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New encryption algorithm based on network RFWKPES8-1 using of the transformations of the encryption algorithm AES

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ABSTRACT

In this paper a new block encryption algorithm is developed based on network RFWKPES8-1 using of the transformations of the encryption algorithm AES, which is called AES-RFWKPES8-1. The block's length of this encryption algorithm is 256 bits, the number of rounds are 10, 12 and 14. The advantages of the encryption algorithm AES-RFWKPES8-1 are that, when encryption and decryption process used the same algorithm. In addition, the encryption algorithm AES-RFWKPES8-1 encrypts faster than AES

Keywords: Advanced Encryption Standard, Feystel network, Lai–Massey scheme, round function, round keys, output transformation, multiplication, addition, multiplicative inverse, additive inverse.

1. INTRODUCTION

In September 1997 the National Institute of Standards and Technology (NIST) issued a public call for proposals for a new block cipher to succeed the Data Encryption Standard (DES) [4]. Out of 15 submitted algorithms the Rijndael cipher by Daemen and Rijmen [1] was chosen to become the new Advanced Encryption Standard (AES) in November 2001 [2]. The Advanced Encryption Standard is a block cipher with a fixed block length of 128 bits. It supports three different key lengths: 128 bits, 192 bits, and 256 bits. Encrypting a 128-bit block means transforming it in n rounds into a 128-bit output block. The number of rounds n depends on the key length: n = 10 for 128-bit keys, n = 12 for 192-bit keys, and n = 14 for 256-bit keys. The 16-byte input block (t_0, t_1, …, t_{15}) which is transformed during encryption is usually written as a 4x4 byte matrix, the called AES *State*.

t_0	t_4	t_8	t_{12}
t_1	t_5	t_9	t_{13}
t_2	t_6	t_{10}	t_{14}
t_3	t_7	t_{11}	t_{15}

The structure of each round of AES can be reduced to four basic transformations occurring to the elements of the *State*. Each round consists in applying successively to the *State* the SubBytes(), ShiftRows(), MixColumns() and AddRoundKey() transformations. The first round does the same with an extra AddRoundKey() at the beginning whereas the last round excludes the MixColumns() transformation.

The SubBytes() transformation is a nonlinear byte substitution that operates independently on each byte of the *State* using a substitution table (S-box). Figure 1 illustrates the SubBytes() transformation on the *State*.

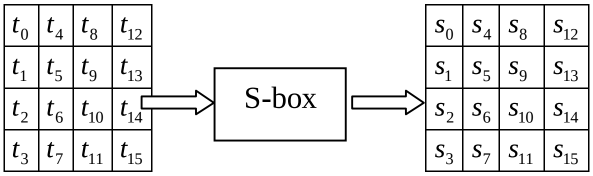

t_0 t_4 t_8 t_{12}
t_1 t_5 t_9 t_{13}
t_2 t_6 t_{10} t_{14}
t_3 t_7 t_{11} t_{15}
S-box
s_0 s_4 s_8 s_{12}
s_1 s_5 s_9 s_{13}
s_2 s_6 s_{10} s_{14}
s_3 s_7 s_{11} s_{15}

Figure 1: SubBytes() transformation

In the ShiftRows() transformation operates on the rows of the *State*; it cyclically shifts the bytes in each row by a certain offset. For AES, the first row is left unchanged. Each byte of the second row is shifted one to the left. Similarly, the third and fourth rows are shifted by offsets of two and three respectively. Figure 2 illustrates the ShiftRows() transformation.

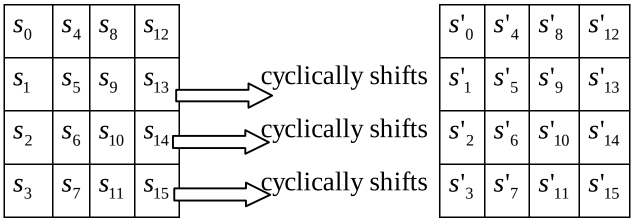

s_0 s_4 s_8 s_{12}
s_1 s_5 s_9 s_{13}
s_2 s_6 s_{10} s_{14}
s_3 s_7 s_{11} s_{15}
cyclically shifts
cyclically shifts
cyclically shifts
s'_0 s'_4 s'_8 s'_{12}
s'_1 s'_5 s'_9 s'_{13}
s'_2 s'_6 s'_{10} s'_{14}
s'_3 s'_7 s'_{11} s'_{15}

Figure 2: ShiftRows() transformation.

