All Your Biases Belong To Us: Breaking RC4 in WPA-TKIP and TLS

Mathy Vanhoef and Frank Piessens, KU Leuven

USENIX Security 2015 (best student paper)

Presentation for USENIC ATC '16

RC4

Intriguingly simple stream cipher

~ 10 lines in Python

WEP
WPA-TKIP

SSL / TLS

PPP/MPPE

And others ...

RC4

Intriguingly simple stream cipher

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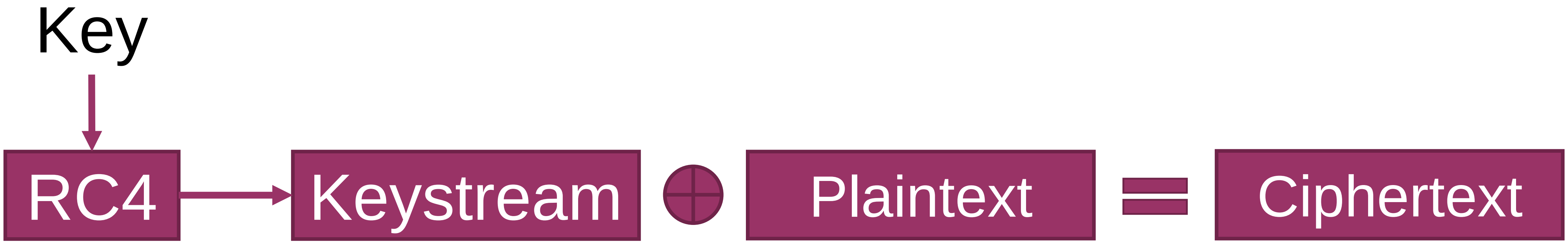

Why study RC4?

Immune to recent attacks on SSL/TLS:

- 2003: Padding oracle
- 2011: BEAST
- 2013: Lucky 13
- 2014: POODLE

Target CBC mode encryption
(block ciphers)

- Solution: use stream cipher or up-to-date TLS library
- Only widely supported option was RC4

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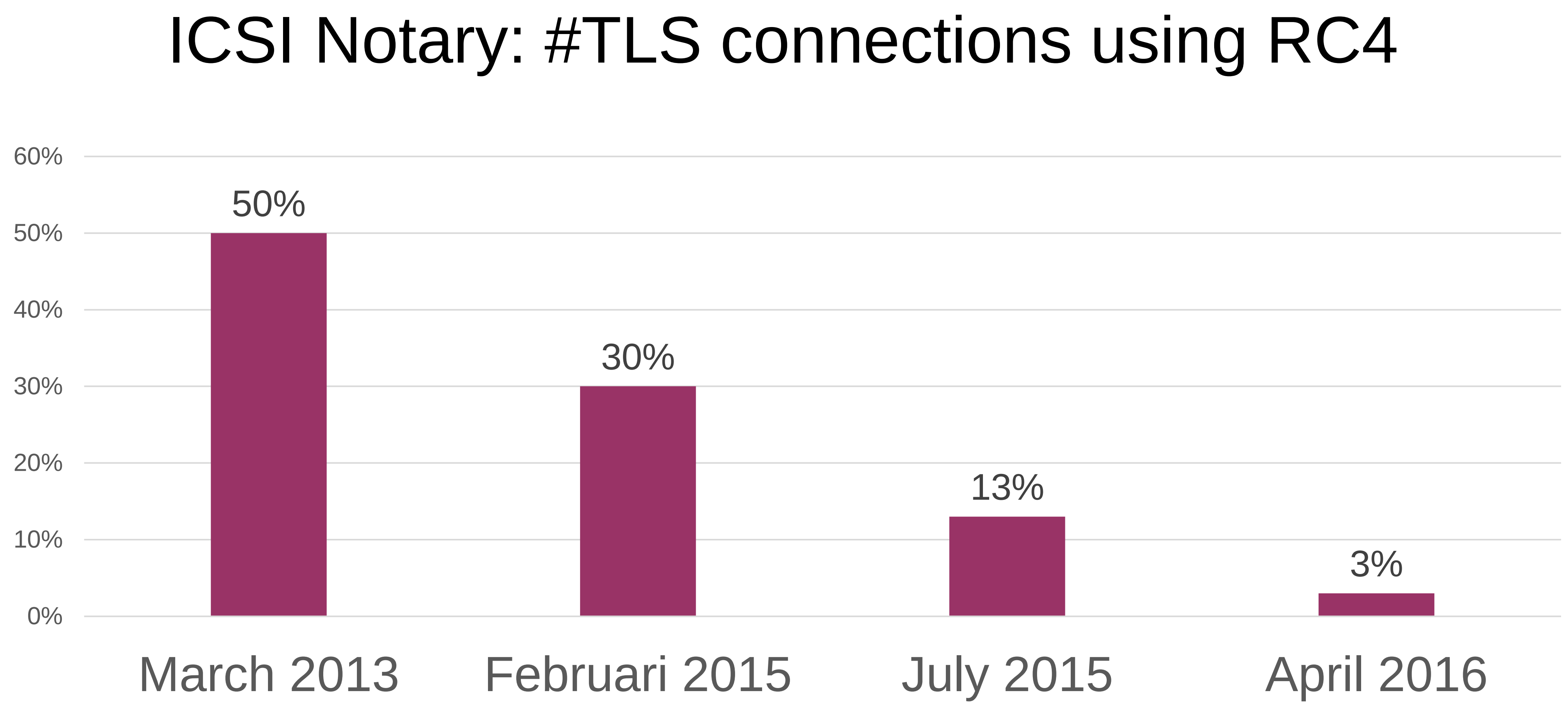
RC4 was heavily used!



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Browser support today (June 2016)

Chrome: dropped support in v48 (20 Jan. 2016)

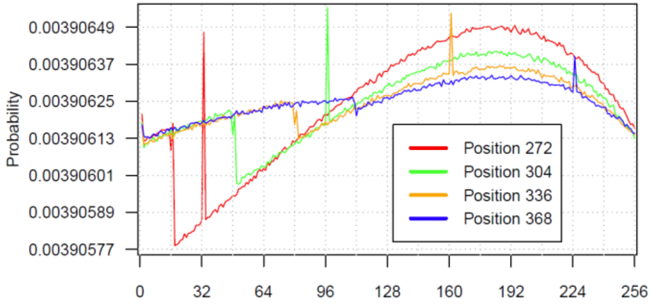
Firefox: dropped support in v44 (26 Jan. 2016)

IE11: supports RC4

Edge: supports RC4

“will be disabled in forthcoming update”

Contributions: why RC4 must die



New Biases

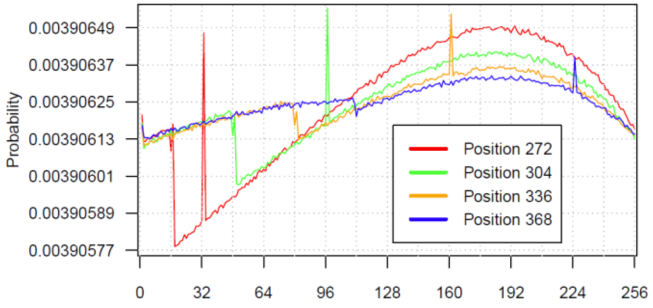
$$\lambda_{\widehat{\mu}} = (1-\alpha(g))^{|C|-|\widehat{u}|} \cdot \alpha(g)^{|\widehat{\mu}|}$$

Plaintext Recovery

Break WPA-TKIP

Attack HTTPS

Contributions: why RC4 must die



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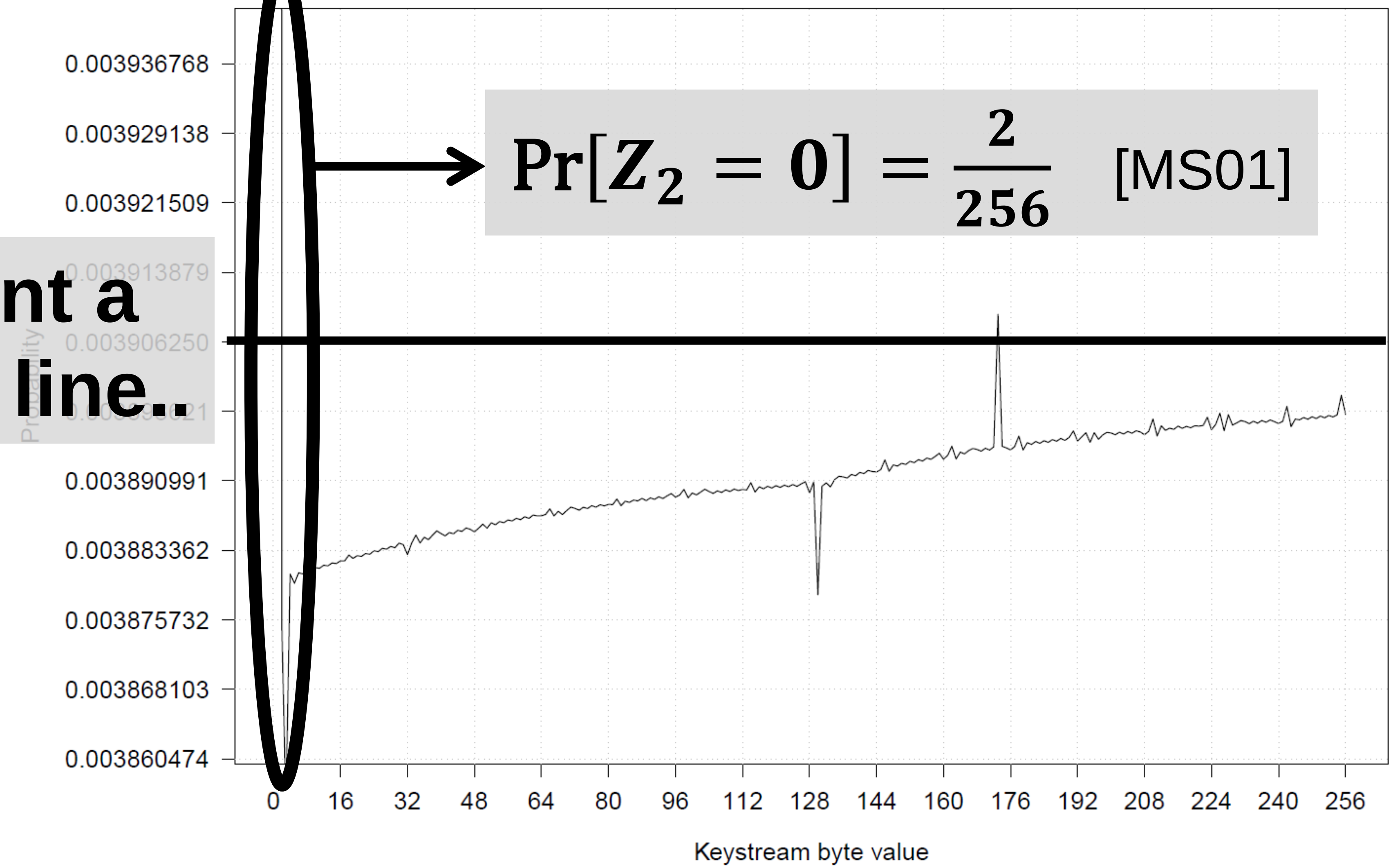
First: Existing Biases

Distribution keystream byte 2



$$\Pr[Z_2 = 0] = \frac{2}{256}$$ [MS01]

We want a straight line..

