Chosen IV Statistical Analysis for Key Recovery Attacks on Stream Ciphers

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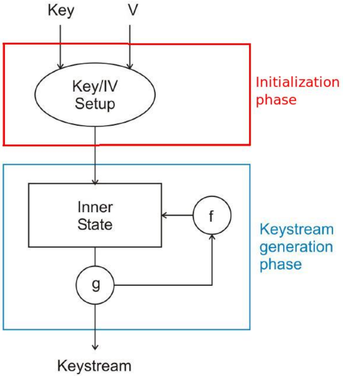
AfricaCrypt 2008, Casablanca - June 11-14

Outline

- A framework for key recovery on a function $z = F(K, V)$ where attacker can choose parameter V.
- Application to reduced-round initialization of Grain-128 and Trivium, two eStream phase 3 candidates.

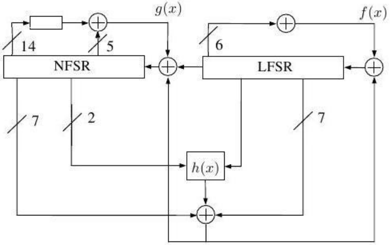
Stream Cipher

Initialization procedure of a stream cipher takes key K and initialization vector (IV) V to produce the initial state.

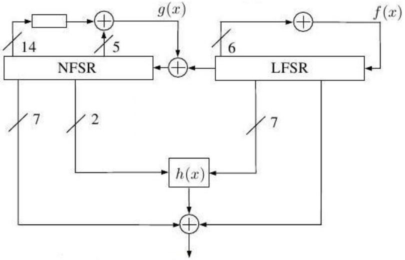


Keystream generator produces a long output sequence from the internal state.

Grain-128



Initialization mode

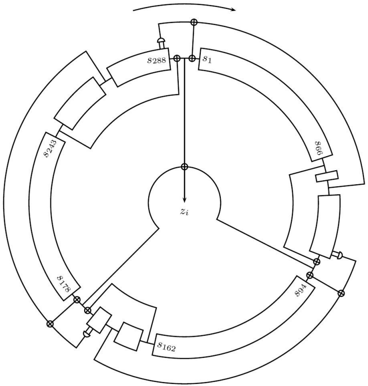


keystream generation mode

Initialization:

- Fill the registers with key, IV and some constants.
- Clock 256 times in initialization mode.

Trivium

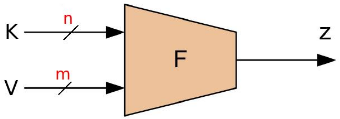


Initialization:

- Fill the registers with key, IV and some constants.
- Clock 1152 times.

Attack Model

We define a related Boolean function $F(K, V) = z$ where z is the first keystream bit.



Threat model: Adversary sends IV's V of his choice to the oracle and gets back z according to fixed unknown secret key K chosen by the oracle.

Goal: Efficient distinguishing or key-recovery attacks.

Requirements

Security: $F(K,V)$ should depend on each key bit and IV bit in a complex way.

Efficiency: Because of limited resources, F is often constructed by a number of simple rounds.

For example, Grain-128 and Trivium use simple round functions of low-degree.

- Is diffusion sufficient for specified number of rounds?
- If no, how to mount an attack?

Previous Works:
Distinguishing Attacks Based on Polynomial Description

Consider $F(K, V)$ with $K = (k_1, \ldots, k_n)$ and $V = (v_1, \ldots, v_m)$.

Idea: Choose a list of l ($\leq m$) IV bits $\{v_{i_1}, v_{i_2}, \ldots, v_{i_l}\}$, consider all key bits and the remaining IV bits as parameters and focus on the resultant parametric Boolean function $g(v_{i_1}, v_{i_2}, \ldots, v_{i_l})$.

Fact: Adversary can compute the truth table (as well as the algebraic normal form (ANF)) of g with 2^l queries by dealing with the oracle.

Expectation: Each monomial must appear with probability $1/2$ and independent from others in the ANF of g.

[Filiol'02],[Saarinen'06],[O'Neil'07],[Englund-Johansson-Turan'07].

Previous Works:
High-degree Monomials

High degree monomials in g are more suspicious to exhibit non-randomness: it will take many clockings before all selected IV bits meet in the same memory cell.

