 sage: s, t = solver(f)
```

CryptoMiniSat solver is more efficient and allows to solve a 6 round GOST equation system on regular laptop with 2 GHz processor in minutes (listing 4.10). Some code is omitted for clarity and is indicated with dots. Full source code for solving 6 rounds polynomial system is presented in appendix B.

Listing 4.10: Solving 6 round GOST system using SAT solver

```
1 ...
2 sage: f = join_systems(mqsystems, gosts)
3 sage: solver = ANFSatSolver(f.ring())
4 sage: print time.ctime(); s, t = solver(f); print time.ctime();
5 Sat May 12 22:13:00 2012
6 Sat May 12 22:13:41 2012
7 ...
8 sage: print key == recovered_key
9 True
10 sage: print gosts[0].encrypt(inputs[0], key) == gosts[0].encrypt(inputs
    [0], recovered_key) == outputs[0]
11 True
```

The MISTY1 equations system may be solved using Sage interface to available SAT-solvers (listing 4.11).

Listing 4.11: Using Sage SAT interface

```
1 sage: from sage.sat.boolean_polynomials import solve as sat_solve
2 sage: m = Misty(4)
3 sage: F = m.polynomial_system()
4 sage: print F
5 Polynomial Sequence with 5156 Polynomials in 2248 Variables
```



### 4.3 Summary

Due to multiple interfaces supported by SAGE it is possible to efficiently combine various tools for achieving optimal results. In this work the interface to Singular has been used for computing reduced Gröbner basis which managed to solve 3 round GOST equation system. CryptoMiniSat solver with `anf2cnf.py` as a conversion layer enabled 6 round equation system to be efficiently solved in minutes. There is a substantial complexity hop for computing 7 rounds, but even though the solution hasn't been found using regular computer, the memory usage is negligible. So further optimizations including parallelizing and tweaking SAT algorithm parameters should result in solving more rounds for GOST 28147 polynomial system.

Current source code of the GOST 28147-89 and MISTY1 polynomial system generator is published by the author at [52] and the thesis sources are published at [53].

## 5 LABOUR PROTECTION AND SAFETY IN EMERGENCIES

PC users working conditions are analyzed for their compliance with normative documents on safety engineering and sanitation. For retrieving and evaluating the influence of possible dangerous or harmful production factors an interaction system “Human–Machine–Environment” (HME) is developed. Safety measures are developed as the result of such system analysis.

### 5.1 Analysis of the workplace working conditions

The administrative building in which the workspace is located situates on the first floor and has dimensions  $6 \times 5.6 \times 3$  m.

There are three workers in the office that use the following equipment:

- Personal computer, 3 pieces;
- LCD monitor, 3 pieces.;
- Printer;
- Monitor.

There are also two windows 1.5 m wide and 1.7 m tall and doors 2.1 m tall and 0.9 m wide. The analysis of the workspace indicates that the office has sufficient area ( $6 \text{ m}^2$ ) and volume ( $20 \text{ m}^3$ ) per worker and is compliant with the sanity standard [54] for working with electronic computer displays (figure 5.2).

The “Human–Machine–Environment” system (figure 5.1) is created with the intention to retrieve possible dangerous and harmful production factors [55]. The list of H–M–E system connections is shown in table 5.2. Its main elements are:

- “Human” — staff that works in the office (2 workers);
- “Machine” — electronic computers;
- “Environment” — workspace environment;
- “Product” — product of the algebraic cryptanalysis task solution.

Each element of the system contains three functional parts. Thereby the “Human” element is split by:

- $H_1$  — execution of certain actions targeted on the main task solution;
- $H_2$  — human as a biological object influencing the environment;

$H_3$  — human from the point of view of her psychophysiologic condition. The main goal of the “Machine” element is influencing the product — execution of the primary technological function. Its auxiliary functions are to generate particular environment parameters and execute emergency surveillance.

$M_1$  — execution of the primary technological function (performing computations using SAGE algebra system, construction and analysis of algebraic quadratic system that defines the GOST 28147-89 cipher);

$M_2$  — emergency protection support;

$M_3$  — influencing the human and the environment.

Table 5.1 — Human–Machine–Environment system connections

Index	Connection direction	Essence of the connections
1	$H_1 \rightarrow M_1$	Human controls equipment providing its correct functioning (operating on computer using peripheral input devices).
2	$M_1 \rightarrow \text{Prod}$	Machine influence on the product (construction of the cryptographic transformation model, research computations).
3	$H_1 \leftrightarrow \text{Prod}$	Human influence on the product and backwards (human is the source of ideas that defines needed actions during the work and analysis the working process; depending on the project complexity and accomplishment success causes mental strain for the workers).
4	$H_2 \rightarrow \text{Env}$	Human influence on the environment (generation of heat and humidity, temperature increase).
5	$\text{Env} \rightarrow H_3$	Environment influence on human health (the psychophysiologic condition working capacity depends on the environment conditions).

Proceeding table 5.1

6	$\text{Prod} \rightarrow H_3$	Product influence on human (complexity and execution progress of the primary task influence the human physical condition).
7	$M_3 \rightarrow \text{Env}$	Machine influence on environment (computer is the source of increased temperature, noise, ionizing and electromagnetic emission).
8	$H_1 \rightarrow H_3$	The working activity influences human psychophysiologic condition (human psychophysiologic condition depends on the success and amount of the completed work).
9	$H_3 \rightarrow H_2$	Influence of psychophysiologic condition on human biological processes density (fatigue, irritability, euphoria).
10	$H_1 \rightarrow M_3$	Human control of the machine influence on environment (normalization of harmful emission, humidity and temperature control).
11	$\text{Env} \rightarrow M_2$	Environment influence on emergency protection abilities (unfavourable environment parameters may lead to insufficient emergency protection).
12	$H_3^* \leftrightarrow H_3^*$	Reciprocal influence of each human's psychophysiologic conditions.
13	$M_1^* \leftrightarrow M_1^*$	Mutual influence of machine side emissions.

Based on the analysed connections harmful and dangerous production factors may be retrieved according to [56]. The following harmful factors are found:

- physical:
  - a) increased electromagnetic emission;
  - b) increased equipment surface temperature;
  - c) reduced air humidity;
- chemical: absent;
- biological: absent;
- psychophysiologic:

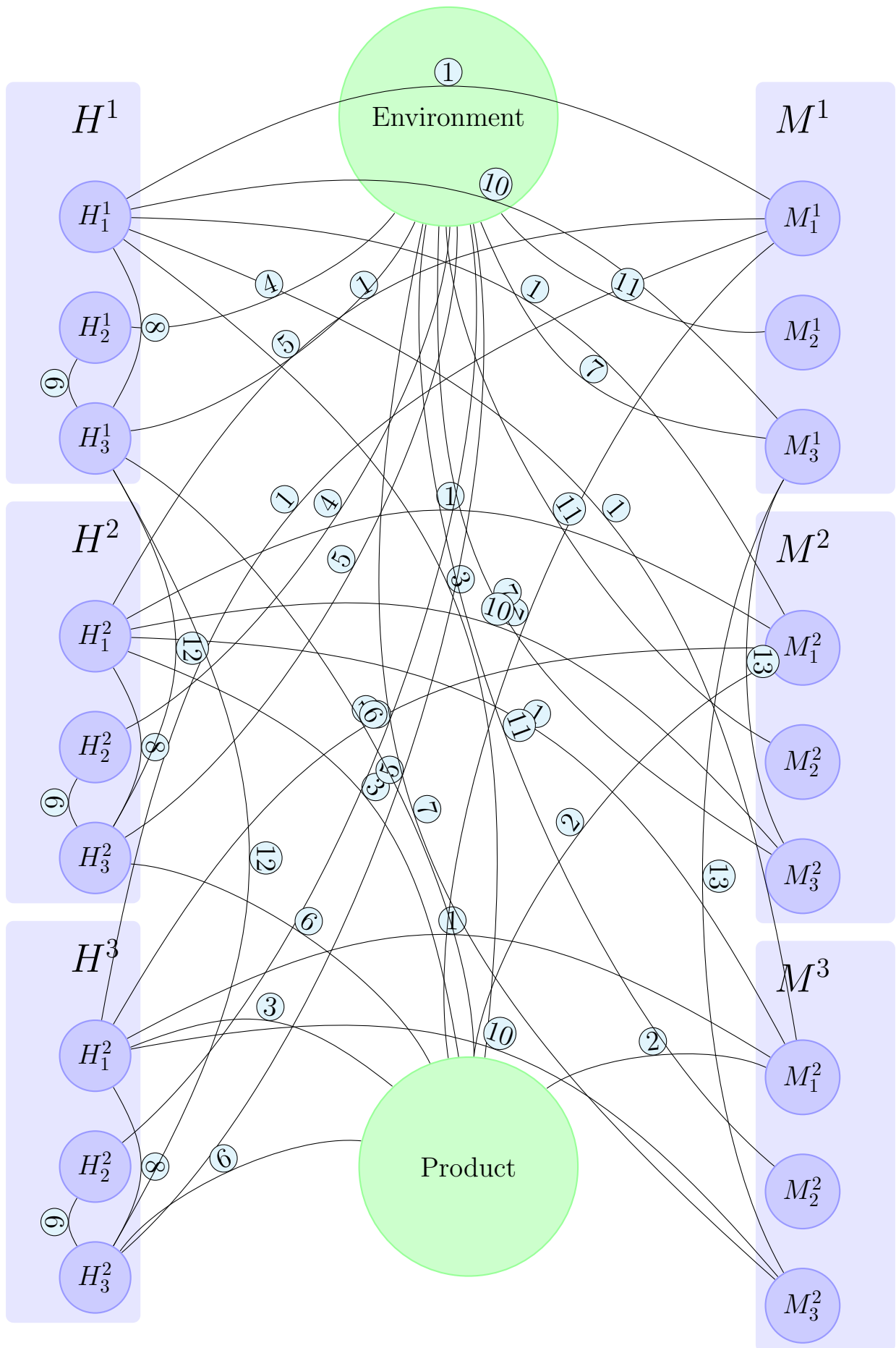


Figure 5.1 — H-M-E system scheme

- a) mental overstress;
- b) overstress of analyzers.

Reduced air humidity is the dominant harmful factor.

Table 5.2 — Evaluation for factors of working environment

Factors	Norm	Fact	1 st.	2 st.	3 st.	duration, % for working shift
Noise	50	49				93
Non-ionising radiation						
5 Hz – 2 kHz	25	less 25				93
2 kHz – 400 kHz	2.5	less 2.5				93
X-ray radiation	less 100	14				93
Micro climate						
Air temp.	22-24 23-25	31.5		+		100
Air movement	0.1 0.1	less 0.1				100
Relative humidity	60-40 60-40	less 65				100
Light						
Natural	1.2	1.2				93
Artificial light	200- 500	370				93
Work intensity						
Attention						
Duration of concentration	25-50	48				48
Signals density	75-175	less 75				93
Density of analyzers						
Eyesight	2-3	3				93

Proceeding table 5.2

Hearing	unders. words 70– 90 %	3				93
Emot. & Intel. density	Resp. for func. qual- ity	Resp. for per- form. tasks				93
Repetitive routines						
Repetitive tasks	100-25	100-25				93
Observ. process	46-80	80				80
Shifts		day				
No. fuctors	9					

The exceeding factor is air temperature. During the working process of the staff because of heat emission the temperature raises to 31.5° C (3 cl. 2 st.) and is harmful for health of the staff. For normalizing the air temperature conditioning system must be set up with precomputed parameters.

## 5.2 Industrial security in production building

Considering the electrical equipment located in the office, organizational and technical countermeasures for protecting workers' safety need to be applied. The workspace belongs to the class of increased fire threat according to [57].

The building power supply is three-phased four-wired electric network with dead-earthed neutral, alternating current, 50 Hz frequency and 380/220 V voltage. Neutral grounding of the equipment is done for providing electrical security according to [58]. The current threshold for automatic overload control exceeds the maximum equipment current consumption 5 times. Triggering time of the overload controller does not exceed 0.2 s.

### 5.3 Labour health at the workplace

According to [54] microclimate the standards for given room that corresponds to power inputs category Ia are shown in table 5.3.

Table 5.3 — Microclimate standards

Season	Air temp., °C	Rel. humid., %	Air movement, m/s
Cold	22-24	60-40	0.1
Hot	23-25	60-40	0.1

For providing the expected climate conditions an air conditioning system needs to be set up in the room. For computing the required parameters of air conditioning system one needs to compute the heat coming into the room from sunlight, artificial light, humans and equipment.

Sources of heat are split into:

$Q_1$  — heating from environment;

$Q_2$  — heating from humans;

$Q_3$  — heating from equipment.

Overall heating is computed by the formula  $Q = Q_1 + Q_2 + Q_3$ . Input heat from environment is computed as follows:

$$Q_1 = (S \cdot h \cdot q)/1000, \quad (5.1)$$

where  $S$  – room area,  $h$  – height of the room,  $q$  – load unit (when mean lightning is  $35 \text{ W}/\text{m}^2$ ). Heat income from humans is estimated as 0.13 kW. Heat income from a PC is estimated in 0.3 kW. Heating income from printer is neglectful. According to these factors the overall heating input equals:

$$Q = Q_1 + Q_2 + Q_3 = (33.6 \cdot 3 \cdot 35)/1000 + 0.13 \cdot 3 + 0.3 \cdot 3 = 4.87 \text{ kW} . \quad (5.2)$$

Power of conditioning system must be in the range  $-5\% - +15\%$  from computed power  $Q$ . So in order to provide the required climate conditions in the room the conditioning system with power 4.87 kW must be installed. According to conditioning power catalogue the most satisfying model is Panasonic CS-E18MKDW with power of 5 kW.



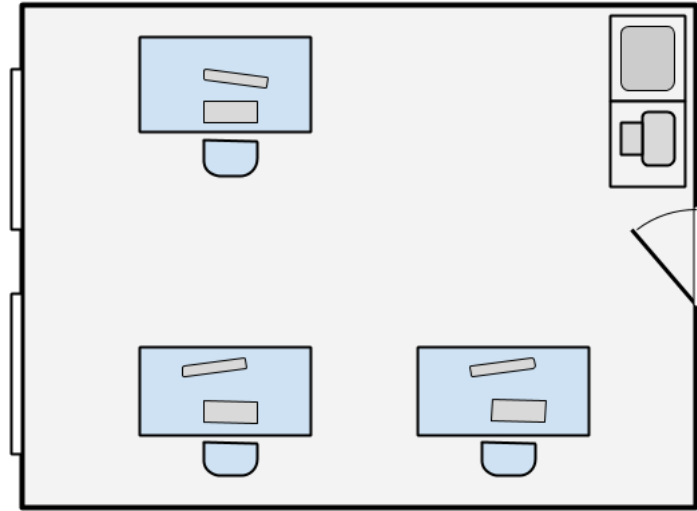


Figure 5.2 — Workstations location in the room

#### 5.4 Fire safety of the production building

Solid ignitable materials are used in the room, the building has brick walls and armoured concrete floor. Therefore the building belongs to 2-nd fire resistance ratio according to [59], production belongs to category B of flammability and explosion risk according to [60].

Pursuant to [61] the building must have two fire extinguishers with up to 6 kg of reactant or one fire extinguisher with at least 8 kg of reactant. Any type of fire extinguishers fits for the category B building.

Evacuation plans that are located in every room and in corridors allow to efficiently leave the building in case of fire through the main exit of 1.9 m high and 1.2 m wide. Two employees work at the office with area of 25 m<sup>2</sup>. Therefore no extra emergency exit is needed. The fire and explosion safety requirements are satisfied.

## CONCLUSIONS

As global shift to portable devices usage spawned demand for very efficient and also secure cryptographic primitives, efficient methods for comprehensive security evaluation of perspective ciphers are required. Current usage of insecure ciphers in various fields of information technologies proves the importance of careful ciphers security evaluation before deploying them into real systems.

The accomplished work resulted in development of methods for defining most widely used cryptographic primitives with system of non-linear equations. The techniques of obtaining equations for bit permutations, modular addition, some logical operations and S-boxes should allow to construct full-scale non-linear equations systems for most modern symmetric ciphers. Best approaches for solving the obtained equations sets are described and allow to solve reduced round versions of analyzed ciphers, research algebraic properties of individual transformations on low-end computers. Usage of resources with more computational power will increase feasibility of full-scale cipher analysis.

As the result of the work software tools for computational algebra that provide needed functionality are described and reference implementation for defining individual transformations with non-linear equations and constructing full-scale system of equations for modern symmetric ciphers is provided.

An algebraic equation system describing GOST 28147-89 cipher and obtained using the suggested method contains 10432 polynomials in 4416 variables. MISTY1 cipher is described with 8448 equations in 3680 variables using the same method. Number of equations and variables in GOST 28147-89 system is resembling that of PRESENT and MISTY1 equations set is larger than that of AES (3680 variables in MISTY1 against 1600 variables in AES).

Using the described techniques it is possible to solve a 6 round GOST 28147-89 polynomial system with 4 pairs of plaintexts and ciphertexts at the moment. Thereby the reduced GOST 28147-89 algorithm using 160 out of 256 key bits is broken by an algebraic attack. Such statistics strengthens the opinion about AES vulnerability to algebraic attacks. The algebraic

attack on MISTY1 is performed. The equations system for two cipher round could be solved and equivalent keys for a given plaintext/ciphertext pair could be found for up to 4 rounds. Solving these systems of equations for additional rounds requires more computation power, however finding the solution may be possible on more efficient hi-end computers. All computations have been executed on **Intel Core i5-3570** CPU at 3.40 GHz with 8 Gb RAM.

The nondetermination of SAT-solver algorithms do not allow to bind characteristics of obtained equations set (like its degree, number of equations and variables, etc.) to some certain time complexity of solving the given system. However these factors may be used to estimate the feasibility of solving the system and rationality of allocating processing time for analysis.

Also algebraic analysis in combination with other known cryptanalytic methods (linear, differential, integral, etc.) proved to be efficient enough for security evaluation of a cipher [26]. Considering this practice algebraic analysis may increase the significance of investigating baby-ciphers that are shrunk versions of original cryptoalgorithms, so such approach is a subject for future researches.

For labour protection the employee working conditions are analysed for their compliance with normative documents on safety engineering and sanitation. Harmful and dangerous production factors are retrieved and evaluated using the built “Human–Machine–Environment” interaction system. Corresponding safety measures are developed in order to provide favourable working conditions.

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## APPENDIX A

### GOST 28147-89 EQUATIONS GENERATOR

