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How to Recover Any Byte of Plaintext on RC4

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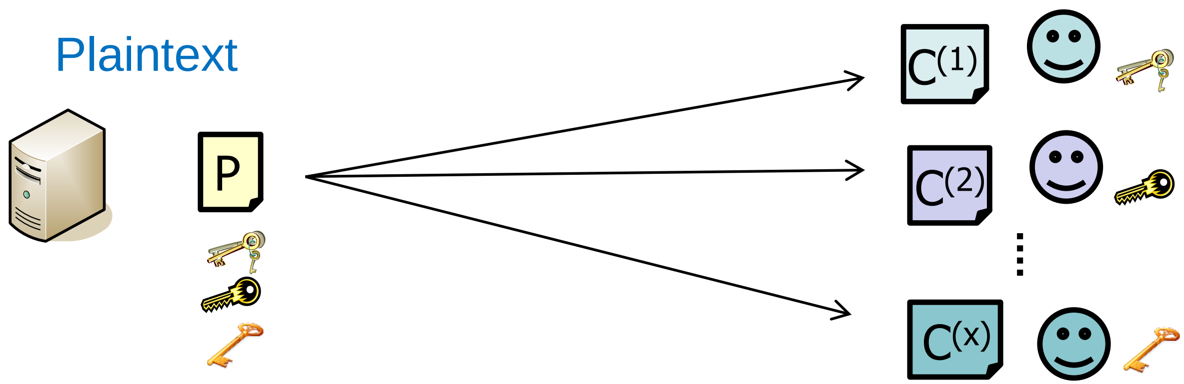
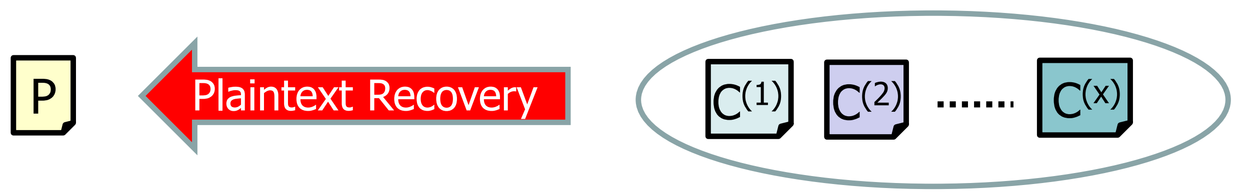
Target

- Broadcast setting
  - Same plaintext is encrypted with different (user) keys (e.g. Group mail)
  - can be easily converted into the multi-session setting of SSL/TLS
    - Target plaintext blocks are repeatedly sent in the same position of plaintext



- Plaintext Recovery Attack in the broadcast/multi-session setting
  - Recover a plaintext from ONLY ciphertexts encrypted by different keys
  - Passive attack
    - What attacker should do is to collect ciphertexts
    - NOT use additional information such as side channel information



Related Works

- Plaintext Recovery Attack on (pure) RC4 in these settings
  - Mantin-Shamir Attack (FSE 2001)
    - recover 2^{nd} byte of a plaintext from $\Omega(N)$ ciphertexts with probability more than a random search, where $N = 256$
  - Maitra-Paul-SenGupta Attack (FSE 2011)
    - recover 3^{rd} to 255^{th} bytes of a plaintext from $\Omega(N^3)$ ciphertexts with probability more than a random search, where $N = 256$
  - Isobe-Ohigashi-Watanabe-Morii Attack (FSE 2013)
    - recover 1^{st} to 257^{th} bytes of a plaintext from 2^{32} ciphertexts with probability of > 0.5
    - recovery first 1 petabytes of a plaintext from 2^{34} ciphertexts with probability closed to one
  - AlFardan-Bernstein-Paterson-Poettering-Schuldt Attack (USENIX Security 2013, Aug. 15, 2013, Today !)
    - recover 1^{st} to 256^{th} bytes of a plaintext from 2^{32} ciphertexts with probability of > 0.96

Related Works

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  - Isobe-Ohigashi-Watanabe-Morii Attack (FSE 2013)
    - recover 1st to 257th bytes of a plaintext from 2^{32} ciphertexts with probability of > 0.5

But, these attacks do not work on a relatively secure implementation of RC4 (RC4-drop)