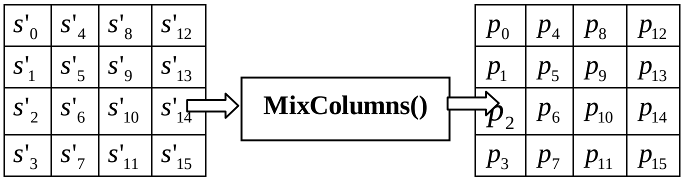
The MixColumns() transformation operates on the *State* column-by-column, treating each column as a four-term polynomial. The columns are considered as polynomials over GF(2^8) and multiplied modulo x^4+1 with a fixed polynomial $a(x)$, given by $a(x)=3x^2+x^2+x+2$. Let $p=a(x)\otimes s'$:

$$\begin{bmatrix} p_{4i} \\ p_{4i+1} \\ p_{4i+2} \\ p_{4i+3} \end{bmatrix} = \begin{bmatrix} 02\,03\,01\,01 \\ 01\,02\,03\,01 \\ 01\,01\,02\,03 \\ 03\,01\,01\,02 \end{bmatrix} \begin{bmatrix} s'_{4i} \\ s'_{4i+1} \\ s'_{4i+2} \\ s'_{4i+3} \end{bmatrix}, i=\overline{0...3}$$

As a result of this multiplication, the four bytes in a column are replaced by the following:

$$y_{4i} = (\{02\} \bullet s'_{4i}) \oplus (\{03\} \bullet s'_{4i+1}) \oplus s'_{4i+2} \oplus s'_{4i+3}$$
$$y_{4i+1} = s'_{4i} \oplus (\{02\} \bullet s'_{4i+1}) \oplus (\{03\} \bullet s'_{4i+2}) \oplus s'_{4i+3}$$
$$y_{4i+2} = s'_{4i} \oplus s'_{4i+1} \oplus (\{02\} \bullet s'_{4i+2}) \oplus (\{03\} \bullet s'_{4i+3})$$
$$y_{4i+4} = (\{03\} \bullet s'_{4i}) \oplus s'_{4i+1} \oplus s'_{4i+2} \oplus (\{02\} \bullet s'_{4i+3}) .$$

Figure 3 illustrates the MixColumns() transformation.



s'_0	s'_4	s'_8	s'_{12}
s'_1	s'_5	s'_9	s'_{13}
s'_2	s'_6	s'_{10}	s'_{14}
s'_3	s'_7	s'_{11}	s'_{15}

p_0	p_4	p_8	p_{12}
p_1	p_5	p_9	p_{13}
p_2	p_6	p_{10}	p_{14}
p_3	p_7	p_{11}	p_{15}

Figure 3: MixColumns() transformation.

Description network RFWKPES8-1 given in [3] and, similarly as in the Feistel network, when it encryption and decryption using the same algorithm. In the network used one round function having four input and output blocks and as the round function can use any transformation.

In this paper developed block encryption algorithm AES-RFWKPES8-1 based network RFWKPES8-1 using transformation of the encryption algorithm AES. The length of block of the encryption algorithm AES-RFWKPES8-1 is 256 bits, the number of rounds n equal to 10, 12, 14 and the length of key is variable from 256 bits to 1024 bits in steps 128 bits, i.e. key length is equal to 256, 384, 512, 640, 768, 896 and 1024 bits.