```

1  from copy import deepcopy
2  from sage.crypto.mq.sbox import SBox
3  from sage.rings.polynomial.multi_polynomial_sequence import
   PolynomialSequence
4  from sage.rings.polynomial.multi_polynomial_sequence import
   PolynomialSequence_generic
5
6
7  def inject(self, vars, values):
8      sub_values = dict(zip(vars, values))
9      return self.subs(sub_values)
10 PolynomialSequence_generic.inject = inject
11
12 def join_systems(mqsystems, instances):
13     var_names = flatten([i.ring.variable_names() for i in instances])
14     common_vars = list(set(var_names))
15     common_ring = BooleanPolynomialRing(len(common_vars), common_vars, \
16                                         order='degrevlex')
17     new_mqsystem = PolynomialSequence([], common_ring)
18     for s in mqsystems:
19         new_mqsystem.extend(list(s))
20     return new_mqsystem
21
22
23 class Gost:
24     def _varformatstr(self, name):
25         l = str(max([len(str(self.nrounds)), len(str(self.block_size -
26         1))]))
27         return name + "%0" + l + "d" + "%0" + l + "d"
28
29     def _varstrs(self, name, round):
30         s = self._varformatstr(name)
31         if s.startswith(self.var_names['block']):
32             return [s % (round, i) for i in range(self.block_size)]
33         else:
34             return [s % (round, i) for i in range(self.halfblock_size)]
35
36     def gen_vars(self, name, round_):
37         return [self.ring(e) for e in self._varstrs(name, round_)]
38
39     def int2bits(self, num, bits):
40         num = Integer(num)
41         return num.digits(base=2, padto=Integer(bits))
42
43     def bits2int(self, num_bits):
44         num = ''.join([str(i) for i in reversed(num_bits)])
45         return int(num, 2)
46
47     def __init__(self, **kwargs):
48         self.SBOX_SIZE = 4
49         self.nrounds = kwargs.get('rounds', 32)
50         if self.nrounds < 8:
51             self.key_length = self.nrounds

```

