A New Encryption Standard of Ukraine: The Kalyna Block Cipher (DSTU 7624:2014)

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ІНСТИТУТ
ІНФОРМАЦІЙНИХ
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Харківський національний університет
імені В.Н. Каразіна

My path: 2009-2015

Outline

- Second generation of block ciphers in the post-Soviet states
- The new Ukrainian block cipher Kalyna
- Performance comparison with other ciphers
- Other sections of the Ukrainian national standard DSTU 7624:2014
- Conclusions

The block cipher GOST 28147-89

Advantages

- a well known and researched cipher, adopted as the national standard in 1990
- acceptable encryption speed
- appropriate for lightweight cryptography
- "good" S-boxes provide practical strength

Disadvantages

- theoretically broken
- huge classes of weak keys
- special S-boxes allow practical ciphertext-only attacks
- significantly slower performance in comparison to modern block ciphers like AES

Replacements for GOST 28147-89 in Belarus

Belarus: STB 34.101.31-2011

- the block length is 128 bits; the key length is 128, 192 or 256 bits
- 8-round Feistel network with a Lai-Massey scheme
- a single byte S-box with good cryptographic properties
- no key schedule like in GOST
- no cryptanalytical attacks better than exhaustive search are known
- faster than GOST, but slower than AES

Replacements for GOST 28147-89 in Russia

Russia: GOST R 34.12-2015

- the block cipher Magma
  - GOST 28147-89 with fixed substitutions
- the block cipher Kuznyechik
  - the block length is 128 bits; the key length is 256 bits
  - 9 rounds of Rijndael-like transformation
  - single byte S-box (common with "Stribog")
  - non-circulant MDS matrix of 16x16 size over $GF(2^8)$ (different from "Stribog")
  - key schedule based on a Feistel network and involves round transformations
  - no cryptanalytical attacks better than exhaustive search are known
  - faster than GOST, slower* than AES

Replacements for GOST 28147-89 in Ukraine

Ukraine: DSTU 7624:2014

- normal, high and ultra high security level
  - the block and key length 128, 256 and 512 bits
- Rijndael-like SPN structure
- four different S-boxes (not CCZ-equivalent) with optimized cryptographic properties
- 8x8 MDS matrix over $GF(2^8)$
- a new construction of Key Schedule based on the round function
- faster than GOST, faster* than AES

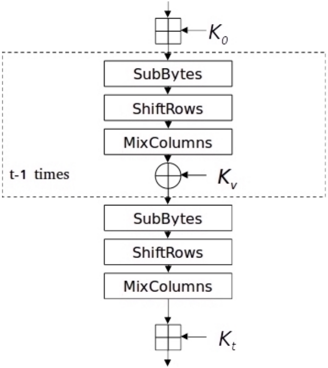
Kalyna: supported block and key lengths

l \ k	128	256	512	c
128	10	14	-	2
256	-	14	18	4
512	-	-	18	8

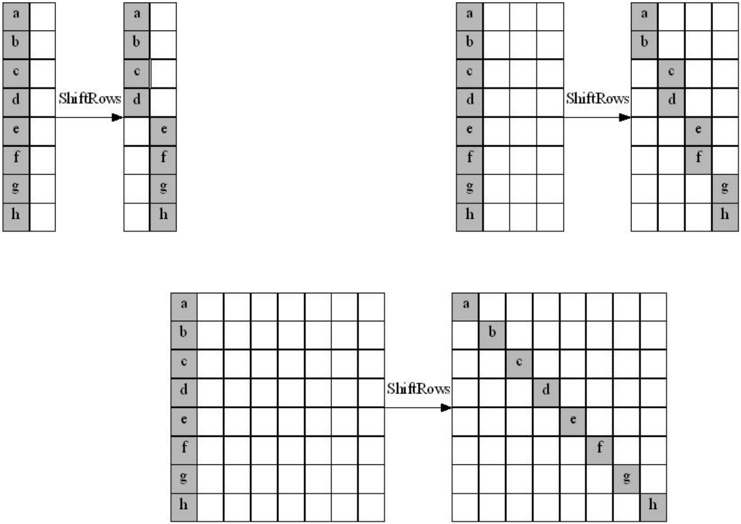
l: the block size; k: the key length;
t: the number of rounds; c: the number of columns

Kalyna: high-level structure

$$T_{l,k}^{(K)} = \eta_l^{(K_t)} \circ \psi_l \circ \tau_l \circ \pi'_l \circ \prod_{\nu=1}^{t-1} (\kappa_l^{(K_\nu)} \circ \psi_l \circ \tau_l \circ \pi'_l) \circ \eta_l^{(K_0)}$$



Kalyna: permutation of elements



Kalyna: properties of S-boxes

Property	S-box			
	1	2	3	4
Nonlinearity	104			
Min. algebraic degree of Boolean functions	7			
Max. value of difference distribution table	8			
Max. value of linear approximation table	24			
Algebraic immunity	3			
Number of cycles	4	4	6	4
Minimal cycle length	6	8	4	4

The best known byte permutations with algebraic immunity is equivalent to 3.