- disregards the first *n* bytes of a keystream of RC4

*** recommendation: *n*=512 or 768, (conservative) *n* = 3072 by Mironov in CRYPTO 2002**

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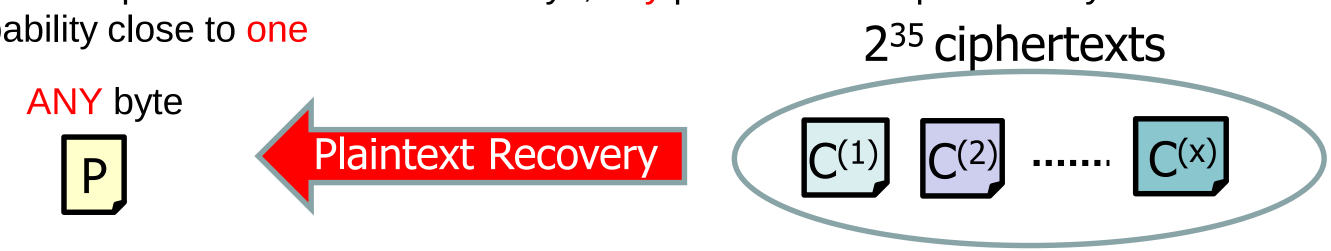
Summary of Our Results

Security Evaluation of RC4-drop in the Broadcast/Multi-session Setting

Results

- **Plaintext recovery attack using Known Partial Plaintext Bytes**
  - Based on Mantin's long-term bias in EUROCRYPT 2005
  - Given consecutive 6 bytes of a target plaintext and 2^{34} ciphertexts with different keys, consecutive 1 petabytes of the plaintext are recovered with probability more than 0.6

- **Guess-and-Determine Plaintext Recovery Attack**
  - Combine use of Mantin's long-term bias and Fluhrer-McGrew long-term bias in FSE 2000
  - Not Require any previous knowledge of a plaintext
  - Given **2^{35}** ciphertexts with different keys, any position of the plaintext byte is recovered with probability close to one



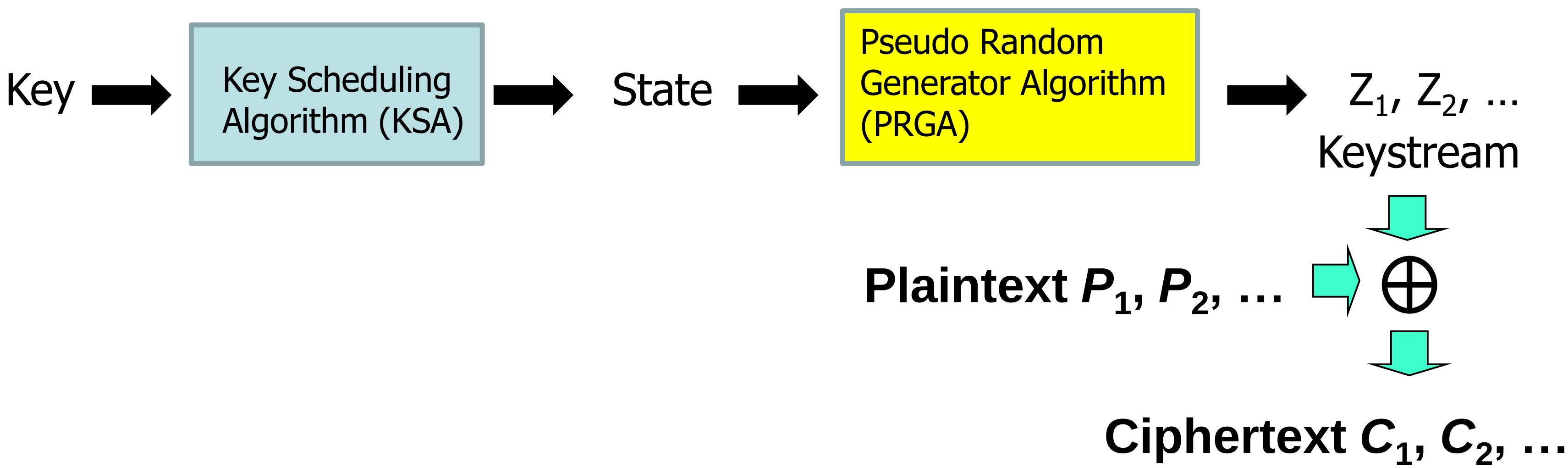
Agenda

- RC4 Stream Cipher
- Previous Plaintext Recovery Attacks
- Plaintext Recovery Attack using Known Partial Plaintext Bytes
- Guess-and-Determine Plaintext Recovery Attack
- Conclusion