```

52         if self.nrounds % 8 != 0:
53             raise ValueError('Number of rounds must be multiple of 8
    ')
54         self.key_length = 8
55         self.block_size = kwargs.get('block_size', 64)
56         if self.block_size % self.SBOX_SIZE != 0 or self.block_size < 8:
57             raise ValueError('Block size must be multiple of 4
58                 (due to SBox) and greater than 8 (due S-box size)')
59         self.halfblock_size = self.block_size / 2
60         self.key_order = kwargs.get('key_order', 'frwrev')
61         if self.key_order not in ['frw', 'frwrev']:
62             raise ValueError('Unsupported key ordering')
63         if self.key_order is 'frwrev' and self.nrounds % 8 != 0:
64             raise ValueError('frwrev key ordering is only possible
65                 for nrounds to be multiple of 8')
66         self.key_add = kwargs.get('key_add', 'mod')
67         if self.key_add not in ['mod', 'xor']:
68             raise ValueError('key_add may be set to 'mod' or 'xor')
69
70         self._init_sboxes(kwargs.get('sboxes', None))
71         pre = kwargs.get('prefix', '')
72         self.var_names = {'key': 'K',
73             'block': pre + 'X',
74             'sum': pre + 'Y',
75             'sbox': pre + 'Z'}
76         self.gen_ring()
77
78     def _init_sboxes(self, sboxes):
79         self._default_sboxes = [
80             [4, 10, 9, 2, 13, 8, 0, 14, 6, 11, 1, 12, 7, 15, 5, 3],
81             [14, 11, 4, 12, 6, 13, 15, 10, 2, 3, 8, 1, 0, 7, 5, 9],
82             [5, 8, 1, 13, 10, 3, 4, 2, 14, 15, 12, 7, 6, 0, 9, 11],
83             [7, 13, 10, 1, 0, 8, 9, 15, 14, 4, 6, 12, 11, 2, 5, 3],
84             [6, 12, 7, 1, 5, 15, 13, 8, 4, 10, 9, 14, 0, 3, 11, 2],
85             [4, 11, 10, 0, 7, 2, 1, 13, 3, 6, 8, 5, 9, 12, 15, 14],
86             [13, 11, 4, 1, 3, 15, 5, 9, 0, 10, 14, 7, 6, 8, 2, 12],
87             [1, 15, 13, 0, 5, 7, 10, 4, 9, 2, 3, 14, 6, 11, 8, 12]
88         ]
89         if not sboxes:
90             sboxes = self._default_sboxes
91         else:
92             for s in sboxes:
93                 if len(s) != 2 ^ self.SBOX_SIZE:
94                     raise TypeError('S-box must be 4x4 bits (0..15)')
95         self.sboxes = [SBox(i, big_endian=False) for i in sboxes]
96
97     def gen_ring(self):
98         nr = self.nrounds
99         bs = self.block_size
100         hbs = self.halfblock_size
101         var_names = []
102         halfblock_vars = [self.var_names['key'], \
103             self.var_names['sum'], \
104             self.var_names['sbox']]
105         for r in range(nr):
106             var_names += [self._varformatstr(v) % (r, b)
107                 for v in halfblock_vars for b in xrange(hbs)]
108         for r in range(nr + 1):
109             var_names += [self._varformatstr(self.var_names['block']) %
    (r, b)

```

```

110         for b in xrange(bs)]
111     self.ring = BooleanPolynomialRing(len(var_names), var_names, \
112                                     order='degrevlex')
113     return self.ring
114
115     def polynomial_system(self):
116         hbs = self.halfblock_size
117         mqs_system_parts = []
118
119         kvars = list()
120         for i in range(self.key_length):
121             kvars.append(map(self.ring, \
122                             self.gen_vars(self.var_names['key'], i)))
123
124         for i in range(self.nrounds):
125             xvars = map(self.ring, self.gen_vars(self.var_names['block'
126 ], i))
127             yvars = map(self.ring, self.gen_vars(self.var_names['sum',
128 i]))
129             zvars = map(self.ring, self.gen_vars(self.var_names['sbox',
130 i]))
131             next_xvars = map(self.ring, \
132                             self.gen_vars(self.var_names['block'], i + 1))
133             polynomials = []
134
135             if self.key_order == 'frwrev' and \
136                 i >= (self.nrounds - self.key_length):
137                 k = self.key_length - 1 - (i % self.key_length)
138             else:
139                 k = i % self.key_length
140             polynomials += self.add_round_key(xvars[:hbs], kvars[k],
141 yvars)
142             polynomials += self.polynomials_sbox(yvars, zvars)
143             zvars = self.shift(zvars)
144             xored = self.xor_blocks(xvars[hbs:], zvars)
145             if i < self.nrounds - 1:
146                 #  $R_{i+1} = L_i \text{ xor } f(R_i)$ 
147                 polynomials += [x + y for x, y in zip(xored, \
148                                                         next_xvars[:hbs
149 ]))]
150                 #  $L_{i+1} = R_i$ 
151                 polynomials += [x + y for x, y in zip(xvars[:hbs], \
152                                                         next_xvars[hbs
153 :])]
154             else:
155                 # No block swapping in the last round.
156                 #  $R_{i+1} = L_i$ 
157                 polynomials += [x + y for x, y in zip(xvars[:hbs], \
158                                                         next_xvars[:hbs
159 ]))]
160                 #  $L_{i+1} = L_i \text{ xor } f(R_i)$ 
161                 polynomials += [x + y for x, y in zip(xored, \
162                                                         next_xvars[hbs
163 :])]
164             mqs_system_parts.append(polynomials)
165         return PolynomialSequence(mqs_system_parts, self.ring)
166
167     def polynomials_sbox(self, yvars, zvars):
168         polynomials = list()
169         sboxes = deepcopy(self.sboxes)

```

```

162         for i in range(self.halfblock_size / self.SBOX_SIZE):
163             nbit = i * self.SBOX_SIZE
164             current_sbox = sboxes[i % len(sboxes)]
165             polys = current_sbox.polynomials()
166             gens = current_sbox.ring().gens()
167             new_gens = yvars[nbit:nbit + self.SBOX_SIZE] + \
168                 zvars[nbit:nbit + self.SBOX_SIZE]
169             sub = dict(zip(gens, new_gens))
170             polys = [p.subs(sub) for p in polys]
171             polynomials += polys
172         return polynomials
173
174     def __repr__(self):
175         gost_id = 'GOST cipher '
176         gost_id += '(Block Size = %d, Rounds = %d, '
177         gost_id += 'Key Addition = %s, Key Order = %s)'
178         params = (self.block_size, self.nrounds, self.key_add, self.
key_order)
179         return gost_id % params
180
181     def add_round_key(self, a, b, r=[]):
182         hbs = self.halfblock_size
183         is_defined = lambda vals: all([p.constant() for p in vals])
184         # If all variables are defined, just compute the result instead
of
185         # generating polynomials.
186         if is_defined(a) and is_defined(b):
187             if self.key_add is 'mod':
188                 data = self.bits2int(a)
189                 subkey = self.bits2int(b)
190                 modulo_mask = (1 << hbs) - 1
191                 result = (data + subkey) & modulo_mask
192                 return [self.ring(i) for i in self.int2bits(result, hbs)
]
193             if self.key_add is 'xor':
194                 return [x + y for x, y, in zip(a, b)]
195         else:
196             if self.key_add is 'mod':
197                 polys = list()
198                 polys.append(a[0] + b[0] + r[0])
199                 for i in range(0, hbs - 1):
200                     polys.append(a[i] + a[i] * r[i] + a[i] * r[i+1] + a[i
] *
201                         a[i+1] + a[i] * b[i+1] + r[i] * r[i+1] + r[i
] *
202                         a[i+1] + r[i] * b[i+1])
203                     polys.append(b[i] + b[i] * r[i] + b[i] * r[i+1] + b[i
] *
204                         a[i+1] + b[i] * b[i+1] + r[i] * r[i+1] + r[i
] *
205                         a[i+1] + r[i] * b[i+1])
206                     polys.append(a[i] * r[i] + b[i] * r[i] + a[i] * b[i]
+ a[i]
207                         + b[i] + r[i+1] + a[i+1] + b[i+1])
208                 return polys
209             if self.key_add is 'xor':
210                 return [x + y + z for x, y, z in zip(r, a, b)]
211
212     def shift(self, halfblock):
213         shift = ceil(self.halfblock_size / 3)

```

```

214         halfblock = halfblock[self.halfblock_size-shift:self.
halfblock_size]+\
215             halfblock[0:self.halfblock_size-shift]
216         return halfblock
217
218     def substitute(self, halfblock):
219         result = []
220         for i in range(self.halfblock_size / self.SBOX_SIZE):
221             nbit = i * self.SBOX_SIZE
222             plain = halfblock[nbit:nbit + self.SBOX_SIZE]
223             sub = self.sboxes[i % len(self.sboxes)](plain)
224             sub = [self.ring(j) for j in sub]
225             result += sub
226         return result
227
228     def xor_blocks(self, left, right):
229         return [x + y for x, y in zip(left, right)]
230
231     def feistel_round(self, block, subkey):
232         hbs = self.halfblock_size
233         bs = self.block_size
234         n1 = block[0:hbs] # left
235         n2 = block[hbs:bs]; # right
236         temp = n1
237         n1 = self.add_round_key(n1, subkey)
238         n1 = self.substitute(n1);
239         n1 = self.shift(n1);
240         n2 = self.xor_blocks(n1, n2)
241         n1 = temp
242         return n2 + n1
243
244     def _cast_params(self, data_, key_):
245         bs = self.block_size
246         data = deepcopy(data_)
247         key = deepcopy(key_)
248         if not isinstance(data, list):
249             data = self.int2bits(data, bs)
250         data = [self.ring(i) for i in data]
251         if len(key) != self.key_length:
252             raise TypeError('Key should be of length ' + str(self.
key_length))
253         # coarse key bits to ring elements
254         for i in range(len(key)):
255             if not isinstance(key[i], list):
256                 key[i] = self.int2bits(key[i], self.halfblock_size)
257             key[i] = [self.ring(j) for j in key[i]]
258         return data, key
259
260     def encrypt(self, data_, key_):
261         hbs = self.halfblock_size
262         bs = self.block_size
263         if isinstance(data_, list):
264             is_list = True;
265         else:
266             is_list = False;
267         data, key = self._cast_params(data_, key_)
268
269         for i in range(self.nrounds):
270             if self.key_order == 'frwrev' and \
271                 i >= (self.nrounds - self.key_length):

```