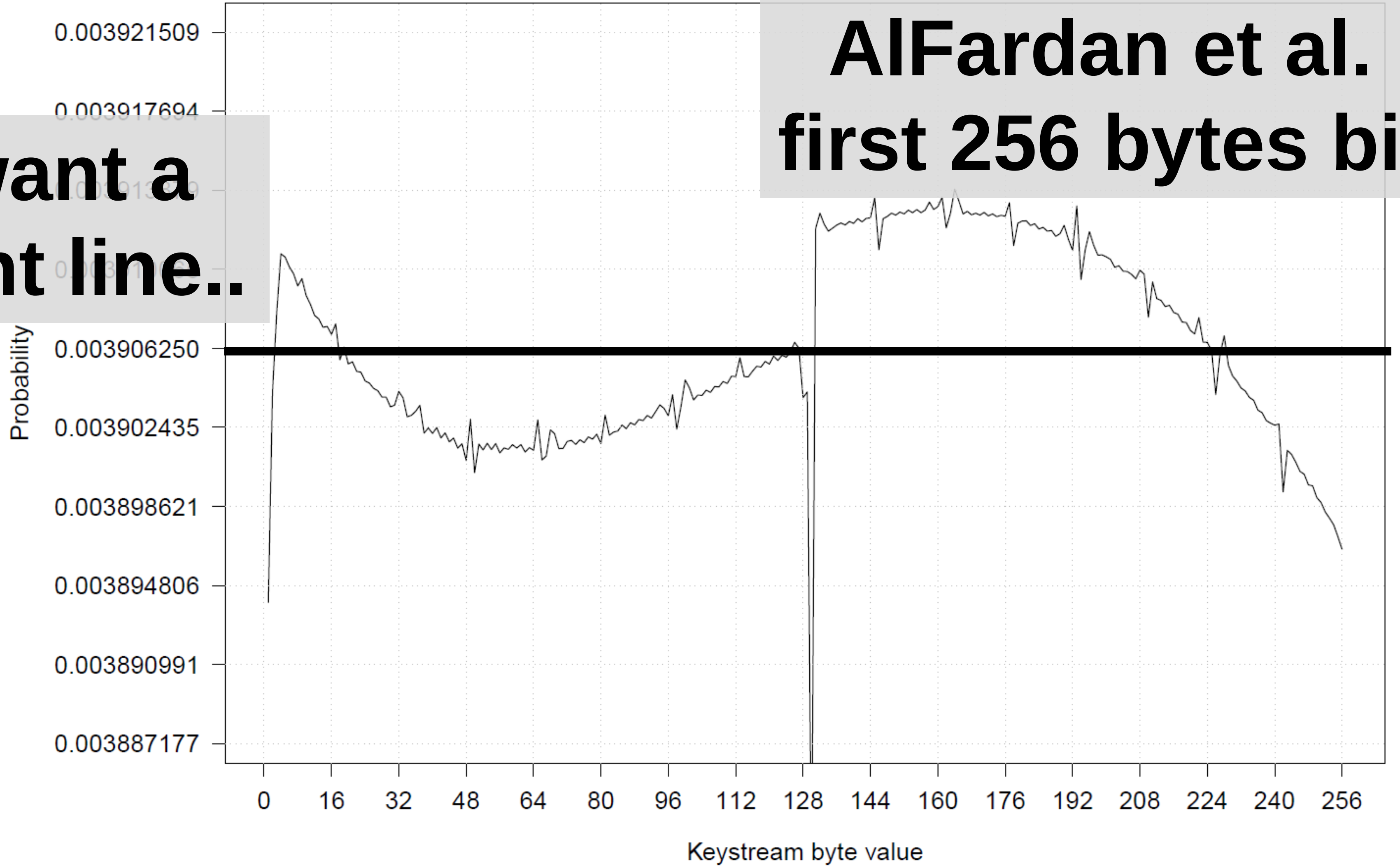
First: Existing Biases

Short-term biases

Distribution keystream byte 1 (to 256)

AlFardan et al. '13: first 256 bytes biased

We want a straight line..



Long-Term Biases

Fluhrer-McGrew (2000):

- Some consecutive values are biased

Examples: $(0, 0)$ and $(0, 1)$

Mantin's ABSAB Bias (2005):

- A byte pair (A, B) likely reappears

A	B	S	A	B

Search for new biases

Traditional emperical approach:

- Generate large amount of keystreams
- Manually inspect data or graph

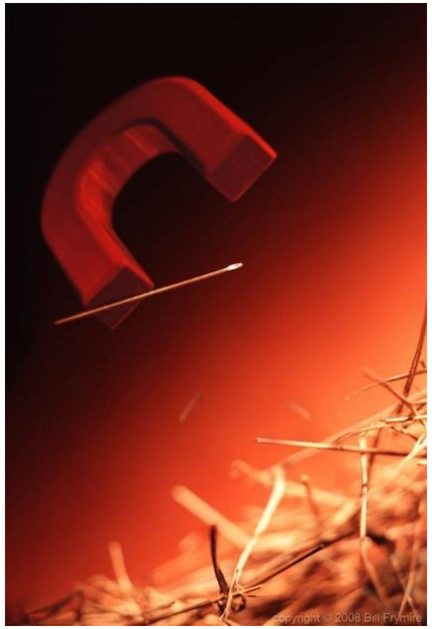
Fluhrer-McGrew biases: only 8 of 65 536 pairs are biased

How to automate the search?

Search for new biases

Traditional emperical approach:

- Generate large amount of keystreams
- Manually inspect data or graph



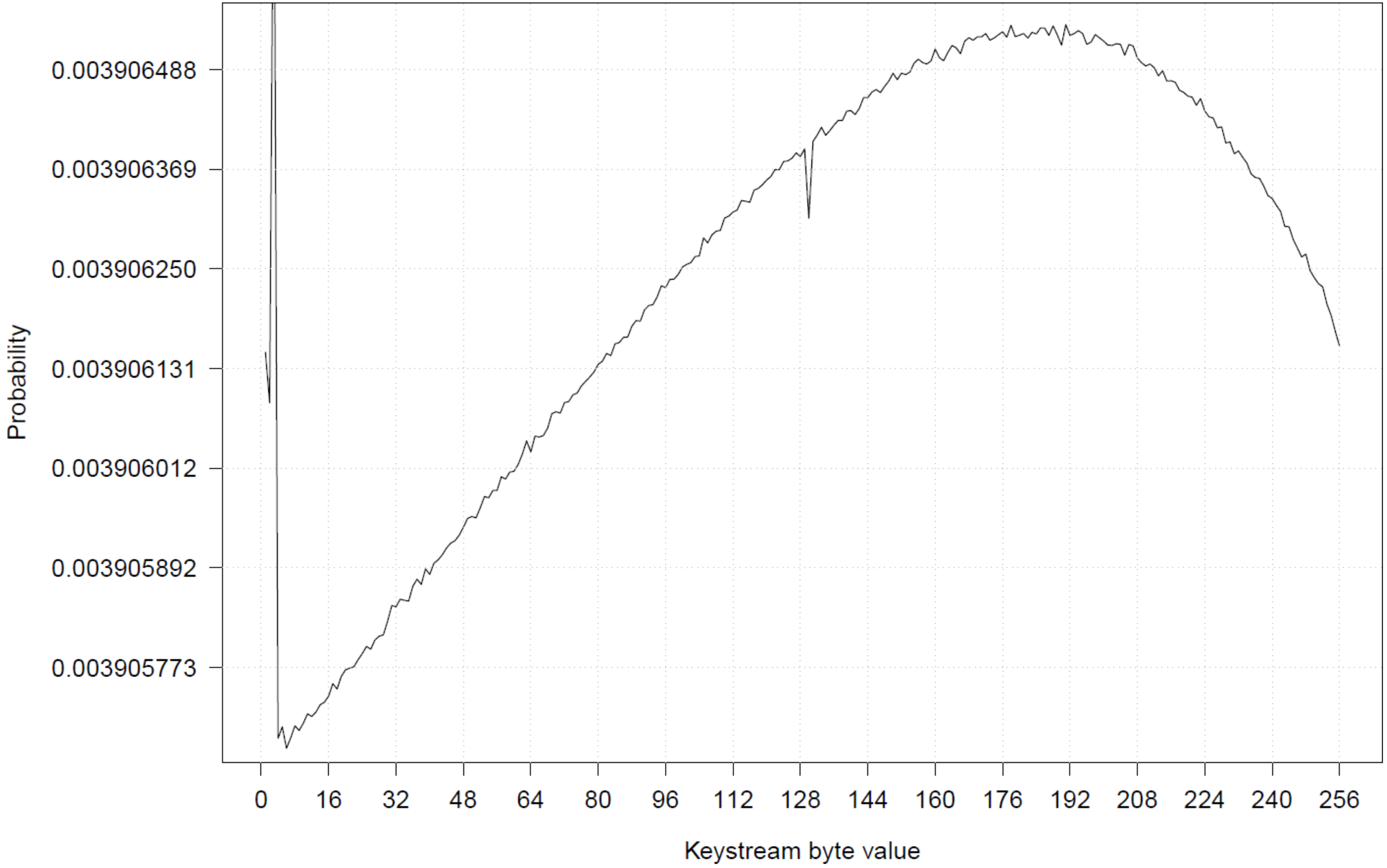
Hypothesis tests!

- Uniformly distributed: Chi-squared test.
- Correlated: M-test (detect outliers = biases)