2. THE ENCRYPTION ALGORITHM AES-RFWKPES8-1.

2.1 The structure of the encryption algorithm AES-RFWKPES8-1.

In the encryption algorithm AES-RFWKPES8-1 as the round function used SubBytes(), ShiftRows(), MixColumns() transformation of the encryption algorithm AES. The scheme n-rounded encryption algorithm AES-RFWKPES8-1 shown in Figure 4, and the length of subblocks X^0, X^1, ..., X^7, length of round keys $K_{8(i-1)}$, $K_{8(i-1)+1}$,..., $K_{8(i-1)+7}$, $i=\overline{1...n+1}$ and K_{8n+8}, K_{8n+9}, ..., K_{8n+23} are equal to 32 bits.

Consider the round function of the encryption algorithm AES-RFWKPES8-1. Initially 32-bit subblocks T^0, T^1, T^2, T^3, are partitioned into 8-bit subblocks, i.e., on bytes:

$t_0 = sb_0(T^0)$, $t_1 = sb_1(T^0)$, $t_2 = sb_2(T^0)$, $t_3 = sb_3(T^0)$,
$t_4 = sb_0(T^1)$, $t_5 = sb_1(T^1)$, $t_6 = sb_2(T^1)$, $t_7 = sb_3(T^1)$, $t_8 = sb_0(T^2)$, $t_9 = sb_1(T^2)$, $t_{10} = sb_2(T^2)$, $t_{11} = sb_3(T^2)$, $t_{12} = sb_0(T^3)$, $t_{13} = sb_1(T^3)$, $t_{14} = sb_2(T^3)$, $t_{15} = sb_3(T^3)$, here $sb_0(X) = x_0x_1...x_7$, $sb_1(X) = x_8x_9...x_{15}$, $sb_2(X) = x_{16}x_{17}...x_{23}$, $sb_0(X) = x_{24}x_{25}...x_{31}$ and $X = x_0x_1...x_{31}$. After which the 8 bit subblocks t_0, t_1, ..., t_{15} are written into the array *State* and are executed the above transformations SubBytes(), ShiftRows(), MixColumns().

After the MixColumns() transformation we obtain 8 bits subblocks p_0, p_1, ..., p_{15}. The resulting 8-bit subblocks are writes on a 32-bit subblocks Y^0, Y^1, Y^2, Y^3 as follows: $Y^0 = p_0 \| p_1 \| p_2 \| p_3$, $Y^1 = p_4 \| p_5 \| p_6 \| p_7$, $Y^2 = p_8 \| p_9 \| p_{10} \| p_{11}$, $Y^3 = p_{12} \| p_{13} \| p_{14} \| p_{15}$.