```

272         k = self.key_length - 1 - (i % self.key_length)
273     else:
274         k = i % self.key_length
275         data = self.feistel_round(data, key[k])
276     data = data[hbs:bs] + data[0:hbs]
277     if is_list:
278         return data
279     else:
280         return self.bits2int(data)
281
282 def decrypt(self, data_, key_):
283     hbs = self.halfblock_size
284     bs = self.block_size
285     if isinstance(data_, list):
286         is_list = True;
287     else:
288         is_list = False;
289     data, key = self._cast_params(data_, key_)
290
291     key.reverse()
292     for i in range(self.nrounds):
293         if self.key_order == 'frwrev' and i < self.key_length:
294             k = self.key_length - 1 - (i % self.key_length)
295         else:
296             k = i % self.key_length
297         data = self.feistel_round(data, key[k])
298     data = data[hbs:bs] + data[0:hbs]
299     if is_list:
300         return data
301     else:
302         return self.bits2int(data)
303
304 def random_key(self):
305     key = [list(random_vector(int(self.halfblock_size), x=2))
306            for _ in range(self.key_length)]
307     key = [map(self.ring, i) for i in key]
308     return key
309
310 def random_block(self):
311     return map(self.ring, list(random_vector(self.block_size, x=2)))
312
313 def test_mqsystem(self, f_):
314     if f_.ring() is not self.ring:
315         raise TypeError('Tested MQ system has been generated by a '
316                        'different GOST instance')
317     f = deepcopy(f_)
318     print 'Testing MQ system', f
319     bs = self.block_size
320     plaintext = self.random_block()
321     key = self.random_key()
322     ciphertext = self.int2bits(self.encrypt(plaintext, key), bs)
323     f = f.subs(dict(zip(self.gen_vars(self.var_names['block'], \
324                                     0), plaintext)))
325     f = f.subs(dict(zip(self.gen_vars(self.var_names['block'], \
326                                     self.nrounds), ciphertext)))
327     for i in range(self.nrounds):
328         k = i % self.key_length
329         f = f.subs(dict(zip(self.gen_vars(self.var_names['key'], i),

```

```

330                                     key[k]))
331     )
332     s = f.ideal().interreduced_basis()
333     if s == [1]:
334         print 'MQ System for' + str(self) + 'is INCORRECT'
335         print f
336         return False
337     else:
338         return True
339
340     def test_cipher(self):
341         keys = [
342             [0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0],
343             [0xFFFFFFFF, 0xFFFFFFFF, 0xFFFFFFFF, 0xFFFFFFFF, \
344              0xFFFFFFFF, 0xFFFFFFFF, 0xFFFFFFFF, 0xFFFFFFFF],
345             [0x01234567, 0x89ABCDEF, 0x01234567, 0x89ABCDEF, \
346              0x01234567, 0x89ABCDEF, 0x01234567, 0x89ABCDEF],
347             [0x6ebabf8d, 0x1a8cad60, 0x124744f9, 0xd400b5d8, \
348              0xa721e3fd, 0x11d0702d, 0x06fd4827, 0x476df4bf]
349         ]
350         plain = [
351             0x0000000000000000, 0xBDBDBDBDACACACAC, 0
352             xFFFFFFFFFFFFFFFFFFFF, \
353             0x89ABCDEF01234567, 0xC0AE942BC8A99A39
354         ]
355         cipher = [
356             0x12610BE2A6C2FDC9, 0xA587E5D3F6DFB6F4, 0
357             x029BFE67A9364E44, \
358             0x523FC1A6AEC71B9A, 0x780CB7CE063F59E2,
359             0x9057C2CF13AAAD6D, 0xF7B085BA4771F406, 0
360             x780416781B29BC06, \
361             0xE596A183FD645558, 0x8EC42736538740AB,
362             0xF1956B1D0A1A67DE, 0x9E4C808408DCDBDC, 0
363             x7738AF92DE8FC770, \
364             0x9C44633FCEC0A03E, 0xC23013406002E268,
365             0x91DB8E1FE489FAEF, 0x547BF353604A8190, 0
366             x92B517E3CC91B9D0, \
367             0x1F5C2195762513E2, 0xE99D1C8DFF44A74C
368         ]
369
370         def show_failed(plain, key, result, expected):
371             print 'GOST FAILED'
372             print 'key:\t\t', ['0x%8.8X' % subk for subk in key]
373             print 'plaintext:\t', "0x%16.16X" % plain
374             print 'expected:\t', "0x%16.16X" % expected
375             print 'actual:\t\t', "0x%16.16X" % result
376
377         if self.block_size == 64 and self.nrounds == 32 and \
378             self.key_add == 'mod' and self.key_order == 'frwrev':
379             print 'Testing ', self, 'using test vectors...'
380             it = cipher.__iter__()
381             for k in keys:
382                 for p in plain:
383                     c = self.encrypt(p, k)
384                     expected = it.next()
385                     if c != expected:
386                         show_failed(p, k, c, expected)
387                         return False
388             print 'Testing', self, 'by correct decryption...'

```



```
384         x = randint(0, 2^self.block_size)
385         key = list(random_vector(self.key_length, x = 2^self.block_size)
386     )
387     c = self.encrypt(x, key)
388     d = self.decrypt(c, key)
389     if x != d:
390         show_failed(x, key, d, x)
391         return False
392     return True
```

## APPENDIX B

### SOLVING 6 ROUNDS OF GOST 28147-89 EQUATIONS SYSTEM

```

1  attach gost.sage
2  attach anf2cnf.py
3
4  nr = 5
5  bs = 64
6  hbs = int(bs/2)
7  varnames = ['a', 'b', 'c', 'd']
8  gosts = [Gost(block_size=bs,
9      rounds=nr,
10     key_add='mod',
11     key_order='frw',
12     prefix=i) for i in varnames]
13
14  print 'constructing MQ systems...'
15  mqsystems = [i.polynomial_system() for i in gosts]
16
17  print 'generating plaintext/ciphertext data...'
18  inputs = [i.random_block() for i in gosts]
19  key = gosts[0].random_key()
20  outputs = [gosts[i].encrypt(inputs[i], key) for i in range(len(gosts))]
21
22  print 'injecting known variables...'
23  for i in range(len(mqsystems)):
24      mqsystems[i] = mqsystems[i].inject(gosts[i].gen_vars(
25          gosts[i].var_names['block'], 0), inputs[i])
26      mqsystems[i] = mqsystems[i].inject(gosts[i].gen_vars(
27          gosts[i].var_names['block'], nr), outputs[i])
28
29  print 'combining MQ systems...'
30  f = join_systems(mqsystems, gosts)
31
32  print 'solving MQ system with SAT solver...'
33  print time.ctime()
34  solver = ANFSatSolver(f.ring())
35  s, t = solver(f)
36  print 'DONE'
37  print time.ctime()
38
39  recovered_key = []
40  r = f.ring()
41  for i in range(len(key)):
42      var_names = map(str, gosts[0].gen_vars(
43          gosts[0].var_names['key'], i))
44      var_names.sort()
45      var_names = map(r, var_names)
46      recovered_key.append([s[j] for j in var_names])
47
48  if gosts[0].int2bits(gosts[0].encrypt(
49      inputs[0], recovered_key), bs) == outputs[0]:
50      if key == recovered_key:
51          print recovered_key
52      else:
53          print 'FOUND ANOTHER KEY'
54          print 'actual'

```

```
55     print key
56     print 'found'
57     print recovered_key
```

## APPENDIX C

### MISTY1 EQUATIONS GENERATOR

```

1  #!/usr/bin/env sage
2  # -*- coding: utf-8 -*-
3
4  import operator
5
6  from sage.rings.polynomial.multi_polynomial_sequence import
   PolynomialSequence
7
8
9  def split(l, chunk_size):
10     """Split flat list into nested lists of length 'chunk_size'. If the
11     'chunk_size' is not multiple of list length, the last sublist is
12     added as
13     is without padding.
14
15     Args:
16     l: List to split into chunks.
17     chunk_size: Length of a single nested list.
18
19     Returns:
20     Nested list of chunks each of the length 'chunk_size'.
21
22     """
23     return [l[i:i + chunk_size] for i in xrange(0, len(l), chunk_size)]
24
25  def reverse(iterable):
26     """Return reversed iterable as list."""
27     return list(reversed(iterable))
28
29
30  def vector_do(operation, a, b):
31     """Perform vector operation on two lists.
32
33     Args:
34     operation: binary operation to perform (from 'operator' module).
35     a: first vector.
36     b: second vector.
37
38     Returns:
39     Resulting vector (represented as list).
40
41     Example:
42     vector_do(operator.__xor__, [1, 1, 1], [1, 0, 1])
43
44     """
45     if operation is operator.__xor__:
46         if is_constant(a) and is_constant(b):
47             return map(lambda x, y: operation(x, y), a, b)
48         else:
49             # Process variables over Boolean Polynomial Ring correctly.
50             return map(lambda x, y: operation.__add__(x, y), a, b)
51     elif operation is operator.__and__:
52         if is_constant(a) and is_constant(b):

```