→ Allows a large-scale search, revealing many new biases

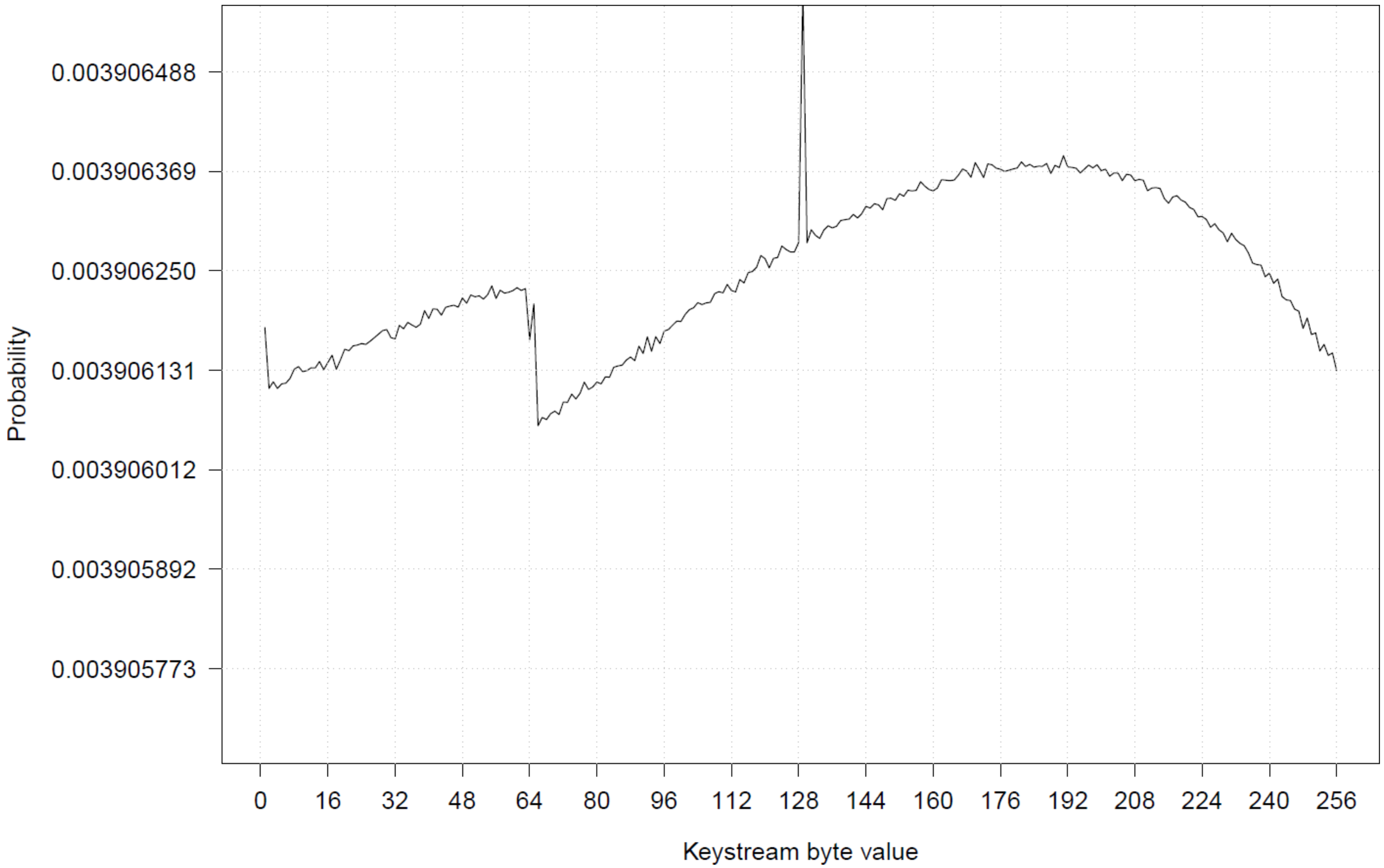
Biases in Bytes 258-513

Example: keystream byte 258



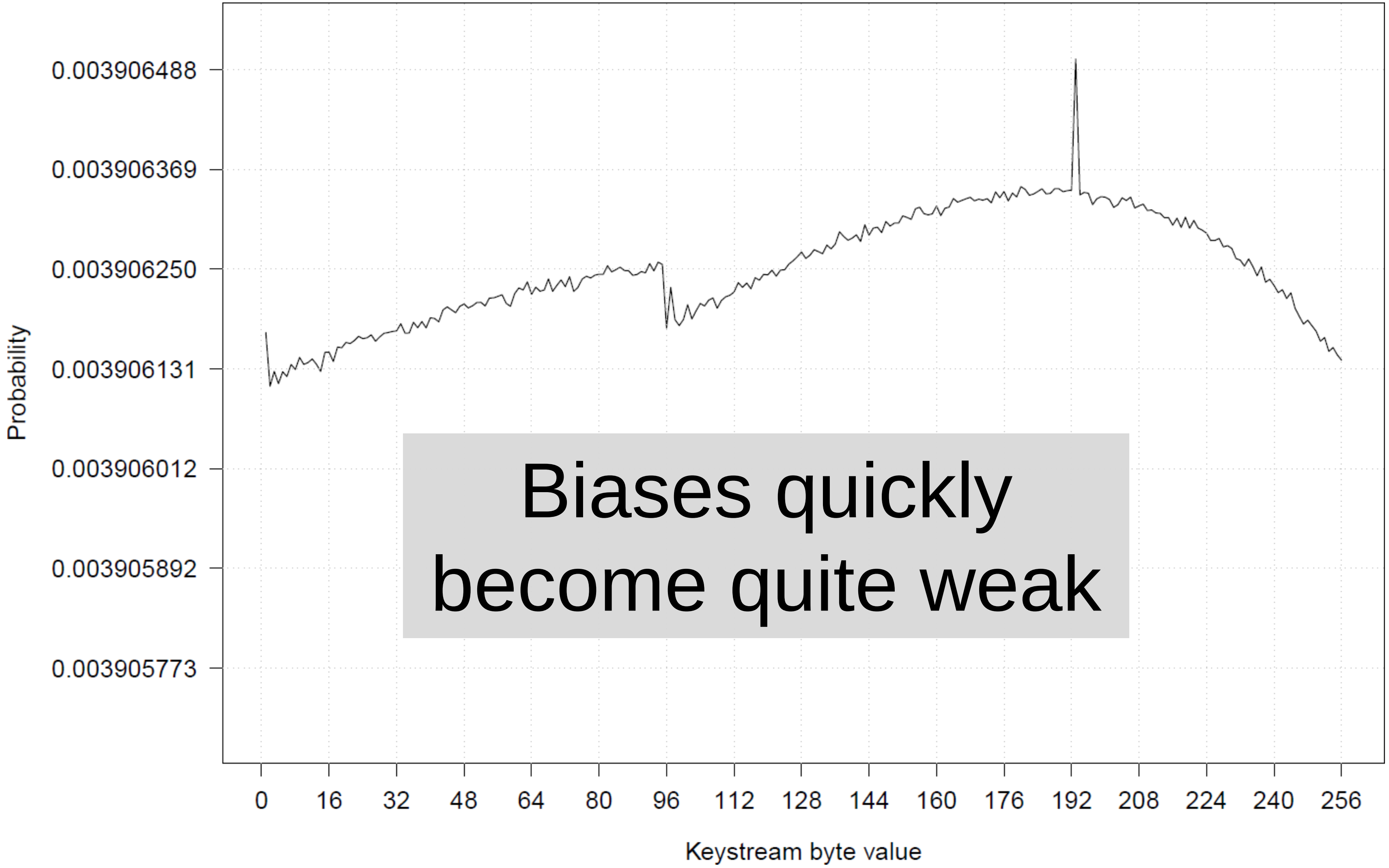
Biases in Bytes 258-513

Example: keystream byte 320



Biases in Bytes 258-513

Example: keystream byte 352



Biases quickly become quite weak

New Long-term Bias

$$(Z_{256\cdot w}, Z_{256\cdot w+2}) = (0, 128)$$

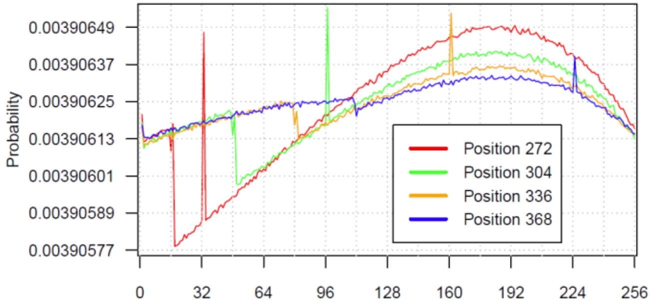
with probability $2^{-16}(1 + 2^{-8})$

Every block of 256 bytes

Additional Biases

See paper!

Contributions: why RC4 must die



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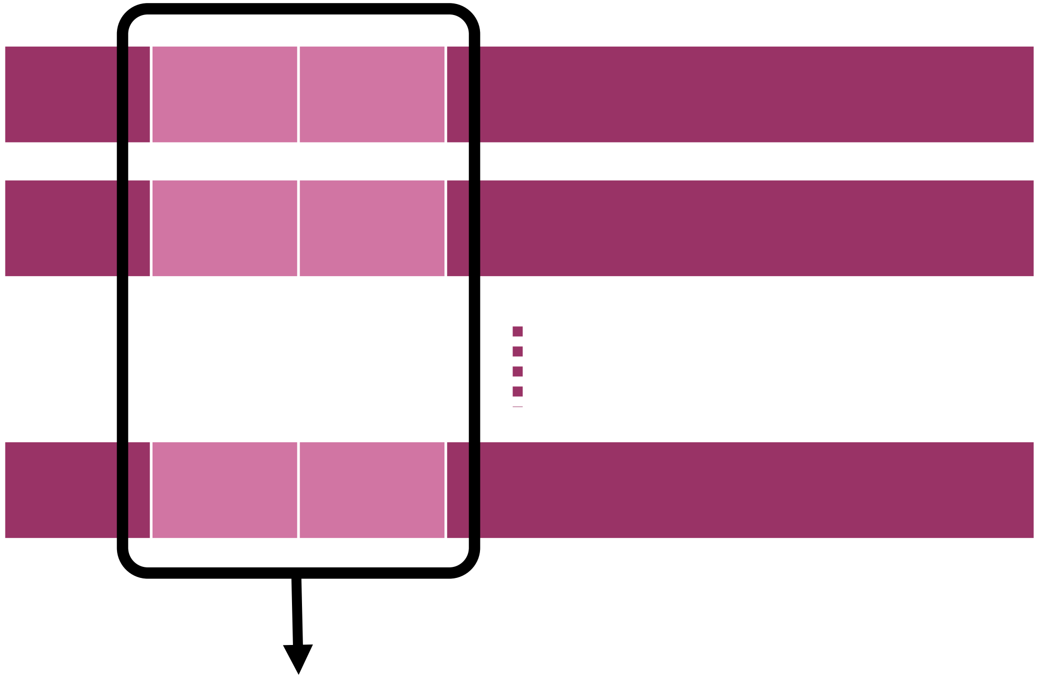
Existing Methods [AlFardan et al. ‘13]

Plaintext encrypted under several keystreams

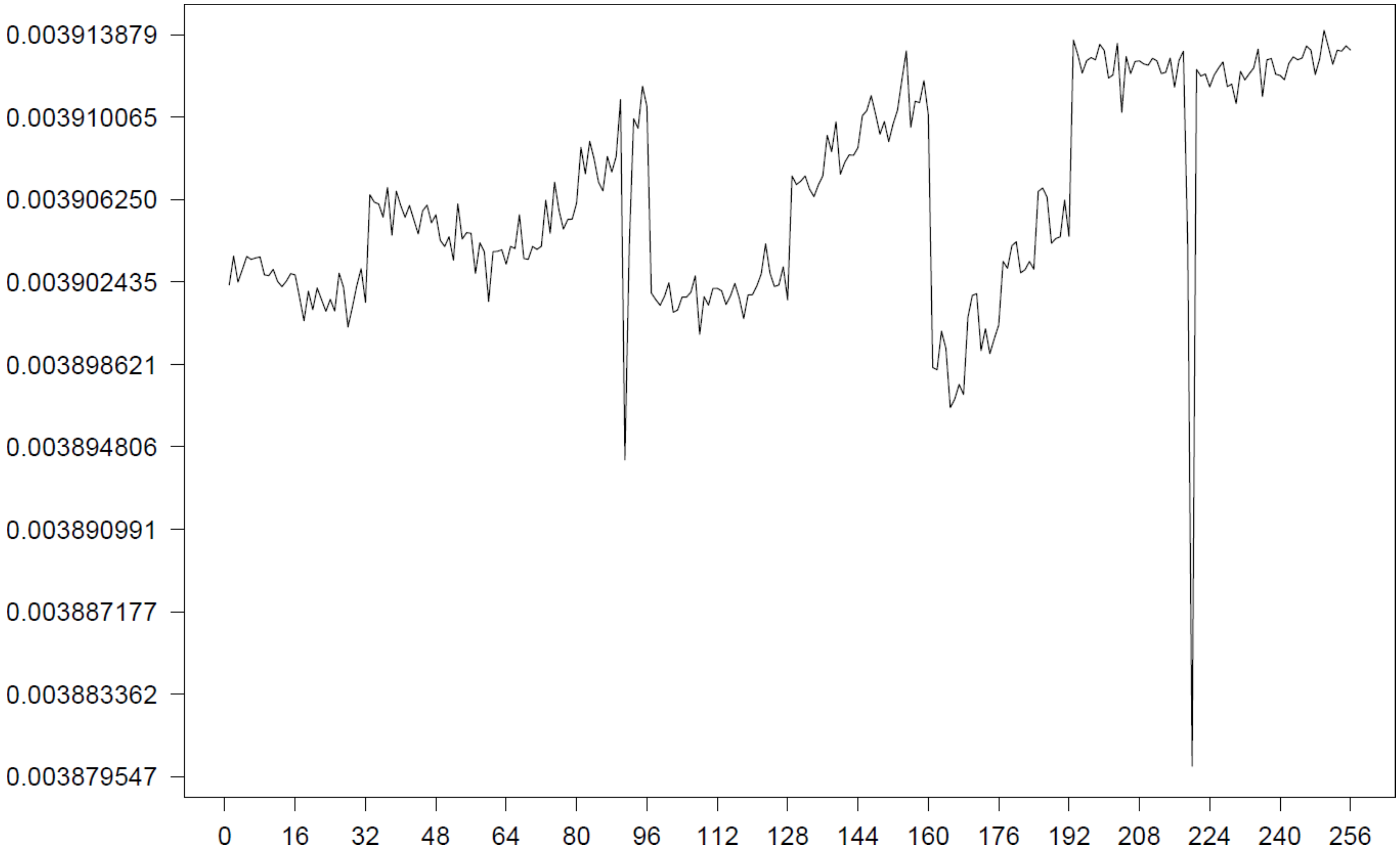


Verify guess: how close to real keystream distribution?

Ciphertext Distribution $\oplus$ Plaintext guess μ $=$ **Induced** keystream distribution

Example: Decrypt byte 1

Ciphertext Distribution



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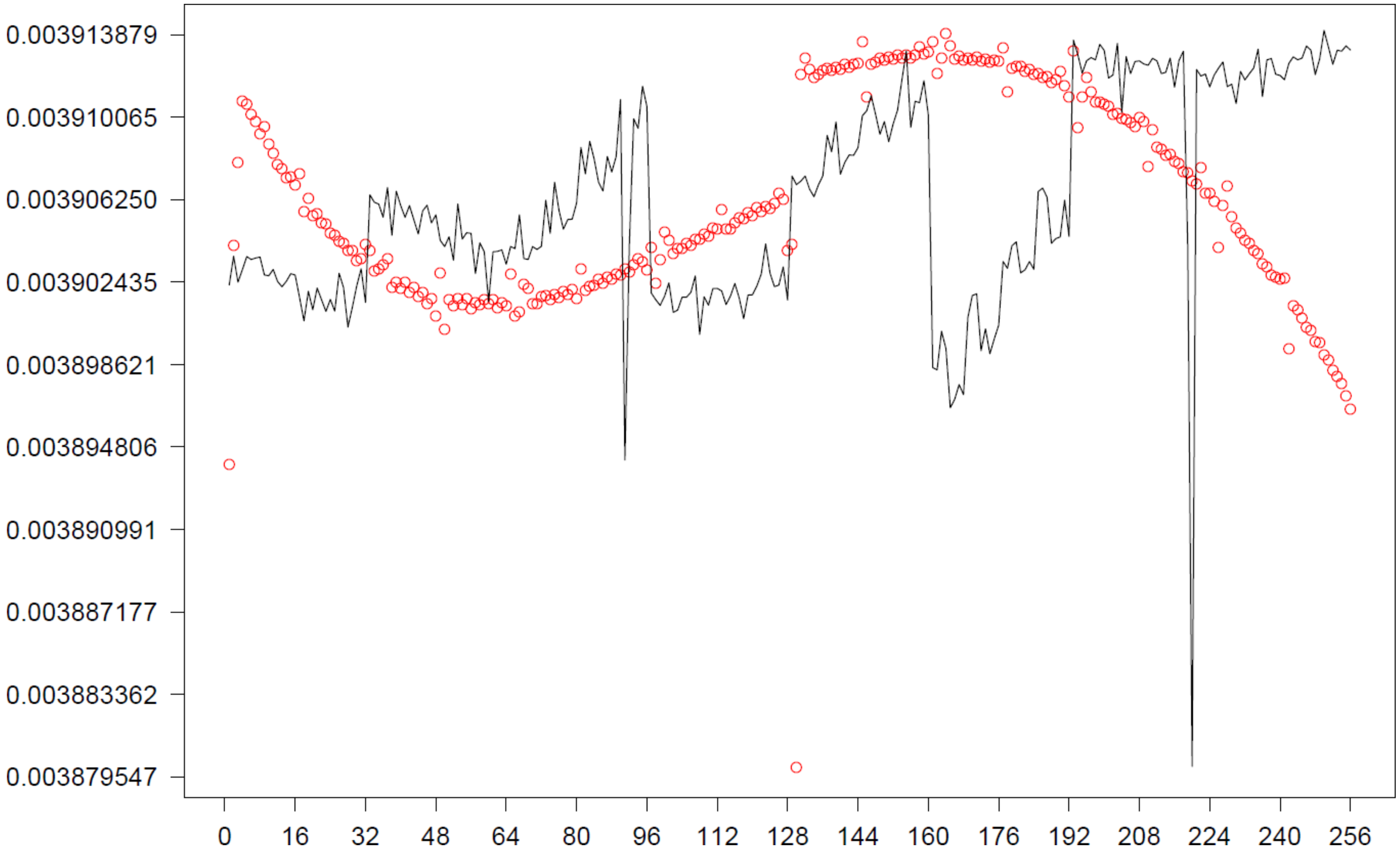
Example: Decrypt byte 1