RC4

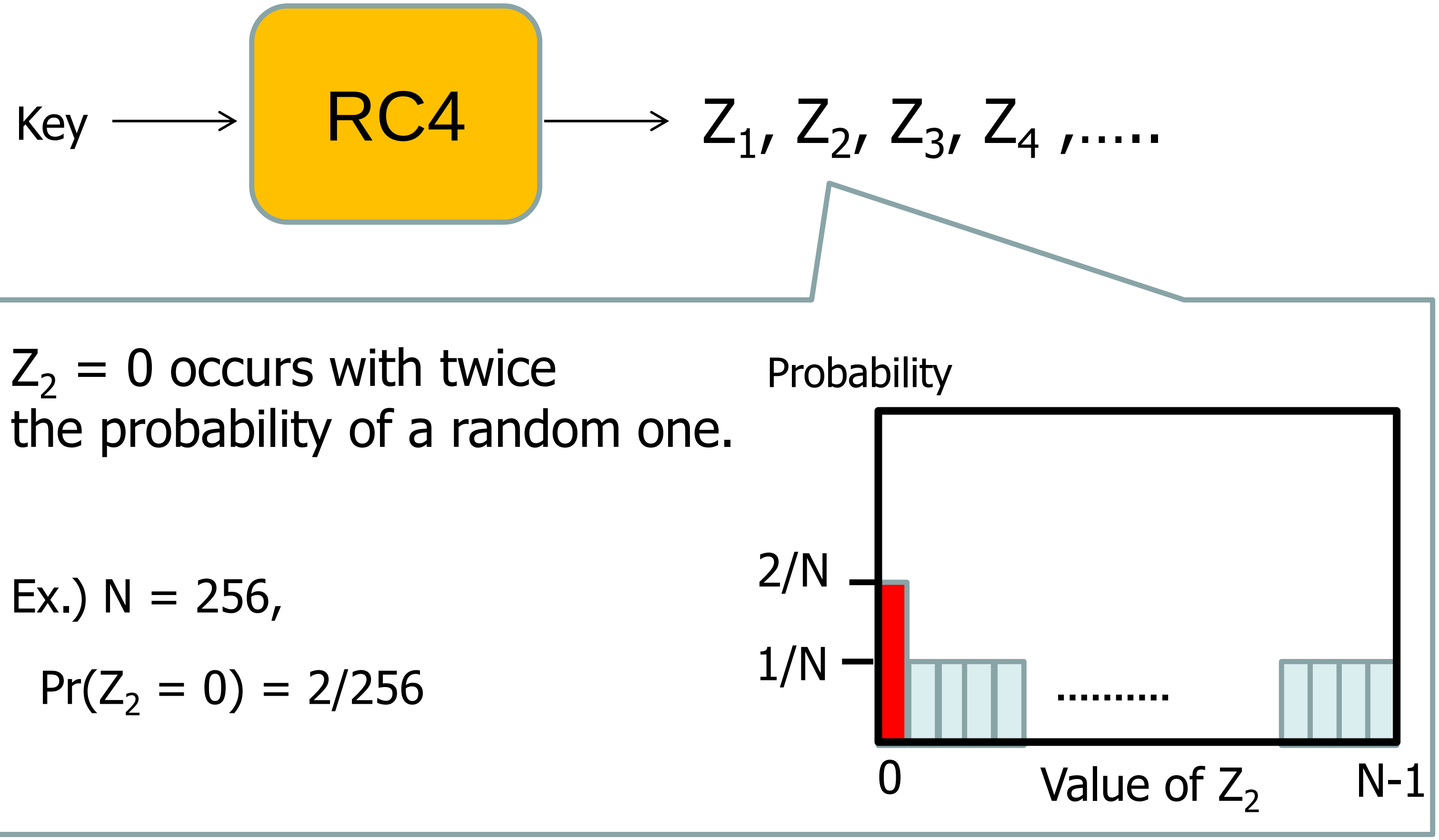
- Stream Cipher designed by Ron Rivest in 1987
  - is widely used, e.g. SSL/TLS, WEP/WPA and more.
- Parameter
  - 1-256 byte key (typically 16 byte (=128 bit) key)
  - State size N bytes (typically N = 256)

