Cryptographic Properties of Boolean Functions: Recent Developments and Open Problems

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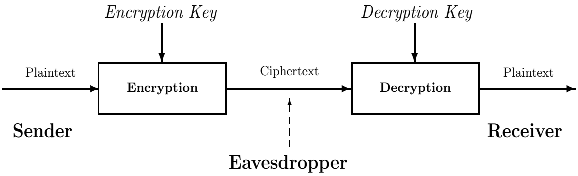
Talk Outline

1. Introduction - Definitions
   - Stream ciphers
   - Block ciphers
2. Properties of cryptographic functions
   - Correlation immunity
   - Nonlinearity
     - Higher-order nonlinearity
   - Algebraic immunity
     - Fast algebraic immunity
3. Conclusions - Open problems

Symmetric ciphers

A typical cryptosystem



Symmetric cryptography

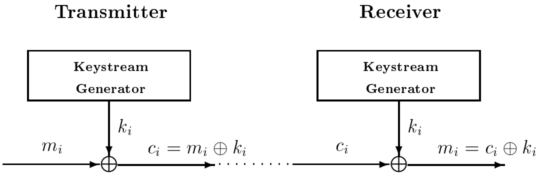
- Encryption Key = Decryption Key
- The key is only shared between the two parties
  - The security rests with the secrecy of the key (Kerchoffs principle)

Two types of symmetric ciphers

- Stream ciphers
- Block ciphers

Stream ciphers

Simplest Case: Binary additive stream cipher



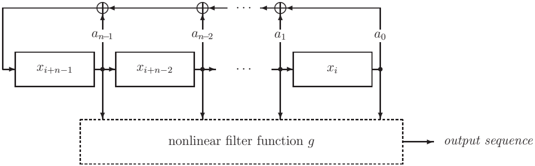
- Suitable in environments characterized by a limited computing power or memory, and the need to encrypt at high speed
- The seed of the keystream generators constitutes the secret key
- Security depends on
  - Pseudorandomness of the keystram k_i
  - Properties of the underlying functions that form the keystream generator

The optimal cipher: one-time pad

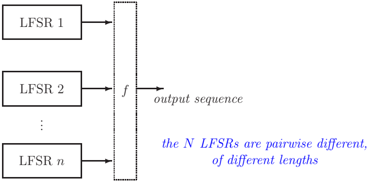
Description

- If $M = m_1 m_2 \ldots m_n$, then $k = k_1 k_2 \ldots k_n$ satisfying
  - k is trully random
  - k is aperiodic
  - For each different message, we use different key
- Encryption: $c_i = m_i \oplus k_i$, $i = 1, 2, \ldots, n$
- Decryption: $m_i = c_i \oplus k_i$, $i = 1, 2, \ldots, n$
- Such cipher is perfectly secure (Claude Shannon - 1949)
  - $p(M|C) = p(M)$ for any pair M, C
- However both randomness as well as aperiodicity can not be ensured in a realistic model
- Designing of stream ciphers strives to resemble the one-time pad

Classical Keystream Generators



(a) Nonlinear filter generator



(b) Nonlinear combiner generator

- Unpredictability of keystreams is ensured by appropriately choosing the underlying Boolean functions
- If these functions though do not satisfy certain properties, the system may be vulnerable to attacks
- More recently, nonlinear FSRs are preferred (although their mathematics are not well-known)

Known stream ciphers

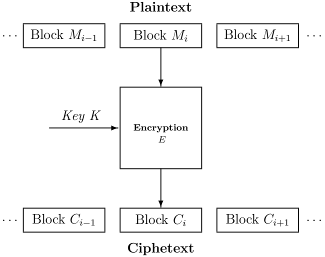
- RC4
  - Used in WEP, WPA, SSL/TLS
- A5/1
  - Used in mobile telephony (GSM)
- E0
  - Used in Bluetooth protocol

eStream project (2004–2008): Effort to promote the design of efficient and compact stream ciphers suitable for widespread adoption.