Kalyna: linear transformation

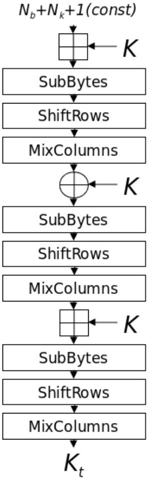
$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \end{bmatrix} = \begin{bmatrix} 01 \cdot a_0 \oplus 01 \cdot a_1 \oplus 05 \cdot a_2 \oplus 01 \cdot a_3 \oplus 08 \cdot a_4 \oplus 06 \cdot a_5 \oplus 07 \cdot a_6 \oplus 04 \cdot a_7 \\ 04 \cdot a_0 \oplus 01 \cdot a_1 \oplus 01 \cdot a_2 \oplus 05 \cdot a_3 \oplus 01 \cdot a_4 \oplus 08 \cdot a_5 \oplus 06 \cdot a_6 \oplus 07 \cdot a_7 \\ 07 \cdot a_0 \oplus 04 \cdot a_1 \oplus 01 \cdot a_2 \oplus 01 \cdot a_3 \oplus 05 \cdot a_4 \oplus 01 \cdot a_5 \oplus 08 \cdot a_6 \oplus 06 \cdot a_7 \\ 06 \cdot a_0 \oplus 07 \cdot a_1 \oplus 04 \cdot a_2 \oplus 01 \cdot a_3 \oplus 01 \cdot a_4 \oplus 05 \cdot a_5 \oplus 01 \cdot a_6 \oplus 08 \cdot a_7 \\ 08 \cdot a_0 \oplus 06 \cdot a_1 \oplus 07 \cdot a_2 \oplus 04 \cdot a_3 \oplus 01 \cdot a_4 \oplus 01 \cdot a_5 \oplus 05 \cdot a_6 \oplus 01 \cdot a_7 \\ 01 \cdot a_0 \oplus 08 \cdot a_1 \oplus 06 \cdot a_2 \oplus 07 \cdot a_3 \oplus 04 \cdot a_4 \oplus 01 \cdot a_5 \oplus 01 \cdot a_6 \oplus 05 \cdot a_7 \\ 05 \cdot a_0 \oplus 01 \cdot a_1 \oplus 08 \cdot a_2 \oplus 06 \cdot a_3 \oplus 07 \cdot a_4 \oplus 04 \cdot a_5 \oplus 01 \cdot a_6 \oplus 01 \cdot a_7 \\ 01 \cdot a_0 \oplus 05 \cdot a_1 \oplus 01 \cdot a_2 \oplus 08 \cdot a_3 \oplus 06 \cdot a_4 \oplus 07 \cdot a_5 \oplus 04 \cdot a_6 \oplus 01 \cdot a_7 \end{bmatrix}$$

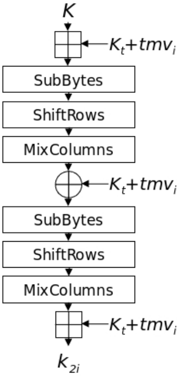
- the brunch number is 9 (the MDS matrix)
- effective software and software-hardware implementations

Requirements to Kalyna's Key Schedule

- non-linear dependence of each round key bit on each encryption key bit
- protection from cryptanalytic attacks aimed to key schedule
- high computation complexity of obtaining encryption key having one or several round keys (one-way transformation, additional protection from side-channel attacks)
- key agility is less than three
- possibility to generate round keys in direct and reverse order
- implementation simplicity (the use of transformations from the round function)

Kalyna: Key Schedule





$$k_{2i+1} = k_{2i} \lll (2 \cdot N_b + 3)$$

$$tmv_0 = 0x01000100..0100$$
$$tmv_{i+2} = tmv_i << 1$$

$$\Theta^{(K)} = \psi_l \circ \tau_l \circ \pi'_l \circ \eta_l^{(K_\alpha)} \circ \psi_l \circ \tau_l \circ \pi'_l \circ \kappa_l^{(K_\omega)} \circ \psi_l \circ \tau_l \circ \pi'_l \circ \eta_l^{(K_\alpha)}$$

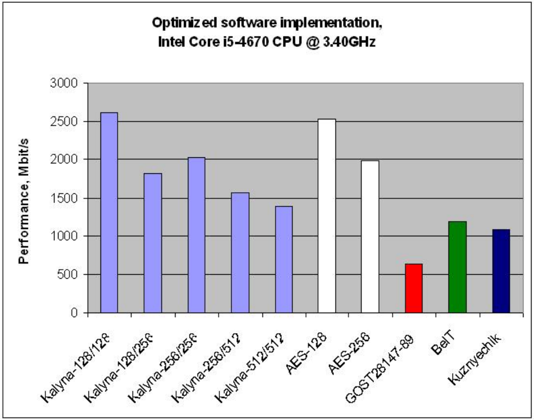
$$\Xi^{(K,K_\sigma,i)} = \eta_l^{(\varphi_i(K_\sigma))} \circ \psi_l \circ \tau_l \circ \pi'_l \circ \kappa_l^{(\varphi_i(K_\sigma))} \circ \psi_l \circ \tau_l \circ \pi'_l \circ \eta_l^{(\varphi_i(K_\sigma))}$$

