Cryptanalysis of JAMBU

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CAESAR Candidate: JAMBU

Designers: Hongjun WU, Tao HUANG (NTU, Singapore)

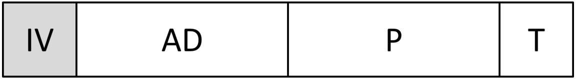
- mode of operation is similar to OFB
- 2n-bit block cipher as underlying cipher
- process blocks of n-bit information

AES–JAMBU: parameters

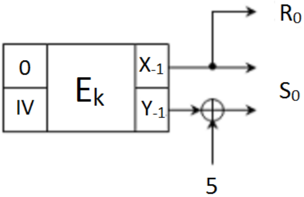
AES–JAMBU is JAMBU with AES-128 as the underlying cipher:

- associated data + plaintext $< 2^{64}$ bits under the same key
- key $=$ 128 bits
- tag $=$ 64 bits
- Initialization Vector/Nonce $=$ 64 bits

AES-JAMBU: initialisation

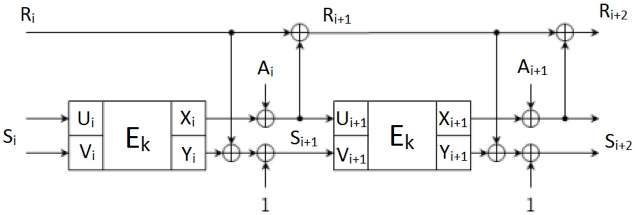


Initial input: 64-bit zeroes and 64-bit nonce (IV)



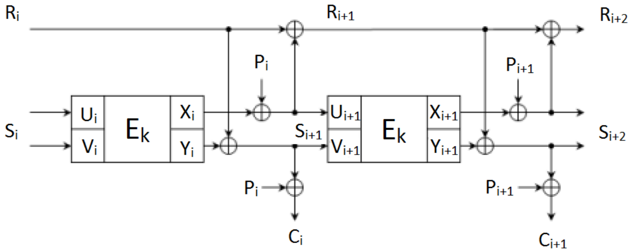
AES-JAMBU: processing of associated data

Associated data A is split into 64-bit blocks A_i

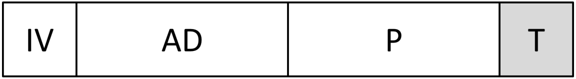


AES-JAMBU: processing of plaintext

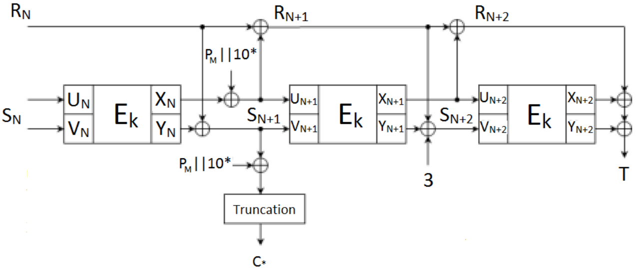
Plaintext P is split into 64-bit blocks P_i
Ciphertext C is split into 64-bit blocks C_i



AES-JAMBU: tag generation



Last block P_M is padded with $1\|0^*$ and output is truncated. If last block is a full block, an additional block of $1\|0^{63}$ is processed without output.



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JAMBU: hardware performance

JAMBU is a hardware-oriented candidate:

compared with other AE modes instantiated with a $2n$-bit block cipher, JAMBU minimizes state size, which is an advantage for hardware implementations.

Modes	State size
GCM	$6n$
OCB3	$6n$
EAX	$8n$
JAMBU	$3n$

JAMBU: software performance

On an Intel Core i5-2540M 2.6GHz processor with AES-NI:

	512-byte messages
AES-128-CCM	5.19 c/B
AES-128-GCM	3.33 c/B
AES-128-OCB3	1.34 c/B
AES−JAMBU	12.27 c/B

According to the designers, AES−JAMBU should be about two times slower than AES-GCM (their implementation is not optimized yet).

JAMBU: security claims

	confidentiality (bits)	**integrity** (bits)
nonce-respecting	128	64
nonce-misuse	128*	not specified

*: except for first block or common prefix of the message.

The designers gave very good arguments why a successful forgery should require 2^{64} computations.

"In case that the IV is reused under the same key, the confidentiality of AES-JAMBU is only partially compromised as it only leaks the information of the first block or the common prefix of the message. And the integrity of AES-JAMBU will be less secure but not completely compromised."