- Finalists:
  - Software implementation: HC-128, Rabbit, Salsa20/12, SOSEMANUK
  - Hardware implementation: Grain v1, MICKEY 2.0, Trivium

Block ciphers

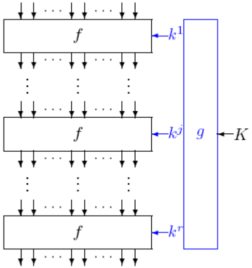
Simplest Case: Electronic Codebook Mode (ECB)



- Encryption on a per-block basis (typical block size: 128 bits)
- The encryption function E performs key-dependent substitutions and permutations (Shannon's principles)
- Security depends on
  - Generation of the sub-keys used in E
  - Properties of the underlying functions of E

The encryption function E in a block cipher

- Iterative structure
  - Several rounds occur
- A sub-key is being used in each round
- The round function f performs substitution and permutations, via multi-output Boolean functions (S-boxes, P-boxes)
  - S-boxes and P-boxes provide the cryptographic properties of diffusion and confusion respectively (Claude Shannon - 1949)



Known block ciphers

- Advanced Encryption Standard (AES)
  - NIST's standard since 2001 (initial submission: Rijndael cipher)
  - Supported key lengths: 128, 192, 256 bits
  - Widespread adoption (SSL/TLS, IPSec, commercial products,...)
- Data Encryption Standard (DES)
  - The predecessor of AES (1976-1996)
  - Official withdrawing: 2004 (although it is still being met today)
  - Key size: 56 bits (actually, the only flaw of the algorithm)
- 3DES
  - Modification of DES, to use key of 112 or 168 bit length
  - Still in use today - although not very efficient
- Other block ciphers: IDEA, MARS, RC6, Serpent, Twofish

A common approach for block and stream ciphers

- Despite their differences, a common study is needed for their building blocks (multi-output and single-output Boolean functions respectively)
- The attacks in block ciphers are, in general, different from the attacks in stream ciphers and vice versa. However:
  - For both cases, almost the same cryptographic criteria of functions should be in place
- Challenges:
  - There are tradeoffs between several cryptographic criteria
  - The relationships between several criteria are still unknown
  - Constructing functions satisfying all the main criteria is still an open problem

Boolean Functions

A Boolean function f on n variables is a mapping from $\mathbb{F}_2^n$ onto $\mathbb{F}_2$

- The vector $f = \big(f(0,0,\ldots,0), f(1,0,\ldots,0),\ldots, f(1,1,\ldots,1)\big)$ of length 2^n is the truth table of f
- The Hamming weight of f is denoted by $\mathrm{wt}(f)$
  - f is balanced if and only if $\mathrm{wt}(f) = 2^{n-1}$
- The support $\mathrm{supp}(f)$ of f is the set $\{\boldsymbol{b} \in \mathbb{F}_2^n : f(\boldsymbol{b}) = 1\}$

Example: Truth table of balanced f with $n = 3$

x_1	0	1	0	1	0	1	0	1
x_2	0	0	1	1	0	0	1	1
x_3	0	0	0	0	1	1	1	1
$f(x_1,x_2,x_3)$	0	1	0	0	0	1	1	1

A vectorial Boolean function f on n variables is a mapping from $\mathbb{F}_2^n$ onto $\mathbb{F}_2^m$, $m > 1$

Algebraic Normal Form and degree of functions

- Algebraic Normal Form (ANF) of f:

$$f(x) = \sum_{\boldsymbol{v} \in \mathbb{F}_2^n} a_{\boldsymbol{v}} x^{\boldsymbol{v}}, \quad \text{where } x^{\boldsymbol{v}} = \prod_{i=1}^{n} x_i^{v_i}$$

.