We focus on
- 16 byte (128 bit) key
- 256 byte state



Mantin-Shamir Attack [MS01]

- Proposed in FSE 2001
- Second byte of the keystream is strongly biased to “0”



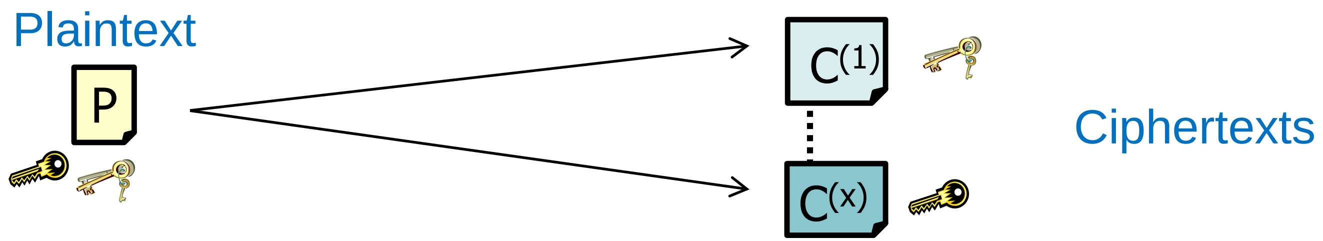
$Z_2 = 0$ occurs with twice the probability of a random one.

Ex.) $N = 256$,

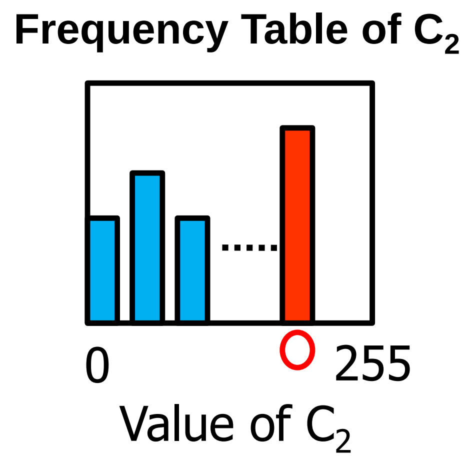
$Pr(Z_2 = 0) = 2/256$

Plaintext Recovery Attack [MS01]

- **Broadcast setting** : same plaintext is encrypted with different keys



- **Relation** : "$C_2 = P_2$ XOR Z_2"
  - If $Z_2 = 0$ (strong bias), then $C_2 = P_2$
  - Most frequent value of C_2 can be regarded as P_2



- **Evaluation**
  - Given Ω (N) ciphertexts encrypted by different keys,
    P_2 can be extracted with higher probability than a random search

Plaintext Recovery Attack in FSE 2013

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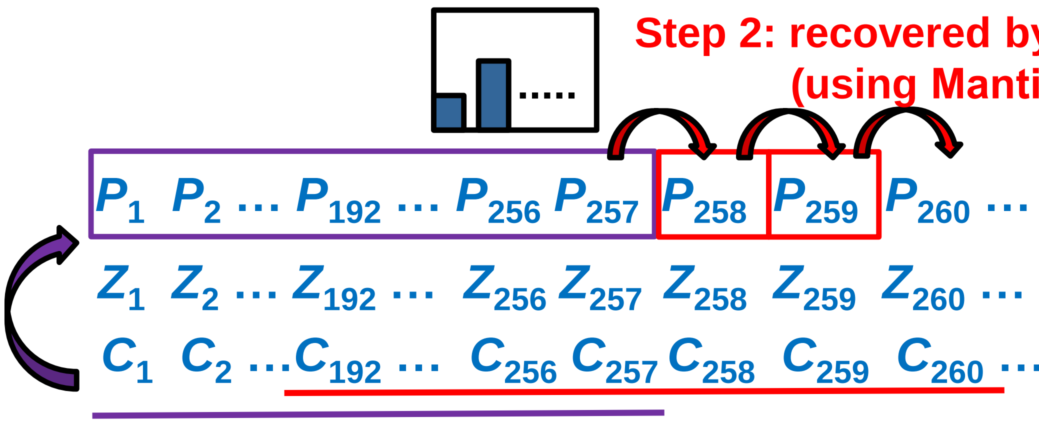
- Proposed by Isobe, Ohigashi, Watanabe and Morii
- is constructed by two phases
  - Initial byte recovery phase: recover initial 257 bytes of a plaintext
  - Sequential recovery phase: recover the later bytes of a plaintext using a knowledge of the first 257 bytes of a plaintext