```

53         return map(lambda x, y: operation(x, y), a, b)
54     else:
55         # Process variables over Boolean Polynomial Ring correctly.
56         return map(lambda x, y: operator.__mul__(x, y), a, b)
57     elif operation is operator.__or__:
58         if is_constant(a) and is_constant(b):
59             return map(lambda x, y: operation(x, y), a, b)
60         else:
61             # Process variables over Boolean Polynomial Ring correctly.
62             return map(lambda x, y: x * y + x + y, a, b)
63     else:
64         return map(lambda x, y: operation(x, y), a, b)
65
66
67 def is_constant(vals):
68     """Check of all elements in list are constants, not variables."""
69     return all([isinstance(i, Integer) for i in vals])
70
71 def groebner_basis(func):
72     """Decorator for Groebner basis reduce of polynomial system."""
73     def wrapper(*args, **kwargs):
74         result = func(*args, **kwargs)
75         if not is_constant(result):
76             F = PolynomialSequence(result)
77             return F.groebner_basis()
78         else:
79             return result
80     return wrapper
81
82
83 class Misty(object):
84     """Misty cipher class.
85
86     All method assume to take bit sequences as input. Use 'get_bits'
87 method to
88 convert integer to Misty bit sequence representation and 'get_integer'
89 to
90 obtain the corresponding integer back.
91
92     """
93
94     def get_bits(self, integer, nbytes=0):
95         """Convert integer to crazy Misty bit ordering. """
96         bytes = reverse(integer.digits(256, padto=nbytes))
97         bits = [reverse(b.digits(2, padto=8)) for b in bytes]
98         return flatten(bits)
99
100     def get_integer(self, bits):
101         """Convert crazy Misty bit sequence to sane ordering. """
102         bytes = reverse(split(bits, 8))
103         bytes = [reverse(b) for b in bytes]
104         return Integer(flatten(bytes), 2)
105
106     def __init__(self, nrounds, prefix='', equations_key_schedule=True):
107         """Create Misty cipher object.
108
109         It's a full scale cipher as well as its polynomial system
110 generator.
111
112         Args:

```

```

110         nrounds: Number of enciphering rounds.
111         prefix: Prefix used for variables identification during
polynomial
112             system construction.
113
114         """
115         self.nrounds = nrounds
116         self.prefix = prefix
117         self.equations_key_schedule = equations_key_schedule
118         self.block_size = 64
119         self.halfblock_size = self.block_size // 2
120         self.halfblock_size_fo = self.halfblock_size // 2
121         self.fi_left_size = 9
122         self.fi_right_size = 7
123         self.key = None
124         self.subkeys = None
125         self.gen_ring()
126         # Subkey type constants.
127         self.KEY_K01 = 'ko1'
128         self.KEY_K02 = 'ko2'
129         self.KEY_K03 = 'ko3'
130         self.KEY_K04 = 'ko4'
131         self.KEY_KI1 = 'ki1'
132         self.KEY_KI2 = 'ki2'
133         self.KEY_KI3 = 'ki3'
134         self.KEY_KL1 = 'kl1'
135         self.KEY_KL2 = 'kl2'
136
137     def kindex(self, subkey_type, i):
138         """Index subkey according to crazy Misty indexing rule.
139
140         Args:
141             subkey_type: string, indicating subkey type.
142             subkeys: list of subkey bits (each element contains 16
subkey
143                 bits).
144             i: Misty round in range 1 <= i <= 8.
145
146         Returns:
147             16-bit subkey for corresponding index.
148         """
149         if i < 1:
150             raise ValueError('Subkey index must start from 1. '
151                             'Got {0} instead.'.format(i))
152
153         def normalize(x):
154             while x > 8:
155                 x = x - 8
156             return x
157
158         if subkey_type == self.KEY_K01:
159             return self.key[i - 1]
160         if subkey_type == self.KEY_K02:
161             i = normalize(i + 2)
162             return self.key[i - 1]
163         if subkey_type == self.KEY_K03:
164             i = normalize(i + 7)
165             return self.key[i - 1]
166         if subkey_type == self.KEY_K04:
167             i = normalize(i + 4)

```

```

168         return self.key[i - 1]
169     if subkey_type == self.KEY_KI1:
170         i = normalize(i + 5)
171         return self.subkeys[i - 1]
172     if subkey_type == self.KEY_KI2:
173         i = normalize(i + 1)
174         return self.subkeys[i - 1]
175     if subkey_type == self.KEY_KI3:
176         i = normalize(i + 3)
177         return self.subkeys[i - 1]
178
179     if subkey_type == self.KEY_KL1:
180         if i % 2 != 0:
181             i = normalize((i + 1) // 2)
182             return self.key[i - 1]
183         else:
184             i = normalize((i // 2) + 2)
185             return self.subkeys[i - 1]
186     if subkey_type == self.KEY_KL2:
187         if i % 2 != 0:
188             i = normalize((i + 1) // 2 + 6)
189             return self.subkeys[i - 1]
190         else:
191             i = normalize((i // 2) + 4)
192             return self.key[i - 1]
193
194     def fi(self, x, subkey_ki):
195         """Misty FI function.
196
197         Args:
198             x: 16-bit input value.
199             subkey_ki: 16-bit KI key chunk for FI function.
200
201         Returns: 16-bit output of FI function.
202
203         """
204         ki7 = subkey_ki[0:self.fi_right_size]
205         ki9 = subkey_ki[self.fi_right_size:]
206
207         d9 = x[0:self.fi_left_size]
208         d7 = x[self.fi_left_size:]
209
210         d9 = vector_do(operator.__xor__, self.s9(d9), [0, 0] + d7)
211         d7 = vector_do(operator.__xor__, self.s7(d7), d9[2:self.
fi_left_size])
212         d7 = vector_do(operator.__xor__, d7, ki7)
213         d9 = vector_do(operator.__xor__, d9, ki9)
214         d9 = vector_do(operator.__xor__, self.s9(d9), [0, 0] + d7)
215         return d7 + d9
216
217     def key_schedule(self, key):
218         """Generate subkeys according to Misty key schedule algorithm.
219
220         Args:
221             key: List of 128 bits.
222
223         Returns:
224             List of 8 subkeys (each containing list of 16 bits).
225         """
226         key_chunks = split(key, 16)

```

```

227         self.key = key_chunks
228
229         subkeys = list()
230         for k in range(len(key_chunks)):
231             if k < 7:
232                 subkeys.append(self.fi(key_chunks[k], key_chunks[k + 1])
233             )
234             else:
235                 subkeys.append(self.fi(key_chunks[k], key_chunks[0]))
236         self.subkeys = subkeys
237         return subkeys
238
239     def fl(self, x, i):
240         """Misty key injection FL function.
241
242         Args:
243             x: 32-bit input.
244             i: number of round.
245
246         Returns:
247             Resulting 32 bits after key injection.
248
249         """
250         left = x[:self.halfblock_size_fo]
251         right = x[self.halfblock_size_fo:]
252
253         kl1 = self.kindex(self.KEY_KL1, i)
254         kl2 = self.kindex(self.KEY_KL2, i)
255
256         temp = vector_do(operator.__and__, left, kl1)
257         right = vector_do(operator.__xor__, right, temp)
258
259         temp = vector_do(operator.__or__, right, kl2)
260         left = vector_do(operator.__xor__, left, temp)
261         return left + right
262
263     #@groebner_basis
264     def s7(self, x, r=None):
265         """Substitute with Misty S7 SBox.
266
267         Bit ordering is reversed due to Crazy Misty Spec bit ordering.
268         """
269         y = [0] * len(x)
270         if not r:
271             y[6] = x[6] ^ x[5] & x[3] ^ x[6] & x[3] & x[2] ^ x[5] & x[1] ^
272             x[6] & x[4] & x[1] ^ x[2] & x[1] ^ x[6] & x[5] & x[0] ^ x[4] & x[0] ^ x[6]
273             & x[1] & x[0] ^ x[3] & x[1] & x[0] ^ 1
274             y[5] = x[6] & x[4] ^ x[6] & x[2] ^ x[3] & x[2] ^ x[5] & x[1] ^
275             x[4] & x[2] & x[1] ^ x[0] ^ x[6] & x[0] ^ x[3] & x[0] ^ x[4] & x[3] & x[0]
276             ^ x[5] & x[2] & x[0] ^ x[6] & x[1] & x[0] ^ 1
277             y[4] = x[5] & x[4] ^ x[6] & x[4] & x[3] ^ x[2] ^ x[5] & x[2] ^
278             x[6] & x[5] & x[2] ^ x[6] & x[1] ^ x[6] & x[2] & x[1] ^ x[3] & x[2] & x[1]
279             ^ x[5] & x[0] ^ x[3] & x[0] ^ x[6] & x[3] & x[0] ^ x[2] & x[0] ^ x[4] & x
280             [2] & x[0]
281             y[3] = x[6] ^ x[5] ^ x[6] & x[5] & x[4] ^ x[6] & x[3] ^ x[4] &
282             x[2] ^ x[5] & x[2] & x[1] ^ x[4] & x[0] ^ x[5] & x[3] & x[0] ^ x[6] & x[2]
283             & x[0] ^ x[1] & x[0] ^ 1
284             y[2] = x[4] & x[3] ^ x[6] & x[2] ^ x[5] & x[3] & x[2] ^ x[1] ^
285             x[4] & x[1] ^ x[5] & x[4] & x[1] ^ x[6] & x[3] & x[1] ^ x[5] & x[0] ^ x[5]
286             & x[1] & x[0] ^ x[2] & x[1] & x[0] ^ 1

```