RC4 & Ciphertext distribution



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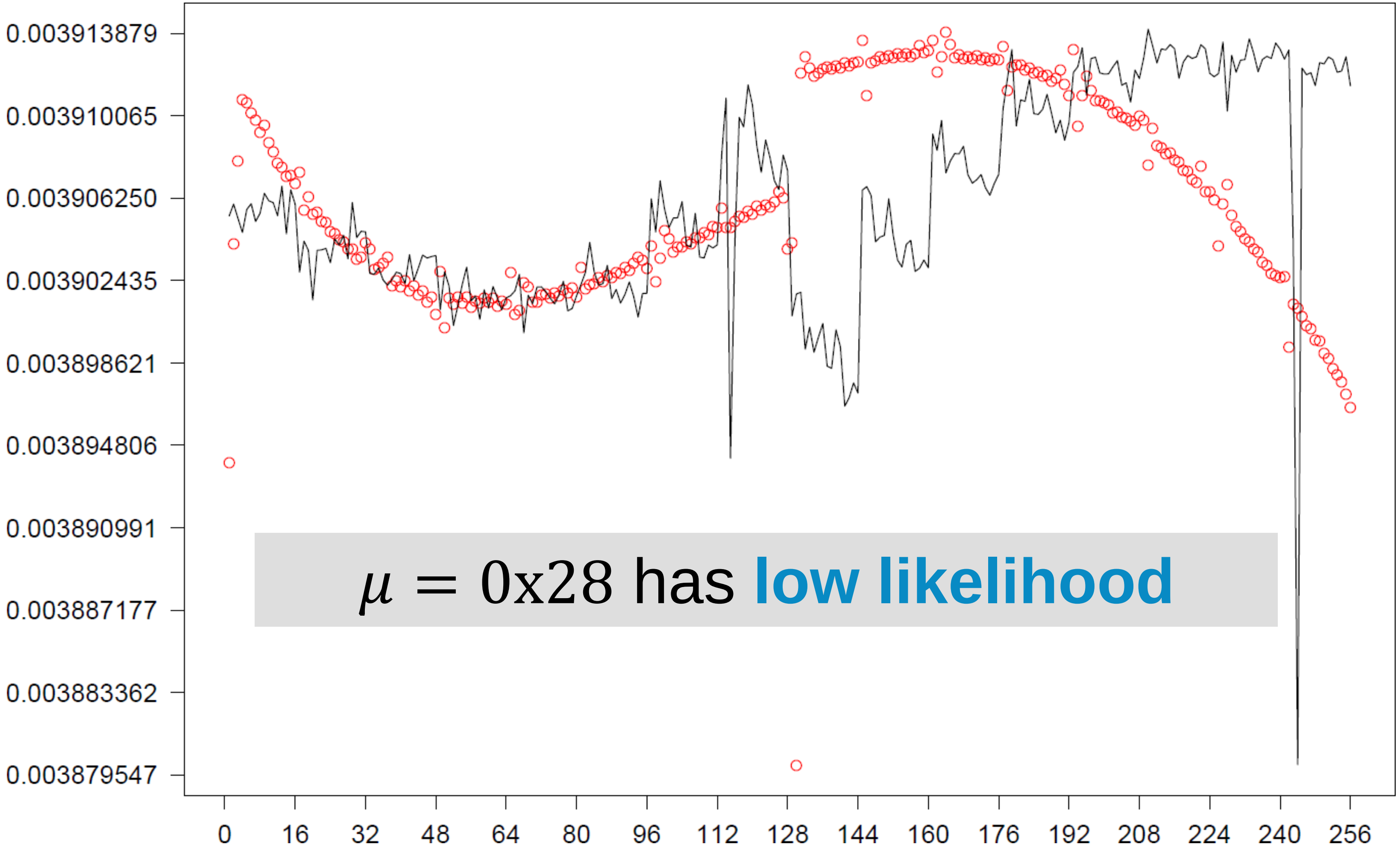
Example: Decrypt byte 1

If plaintext byte $\mu = 0\text{x}28$: **RC4** & **Induced**



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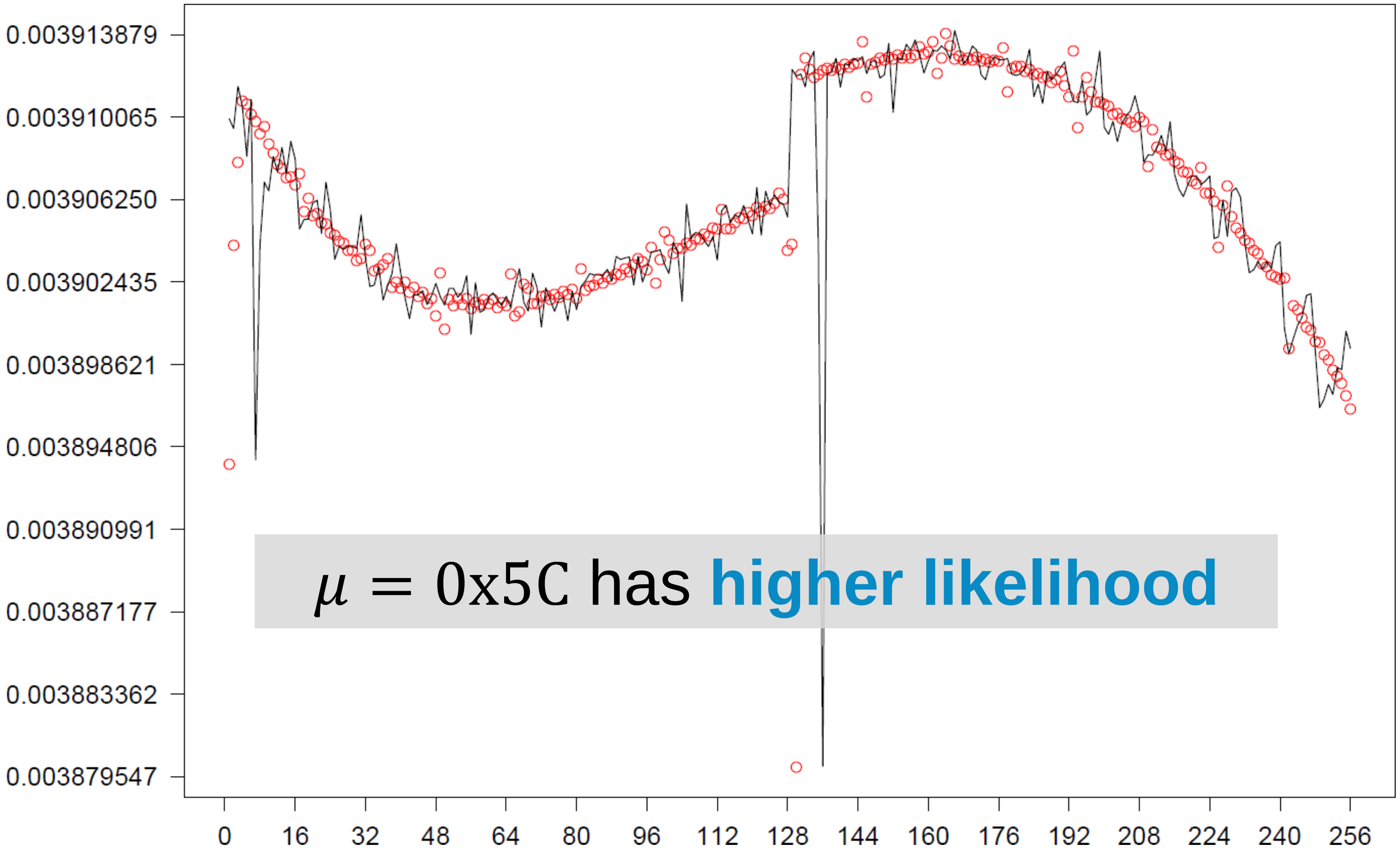
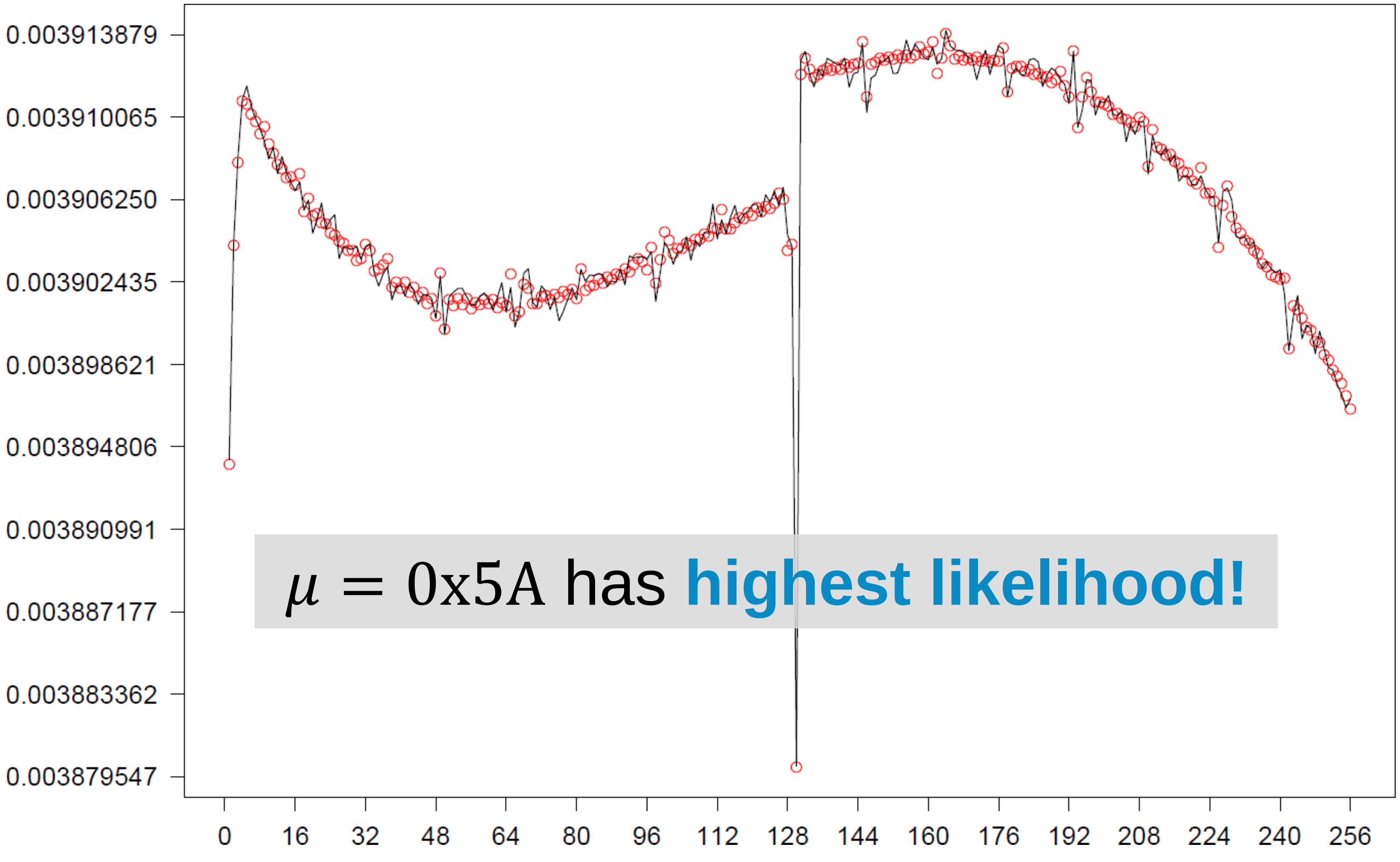
Example: Decrypt byte 1

If plaintext byte $\mu = \mathrm{0x5C}$: **RC4** & **Induced**



Example: Decrypt byte 1

If plaintext byte $\mu = 0\mathrm{x}5\mathrm{A}$: **RC4** & **Induced**



$\mu = 0\mathrm{x}5\mathrm{A}$ has **highest likelihood!**

Types of likelihood estimates

Previous works: pick value with highest likelihood.