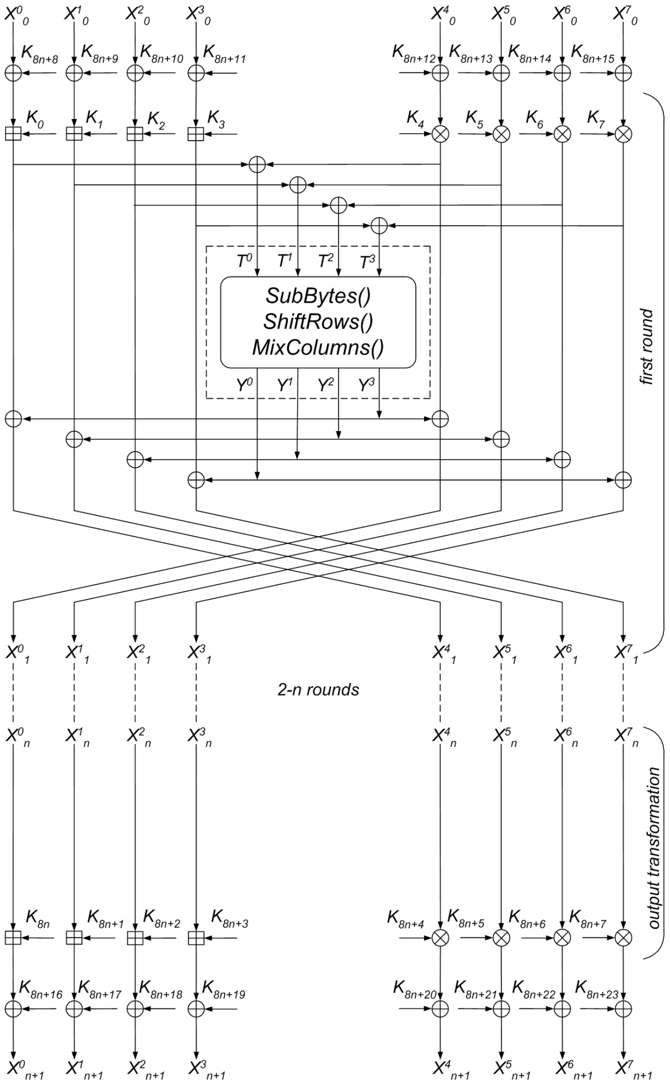

X^0_0 X^1_0 X^2_0 X^3_0 X^4_0 X^5_0 X^6_0 X^7_0
K_{8n+8} K_{8n+9} K_{8n+10} K_{8n+11} K_{8n+12} K_{8n+13} K_{8n+14} K_{8n+15}
K_0 K_1 K_2 K_3 K_4 K_5 K_6 K_7
T^0 T^1 T^2 T^3
SubBytes()
ShiftRows()
MixColumns()
Y^0 Y^1 Y^2 Y^3
first round
X^0_1 X^1_1 X^2_1 X^3_1 X^4_1 X^5_1 X^6_1 X^7_1
2-n rounds
X^0_n X^1_n X^2_n X^3_n X^4_n X^5_n X^6_n X^7_n
output transformation
K_{8n} K_{8n+1} K_{8n+2} K_{8n+3} K_{8n+4} K_{8n+5} K_{8n+6} K_{8n+7}
K_{8n+16} K_{8n+17} K_{8n+18} K_{8n+19} K_{8n+20} K_{8n+21} K_{8n+22} K_{8n+23}
X^0_{n+1} X^1_{n+1} X^2_{n+1} X^3_{n+1} X^4_{n+1} X^5_{n+1} X^6_{n+1} X^7_{n+1}

Figure 4: The scheme n-rounded encryption algorithm AES-RFWKPES8-1

The S-box SubBytes() transformation shown in Table 1 and it is the only nonlinear transformation. The length of the input and output blocks S-box is eight bits. For example, if the input value the S-box is equal to 0xE7, then the output value is equal to 0xA8, i.e. it is selected elements of intersection row 0xE and column 0x7.

Table 1: The S-box of encryption algorithm AES-RFWKPES8-1

	0x0	0x1	0x2	0x3	0x4	0x5	0x6	0x7	0x8	0x9	0xA	0xB	0xC	0xD	0xE	0xF
0x0	0xF8	0xF0	0xE9	0x08	0xCB	0x57	0x19	0x43	0x8E	0xD5	0xB6	0xC8	0x2A	0x81	0x8F	0xC2
0x1	0x14	0x24	0xA2	0xDB	0x64	0xBA	0x99	0x56	0x5C	0x37	0x0B	0xC1	0x07	0xD8	0x8C	0x26
0x2	0x31	0x9C	0x50	0x02	0x5D	0xD9	0xAE	0xC7	0xC0	0xF3	0x6C	0x7D	0x3A	0xD6	0xA5	0xC4
0x3	0xB0	0xDE	0x67	0x90	0x0E	0x35	0x9B	0xD4	0x06	0x3C	0xB9	0x94	0x10	0x29	0x54	0x74
0x4	0x7A	0x0F	0x30	0x93	0xB8	0x32	0x0C	0x96	0xA3	0x97	0xAA	0x7F	0x55	0xBF	0x86	0xF7
0x5	0x88	0x52	0xFE	0xC3	0xD1	0xB7	0xE2	0x27	0x7C	0x3F	0xB5	0x0A	0x53	0x80	0x91	0x71
0x6	0x79	0x5E	0xA4	0x4F	0xD7	0xAB	0x38	0xDC	0x04	0xD2	0x63	0x46	0x3E	0x6F	0xB1	0x39
0x7	0x15	0x20	0x61	0xEE	0x7B	0x2C	0x21	0x33	0x28	0x1A	0x4B	0xFA	0xA1	0x01	0xE0	0xE4
0x8	0xEC	0x1F	0x17	0xE8	0x69	0x1E	0x2F	0x59	0x68	0x6E	0x6D	0x44	0x00	0xF4	0x25	0xA7
0x9	0x4E	0x92	0x36	0x98	0x4C	0xE3	0xE6	0x16	0xB2	0x75	0x66	0xEF	0x05	0x42	0xE7	0x60
0xA	0x09	0x13	0xBC	0xCC	0xE5	0x2D	0x9F	0xDF	0xBB	0xCF	0x77	0xD3	0xCD	0x83	0x47	0x95
0xB	0xF1	0x89	0x76	0x84	0x73	0x1C	0x1D	0x12	0xAF	0xED	0x18	0x3B	0x2B	0x23	0xEA	0x51
0xC	0xFB	0xBE	0xB4	0xAD	0x40	0x45	0x87	0xF5	0xA6	0xB3	0x5F	0xF6	0x78	0x03	0xA0	0x8B
0xD	0x11	0xF2	0xAC	0x9D	0xCE	0x48	0x85	0x82	0x65	0xEB	0xC6	0x4D	0x6A	0x0D	0x6B	0x9A
0xE	0x22	0xF9	0x49	0x8A	0xCA	0xFD	0xC5	0xA8	0xFF	0xDD	0x41	0x8D	0x5A	0x5B	0x7E	0x2E
0xF	0x58	0xBD	0x3D	0x34	0x9E	0xDA	0xFC	0xE1	0x4A	0x62	0x1B	0xA9	0xC9	0x70	0xD0	0x72