  - The sum is performed over $\mathbb{F}_2$ (XOR addition)
- The degree $\deg(f)$ of f is the highest number of variables that appear in a product term in its ANF.
- If $\deg(f) = 1$, then f is called affine function
  - If, in addition, the constant term is zero, then the function is called linear
- In the previous example: $f(x_1, x_2, x_3) = x_1x_2 + x_2x_3 + x_1$.
- $\deg(f) = 2$

Univariate representation of Boolean functions

- $\mathbb{F}_2^n$ is isomorphic to the finite field $\mathbb{F}_{2^n}$,
- $\Rightarrow$ Any function $f \in \mathbb{B}_n$ can also be represented by a univariate polynomial, mapping $\mathbb{F}_{2^n}$ onto $\mathbb{F}_2$, as follows

$$f(x) = \sum_{i=0}^{2^n-1} \beta_i x^i$$

  where $\beta_0, \beta_{2^n-1} \in \mathbb{F}_2$ and $\beta_{2i} = \beta_i^2 \in \mathbb{F}_{2^n}$ for $1 \leq i \leq 2^n - 2$
- The coefficients of the polynomial determine the Discrete Fourier Transform of f
- The degree of f can be directly deduced by the univariate representation
- The univariate representation is more convenient in several cases

Walsh transform

Definition

The Walsh transform $\widehat{\chi}_f(a)$ at $a \in \mathbb{F}_2^n$ of $f : \mathbb{F}_2^n \to \mathbb{F}_2$ is

$$\widehat{\chi}_f(a) = \sum_{x \in \mathbb{F}_2^n} (-1)^{f(x)+ax^T} = 2^n - 2\,\mathrm{wt}(f + \phi_a)$$

where $\phi_a(x) = ax^T = a_1x_1 + \cdots + a_nx_n$

- Computational complexity: $\mathcal{O}(n2^n)$ (via fast Walsh transform)
- Parseval's theorem: $\sum_{a \in \mathbb{F}_2^n} \widehat{\chi}_f(a)^2 = 2^{2n}$

Correlation immunity

- If the output of a Boolean function f is correlated to at least one of its inputs, then it is vulnerable to correlation attacks (Siegenthaler, 1984).
- The $f \in \mathbb{B}_n$ is t-th correlation immune if it is not correlated with any t-subset of $\{x_1, \ldots, x_n\}$; namely if

$$Pr(f(\boldsymbol{x}) = 0 | x_{i_1} = b_{i_1}, \ldots, x_{i_t} = b_{it}) = Pr(f(\boldsymbol{x}) = 0)$$

  for any t positions $x_{i_1}, \ldots, x_{i_t}$ and any $b_{i_1}, \ldots, b_{i_t} \in \mathbb{F}_2$
- If a t-th order correlation immune function is also balanced, then it is called t-th order resilient.

Properties of correlation immunity

- Siegenthaler, 1984: A known trade-off: If f is k-th order resilient for $1 \leq k \leq n-2$, then $\deg(f) \leq n-k-1$.
- Xiao-Massey, 1988: A function $f \in \mathbb{B}_n$ is t-th order correlation immune iff its Walsh transform satisfies

$$\widehat{\chi}_f(a) = 0, \forall\ 1 \leq \mathrm{wt}(a) \leq t$$

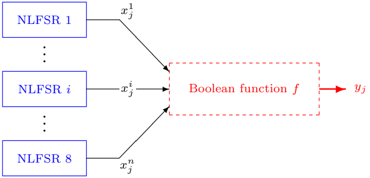
  - Note that f is balanced iff $\widehat{\chi}_f(\mathbf{0}) = 0$.
  - $\Rightarrow$ A function $f \in \mathbb{B}_n$ is t-th order resilient iff its Walsh transform satisfies $\widehat{\chi}_f(a) = 0, \forall\ 0 \leq \mathrm{wt}(a) \leq t$
- Siegenthaler also proposed a recursive procedure to construct m-th order resilient Boolean functions, for any desired m, with the maximum possible degree
- Several other constructions are currently known