Better idea: list of candidates in decreasing likelihood:

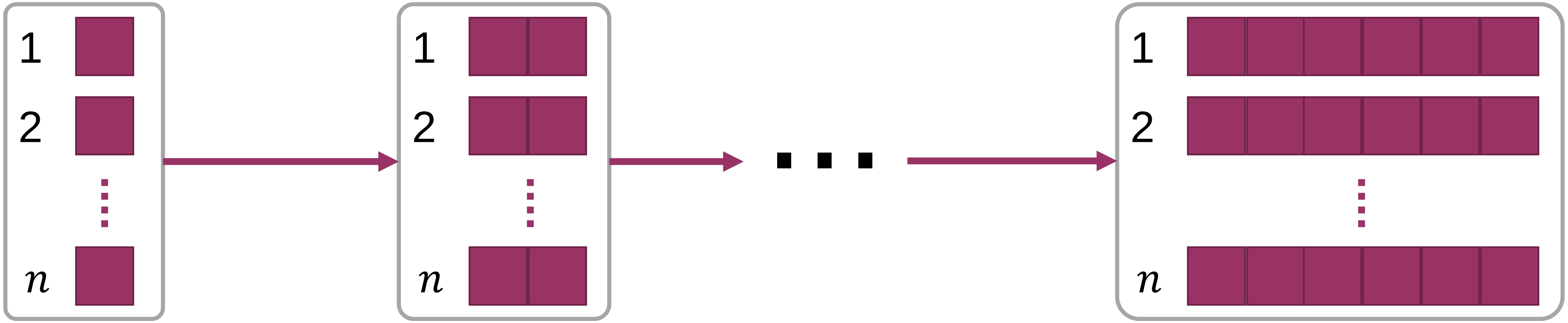
- Most likely one may not be correct!
- Prune bad candidates (e.g. bad CRC)
- Brute force cookies or passwords

How to calculate list of candidates?

1^{st} idea: Generate List of Candidatess

Gist of the Algorithm: Incremental approach

Calculate candidates of length 1, length 2, ...



2^{nd} idea: abusing the ABSAB bias

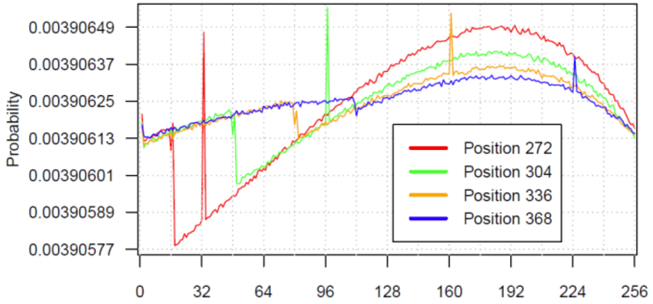
Known Plaintext   Unknown Plaintext

Assume there's **surrounding known plaintext** !

- Derive values of (A, B)
- Combine with ABSAB bias to (probablisticly) predict $(\mathrm{A}', \mathrm{B}')$
- Ordinary likelihood calculation over only $(\mathrm{A}', \mathrm{B}')$

Likelihood estimate: $\lambda_{\hat{\mu}} = (1 - \alpha(g))^{|\mathcal{C}| - |\hat{u}|} \cdot \alpha(g)^{|\hat{\mu}|}$

Contributions: why RC4 must die



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Plaintext Recovery

Break WPA-TKIP

Attack HTTPS

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TKIP Background

How are packets sent/received?

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1. Add Message Integrity Check (**MIC**)

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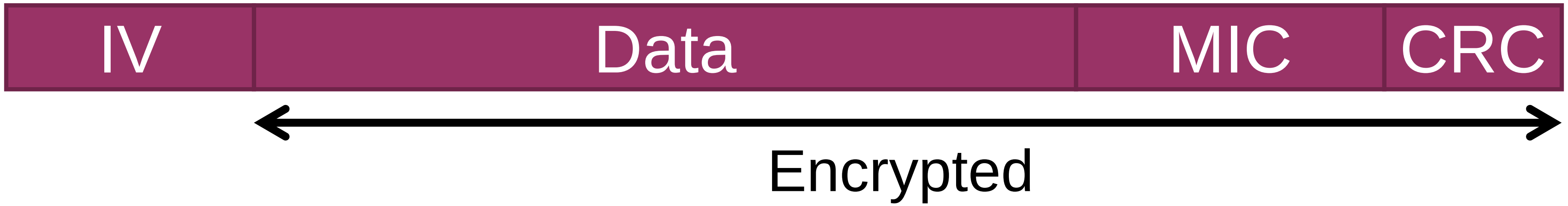


1. Add Message Integrity Check (**MIC**)
2. Add **CRC** (leftover from WEP)
3. Add **IV** (increments every frame)
4. Encrypt using **RC4** (per-packet key)

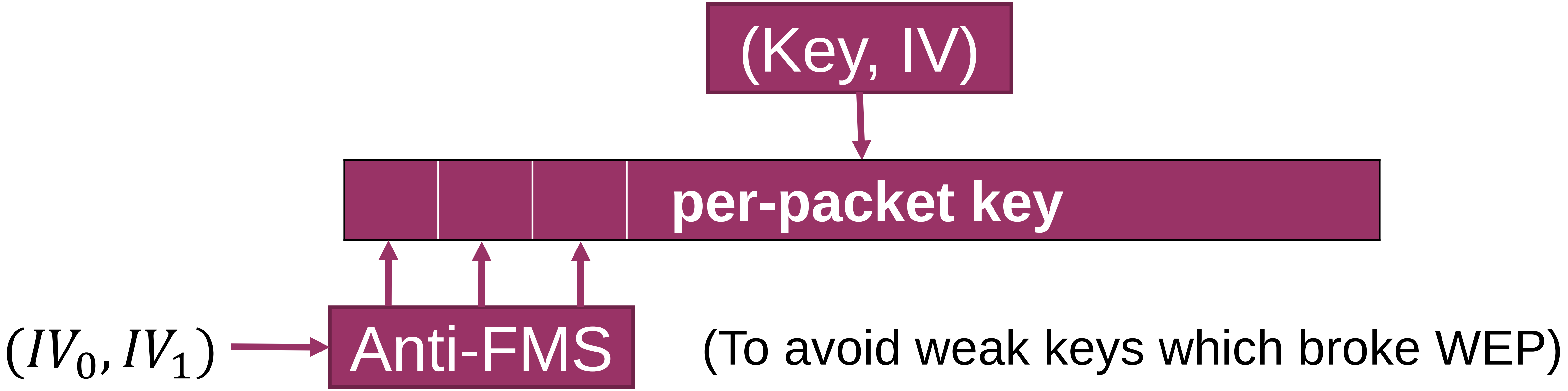
Flaw #1: TKIP Per-packet Key

(Key, IV)

↓

per-packet key

Flaw #1: TKIP Per-packet Key



→ IV-dependent biases in keystream

[Gupta/Paterson et al.]

Flaw #2: MIC is invertible

If decrypted, reveals MIC key

→ With the MIC key, an attacker can inject and decrypt some packets [AsiaCCS ‘13]

Goal: decrypt data and MIC

IV	Data	MIC	CRC

If decrypted, reveals MIC key

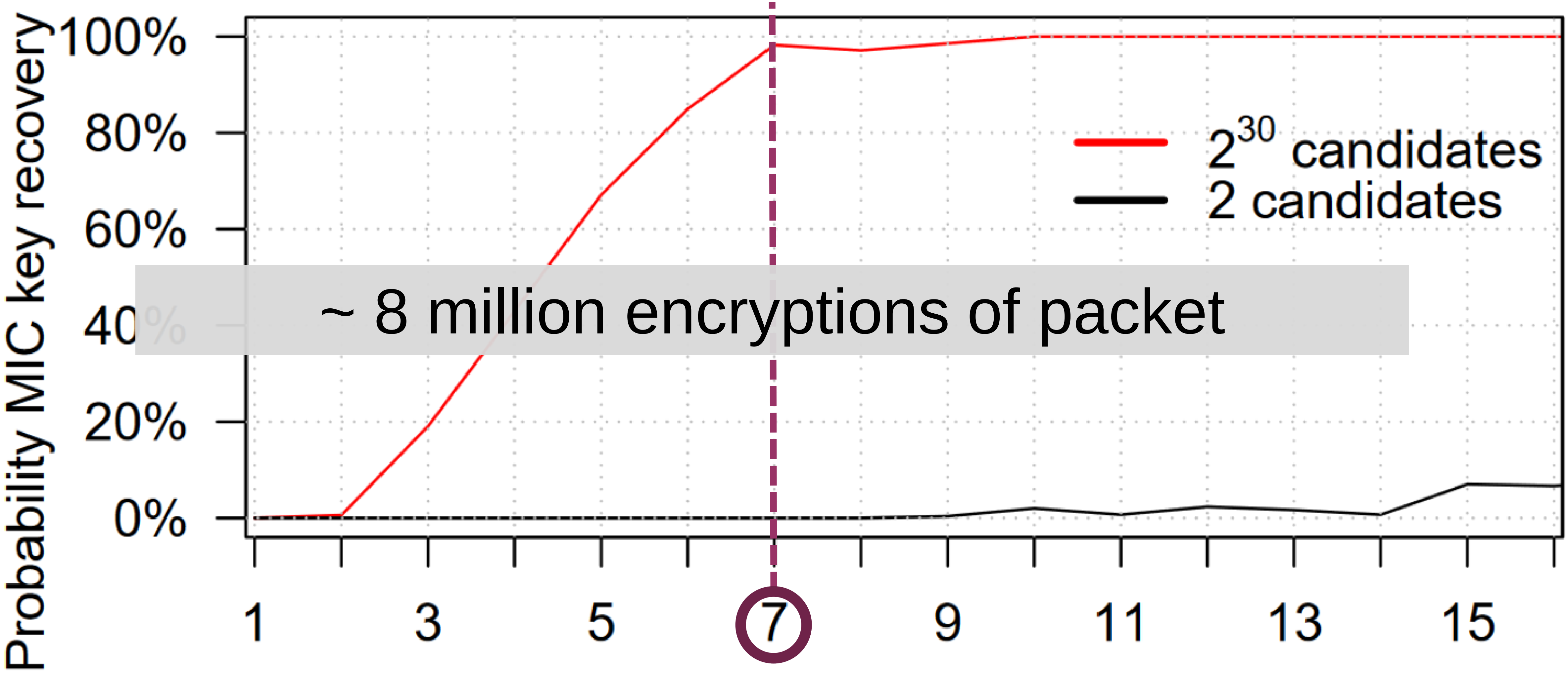
Goal: decrypt packet using RC4 biases & derive MIC key

- Problem: must generate many identical WPA-TKIP packets
- Solution: make victim connect to our server and retransmit identical TCP packets