```

275         y[1] = x[6] ^x[5] ^x[4] ^x[6] &x[5] &x[4] ^x[6] &x[3]
^x[5] &x[4] &x[3] ^x[5] &x[2] ^x[6] &x[4] &x[2] ^x[6] &x[1] ^x
276         y[0] = x[6] &x[5] ^x[3] ^x[6] &x[3] ^x[4] &x[3] &x[2] ^
x[6] &x[1] ^x[4] &x[1] ^x[3] &x[1] ^x[5] &x[3] &x[1] ^x[5] &x[0]
^x[5] &x[4] &x[0] ^x[6] &x[3] &x[0] ^x[2] &x[0] ^x[4] &x[1] &x[0]
277         return y
278     else:
279         # Process variables over Boolean Polynomial Ring correctly.
280         polynomials = [
281             r[6] + x[6] + x[5] * x[3] + x[6] * x[3] * x[2] + x[5] * x[1]
+ x[6] * x[4] * x[1] + x[2] * x[1] + x[6] * x[5] * x[0] + x[4] * x
282             [0] + x[6] * x[1] * x[0] + x[3] * x[1] * x[0] + 1,
r[5] + x[6] * x[4] + x[6] * x[2] + x[3] * x[2] + x[5] * x[1]
283             + x[4] * x[2] * x[1] + x[0] + x[6] * x[0] + x[3] * x[0] + x[4] * x
[3] * x[0] + x[5] * x[2] * x[0] + x[6] * x[1] * x[0] + 1,
284             r[4] + x[5] * x[4] + x[6] * x[4] * x[3] + x[2] + x[5] * x[2]
+ x[6] * x[5] * x[2] + x[6] * x[1] + x[6] * x[2] * x[1] + x[3] * x
285             [2] * x[1] + x[5] * x[0] + x[3] * x[0] + x[6] * x[3] * x[0] + x[2] *
x[0] + x[4] * x[2] * x[0],
r[3] + x[6] + x[5] + x[6] * x[5] * x[4] + x[6] * x[3] + x[4]
286             * x[2] + x[5] * x[2] * x[1] + x[4] * x[0] + x[5] * x[3] * x[0] + x
[6] * x[2] * x[0] + x[1] * x[0] + 1,
r[2] + x[4] * x[3] + x[6] * x[2] + x[5] * x[3] * x[2] + x[1]
287             + x[4] * x[1] + x[5] * x[4] * x[1] + x[6] * x[3] * x[1] + x[5] * x
[0] + x[5] * x[1] * x[0] + x[2] * x[1] * x[0] + 1,
r[1] + x[6] + x[5] + x[4] + x[6] * x[5] * x[4] + x[6] * x[3]
288             + x[5] * x[4] * x[3] + x[5] * x[2] + x[6] * x[4] * x[2] + x[6] * x
[1] + x[6] * x[5] * x[1] + x[3] * x[1] + x[6] * x[0] + x[4] * x[1] *
x[0],
289             r[0] + x[6] * x[5] + x[3] + x[6] * x[3] + x[4] * x[3] * x[2]
+ x[6] * x[1] + x[4] * x[1] + x[3] * x[1] + x[5] * x[3] * x[1] + x
290             [5] * x[0] + x[5] * x[4] * x[0] + x[6] * x[3] * x[0] + x[2] * x[0] +
x[4] * x[1] * x[0]
291             ]
292         return polynomials
293
294     #@groebner_basis
295     def s9(self, x, r=None):
296         """Substitute with Misty S9 SBox. """
297         y = [0] * len(x)
298         if not r:
299             y[8] = x[8] & x[4] ^x[8] & x[3] ^x[7] & x[3] ^x[7]
& x[2] ^x[6] & x[2] ^x[6] & x[1] ^x[5] & x[1] ^x[5] & x
300             [0] ^x[4] & x[0] ^1
y[7] = x[8] & x[6] ^x[5] ^x[7] & x[5] ^x[6] & x[5]
301             ^x[5] & x[4] ^x[4] & x[3] ^x[8] & x[2] ^x[6] & x[2] ^x
[1] ^x[8] & x[0] ^x[5] & x[0] ^x[3] & x[0] ^1
302             y[6] = x[8] & x[7] ^x[7] & x[5] ^x[4] ^x[8] & x[4]
^x[6] & x[4] ^x[5] & x[4] ^x[4] & x[3] ^x[8] & x[2] ^x
[3] & x[2] ^x[7] & x[1] ^x[5] & x[1] ^x[0]
y[5] = x[8] ^x[7] & x[6] ^x[6] & x[4] ^x[3] ^x[7]
303             & x[3] ^x[5] & x[3] ^x[4] & x[3] ^x[3] & x[2] ^x[7] & x
[1] ^x[2] & x[1] ^x[6] & x[0] ^x[4] & x[0]
y[4] = x[7] ^x[8] & x[5] ^x[6] & x[5] ^x[8] & x[3]
304             ^x[5] & x[3] ^x[2] ^x[6] & x[2] ^x[4] & x[2] ^x[3] & x
[2] ^x[2] & x[1] ^x[6] & x[0] ^x[1] & x[0]
y[3] = x[6] ^x[8] & x[5] ^x[7] & x[4] ^x[5] & x[4]
305             ^x[7] & x[2] ^x[4] & x[2] ^x[1] ^x[5] & x[1] ^x[3] & x

```

```

[1] ^^ x[2] & x[1] ^^ x[8] & x[0] ^^ x[1] & x[0]
303     y[2] = x[8] & x[7] ^^ x[5] ^^ x[7] & x[4] ^^ x[6] & x[3]
    ^^ x[4] & x[3] ^^ x[6] & x[1] ^^ x[3] & x[1] ^^ x[0] ^^ x[8] & x
    [0] ^^ x[4] & x[0] ^^ x[2] & x[0] ^^ x[1] & x[0] ^^ 1
304     y[1] = x[7] ^^ x[8] & x[7] ^^ x[7] & x[6] ^^ x[6] & x[5]
    ^^ x[8] & x[4] ^^ x[3] ^^ x[7] & x[2] ^^ x[5] & x[2] ^^ x[8] & x
    [1] ^^ x[4] & x[1] ^^ x[2] & x[1] ^^ x[7] & x[0] ^^ 1
305     y[0] = x[8] ^^ x[8] & x[7] ^^ x[7] & x[6] ^^ x[4] ^^ x[8]
    & x[3] ^^ x[6] & x[3] ^^ x[5] & x[2] ^^ x[3] & x[2] ^^ x[8] & x
    [1] ^^ x[8] & x[0] ^^ x[5] & x[0] ^^ x[2] & x[0] ^^ 1
306     return y
307     else:
308         # Process variables over Boolean Polynomial Ring correctly.
309         polynomials = [
310             r[8] + x[8] * x[4] + x[8] * x[3] + x[7] * x[3] + x[7] * x[2]
    + x[6] * x[2] + x[6] * x[1] + x[5] * x[1] + x[5] * x[0] + x[4] * x
    [0] + 1,
311             r[7] + x[8] * x[6] + x[5] + x[7] * x[5] + x[6] * x[5] + x[5]
    * x[4] + x[4] * x[3] + x[8] * x[2] + x[6] * x[2] + x[1] + x[8] * x
    [0] + x[5] * x[0] + x[3] * x[0] + 1,
312             r[6] + x[8] * x[7] + x[7] * x[5] + x[4] + x[8] * x[4] + x[6]
    * x[4] + x[5] * x[4] + x[4] * x[3] + x[8] * x[2] + x[3] * x[2] + x
    [7] * x[1] + x[5] * x[1] + x[0],
313             r[5] + x[8] + x[7] * x[6] + x[6] * x[4] + x[3] + x[7] * x[3]
    + x[5] * x[3] + x[4] * x[3] + x[3] * x[2] + x[7] * x[1] + x[2] * x
    [1] + x[6] * x[0] + x[4] * x[0],
314             r[4] + x[7] + x[8] * x[5] + x[6] * x[5] + x[8] * x[3] + x[5]
    * x[3] + x[2] + x[6] * x[2] + x[4] * x[2] + x[3] * x[2] + x[2] * x
    [1] + x[6] * x[0] + x[1] * x[0],
315             r[3] + x[6] + x[8] * x[5] + x[7] * x[4] + x[5] * x[4] + x[7]
    * x[2] + x[4] * x[2] + x[1] + x[5] * x[1] + x[3] * x[1] + x[2] * x
    [1] + x[8] * x[0] + x[1] * x[0],
316             r[2] + x[8] * x[7] + x[5] + x[7] * x[4] + x[6] * x[3] + x[4]
    * x[3] + x[6] * x[1] + x[3] * x[1] + x[0] + x[8] * x[0] + x[4] * x
    [0] + x[2] * x[0] + x[1] * x[0] + 1,
317             r[1] + x[7] + x[8] * x[7] + x[7] * x[6] + x[6] * x[5] + x[8]
    * x[4] + x[3] + x[7] * x[2] + x[5] * x[2] + x[8] * x[1] + x[4] * x
    [1] + x[2] * x[1] + x[7] * x[0] + 1,
318             r[0] + x[8] + x[8] * x[7] + x[7] * x[6] + x[4] + x[8] * x[3]
    + x[6] * x[3] + x[5] * x[2] + x[3] * x[2] + x[8] * x[1] + x[8] * x
    [0] + x[5] * x[0] + x[2] * x[0] + 1
319         ]
320     return polynomials
321
322 def fo(self, x, i):
323     """Misty FO function.
324
325     Second level nested Feistel network.
326
327     Args:
328         x: 32-bit input list.
329         i: number of rounds.
330
331     Returns:
332         Resulting bits list.
333     """
334
335
336     left = x[0:self.halfblock_size_fo]
337     right = x[self.halfblock_size_fo:]

```

```

338
339     ki1 = self.kindex(self.KEY_KI1, i)
340     ki2 = self.kindex(self.KEY_KI2, i)
341     ki3 = self.kindex(self.KEY_KI3, i)
342
343     ko1 = self.kindex(self.KEY_KO1, i)
344     ko2 = self.kindex(self.KEY_KO2, i)
345     ko3 = self.kindex(self.KEY_KO3, i)
346     ko4 = self.kindex(self.KEY_KO4, i)
347
348     left = vector_do(operator.__xor__, left, ko1)
349     temp = self.fi(left, ki1)
350     left = vector_do(operator.__xor__, temp, right)
351
352     right = vector_do(operator.__xor__, right, ko2)
353     temp = self.fi(right, ki2)
354     right = vector_do(operator.__xor__, left, temp)
355
356     left = vector_do(operator.__xor__, left, ko3)
357     temp = self.fi(left, ki3)
358     left = vector_do(operator.__xor__, temp, right)
359
360     right = vector_do(operator.__xor__, right, ko4)
361
362     return right + left
363
364 def feistel_round(self, data, i):
365     """Misty Feistel network single run.
366
367     It actually performs first 2 rounds (look for Misty specs).
368
369     Args:
370         data: 64-bit input list.
371         i: number of actual round (pay attention to indices
372 according         to Misty specification). Rounds are in range 1 <= i <= n
373         + 2,         where 'n' is total number of rounds
374     Returns:
375         Resulting 64-bit list.
376
377     """
378     left = data[0:self.halfblock_size]
379     right = data[self.halfblock_size:]
380
381     # FL1
382     left = self.fl(left, i)
383     # FL2
384     right = self.fl(right, i + 1)
385
386     # F01
387     temp = self.fo(left, i)
388     right = vector_do(operator.__xor__, right, temp)
389
390     # F02
391     temp = self.fo(right, i + 1)
392     left = vector_do(operator.__xor__, temp, left)
393
394     return left + right
395

```