JAMBU: security claims

	confidentiality (bits)	**integrity** (bits)
nonce-respecting	128	64
nonce-misuse	128*	not specified

*: except for first block or common prefix of the message.

Our attack:

with about 2^{34} queries and computations, we can produce a valid ciphertext block corresponding to some plaintext with a prefix that has never been queried before.

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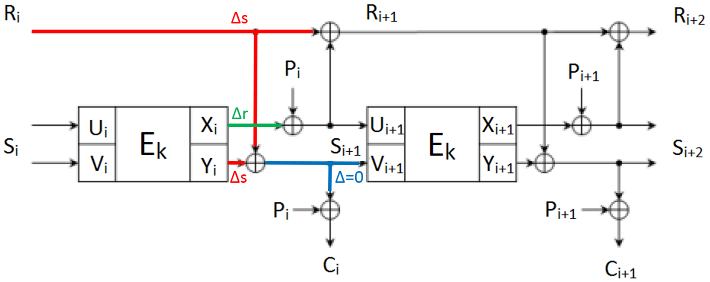
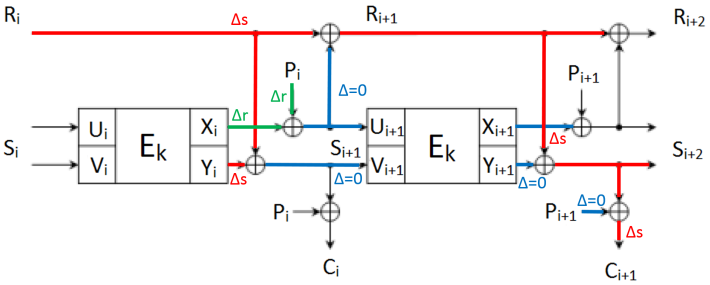
Observation 1

- no difference in V_{i+1}
  $\Rightarrow$ the differences in R_i and Y_i are the same Δs
- let the difference in X_i be Δr



Observation 2

- if the input difference in P_i is equal to Δr
  $\Rightarrow$ the difference in U_{i+1} will be cancelled out, and with no difference in P_{i+1}
  $\Rightarrow$ the output difference in C_{i+1} will be Δs



Attack Overview

Objective

Find such a diff. structure, and find the values of Δr and Δs.

Problem

Seems hard to achieve: naively building the structure costs 2^{64} computations, and we have no way of checking if we indeed found it (Δs is unknown).

Solution

"Divide-and-conquer"

- use birthday attack to find a pair of nonce values partially follows this differential structure (nonce-respecting)
- enumerate all possible input differences in the plaintext block to force the rest of the differential structure and to find Δr and Δs (nonce-misuse)

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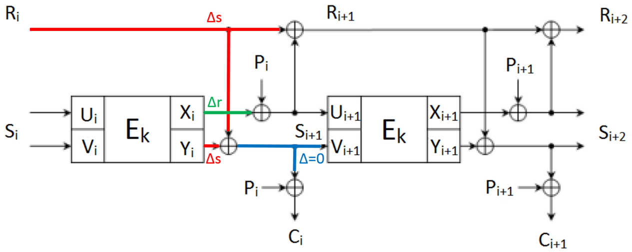
Step 1: birthday attack on V_{i+1}

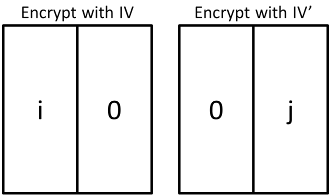
Using birthday attack, a collision on V_{i+1} can be found with about 2^{32} encryption queries:

- query for encryption for the same one block of plaintext P_1 with 2^{32} difference nonce IV
- find a collision in the ciphertext $C_1 = C'_1$
- store the pair of nonce values IV and IV'



Step 2: finding Δr and Δs

To enumerate all 2^{64} possible input differences of P_i, we use 2 sets of 2^{32} plaintext blocks.

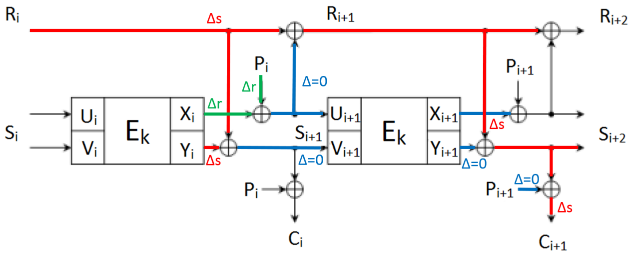


i and j ranged from 0 to $2^{32} - 1$

Any possible input difference $[i \| j]$ can be formed with a pair of plaintext blocks $[i \| 0^{32}]$ and $[0^{32} \| j]$.