Generate list of packet candidates

- Prune bad candidates based on CRC

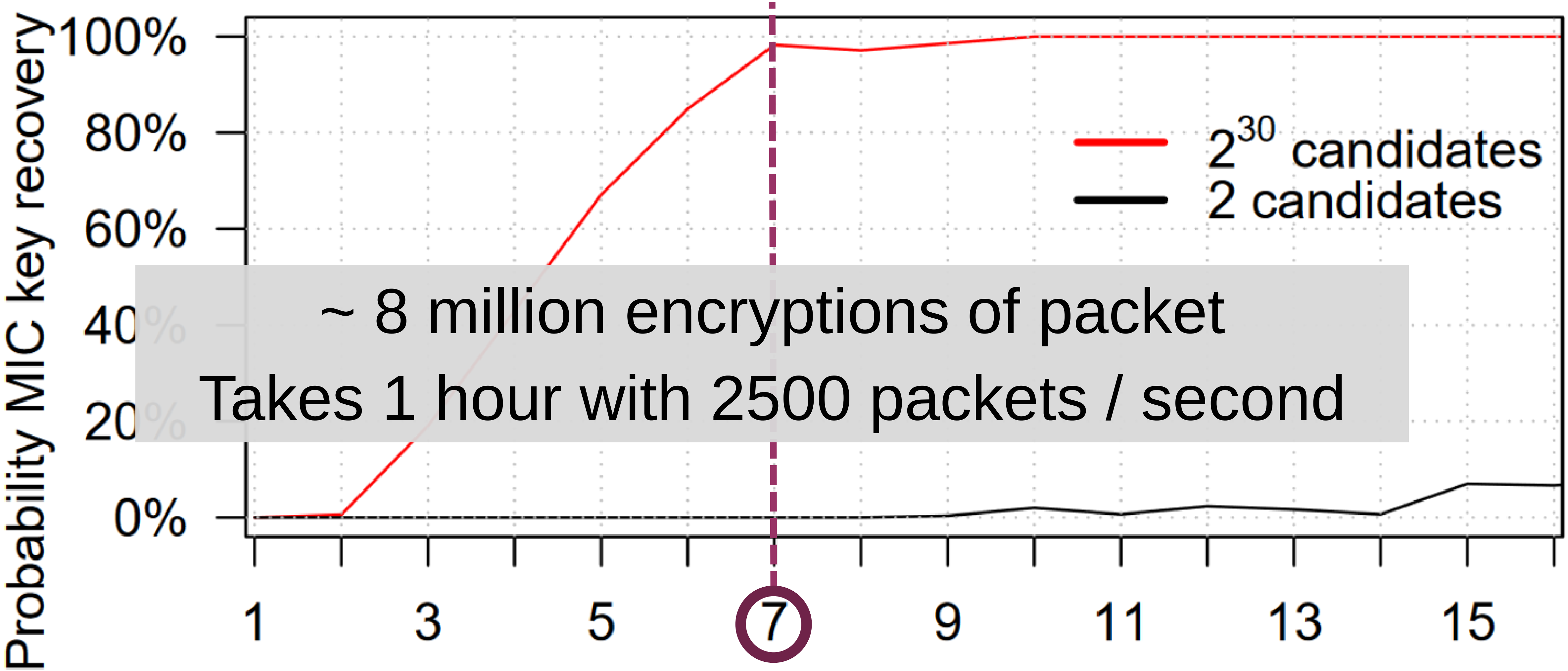
Evaluation



~ 8 million encryptions of packet

Ciphertext copies times 2^{20}

Evaluation

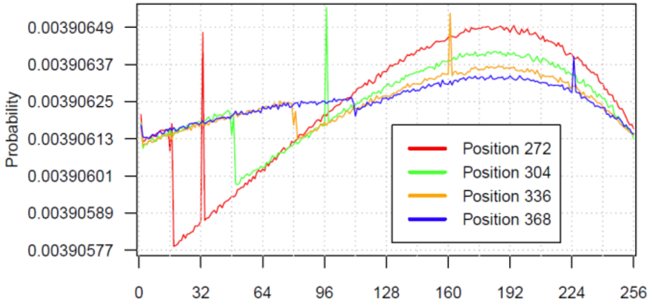


~ 8 million encryptions of packet

Takes 1 hour with 2500 packets / second

Ciphertext copies times 2^{20}

Contributions: why RC4 must die



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Attack HTTPS

TLS Background

Negotiate keys

Handshake protocol

Record protocol

Client

Encrypt data

Server

→ Focus on **record protocol with RC4** as cipher

Targeting HTTPS Cookies

Previous attacks only used Fluhrer-McGrew (FM) biases

We **combine FM biases and ABSAB biases**

To use ABSAB biases we first surround cookie with known data

1. Remove unknown plaintext arround cookie
2. Inject known plaintext arround cookie

Example: manipulated HTTP request

```
User-Agent: Mozilla/5.0 (Windows NT 6.1; WOW64; Trident/7.0; rv:11.0) like Gecko
Host: a.site.com
Connection: Keep-Alive
Cache-Control: no-cache
Cookie: auth=????????????????; P=aaaaaaaaaaaaaaaa
```

Headers are predictable

Surrounded by known plaintext at both sides

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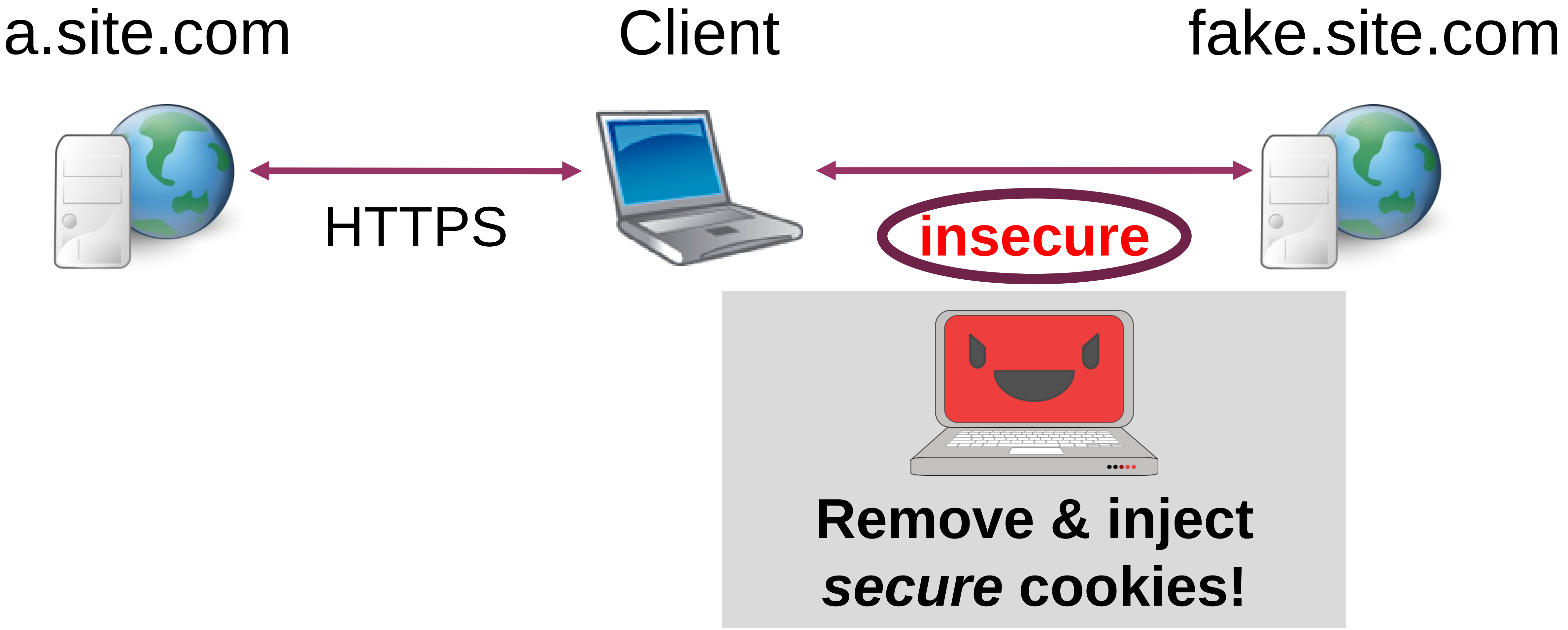
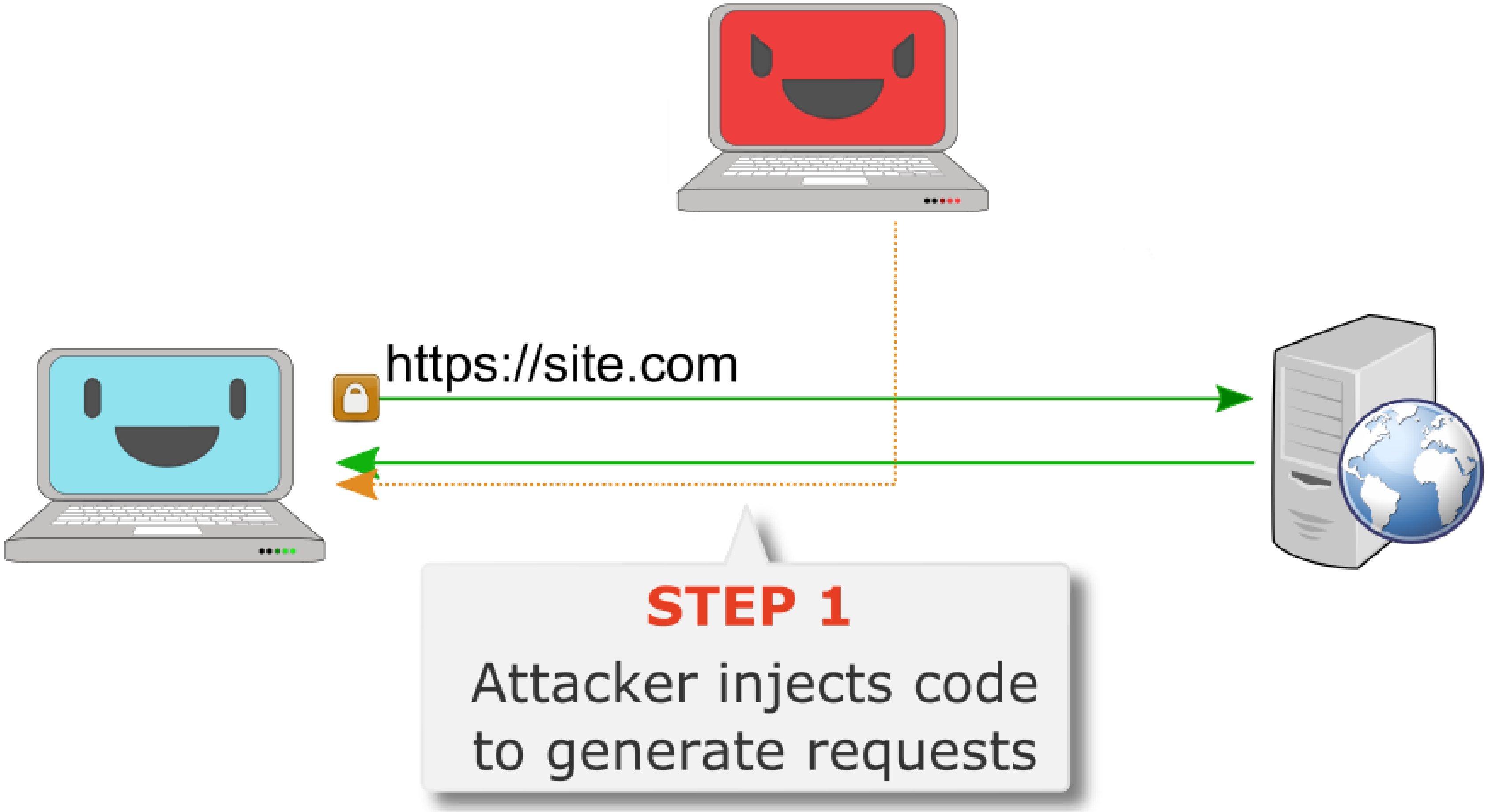
Preparation: manipulating cookies

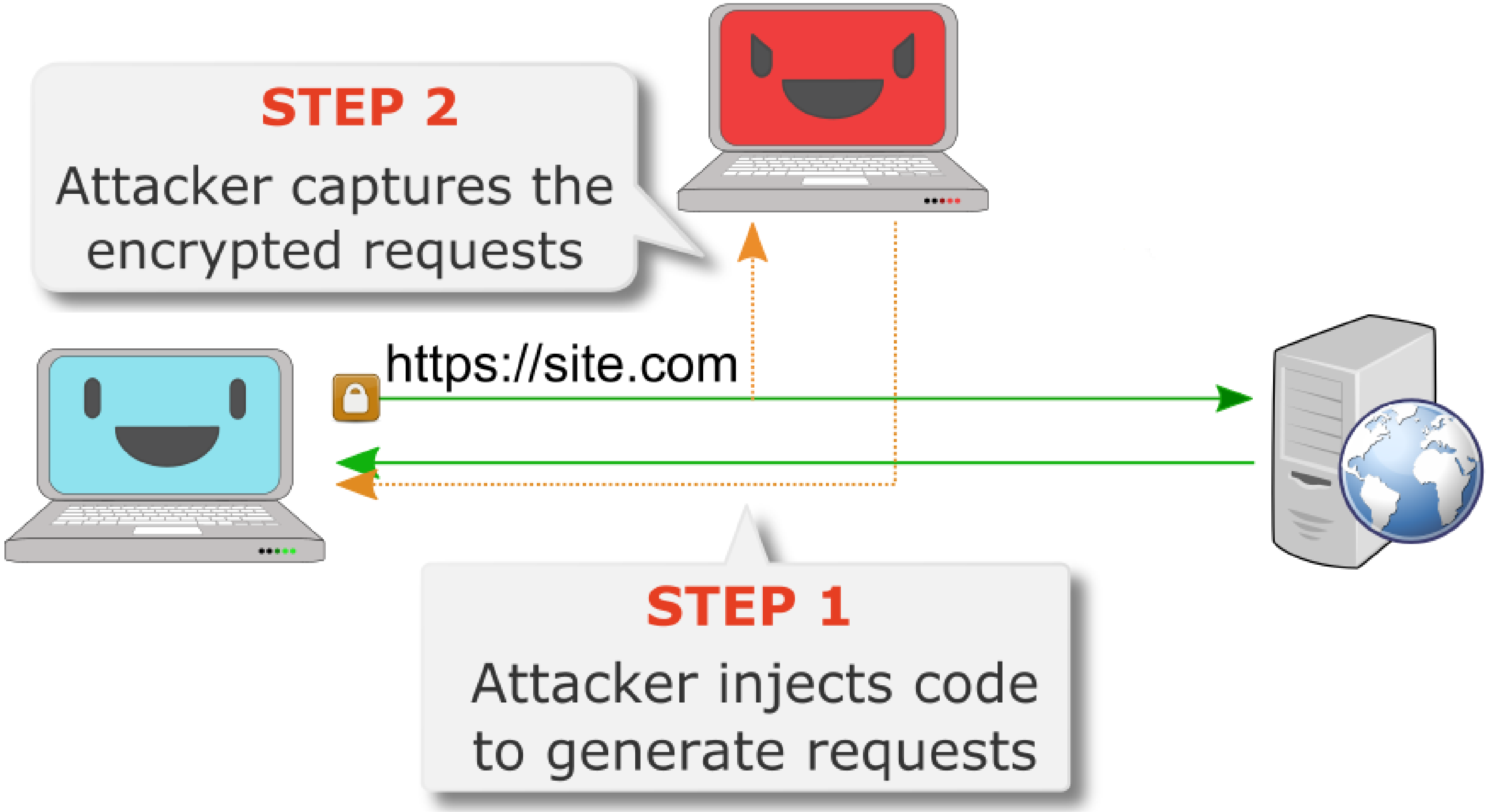


Performing the attack!