Maximum degree (MD) test in [Englund-Johansson-Turan'07]: check if the maximum degree monomial is produced by g.

The MD test turned out to be a suitable measure for diffusion.

They reported a distinguishing attack on

- 192/256 rounds in Grain-128
- 736/1152 rounds in Trivium

Our Contribution: Providing key-recovery attacks

Generalization

Make partition $V = (U, W)$ with $U = \{v_{i_1}, v_{i_2}, \ldots, v_{i_l}\}$ as input to g. Focus on a single coefficient C of $g(U)$, e.g. maximum degree monomial.

Fact: $C = C(K, W)$ depends on the key and remaining IV bits, and can be evaluated for every W of our choice by dealing with the oracle.

Scenarios of attacks (if mixing is not complete):

- Imbalance of C can be used for distinguish attacks.
- Sometimes, $C(K, W)$ for some fixed W does not involve all key bits: key recovery attack on 576/1152 rounds of Trivium [Vielhaber'07].
- More generally: some key bits in $C(K, W)$ may have only a limited influence ...

New Scenario

Given $C(K, W)$, find approximation A which depends on subkey of only $t < n$ key bits.

Reduce the search space from 2^n to 2^t. Method of probabilistic neutral key bits [Aumasson-Fischer-Khazaei-Meier-Rechberger'08].

Partition of $K = (L, M)$ with significant key bits L and non-significant key bits M. $A(L, W)$ is defined by replacing non-significant key bits in $C(K, W)$ with fixed values.

Definition: Let γ_i be the bias that complementing the key bit k_i does not change the output of C (neutrality measure).

Significant key bits L: all key bits k_i with $|\gamma_i| <$ threshold.

Key Recovery Attacks

Probabilistic guess and determine: try all possible subkeys L and distinguish correct guess L from incorrect ones.

1. Compute $C(K, W)$ through oracle, for unknown key and N random values of W.
2. For each choice of L do
   - Compute $A(L, W)$ for the same N values of W.
   - Check if $C(K, W)$ is equal to $A(L, W)$ for most of the N samples (optimal distinguisher)

Given a candidate subkey L, the entire key is verified by exhaustive search over remaining key part M.

Complexity

Required number of samples N depends on:

- Correlation ε between $A(L, W)$ and $C(K, W)$ if guessed part L is correct resp. incorrect.
- The desired levels of p_{fa} and p_{mis}.

Computation of N values of $A(L, W)$ has a cost of $N2^l$.
Repeat for all 2^t guesses of L, hence $N2^{l+t}$.

Set of candidates for subkey L has size $2^t \cdot p_{\mathrm{fa}}$.
Verification of entire key in $2^t p_{\mathrm{fa}} \cdot 2^{n-t} = 2^n p_{\mathrm{fa}}$.

Total complexity: $N2^{l+t} + 2^n p_{\mathrm{fa}}$.

Experimental Results: Trivium

Trivium has internal state of 288 bits.
$n = 80$ key bits, $m = 80$ IV bits, $R = 1152$ rounds.

Example:

- $F(K, V)$ computes first keystream bit after $r = 672$ rounds.
- Variable IV part U of $l = 11$ bits, get $f(U)$, focus on coefficient $C(K, W)$ of maximum degree monomial.
- Compute neutrality measure of key bits (with $|W|$=5). A set of $t = 29$ key bits ruled out as significant.
- Leads to approximating function $A(L, W)$ with some correlation to $C(K, W)$.
- Correct subkey can be detected with time complexity 2^{55}.

Experimental Results: Grain-128

Grain-128 has internal state of 256 bits.
$n = 128$ key bits, $m = 96$ IV bits, $R = 256$ rounds.

Example:

- Consider $r = 180$ rounds, and use IV part U of $l = 7$ bits.
- Focus on coefficient $C(K, W)$ of maximum degree monomial.
- Identify $t = 110$ significant key bits for L and get $A(L, W)$.
- Can detect subkey in estimated time complexity 2^{124}, i.e. improvement factor 2^4.

Open Question: How to find weak IV bits?

Conclusions

- Have applied the recently introduced technique of probabilistic neutral bits.
- Useful in analysis of initialization of stream ciphers.
- Contributes to the recent framework of chosen IV statistical analysis.
- Key recovery with complexity lower than exhaustive key search for simplified versions of two phase 3 eSTREAM candidates.

Thank you!