Step 2: recovered by the sequential recovery phase (using Mantin's long-term bias)



Step 1: Recovered by the initial bytes recovery phase

Other previous attacks are also included

Conditional bias $Z_1=0|Z_2=0$

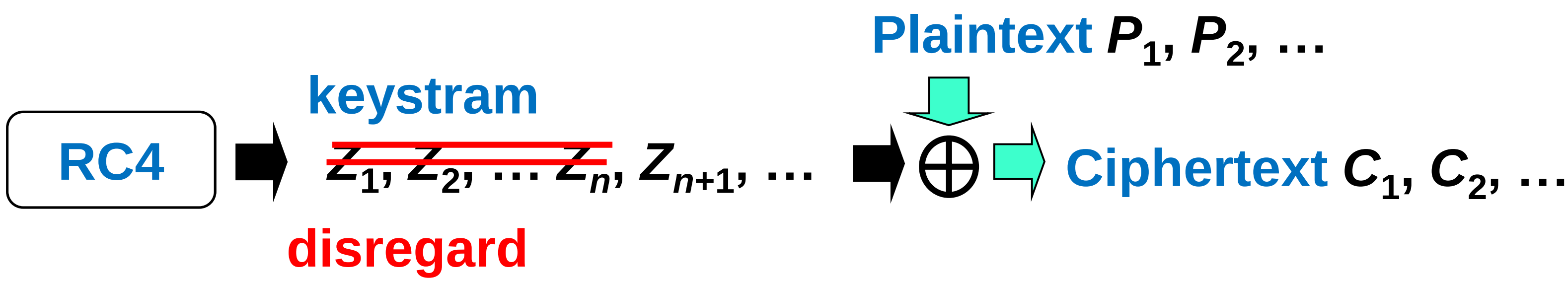
Single byte biases:

$Z_2 = 0$, $Z_3 = 131$, $Z_4 = 0$, $Z_r = r$ for $r = 5 \ldots 31$, $Z_0 = 0$ for $r = 32 \ldots 256$

$Z_r = -r$ for $r = 16,32,48,64,80,96,112$, $Z_{257} != 0$ (negative bias)

Countermeasure: RC4-drop

- is relatively secure RC4 implementation
- disregards the first n bytes of a keystream of RC4
  - recommendation(conservative) : n=3072



Initial byte biases are removed in RC4-drop

(Initial bytes recovery phase does not work)

Previous Attacks does not work on RC4-drop

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- Plaintext Recovery Attack using Known Partial Plaintext Bytes
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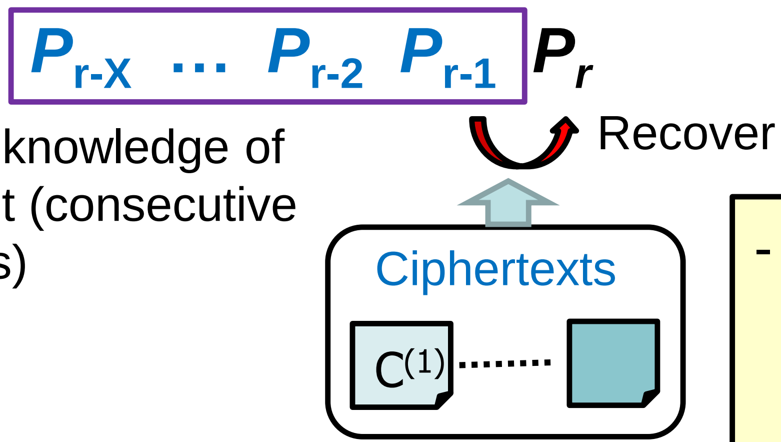
Plaintext Recovery Attack using Known Partial Plaintext Bytes