Linear approximation attacks

- Cryptographic functions need to be balanced, as well as of high degree
  - The maximum possible degree of a balanced Boolean function with n variables is $n-1$
- High degree though is not adequate to prevent linear cryptanalysis (in block ciphers - Matsui, 1992) or best affine approximation attacks (in stream ciphers - Ding et. al., 1991)
  - A function should not be well approximated by a linear/affine function
  - Any function of degree 1 that best approximates f is a best affine/linear approximation of f

Example of approximation attacks

The Achterbahn cipher [Gammel-Göttfert-Kniffler,2005] (candidate in eSTREAM project)



- Lengths of nonlinear FSRs: 22-31
- $f(x_1, \ldots, x_8) = \sum_{i=1}^{4} x_i + x_5x_7 + x_6x_7 + x_6x_8 + x_5x_6x_7 + x_6x_7x_8$
- Johansson-Meier-Muller, 2006: cryptanalysis via the linear approximation $g(x_1, \ldots, x_8) = x_1 + x_2 + x_3 + x_4 + x_6$, satisfying $\mathrm{wt}(f+g) = 64$ $(p(f = g) = 3/4)$

The notion of nonlinearity

- The minimum distance between f and all affine functions is the nonlinearity of f:

$$\mathsf{nl}(f) = \min_{l \in \mathbb{B}_n : \deg(l)=1} \mathrm{wt}(f + l)$$

- Relathionship with Walsh transform

$$\mathsf{nl}(f) = 2^{n-1} - \frac{1}{2} \max_{a \in \mathbb{F}_2^n} |\widehat{\chi}_f(a)|$$

  - $\Rightarrow$ Nonlinearity is computed via the Fast Walsh Transform
- High nonlinearity is prerequisite for thwarting attacks based on affine (linear) approximations

Known results on nonlinearity of Boolean functions

- For even n, the maximum possible nonlinearity is $2^{n-1} - 2^{n/2-1}$, achieved by the so-called bent functions
  - Many constructions are known (not fully classified yet)
  - But bent functions are never balanced!
- For odd n, the maximum possible nonlinearity is still unknown
  - By concatenating bent functions, we can get nonlinearity $2^{n-1} - 2^{\frac{n-1}{2}}$. Can we impove this?
    - For $n \leq 7$, the answer is no
    - For $n \geq 15$, the answer is yes (Patterson-Wiedemann, 1983 - Dobbertin, 1995 - Maitra-Sarkar, 2002)
    - For $n = 9, 11, 13$, such functions have been found more recently (Kavut, 2006)
- Several constructions of balanced functions with high nonlinearity exist (e.g. Dobbertin, 1995). However:
  - Finding the highest possible nonlinearity of balanced Boolean functions is still an open problem

Nonlinearity and correlation immunity

- If $f \in \mathbb{B}_n$ is m-th order resilient, then $\mathsf{nl}(f) \leq 2^{n-1} - 2^{m+1}$ (Sarkar-Maitra, 2000)
- If the upper bound is achieved, the Walsh transform takes 3 values
- For n even, the best possible nonlinearity is $2^{n-1} - 2^{n/2-1}$ (bent functions)
  - If $f \in \mathbb{B}_n$ is m-th order resilient, n even, with $m \leq n/2 - 2$, then $\mathsf{nl}(f) \leq 2^{n-1} - 2^{n/2-1} - 2^{m+1}$
- For n odd, the maximum possible nonlinearity nl_{max} is unknown
  - The above bound holds if $2^{m+1} \leq 2^{n-1} - \mathsf{nl}_{max}$

The Maiorana-McFarland class of functions

- A widely known class of functions with nice cryptographic properties
- $f \in \mathbb{B}_{k+s}$ satisfying the following:

$$f(y,x) = F(y)x + h(y), \;\; x \in \mathbb{F}_2^k, \;\; y \in \mathbb{F}_2^s$$

  - F is any mapping from $\mathbb{F}_2^k$ to $\mathbb{F}_2^s$
  - $h \in \mathbb{B}_s$
- If $k = s$ and F is a permutation over $\mathbb{F}_2^k \Rightarrow f$ is bent (e.g. Dillon, 1974)
- For injective F, if $\mathrm{wt}(F(\tau)) \geq t+1$ for all $\tau \in \mathbb{F}_2^s$, then f is t-resilient (Camion et. al., 1992).