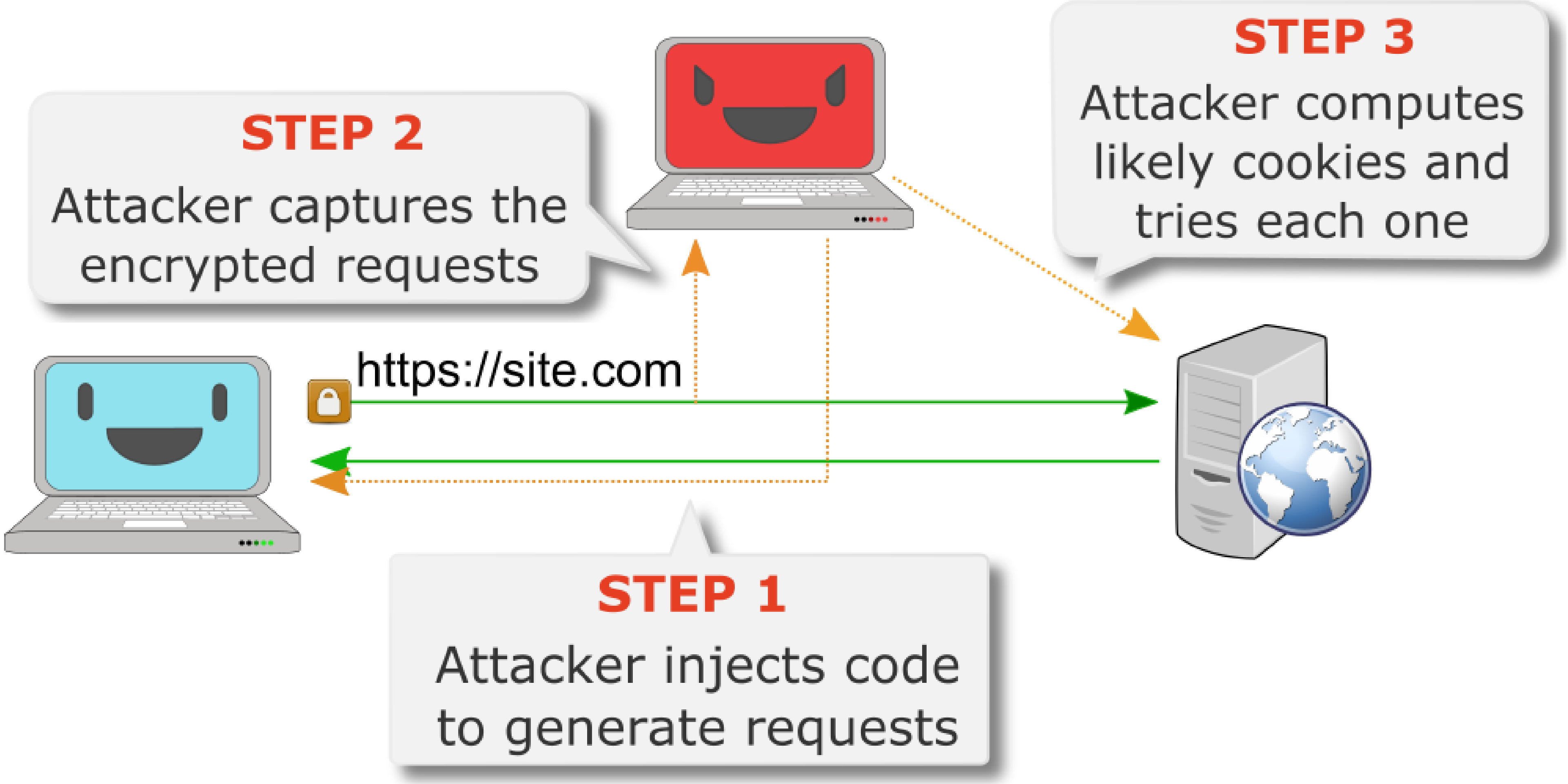
JavaScript: Cross-Origin requests in WebWorkers

Performing the attack!



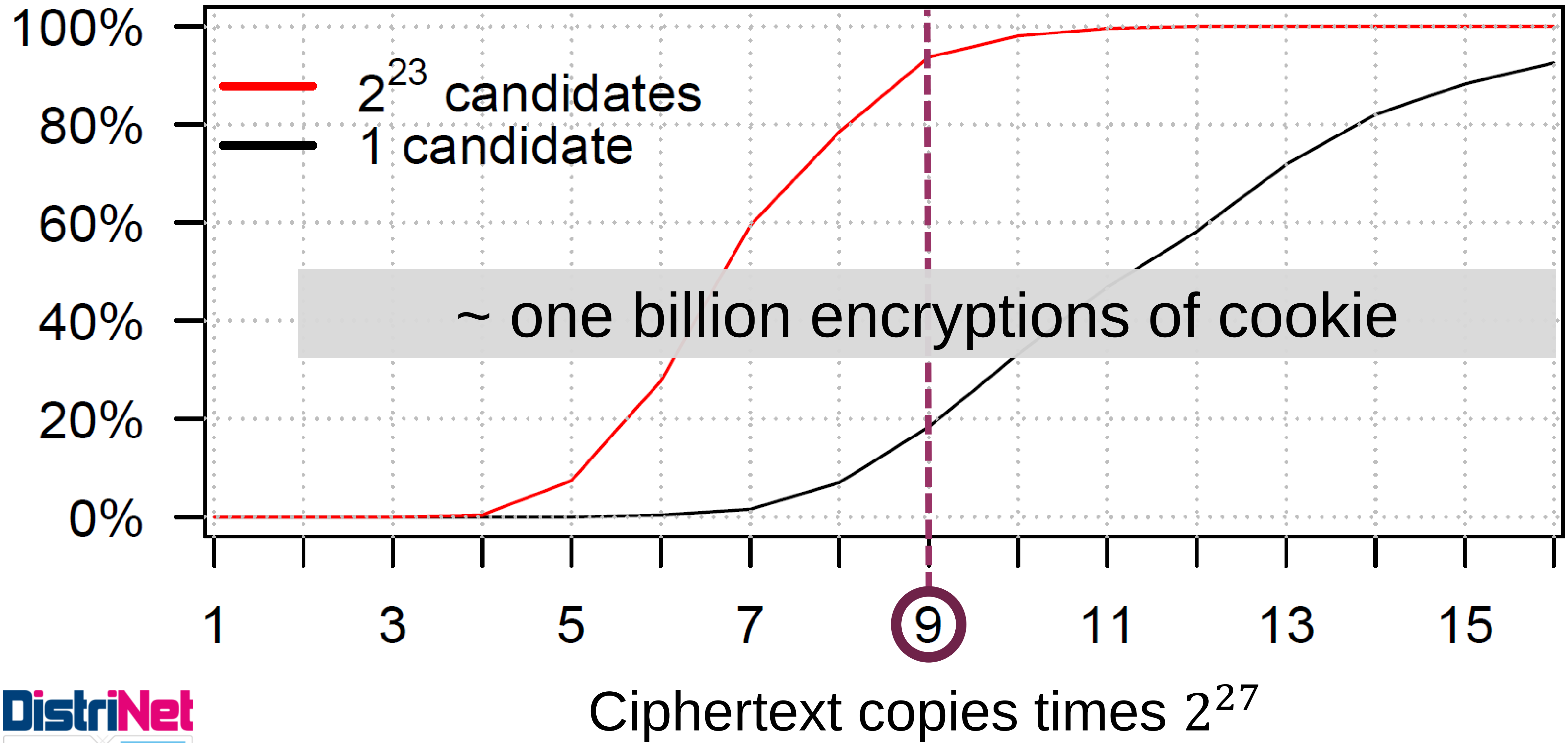
Keep-Alive connection to generate them fast

Performing the attack!



Combine Fluhrer-McGrew and ABSAB biases

Decrypting 16-character cookie



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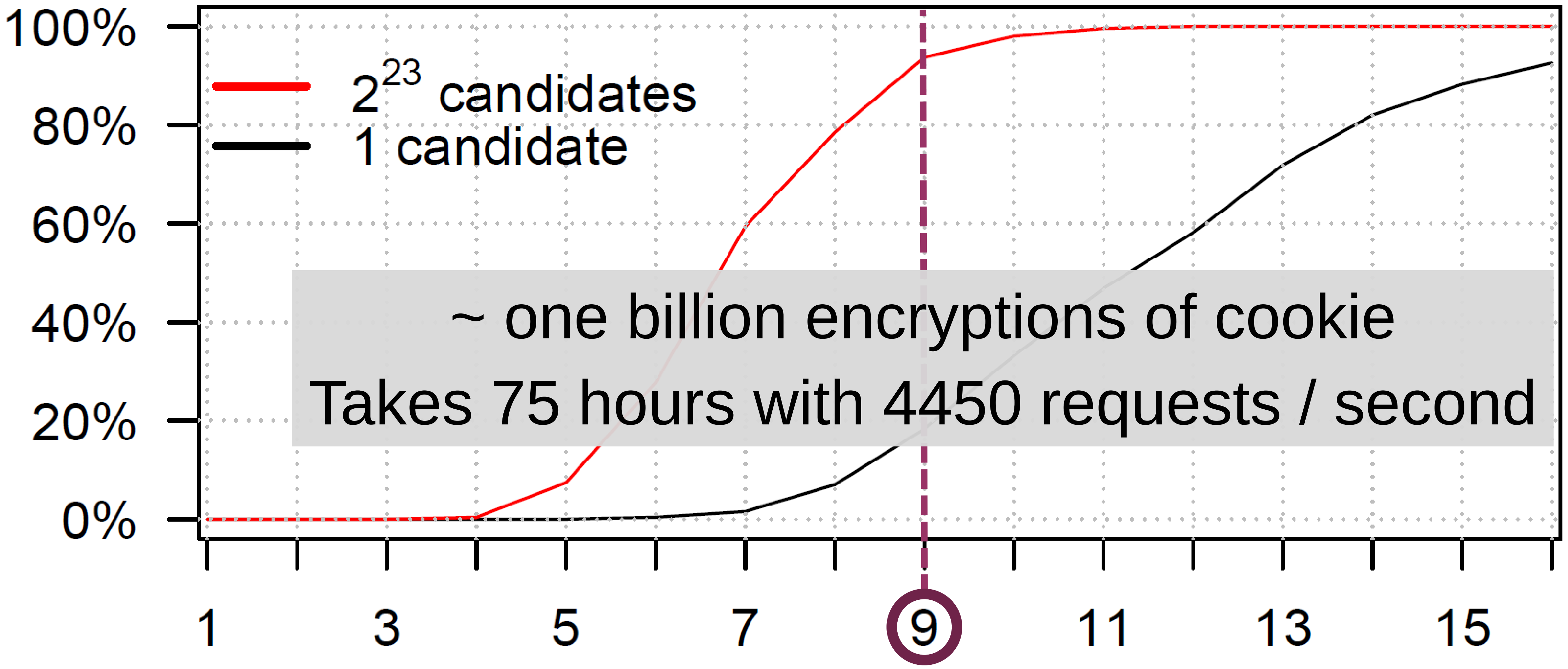
Decrypting 16-character cookie



~ one billion encryptions of cookie

Takes 75 hours with 4450 requests / second

Ciphertext copies times 2^{27}

Decrypting 16-character cookie

DEMO!

rc4nomore.com

Questions?

May the bias be ever in your favor

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Questions?