Cryptanalytic attack against Kalyna

Kalyna is resistant to known cryptanalytic methods (based on public information):

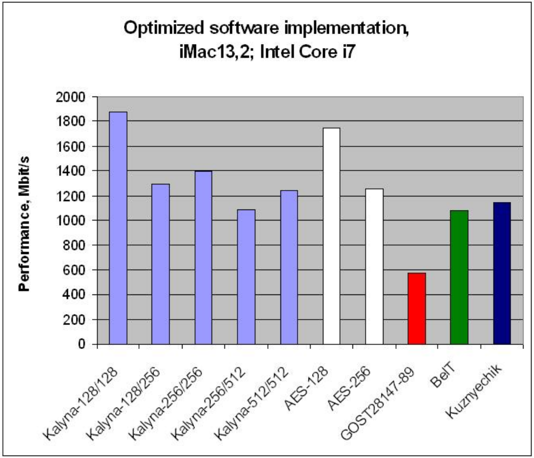
- Kalyna-128/128: from 6^{th} round (out of 10)
- Kalyna-128/256: from 10^{th} round* (out of 14)
- Kalyna-256/256: from 7^{th} round (out of 14)
- Kalyna-256/512: from 10^{th} round* (out of 18)
- Kalyna-512/512: from 9^{th} round (out of 18)

Kalyna: performance comparison with other block ciphers
(Intel Core i5, 64-bit Linux, gcc v4.9.2, best compiler optimization)



https://github.com/Roman-Oliynykov/ciphers-speed/

Kalyna: performance comparison with other block ciphers
(iMac 13.2, Intel Core i7, best compiler optimization)



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NIST STS of Kalyna's output sequences

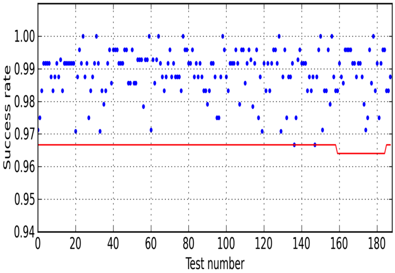

Figure: Even round keys

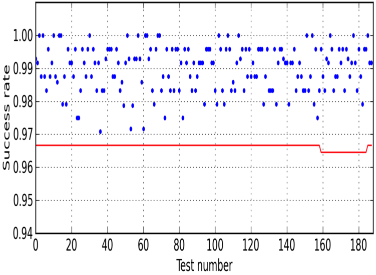

Figure: CTR encryption

DSTU 7624:2014: modes of operation

#	Description	Name	Property
1	Electronic Codebook	ECB	confidentiality
2	Counter	CRT	confidentiality
3	Cipher Feedback	CFB	confidentiality
4	Cipher-based Message Authentication Code	CMAC	integrity
5	Cipher Block Chaining	CBC	confidentiality
6	Output Feedback	OFB	confidentiality
7	Galois Counter Mode	GCM	confidentiality and integrity
	Galois Message Authentication Code	GMAC	integrity
8	Counter with CBC-MAC	CCM	confidentiality and integrity
9	XEX-based tweaked-codebook mode with ciphertext stealing	XTS	confidentiality
10	Key Wrap	KW	confidentiality and integrity

DSTU 7624:2014 also includes

- Ten modes of operation for the new block cipher
  - ISO 10116: ECB, CBC, CFB, OFB, CTR
  - additional modes, simplified/improved comparing to NIST SP 800-38: GCM/GMAC, CCM, XTS, KW
- Test vectors (including not aligned to the block length and, for some modes, byte length)
- Requirements to implementation:
  - general concepts paying developer's attention to take steps for prevention of side-channel attacks, timing attacks, CRIME/BREACH specific vulnerabilities, etc.
  - limits on the total number of invocation of the block cipher during the encryption key lifetime
  - message replay prevention
- etc.

Conclusions

The Kalyna block cipher provides

- normal, high and ultra high security level
- transparent construction and conservative design
- fast and effective software and software-hardware implementations on modern 64-bit platforms
- optimized construction for better performance on encryption and decryption for CTR, CFB, CMAC, OFB, GCM, GMAC, CCM
- a new construction of key schedule based on the round transformation
- common look-up tables with the hash function "Kupyna" (the new Ukrainian standard DSTU 7564:2014)

Besides the block cipher, the new Ukrainian standard DSTU 7624:2014 defines ten modes of operation, test vectors, requirements for implementation, limits on protected information amount for a single key application, etc.

Title

Figure: Kalyna / Viburnum / Krossvedslekta