Higher-order nonlinearity

- Approximating a function by a low-order function (not necessarily linear) may also lead to cryptanalysis (Non–linear cryptanalysis - Knudsen-1996, low-order approximation attacks - Kurosawa et. al. - 2002)
- The rth order nonlinearity of a Boolean function $f \in \mathbb{B}_n$ is given by

$$\mathsf{nl}_r(f) = \min_{g \in \mathbb{B}_n : \deg(g) \leq r} \mathrm{wt}(f+g)$$

- The rth order nonlinearity remains unknown for $r > 1$
  - Recursive lower bounds on $\mathsf{nl}_r(f)$ (Carlet, 2008)
  - Specific lower and upper bounds for $\mathsf{nl}_2(f)$ (Cohen, 1992 - Carlet, 2007)
  - More recent lower bounds for 2-nd order nonlinearity: Gangopadhyay et. al. - 2010, Garg et. al. - 2011, Singh - 2011, Singh et. al. - 2013

Computing best low order approximations

- Computing even the best 2-nd order approximations is a difficult task
  - Efficient solution for specific class of 3-rd degree functions (Kolokotronis-Limniotis-Kalouptsidis, 2009)
    - The problem is appropriately reduced in computing best affine approximation attacks of the underlying 2-nd degree sub-functions
  - For the Achterbahn's combiner function: $q(x) = x_5x_7 + x_6x_8 + x_1 + x_2 + x_3 + x_4$ is a best 2-nd approximation
  - $\mathrm{wt}(f+q) = 32$ $(p(f=q) = 7/8 > 3/4)$
- No much is known regarding constructions of functions with high r-th nonlinearity, for $r \geq 2$
  - Even if a high lower bound on the nonlinearity is proved, best r-th order approximations can not be computed

A case of highly nonlinear function f with $\mathsf{nl}_2(f) = \mathsf{nl}(f)$

Cubic functions in the general Maiorana–McFarland class

$$f(x,y) = F(x)y^T, \qquad (x,y) \in \mathbb{F}_2^n \times \mathbb{F}_2^m .$$

- $F : \mathbb{F}_2^n \to \mathbb{F}_2^m$: quadratic vectorial Perfect Nonlinear (PN) function
- All linear combinations of the m underlying Boolean functions are bent
- (Kolokotronis-Limniotis, 2012): Let $f \in \mathbb{B}_{n+m}$ be cubic function of the above form, where each linear combination of the Boolean functions of F is bent of minimal weight, and $m \leq \lfloor \frac{n}{4} \rfloor$. Then,

$$\mathsf{nl}_2(f) = 2^{n+m-1} - 2^{n/2-1}(2^{n/2} + 2^m - 1) = \mathsf{nl}(f)$$

- Best 2-nd order approximations are also efficiently computed

More recent attacks: Algebraic attacks

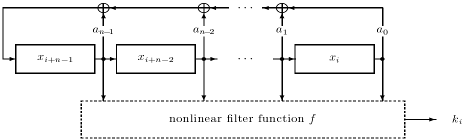
Milestones

- Algebraic attacks (Courtois-Meier, 2003)
- Fast algebraic attacks (Courtois, 2003)
- The basic idea is to reduce the degree of the mathematical equations employing the secret key
- Known cryptographic Boolean functions failed to thwart these attacks
- Some applications of algebraic attacks
  - Six rounds of DES, with only one known plaintext (Courtois-Bard, 2006)
  - Keeloq block cipher (Courtois-Bard-Wagner, 2008)
  - Hitag2 stream cipher (Courtois et. al., 2009)