Consider the encryption process of encryption algorithm AES-RFWKPES8-1. Initially the 256-bit plaintext X partitioned into subblocks of 32 bits X_0^0, X_0^1, …, X_0^7, and performs the following steps:

1) Subblocks X_0^0, X_0^1, …, X_0^7 summed by XOR respectively with round key K_{8n+8}, K_{8n+9}, …, K_{8n+15}: $X_0^j = X_0^j \oplus K_{8n+8+j}$, $i = \overline{0...7}$

2) Subblocks X_0^0, X_0^1, …, X_0^7 multiplied and summed respectively with the round key $K_{8(i-1)}$, $K_{8(i-1)+1}$, …, $K_{8(i-1)+7}$ and calculated 32-bit subblocks T^0, T^1, T^2, T^3. This step can be represented as follows:

$$T^0 = (X_{i-1}^0 + K_{8(i-1)}) \oplus (X_{i-1}^4 \cdot K_{8(i-1)+4}),$$

$$T^1 = (X_{i-1}^1 + K_{8(i-1)+1}) \oplus (X_{i-1}^5 \cdot K_{8(i-1)+5}),$$

$$T^2 = (X_{i-1}^2 + K_{8(i-1)+2}) \oplus (X_{i-1}^6 \cdot K_{8(i-1)+6}),$$

$$T^3 = (X_{i-1}^3 + K_{8(i-1)+3}) \oplus (X_{i-1}^7 \cdot K_{8(i-1)+7}), i = 1.$$

3) Subblocks T^0, T^1, T^2, T^3 is split into 8 bit subblocks t_0, t_1, …, t_{15} and performed SubBytes(), ShiftRows(), MixColumns(), AddRoundKey() transformations. Output subblocks of the round function of the encryption algorithm are Y^0, Y^1, Y^2, Y^3.

4) Subblocks Y^0, Y^1, Y^2, Y^3 are summed to XOR with subblocks X_{i-1}^0, X_{i-1}^1, …, X_{i-1}^7, i.e. $X_{i-1}^j = X_{i-1}^j \oplus Y_{3-j}$, $X_{i-1}^{j+4} = X_{i-1}^{j+4} \oplus Y_{3-j}$, $j = \overline{0...3}$, $i = 1$.

5) at the end of the round subblocks are swapped, i.e., $X_i^j = X_{i-1}^{j+4}$, $X_i^{j+4} = X_{i-1}^j$, $j = \overline{0...3}$, $i = 1$.