- is simply extension of FSE 2013 attack
  - **use partial knowledge of a target plaintext**
  - Based on **sequential recovery phase (Mantin's long-term bias)**

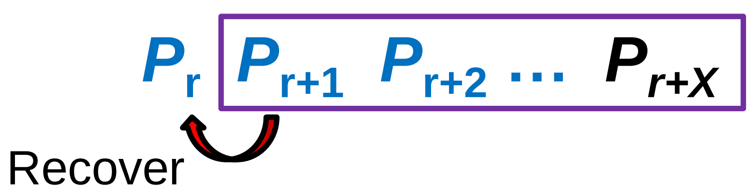
Forward attack function

Partial knowledge of a target (consecutive X bytes)



- The success probability increases with the increasing the value of X (when X < 67)
- If X=66, then the function is equivalent to that of sequential recovery phase of FSE 2013 attack

Backward attack function



Attack Procedure

- Example: consecutive 6 bytes of a target plaintext are known

Pre-known

$P_{r-6}\ P_{r-5} \cdots P_{r-2}\ P_{r-1}$ P_r — recover P_r with X = 6

$P_{r-6}\ P_{r-5} \cdots P_{r-2}\ P_{r-1}\ P_r$ P_{r+1} — recover P_{r+1} with X = 7

⋮

$P_{r-6}\ P_{r-5} \cdots P_{r-2}\ P_{r-1}\ P_r\ P_{r+1} \cdots P_{r+59}$ P_{r+60} — recover P_{r+60} with X = 66

P_{r-6} $P_{r-5} \cdots P_{r-2}\ P_{r-1}\ P_r\ P_{r+1} \cdots P_{r+59}\ P_{r+60}$ P_{r+61} — recover P_{r+61} with X = 66

⋮ (later processes are similar to FSE2013 attack)

Experimental Result

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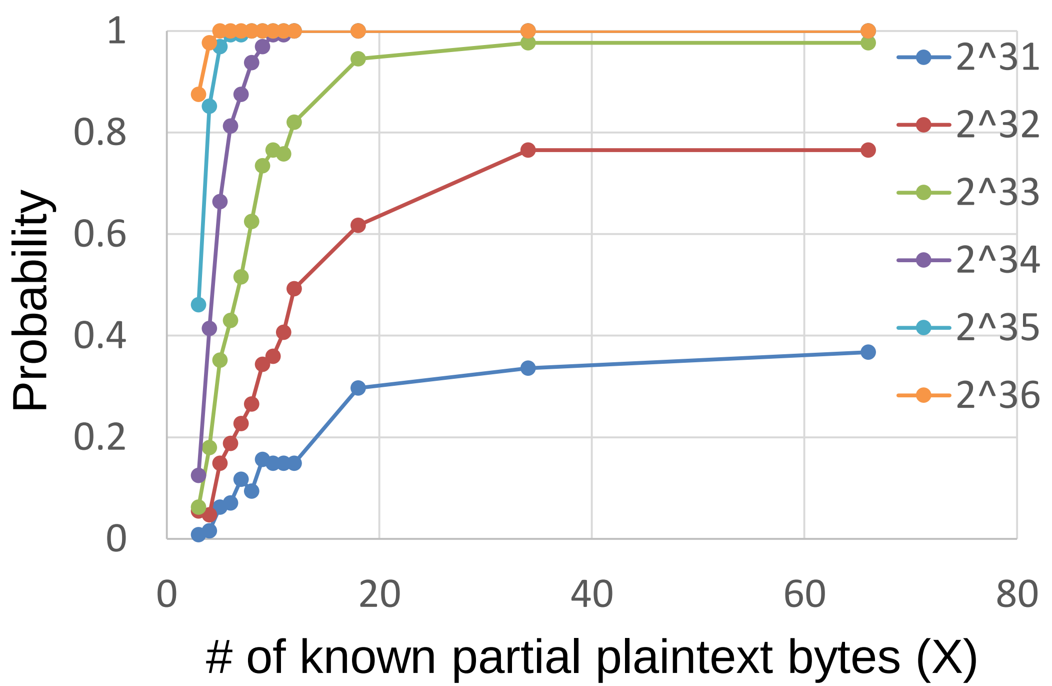
- Probability for recovering (X+1)th byte of a plaintext using the knowledge of X bytes of the plaintext on RC4-drop(3072)
- Obtained from 128 test
- # of ciphertexts:
  $2^{31}, 2^{32}..., 2^{36}$
- X = 3, 4, …, 66