Step 2: finding Δr and Δs

P_{i+1} is set to a constant value (e.g. all zeros)

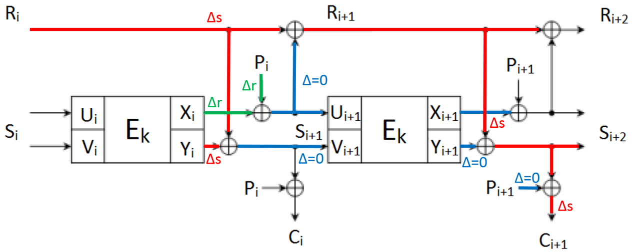


We ask for the encryption of $[i \| 0^{32}] \| [0^{64}]$ with nonce IV and $[0^{32} \| j] \| [0^{64}]$ with nonce IV'.

Step 2: finding Δr and Δs

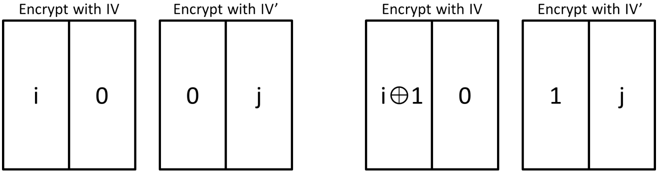
Question: how do we know that we insert the right Δr in P_i?

Answer: the right Δr will give the same output difference Δs in the second block independent of the plaintext value in the first block.



Step 2: finding Δr and Δs

The right Δr will give the same output difference Δs independent of the value of P_i, so we build a few tables.



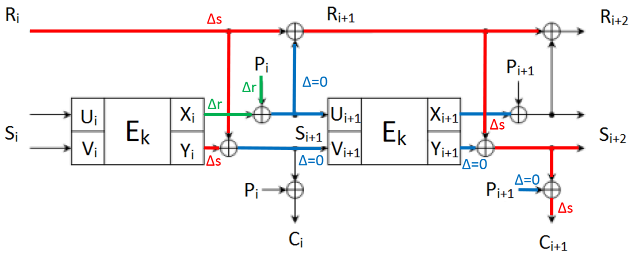
i and j ranged from 0 to $2^{32}-1$

If $\Delta r = [i \| j]$, then $C_2[i \| 0] \oplus C_2[0 \| j] = C_2[i \oplus 1 \| 0] \oplus C_2[1 \| j] = \Delta s$.

Note that first and third tables are the same up to permutation.
Hence, we need $3 \cdot 2^{32}$ encryption queries.

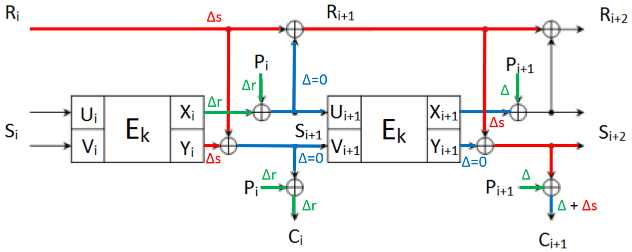
Step 2: summary

- query for $3 \cdot 2^{32}$ encryptions
- compute and store the difference of the second block of the ciphertexts
- find the collision
  $C_2[i\|0] \oplus C_2[0\|j] = C_2[i \oplus 1\|0] \oplus C_2[1\|j] = \Delta s$.
- obtain $\Delta r = [i\|j]$ and $\Delta s = C_2[i\|0] \oplus C_2[0\|j]$.



Step 3: forging a valid ciphertext block

For any choice of plaintext blocks P_1, P_2, by querying $[P_1 \oplus \Delta r] \| [P_2 \oplus \Delta]$ with nonce IV and obtaining the ciphertext $[C_1 \| C_2]$, we can deduce the ciphertext of $[P_1 \| P_2]$ encrypted with nonce IV' to be $[C_1 \oplus \Delta r] \| [C_2 \oplus \Delta \oplus \Delta s]$, where Δ can be any difference.



Note that $[P_1]$ is a different prefix that has never been queried before.