6) Repeating steps 2-5 n times, i.e., $i = \overline{2...n}$ we obtain subblocks X_n^0, X_n^1, …, X_n^7.

7) in output transformation round keys are multiplied and summed into subblocks, i.e. $X_{n+1}^0 = X_n^0 + K_{8n}$, $X_{n+1}^1 = X_n^1 + K_{8n+1}$, $X_{n+1}^2 = X_n^2 + K_{8n+2}$, $X_{n+1}^3 = X_n^3 + K_{8n+3}$, $X_{n+1}^4 = X_n^4 \cdot K_{8n+4}$, $X_{n+1}^5 = X_n^5 \cdot K_{8n+5}$, $X_{n+1}^6 = X_n^6 \cdot K_{8n+6}$, $X_{n+1}^7 = X_n^7 \cdot K_{8n+7}$.

8) Subblocks X_{n+1}^0, X_{n+1}^1, …, X_{n+1}^7 are summed to XOR with the round key K_{8n+16}, K_{8n+17}, …, K_{8n+23}: $X_{n+1}^j = X_{n+1}^j \oplus K_{8n+16+j}$, $j = \overline{0...7}$. As cipher text plaintext X receives the combined 32-bit subblocks $X_{n+1}^0 \| X_{n+1}^1 \| ... \| X_{n+1}^7$.

2.2 Key generation of the encryption algorithm AES-RFWKPES8-1.

In the n-round encryption algorithm AES-RFWKPES8-1 in each round we applied eight round keys of the 32 bits and output transformation eight round keys of 32 bits. In addition, before the first round and after the output transformation we used eight round keys of 32 bits. Total number of 32-bit round keys is equal to $8n + 24$. In Figure 4 encryption used encryption round keys K_i^c instead of K_i, while decryption used decryption round keys K_i^d.

When generating round keys like the AES encryption algorithm uses an array Rcon: Rcon=[0x00000001, 0x00000002, 0x00000004, 0x00000008, 0x00000010, 0x00000020, 0x00000040, 0x00000080, 0x00000100, 0x00000200, 0x00000400, 0x00000800, 0x00001000, 0x00002000, 0x00004000, 0x00008000, 0x00010000, 0x00020000, 0x00040000, 0x00080000, 0x00100000, 0x00200000, 0x00400000, 0x00800000, 0x01000000, 0x02000000, 0x04000000, 0x08000000, 0x10000000, 0x20000000, 0x40000000, 0x80000000].

The key encryption algorithm K of length l ($256 \le l \le 1024$) bits is divided into 32-bit round keys K_0^c, K_1^c,..., $K_{Lenght-1}^c$, $Lenght = l/32$, here $K = \{k_0, k_1, ..., k_{l-1}\}$, $K_0^c = \{k_0, k_1, ..., k_{31}\}$, $K_1^c = \{k_{32}, k_{33}, ..., k_{63}\}$,..., $K_{Lenght-1}^c = \{k_{l-32}, k_{l-31}, ..., k_{l-1}\}$ and $K = K_0^c \| K_1^c \| ... \| K_{Lenght-1}^c$. Then we calculate $K_L = K_0^c \oplus K_1^c \oplus ... \oplus K_{Lenght-1}^c$. If $K_L = 0$ then K_L is chosen as 0xC5C31537, i.e. $K_L = 0\text{xC5C31537}$. When generating a round key K_i^c, $i = \overline{Lenght...8n+23}$, we used transformation *SubBytes32()* and *RotWord32()*, here

SubBytes32()-is transformation 32-bit subblock into S-box and $SubBytes32(X) = S(sb_0(X)) \| S(sb_1(X)) \| S(sb_2(X)) \| S(sb_3(X))$, *RotWord32()*-cyclic shift to the left of 1 bit of the 32 bit subblock. When the condition $i \bmod 3 = 1$ is true, then the round keys are computed as $K_i^c = SubBytes32(K_{i-Lenght+1}^c)\wedge SubBytes32(RotWord32(K_{i-Lenght}^c)) \wedge Rcon[i \bmod 32] \wedge K_L$, otherwise $K_i^c = SubBytes32(K_{i-Lenght}^c)\wedge SubBytes32(K_{i-Lenght+1}^c)\wedge K_L$. After each round key generation the value K_L is cyclic shift to the left by 1 bit.