Evaluation

ex.) consecutive 6 bytes of a target plaintext and 2^{34} ciphertexts are given
Consecutive 1petabyte of plaintext are recovered with probability of

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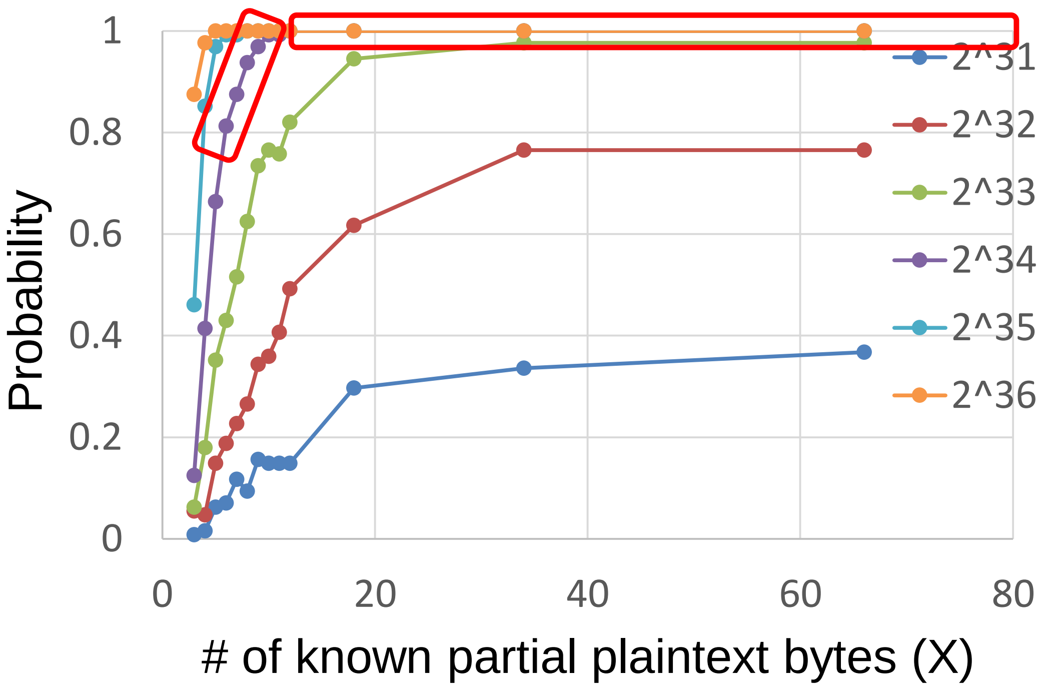

Evaluation

ex.) consecutive 6 bytes of a target plaintext and 2^{34} ciphertexts are given

Consecutive 1petabyte of plaintext are recovered with probability of

$$\mathbf{0.8125 \times 0.8750 \times 0.9375 \times 0.9688 \times 0.9922 \times 0.9922 \sim 0.636}$$

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Guess and Determine Plaintext Recovery Attack

- does not require any previous knowledge of a plaintext
- uses attack functions based on two long-term biases
  - Mantin's long-term bias in EUROCRYPT 2005 (ABSAB bias)
  - Fluhrer-McGrew long-term bias in FSE 2000 (FM00 bias)

Attack function based on ABSAB bias (the same as the first attack)

P_{r-X} … P_{r-2} P_{r-1} P_r

$f_{ABSAB\_F}()$ Recover

P_r P_{r+1} P_{r+2} … P_{r+X}

Recover $f_{ABSAB\_B}()$

Attack function based on FM00 bias (NEW)
(conditional bias of FM00 bias)