Complexity Evaluation of the Attack

- Step 1 requires about 2^{32} queries (nonce-respecting)
- Step 2 requires $3 \cdot 2^{32}$ queries (nonce-misuse)
- Step 3 requires a single query

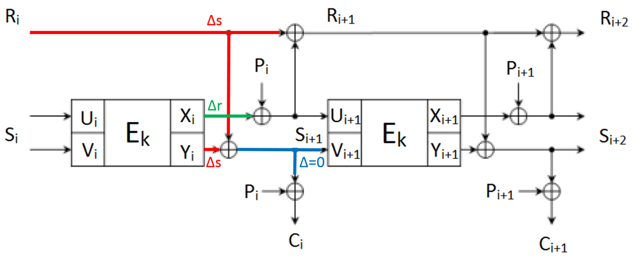
With only about 2^{34} queries, we can deduce the ciphertext corresponding to a plaintext with a prefix that has never been queried before.

Attack has been implemented and verified!

Numerical Example: Step 1

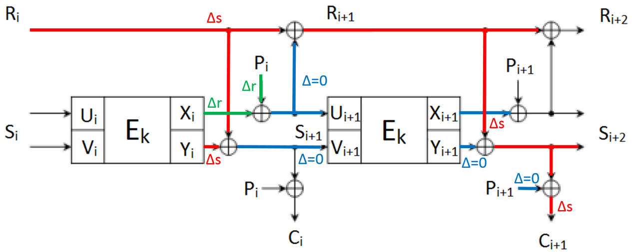
For simplicity, the associated data was set to be empty.

K :	01	02	03	04	05	06	07	08	09	0a	0b	0c	0d	0e	0f	10
IV :	b1	ef	89	a0	4e	21	30	bd								
IV' :	10	5a	1f	5b	34	49	1e	5c								
P_1 :	7f	95	77	ca	09	77	a8	a5								
C_1 :	2d	2b	58	18	fa	f5	af	f1								
C'_1 :	2d	2b	58	18	fa	f5	af	f1								



Numerical Example: Step 2

$[i\|0^{32}]\|[P_2]$	:	60	28	6d	74	00	00	00	00	00	00	00	00	00	00	00	00
$C_2[i\|0]$	:									af	45	56	9e	26	c6	7e	d0
$[0^{32}\|j]\|[P_2]$	:	00	00	00	00	93	47	1e	92	00	00	00	00	00	00	00	00
$C_2[0\|j]$	:									73	79	44	54	a7	b4	5b	4c
Δr	:	60	28	6d	74	93	47	1e	92								
Δs	:									dc	3c	12	ca	81	72	25	9c



Numerical Example: Step 3

We query arbitrary plaintext blocks $[P_1]\|[P_2]$ with IV and deduce the ciphertext of $[P_1 \oplus \Delta r]\|[P_2]$ with IV' as $[C_1 \oplus \Delta r]\|[C_2 \oplus \Delta s]$. Note that $[P_1 \oplus \Delta r]$ is a prefix that has never been queried before.

IV :	b1 ef 89 a0 4e 21 30 bd	
$[P_1]\|[P_2]$:	95 d9 43 9e 0b 4d 6d 27	6a ba db 0a 12 f8 13 45
$[C_1]\|[C_2]$:	c7 67 6c 4c f8 cf 6a 73	6b 05 9b c6 fc e6 7a ee
Δr :	60 28 6d 74 93 47 1e 92	
Δs :		dc 3c 12 ca 81 72 25 9c
$[C_1^D]\|[C_2^D]$:	a7 4f 01 38 6b 88 74 e1	b7 39 89 0c 7d 94 5f 72

Lastly, we verify our deduced ciphertext.

IV' :	10 5a 1f 5b 34 49 1e 5c	
$[P_1 \oplus \Delta r]\|[P_2]$:	f5 f1 2e ea 98 0a 73 b5	6a ba db 0a 12 f8 13 45
$[C_1']\|[C_2']$:	a7 4f 01 38 6b 88 74 e1	b7 39 89 0c 7d 94 5f 72

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Conclusion

We have shown a generic confidentiality attack on the JAMBU operating mode:

- the attack is independent of the underlying block cipher
- in the nonce-misuse scenario
- practical when instantiated with AES: only about 2^{34} queries
- attack verified by implementation

How about nonce-respecting scenario?

One can apply the same idea to break IND-CCA2 security of JAMBU in the nonce-respecting scenario:

- during Step 2 of the attack, use decryption queries in order to repeat nonces...
- ... but one has to pay 2^{64} to guess the tag and get corresponding plaintext from the oracle
- final complexity of $O(2^{32}) \times 2^{64} = O(2^{96})$ queries and computations to break IND-CCA2 security

but the security model for the security claims of JAMBU was not given by the designers (they didn't mean IND-CCA2)

Thank you. :)