```

396 def encipher(self, data, key):
397     """Encipher plaintext with Misty cryptoalgorithm.
398
399     Args:
400         data: 64-bit input list (plaintext).
401         key: 128-bit input list (key).
402
403     Returns:
404         64-bit list (ciphertext).
405
406     """
407     for i in range(1, self.nrounds + 1, 2):
408         data = self.feistel_round(data, i)
409
410     left = data[0:self.halfblock_size]
411     right = data[self.halfblock_size:]
412     # FL n+1
413     left = self.fl(left, self.nrounds + 1)
414     # FL n+2
415     right = self.fl(right, self.nrounds + 2)
416     return right + left
417
418 def selftest(self):
419     """Check Misty test vectors compliance."""
420     plaintext = 0x0123456789ABCDEF
421     key = 0x00112233445566778899AABBCCDDEEFF
422     self.key_schedule(self.get_bits(key, 16))
423     c = self.encipher(self.get_bits(plaintext, 8),
424                       self.get_bits(key, 16))
425     result = self.get_integer(c)
426     expected = 0x8b1da5f56ab3d07c
427     return result == expected
428
429 def _varformatstr(self, name):
430     """Prepare formatting string for variables notation.
431
432     Args:
433         name: Variable identifier string.
434
435     Returns:
436         Variable identifier string appended with format
437         specifiers
438         that contains round number and block bit number.
439         Format: R<round number>_<var id>_<bit number>
440
441     """
442     l = str(len(str(self.block_size - 1)))
443     return "R%s_" + name + "_%0" + l + "d"
444
445 def _varstrs(self, name, nbits, round='', start_from=0):
446     """Construct strings with variables names.
447
448     Args:
449         name: variable string identifier.
450         nbits: number of variables set of the same type.
451         round: number of round for which variables are defined. If
452         not
453             specified, no round prefix is prepended to the string.
454
455     Returns:

```

```

454         List of strings with variables names.
455
456         """
457         round = str(round)
458         s = self._varformatstr(name)
459         if not round:
460             # Exclude round prefix.
461             s = s[s.find('_') + 1:]
462             var_names = [s % (i) for i in range(start_from, start_from +
nbits)]
463         else:
464             var_names = [s % (round, i) for i in range(start_from,
start_from + nbits)]
465             if not name == 'K' and not name == 'KS' and not name.startswith(
'FIKS'):
466                 # Include polynomial system prefix.
467                 var_names = [self.prefix + var for var in var_names]
468             return var_names
469
470     def vars(self, name, nbits, round='', start_from=0):
471         """Construct variables in predefined Misty ring.
472
473         Refer to '_varstrs()' and 'gen_ring()' for details.
474
475         """
476         var_names = self._varstrs(name, nbits, round=round, start_from=
start_from)
477         return [self.ring(e) for e in var_names]
478
479     def gen_round_var_names(self, round):
480         """Generate variables names set for given round number."""
481         var_names = list()
482         # FL
483         var_names += self._varstrs('FL_KL1', 16, round)
484         var_names += self._varstrs('FL_KL2', 16, round)
485         var_names += self._varstrs('FL_XOR', 16, round)
486         var_names += self._varstrs('FL', 32, round)
487         # FI
488         for i in range(1, 4):
489             # FI has 3 subrounds in FO function.
490             var_names += self._varstrs('FI' + str(i), 16, round)
491             var_names += self._varstrs('FI' + str(i) + '_S9', 9, round)
492             var_names += self._varstrs('FI' + str(i) + '_S7', 7, round)
493             var_names += self._varstrs('FI' + str(i) + '_SS9', 9, round)
494             var_names += self._varstrs('FI' + str(i) + '_KI2', 16, round
)
495         # FO
496         var_names += self._varstrs('FO', 32, round)
497         var_names += self._varstrs('FO_K01', 16, round)
498         var_names += self._varstrs('FO_K02', 16, round)
499         var_names += self._varstrs('FO_K03', 16, round)
500
501
502         return var_names
503
504     def gen_ring(self):
505         """Generate ring for Misty polynomial equations system.
506
507         Construct all variables needed for describing Misty
cryptoalgorithm

```

```

508     with polynomial equations system and generate the corresponding
509     Boolean Polynomial Ring.
510
511     """
512     var_names = list()
513
514     # Input plaintext.
515     var_names += self._varstrs('IN', 64)
516     # Output ciphertext.
517     var_names += self._varstrs('OUT', 64)
518
519     # Key variables.
520     var_names += self._varstrs('K', 128)
521     # Subkey variables.
522     var_names += self._varstrs('KS', 128)
523
524     if self.equations_key_schedule == True:
525         for i in range(8):
526             var_names += self._varstrs('FIKS' + str(i), 16)
527             var_names += self._varstrs('FIKS' + str(i) + '_S9', 9)
528             var_names += self._varstrs('FIKS' + str(i) + '_S7', 7)
529             var_names += self._varstrs('FIKS' + str(i) + '_SS9', 9)
530             var_names += self._varstrs('FIKS' + str(i) + '_KI2', 16)
531
532     for i in range(1, self.nrounds + 1):
533         var_names += self.gen_round_var_names(i)
534     for i in range(1, self.nrounds + 1):
535         if i % 2 == 1:
536             var_names += self._varstrs('FX', 32, i)
537         else:
538             var_names += self._varstrs('F', 64, i)
539     for i in range(self.nrounds + 1, self.nrounds + 3):
540         # FL
541         var_names += self._varstrs('FL_KL1', 16, i)
542         var_names += self._varstrs('FL_KL2', 16, i)
543         var_names += self._varstrs('FL_XOR', 16, i)
544         var_names += self._varstrs('FL', 32, i)
545
546     self.ring = BooleanPolynomialRing(len(var_names), var_names,
547     order='degrevlex')
548
549     def polynomials_fl(self, x, i):
550         """Construct polynomials for Misty FL function."""
551
552         left = x[:self.halfblock_size_fo]
553         right = x[self.halfblock_size_fo:]
554
555         kl1 = self.kindex(self.KEY_KL1, i)
556         kl2 = self.kindex(self.KEY_KL2, i)
557
558         polynomials = list()
559
560         ## Generate variables for given round
561         vars_kl1 = self.vars('FL_KL1', 16, i)
562         vars_kl2 = self.vars('FL_KL2', 16, i)
563         vars_xor = self.vars('FL_XOR', 16, i)
564         vars_out = self.vars('FL', 32, i)
565
566         temp = vector_do(operator.__and__, left, kl1)

```

```

567     polynomials.extend(vector_do(operator.__xor__, temp, vars_kl1))
568
569     right = vector_do(operator.__xor__, right, vars_kl1)
570     polynomials.extend(vector_do(operator.__xor__, right, vars_xor))
571
572     # Replace 'x or y' operation with equivalent 'x * y ^ x + y'.
573     temp = vector_do(operator.__or__, vars_xor, kl2)
574     polynomials.extend(vector_do(operator.__xor__, temp, vars_kl2))
575
576     left = vector_do(operator.__xor__, left, vars_kl2)
577     polynomials.extend(vector_do(operator.__xor__, left, vars_out
[0:16]))
578     polynomials.extend(vector_do(operator.__xor__, vars_xor,
vars_out[16:32]))
579
580     return flatten(polynomials)
581
582 def polynomials_fi(self, x, subkey_ki, subround, r=''):
583     """Construct polynomials for Misty FI function.
584
585     Args:
586         x: list of 16 input variables.
587         subkey_ki: 16-bit key chunk.
588         subround: number of FI round in FO function (1..3).
589         r: number of actual outer Feistel network enciphering round.
590
591     """
592     ki7 = subkey_ki[0:self.fi_right_size]
593     ki9 = subkey_ki[self.fi_right_size:]
594
595     d9 = x[0:self.fi_left_size]
596     d7 = x[self.fi_left_size:]
597
598     subround = str(subround)
599
600     if subround in ['1', '2', '3']:
601         vars_fi = self.vars('FI' + subround, 16, r)
602     else:
603         vars_fi = self.vars('KS', 16, start_from=int(subround[2])) *
16)
604
605     vars_s9 = self.vars('FI' + subround + '_S9', 9, r)
606     vars_s7 = self.vars('FI' + subround + '_S7', 7, r)
607     vars_ss9 = self.vars('FI' + subround + '_SS9', 9, r)
608     vars_ki2 = self.vars('FI' + subround + '_KI2', 9, r)
609
610     polynomials = list()
611     pad = [self.ring(0)] * 2
612
613     polynomials.extend(self.s9(d9, vars_s9))
614     d9 = vector_do(operator.__xor__, vars_s9, pad + d7) # add to
pols
615
616     polynomials.extend(self.s7(d7, vars_s7))
617     d7 = vector_do(operator.__xor__, vars_s7, d9[2:self.fi_left_size
]) # add to pols
618     d7 = vector_do(operator.__xor__, d7, ki7)
619
620     d9 = vector_do(operator.__xor__, d9, ki9)
621     polynomials.extend(vector_do(operator.__xor__, d9, vars_ki2))

```