P_{r-1} P_r

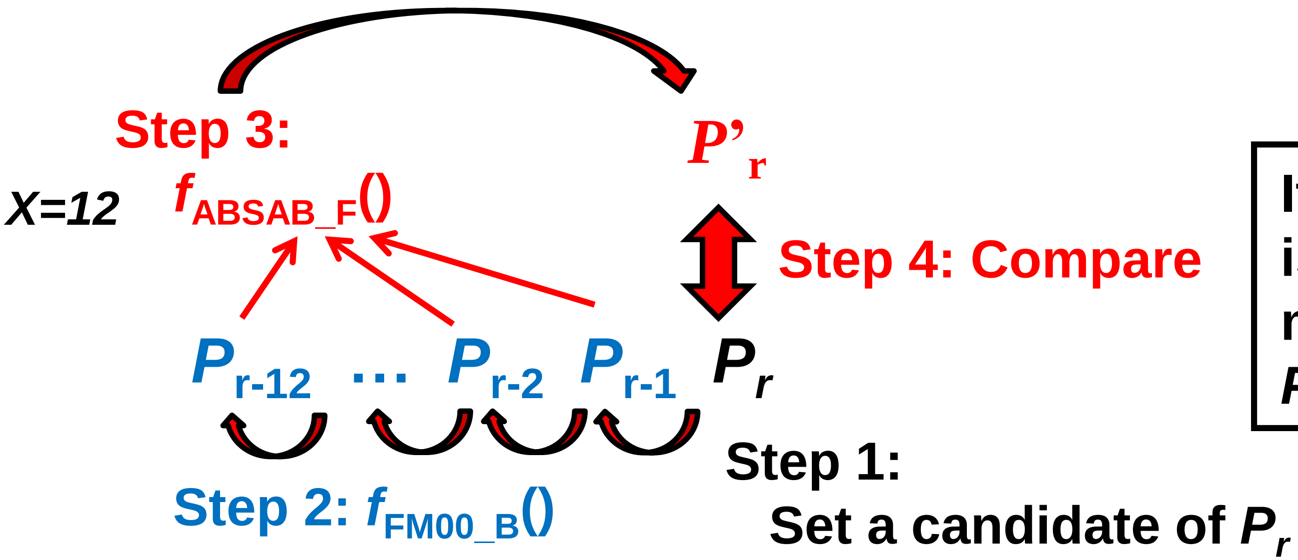
$f_{FM00\_F}()$ Recover

P_{r-1} P_r

Recover $f_{FM00\_B}()$

Attack Procedure

- 1. Guess the value of P_r
- 2. Recover X bytes of the plaintext from P_r (guessed in Step 1) by using the attack function based on FM00 bias
- 3. Recover P'_r from P_{r-x}, …, P_{r-1} (guessed in Step 2) by using the attack function based on ABSAB bias
- 4. If P'_r is not equal to P_r guessed in Step 1, the value is wrong. Otherwise the value is regarded as a candidate of correct P_r



If # of candidates of P_r is not one, the same method is repeated for P'_{r-1}, P'_{r-2}, …

Experimental Result

- Probability for recovering a byte of a plaintext on RC4-drop(3072)
- Obtained from 256 test
- # of ciphertexts: 2^{32}, 2^{33}, 2^{34}, 2^{35}
- Target Plaintext byte in this experiment: P_{128}

	# of ciphertexts			
	2^{32}	2^{33}	2^{34}	2^{35}
P_{128}	0.0039	0.1133	0.9102	1.0000

- Given 2^{35} ciphertexts, our attack can recover any plaintext byte with probability close to one
- Given 2^{34} ciphertexts, our attack can recover any plaintext byte with probability of about 0.91

Conclusion

Security Evaluation of RC4-drop in the Broadcast/Multi-session Setting

Results

- **Plaintext recovery attack using Known Partial Plaintext Bytes**
  - Given consecutive 6 bytes of a target plaintext and 2^{34} ciphertexts with different keys, consecutive 1 petabytes of the plaintext are recovered with probability of more than 0.6

- **Guess-and-Determine Plaintext Recovery Attack**
  - Not Require any previous knowledge of a plaintext
  - Given $\mathbf{2^{35}}$ ciphertexts with different keys, any position of the plaintext byte is recovered with probability of close to one

RC4 is not secure even if initial keystream bytes are dropped