Algebraic attacks

Example

- Stream cipher based on a nonlinear filter generator



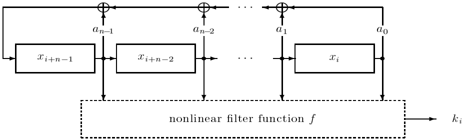
- $k_i = f(L^i(x_0, x_1, \ldots, x_{N-1}))$ - the filter function f has high degree
- Assume that there exists $g \in \mathbb{B}_n$ of low degree such that $f * g = h$, where h is also of low degree. Then,

$$k_i g(L^i(x_0, x_1, \ldots, x_{N-1})) = h(L^i(x_0, x_1, \ldots, x_{N-1}))$$

- Several other proper choices of g, h may also reduce the degree of the system

An example: The Toyocrypt cipher

- A submission to a Japanese government call



- The nonlinear filter function is

$$f(x_1,\ldots,x_{128}) = q(x_1,\ldots,x_{128}) + x_{10}x_{23}x_{32}x_{42} + \prod_{i=1}^{62} x_i +$$

$$+ x_1x_2x_9x_{12}x_{18}x_{20}x_{23}x_{25}x_{26}x_{28}x_{33}x_{38}x_{41}x_{42}x_{51}x_{53}x_{59}$$

where $\deg(q) = 2$.

- By multiplying f with the affine functions $1 + x_{23}$ or $1 + x_{42}$, we get two functions of degree only 3

How to proceed with algebraic attacks

- Once the degree of the equations have been reduced, several algebraic techniques have been proposed for solving the (still nonlinear) system:
  - Linearization of the system
  - Use of Gröbner bases
  - More specific techniques: XL, XSL
- Hence, the core of the algebraic attacks is the transformation of the initial system to a new one having low degree

Annihilators and algebraic immunity

Definition

Given $f \in \mathbb{B}_n$, we say that $g \in \mathbb{B}_n$ is an annihilator of f if and only if g lies in the set

$$\mathcal{AN}(f) = \{g \in \mathbb{B}_n : f * g = 0\}$$

Definition

The algebraic immunity $\mathsf{AI}_n(f)$ of $f \in \mathbb{B}_n$ is defined by

$$\mathsf{AI}_n(f) = \min_{g \neq 0}\{\deg(g) : \ g \in \mathcal{AN}(f) \cup \mathcal{AN}(f+1)\}$$

- A high algebraic immunity is prerequisite for preventing algebraic attacks (Meier-Pasalic-Carlet, 2004)
- Well-known upper bound: $\mathsf{AI}_n(f) \leq \lceil \frac{n}{2} \rceil$

Algebraic immunity and nonlinearity

- Carlet *et. al.*, 2006: $\mathsf{nl}_r(f) \geq \sum_{i=0}^{\mathsf{AI}_n(f)-r-1} \binom{n}{i}$
  - Low nonlinearity implies low algebraic immunity
- Especially for $r = 1$ (Lobanov, 2005): $\mathsf{nl}(f) \geq 2\sum_{i=0}^{\mathsf{AI}_n(f)-2} \binom{n-1}{i}$
- Mesnager, 2008: Improvements one the above bounds:

$$\mathsf{nl}_r(f) \geq \sum_{i=0}^{\mathsf{AI}_n(f)-r-1} \binom{n}{i} + \sum_{i=\mathsf{AI}_n(f)-2r}^{\mathsf{AI}_n(f)-r-1} \binom{n-r}{i},$$

- Rizomiliotis, 2010: Further improvements
  - The notion of complementary algebraic immunity is defined

$$\overline{\mathsf{AI}_n(f)} \triangleq \max\{\min_{\deg(g)}\{f * g = 0\}, \min_{\deg(g)}\{(f+1) * g = 0\}\}$$

Fast algebraic attacks

- Consider again the filter generator: $k_i = f(L^i(x_0, x_1, \ldots, x_{N-1}))$
- Assume that there exists a low degree $g \in \mathbb{B}_n$ such that $h = f * g$ is of reasonable degree. Then again,

$$k_i g(L^i(x_0, x_1, \ldots, x_{N-1})) = h(L^i(x_0, x_1, \ldots, x_{N-1}))$$

- There exists a linear combination of the first $\sum_{i=0}^{\deg(h)} \binom{N}{i}$ equations that sum the right-hand part to zero $\Rightarrow$ We get one equation of degree at most $\deg(g)$