Decryption round keys are computed on the basis of encryption round keys and decryption round keys of the output transformation associate with of encryption round keys as follows:

$$(K_{8n}^d, K_{8n+1}^d, K_{8n+2}^d, K_{8n+3}^d, K_{8n+4}^d, K_{8n+5}^d, K_{8n+6}^d, K_{8n+7}^d) =$$
$$(-K_0^c, -K_1^c, -K_2^c, -K_3^c, (K_4^c)^{-1}, (K_5^c)^{-1}, (K_6^c)^{-1}, (K_7^c)^{-1}).$$

Likewise, the decryption round keys of the first, second, third, and *n*–round associates with the encryption round keys as follows:

$$(K_{8(i-1)}^d, K_{8(i-1)+1}^d, K_{8(i-1)+2}^d, K_{8(i-1)+3}^d, K_{8(i-1)+4}^d, K_{8(i-1)+5}^d, K_{8(i-1)+6}^d,$$
$$K_{8(i-1)+7}^d) = (-K_{8(n-i+1)}^c, -K_{8(n-i+1)+1}^c, -K_{8(n-i+1)+2}^c, -K_{8(n-i+1)+3}^c,$$
$$(K_{8(n-i+1)+4}^c)^{-1}, (K_{8(n-i+1)+5}^c)^{-1}, (K_{8(n-i+1)+6}^c)^{-1}, (K_{8(n-i+1)+7}^c)^{-1}),$$
$$i = \overline{1...n}.$$

Decryption round keys applied to the first round and after the output transformation associated with the encryption round keys as follows: $K_{8n+8+j}^d = K_{8n+16+j}^c$, $K_{8n+16+j}^d = K_{8n+8+j}^c$, $j = \overline{0...7}$.

3. RESULTS

Using the transformations SubBytes(), ShiftRows(), MixColumns() of the encryption algorithm AES as the round transformation network RFWKPES8-1 we developed block cipher algorithm AES-RFWKPES8-1. In the algorithm, the number of rounds of encryption and key's length is variable and the user can select the number of rounds and the key's length in dependence of the degree of secrecy of information and speed encryption.

As in the encryption algorithms based on the Feistel network, the advantages of the encryption algorithm AES-RFWKPES8-1 are that, when encryption and decryption process used the same algorithm. In the encryption algorithm AES-RFWKPES8-1 in decryption process encryption round keys are used in reverse order, thus on the basis of operations necessary to compute the inverse. For example, if the round key is multiplied by the subblock, while decryption is is necessary to calculate the multiplicative inverse, if summarized, it is necessary to calculate the additive inverse.

It is known that the resistance of AES encryption algorithm is closely associated with resistance S-box, applied in the algorithm. In the S-box's encryption algorithm AES algebraic degree of nonlinearity $\deg = 7$, nonlinearity $NL = 112$, resistance to linear cryptanalysis $\lambda = 32/256$, resistance to differential cryptanalysis $\delta = 4/256$, strict avalanche criterion SAC = 8, bit independence criterion BIC = 8.

In the encryption algorithm AES-RFWKPES8-1 resistance S-box is equal to resistance S-box's encryption algorithm AES, i.e., $\deg = 7$, $NL = 112$, $\lambda = 32/256$, $\delta = 4/256$, SAC= BIC=8.

Research indicates that the speed of the encryption algorithm AES-RFWKPES8-1 is faster than AES. The encryption speed of the 14 rounds encryption algorithm AES-RFWKPES8-1 1.25 times faster than the 14 rounds encryption algorithm AES.

4. CONCLUSION

It is known that as a network-based algorithms Feystel the resistance algorithm based on network RFWKPES8-1 closely associated with resistance round function. Therefore, selecting the transformations SubBytes(), ShiftRows(), MixColumns() of the encryption algorithm AES, based on round function network RFWKPES8-1 developed relatively resistant encryption algorithm.

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