```

622     polynomials.extend(self.s9(vars_ki2, vars_ss9))
623     d9 = vector_do(operator.__xor__, vars_ss9, pad + d7) # add to
624     polys
625
626     polynomials.extend(vector_do(operator.__xor__, vars_fi[0:7], d7)
627 )
628     polynomials.extend(vector_do(operator.__xor__, vars_fi[7:16], d9
629 ))
630     return polynomials
631
632 def polynomials_fo(self, x, i):
633     """Construct polynomials for Misty FI function."""
634
635     left = x[0:self.halfblock_size_fo]
636     right = x[self.halfblock_size_fo:]
637
638     ki1 = self.kindex(self.KEY_KI1, i)
639     ki2 = self.kindex(self.KEY_KI2, i)
640     ki3 = self.kindex(self.KEY_KI3, i)
641
642     ko1 = self.kindex(self.KEY_KO1, i)
643     ko2 = self.kindex(self.KEY_KO2, i)
644     ko3 = self.kindex(self.KEY_KO3, i)
645     ko4 = self.kindex(self.KEY_KO4, i)
646
647     vars_fo = self.vars('FO', 32, i)
648     vars_ko1 = self.vars('FO_KO1', 16, i)
649     vars_ko2 = self.vars('FO_KO2', 16, i)
650     vars_ko3 = self.vars('FO_KO3', 16, i)
651     vars_fi1 = self.vars('FI1', 16, i)
652     vars_fi2 = self.vars('FI2', 16, i)
653     vars_fi3 = self.vars('FI3', 16, i)
654
655     polynomials = list()
656
657     left = vector_do(operator.__xor__, left, ko1)
658     polynomials.extend(vector_do(operator.__xor__, left, vars_ko1))
659     polynomials.extend(self.polynomials_fi(vars_ko1, ki1, 1, i)) #
660 FI1 variables introduced.
661     left = vector_do(operator.__xor__, vars_fi1, right)
662
663     right = vector_do(operator.__xor__, right, ko2)
664     polynomials.extend(vector_do(operator.__xor__, right, vars_ko2))
665     polynomials.extend(self.polynomials_fi(vars_ko2, ki2, 2, i)) #
666 FI2 variables introduced.
667     right = vector_do(operator.__xor__, vars_fi2, left)
668
669     left = vector_do(operator.__xor__, left, ko3)
670     polynomials.extend(vector_do(operator.__xor__, left, vars_ko3))
671     polynomials.extend(self.polynomials_fi(vars_ko3, ki3, 3, i)) #
672 FI3 variables introduced.
673     left = vector_do(operator.__xor__, vars_fi3, right)
674
675     right = vector_do(operator.__xor__, right, ko4)
676     polynomials.extend(vector_do(operator.__xor__, right, vars_fo
677 [0:16]))
678     polynomials.extend(vector_do(operator.__xor__, left, vars_fo
679 [16:32]))

```



```

674         return polynomials
675
676     def polynomials_round(self, data, i):
677         """Construct polynomials for Misty Feistel single run."""
678         left = data[0:self.halfblock_size]
679         right = data[self.halfblock_size:]
680
681         vars_fl1 = self.vars('FL', 32, i)
682         vars_fl2 = self.vars('FL', 32, i + 1)
683         vars_fo1 = self.vars('FO', 32, i)
684         vars_fo2 = self.vars('FO', 32, i + 1)
685         vars_fx = self.vars('FX', 32, i)
686         vars_f = self.vars('F', 64, i + 1)
687
688         polynomials = list()
689
690         polynomials.extend(self.polynomials_fl(left, i))    # FL1
691         variables introduced.
692         polynomials.extend(self.polynomials_fl(right, i + 1)) # FL2
693         variables introduced.
694
695         polynomials.extend(self.polynomials_fo(vars_fl1, i)) # FO1
696         variables introduced.
697         right = vector_do(operator.__xor__, vars_fo1, vars_fl2)
698         polynomials.extend(vector_do(operator.__xor__, right, vars_fx))
699
700         polynomials.extend(self.polynomials_fo(vars_fx, i + 1)) # FO2
701         variables introduced.
702         left = vector_do(operator.__xor__, vars_fo2, vars_fl1)
703         polynomials.extend(vector_do(operator.__xor__, left, vars_f
704         [0:32]))
705         polynomials.extend(vector_do(operator.__xor__, vars_fx, vars_f
706         [32:64]))
707
708     return polynomials
709
710     def polynomials_key_schedule(self):
711         """Construct polynomials for Misty key scheduling."""
712         self.key = split(self.vars('K', 128), 16)
713
714         polynomials = list()
715         for k in range(len(self.key)):
716             subround = 'KS' + str(k)
717             if k < 7:
718                 polynomials.extend(self.polynomials_fi(self.key[k], self
719                 .key[k + 1], subround))
720             else:
721                 polynomials.extend(self.polynomials_fi(self.key[k], self
722                 .key[0], subround))
723             self.subkeys = split(self.vars('KS', 128), 16)
724             return polynomials
725
726     def polynomial_system(self):
727         """Construct polynomials system for Misty cipher."""
728         polynomials = list()
729
730         plain = self.vars('IN', 64)
731         if self.equations_key_schedule is True:
732             polynomials.extend(self.polynomials_key_schedule())
733         else:

```

```

726         self.key = split(self.vars('K', 128), 16)
727         self.subkeys = split(self.vars('KS', 128), 16)
728
729         polynomials.extend(self.polynomials_round(plain, 1)) # R2_F
variables introduced.
730         for i in range(3, self.nrounds + 1, 2):
731             vars_f_prev = self.vars('F', 64, i - 1)
732             polynomials.extend(self.polynomials_round(vars_f_prev, i))
733
734             vars_f = self.vars('F', 64, self.nrounds)
735             vars_fl1 = self.vars('FL', 32, self.nrounds + 1)
736             vars_fl2 = self.vars('FL', 32, self.nrounds + 2)
737             vars_out = self.vars('OUT', 64)
738
739             left = vars_f[0:self.halfblock_size]
740             right = vars_f[self.halfblock_size:]
741
742             polynomials.extend(self.polynomials_fl(left, self.nrounds + 1))
743             polynomials.extend(self.polynomials_fl(right, self.nrounds + 2)
744         )
745         polynomials.extend(vector_do(operator.__xor__, vars_fl1,
vars_out[32:64]))
746         polynomials.extend(vector_do(operator.__xor__, vars_fl2,
vars_out[0:32]))
747         return PolynomialSequence(polynomials)

```

## APPENDIX D

### SOLVING 2 ROUNDS OF MISTY1 EQUATIONS SYSTEM

```

1  from sage.rings.polynomial.multi_polynomial_sequence import
    PolynomialSequence
2  from sage.rings.polynomial.multi_polynomial_sequence import
    PolynomialSequence_generic
3
4  from sage.sat.boolean_polynomials import solve as sat_solve
5
6  load('misty.sage')
7
8  def inject_vars(F, vars, values):
9      """Inject vars values into polynomial system. """
10     sub_values = dict(zip(vars, values))
11     return F.subs(sub_values)
12
13
14 def get_vars(solution, vars):
15     """Obtain variable values from solution dict. """
16     var_names = map(str, vars)
17     solution = dict(zip(map(str, solution.keys()), solution.values()))
18     values = list()
19     for i in var_names:
20         values.append(solution.get(i))
21     return values
22
23
24 def join_systems(mqsystems):
25     """Join polynomial systems into one.
26
27     Key variables aren't prefixed since they must be the same through
28     all
29     systems. Joined systems with different keys injected are incorrect.
30
31     """
32     var_names = flatten([system.ring().variable_names() for system in
33         mqsystems])
34     common_vars = list(set(var_names))
35     common_ring = BooleanPolynomialRing(len(common_vars), common_vars,
36         order='degrevlex')
37     new_mqsystem = PolynomialSequence([], common_ring)
38     for s in mqsystems:
39         new_mqsystem.extend(list(s))
40     return new_mqsystem
41
42
43 def solve_single_system():
44     m = Misty(2)
45     plaintext = [1] * 64
46     key = [1] * 128
47     m.key_schedule(key)
48     ciphertext = m.encrypt(plaintext, key)
49
50     print 'constructing polynomials...'
51     polynomials = m.polynomial_system()
52     print 'constructing equations system...'
53     F = PolynomialSequence(polynomials)

```

```

50     print 'injecting variables...'
51     F = inject_vars(F, m.vars('IN', 64), plaintext)
52     F = inject_vars(F, m.vars('OUT', 64), ciphertext)
53     print 'solving system...'
54     result = sat_solve(F)
55     print 'Done.'
56     key = get_vars(result[0], m.vars('K', 128))
57     print key
58
59
60 def solve_joined_systems():
61     nrounds = 2
62     instances = [Misty(nrounds, prefix) for prefix in ['a', 'b']]
63
64     print 'constructing equation systems...'
65     eqsystems = [i.polynomial_system() for i in instances]
66
67     inputs = [[0] * 64, [1] * 64]
68     key = [1] * 128
69     outputs = list()
70     for i, m in enumerate(instances):
71         m.key_schedule(key)
72         outputs.append(m.encipher(inputs[i], key))
73     print 'INPUTS:'
74     for i in inputs:
75         print hex(instances[0].get_integer(i))
76     print 'KEY:'
77     print hex(instances[0].get_integer(key))
78     print 'OUTPUTS:'
79     for i in outputs:
80         print hex(instances[0].get_integer(i))
81
82     print '\ninjecting known variables...'
83     for i, m in enumerate(instances):
84         eqsystems[i] = inject_vars(eqsystems[i], m.vars('IN', 64),
inputs[i])
85         eqsystems[i] = inject_vars(eqsystems[i], m.vars('OUT', 64),
outputs[i])
86
87     for i in eqsystems:
88         print i.__str__()
89
90     print '\ncombining equation systems...'
91     eqsystem = join_systems(eqsystems)
92     print eqsystem.__str__()
93
94     print '\nsolving equation system...'
95     solution = sat_solve(eqsystem)[0]
96     print solution

```

# APPENDIX E S-BOXES FOR GOST 28147-89 IMPLEMENTATION

$$\begin{aligned}
S_1 &= \{4, 10, 9, 2, 13, 8, 0, 14, 6, 11, 1, 12, 7, 15, 5, 3\} \\
S_2 &= \{14, 11, 4, 12, 6, 13, 15, 10, 2, 3, 8, 1, 0, 7, 5, 9\} \\
S_3 &= \{5, 8, 1, 13, 10, 3, 4, 2, 14, 15, 12, 7, 6, 0, 9, 11\} \\
S_4 &= \{7, 13, 10, 1, 0, 8, 9, 15, 14, 4, 6, 12, 11, 2, 5, 3\} \\
S_5 &= \{6, 12, 7, 1, 5, 15, 13, 8, 4, 10, 9, 14, 0, 3, 11, 2\} \\
S_6 &= \{4, 11, 10, 0, 7, 2, 1, 13, 3, 6, 8, 5, 9, 12, 15, 14\} \\
S_7 &= \{13, 11, 4, 1, 3, 15, 5, 9, 0, 10, 14, 7, 6, 8, 2, 12\} \\
S_8 &= \{1, 15, 13, 0, 5, 7, 10, 4, 9, 2, 3, 14, 6, 11, 8, 12\}
\end{aligned}$$

## APPENDIX F

### LIST OF PUBLICATIONS

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  11. Kiyanchuk R. I. Algebraic cryptanalysis of GOST 28147-89 Radioelectronics and youth in XXI century / Kharkiv National University of Radio and Electronics. Kharkiv, 2013. P. 119 – 120.