Comparison with conventional algebraic attacks

- $g + h \in \mathcal{AN}(f) \Rightarrow$ the degree of $g + h$ may be greater than $\mathrm{AI}_n(f)$,
  - Maximum AI does not imply resistance to fast algebraic attacks
- But: Knowledge of consecutive keystream bits is required

Fast Algebraic Immunity

Known result: For any pair of integers (e, d) such that $e + d \geq n$, there exists a nonzero function g of degree at most e such that $f * g$ has degree at most d.

Definition

The fast algebraic immunity $\mathsf{FAI}_n(f)$ of $f \in \mathbb{B}_n$ is defined by

$$\mathsf{FAI}_n(f) = \min_{1 \leq \deg(g) \leq \mathsf{AI}_n(f)} \{2\,\mathsf{AI}_n(f), \deg(g) + \deg(f * g)\}$$

- Upper bound: $\mathsf{FAI}_n(f) \leq n$

Constructions of functions with maximum AI

- Dalai-Maitra-Sarkar, 2006: Majority function
  - For even n, a slight modification of the majority function also preserves maximum AI
- Carlet-Dalai-Gupta-Maitra-Sarkar, 2006: Iterative construction
- Li-Qi, 2006: Modification of the majority function
- Sarkar-Maitra, 2007: Rotation Symmetric functions of odd n
- Carlet, 2008: Based on properties of affine subspaces
  - Further investigation in Carlet-Zeng-Li-Hu, 2009
  - Generalization (for odd n) in Limniotis-Kolokotronis-Kalouptsidis, 2011
- Balanceness and/or high nonlinearity are not always attainable, whereas their fast algebraic immunity remains unknown

The Carlet-Feng construction

- Carlet-Feng, 2008: $\mathrm{supp}(f) = \{0, 1, \alpha, \alpha^2, \ldots, \alpha^{2^{n-1}-2}\}$, where α a primitive element of the finite field $\mathbb{F}_{2^n}$.
  - Degree $n-1$ (i.e. the maximum possible)
  - High (first-order) nonlinearity is ensured
    - Best currently known lower bound (Tang et. al., 2013:)

$$\mathsf{nl}(f) \geq 2^{n-1} - (\frac{n\ln(2)}{\pi} + 0.74)2^{n/2} - 1$$

    - Experiments show that the actual values of nonlinearities may be higher enough
  - Optimal against fast algebraic attacks, as subsequently shown (Liu-Zhang-Lin, 2012)

Generalizations of Carlet-Feng construction

- Rizomiliotis, 2010: A new construction based on the univariate representation
  - For odd n, it is affine equivalent to the Carlet-Feng construction
- Zeng-Carlet-Shan-Hu, 2011: Modifications of the Rizomiliotis construction
- Further generalizations in Limniotis-Kolokotronis-Kalouptsidis, 2013:
  - Finding swaps between $\text{supp}(f)$ and $\text{supp}(f+1)$ that preserve maximum AI
    - Via solving a system of linear equations, with upper-triangular coefficient matrix
    - Each nonzero entry in the solution vector indicates a swapping

Conclusions - Open problems

- Evaluation of known families of cryptographic functions in terms of resistance against (fast) algebraic attacks
- Construction of functions with maximum (fast) algebraic immunity
    - Much progress on constructing functions with maximum AI, but the case of maximum FAI is much more difficult
    - High r-th order nonlinearity, for $r > 1$, has not been studied at all
- Relationships between (fast) algebraic immunity and correlation immunity
    - A preliminary result is only known (Limniotis, 2013)
- Improve our knowledge regarding relationships between AI and nl
- Nonlinear FSRs (or other nonlinear structures) have not been studied to the same extent w.r.t. algebraic attacks

Questions & Answers

Thank you for your attention!