May the bias be ever in your favor

High level description

Shuffles permutation of [0..255]

77	37	102	233	…	151	14	198	0	56

Secret index j

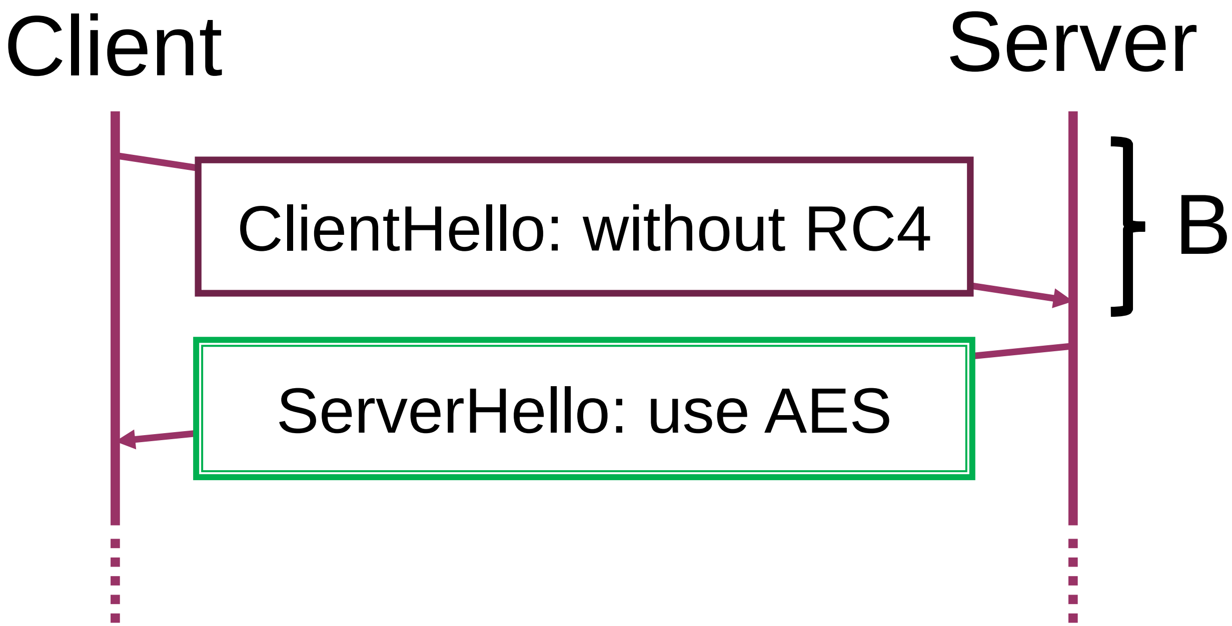
pseudo-randomly
updated value

Public index i

= keystream
position mod 256

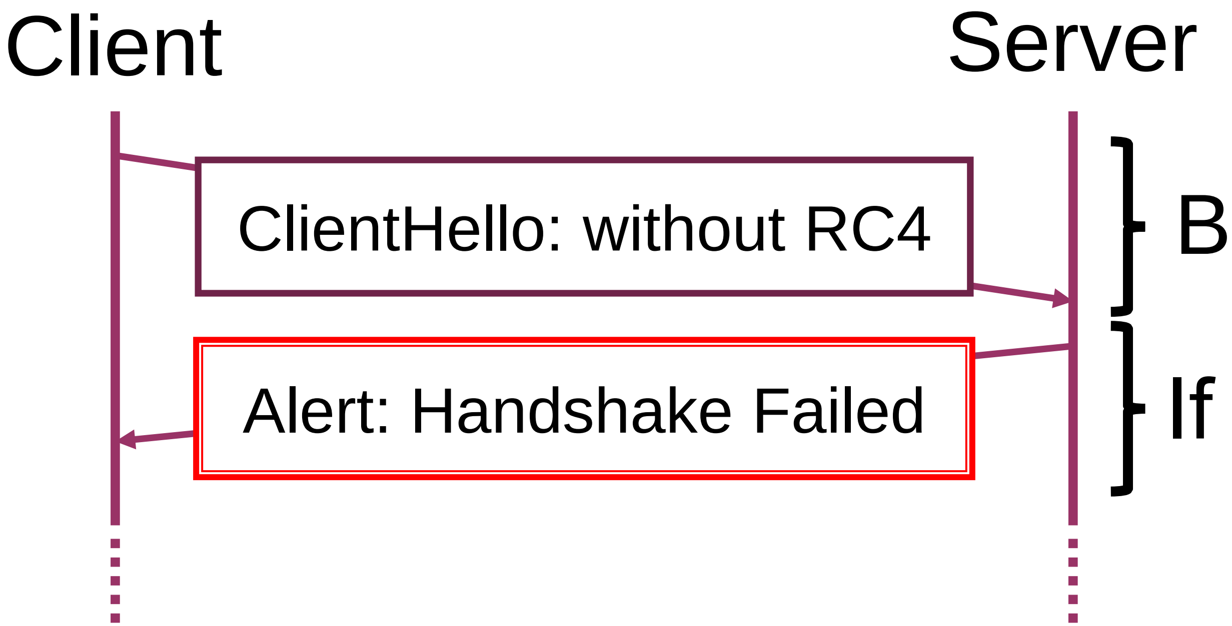
→ Output byte selected based on index j and i

Fallback to RC4



Browser first tries without RC4

Fallback to RC4



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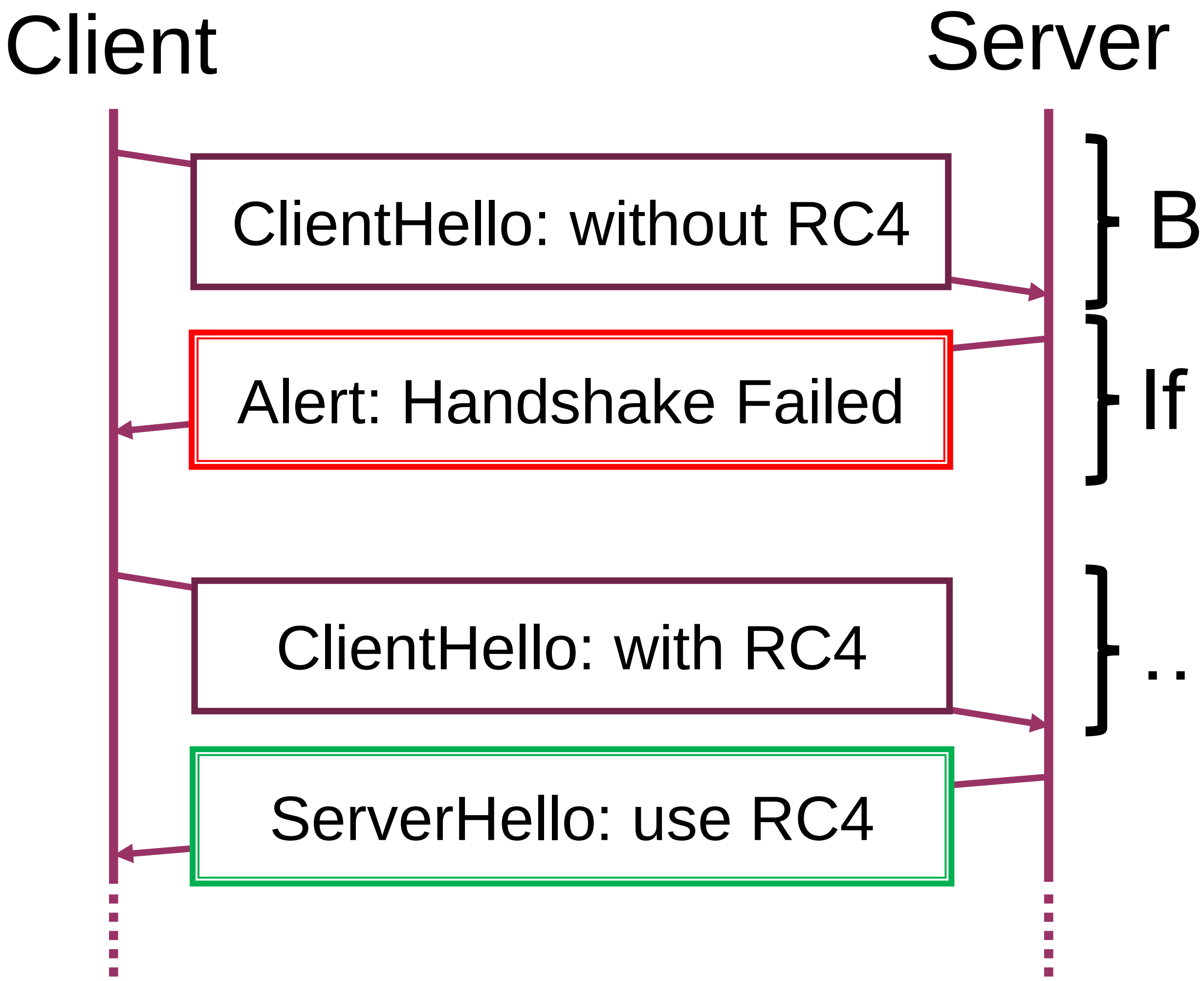
If that fails …

Fallback to RC4



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If that fails …

… fallback to RC4

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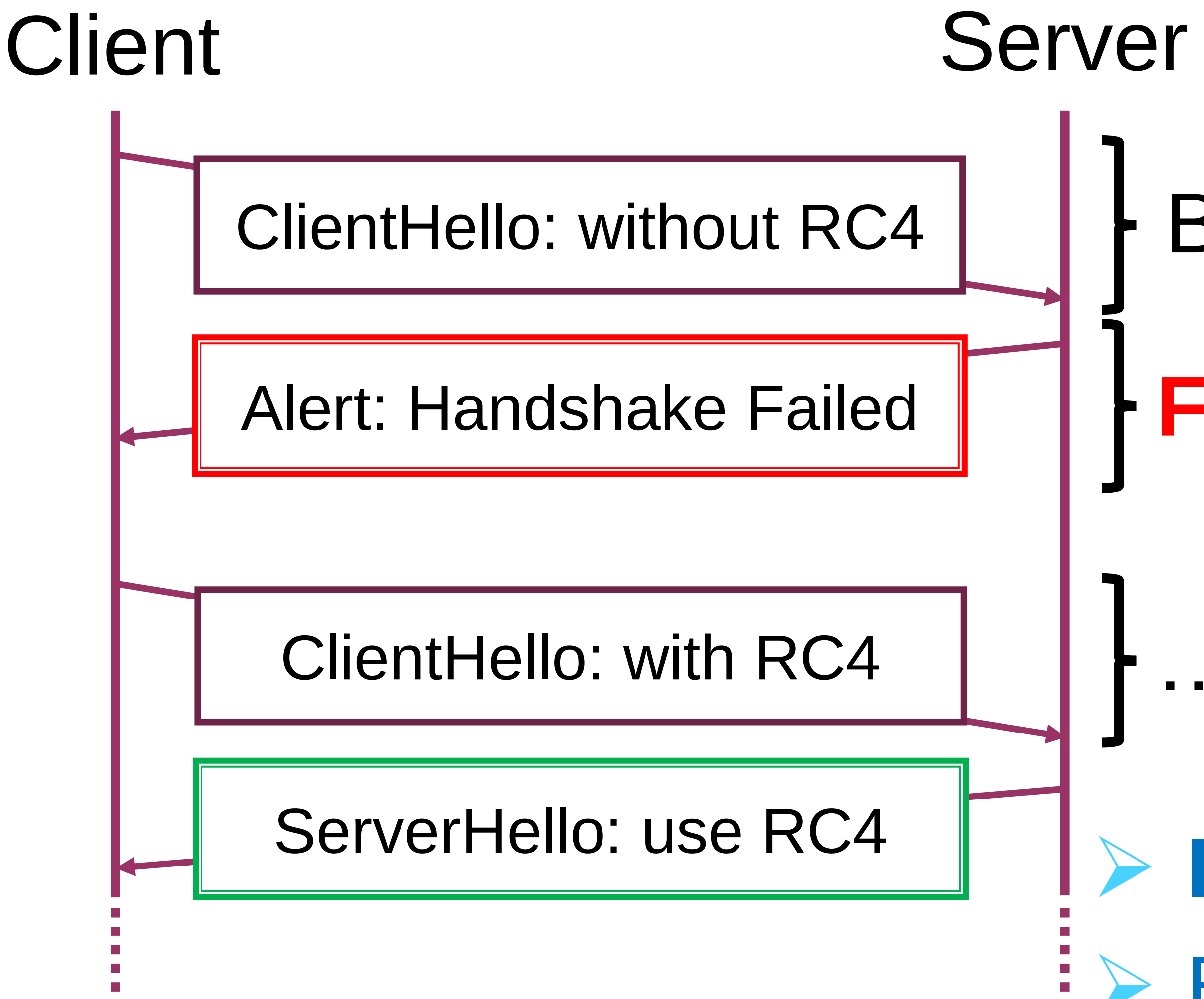
Fallback to RC4



Browser first tries without RC4

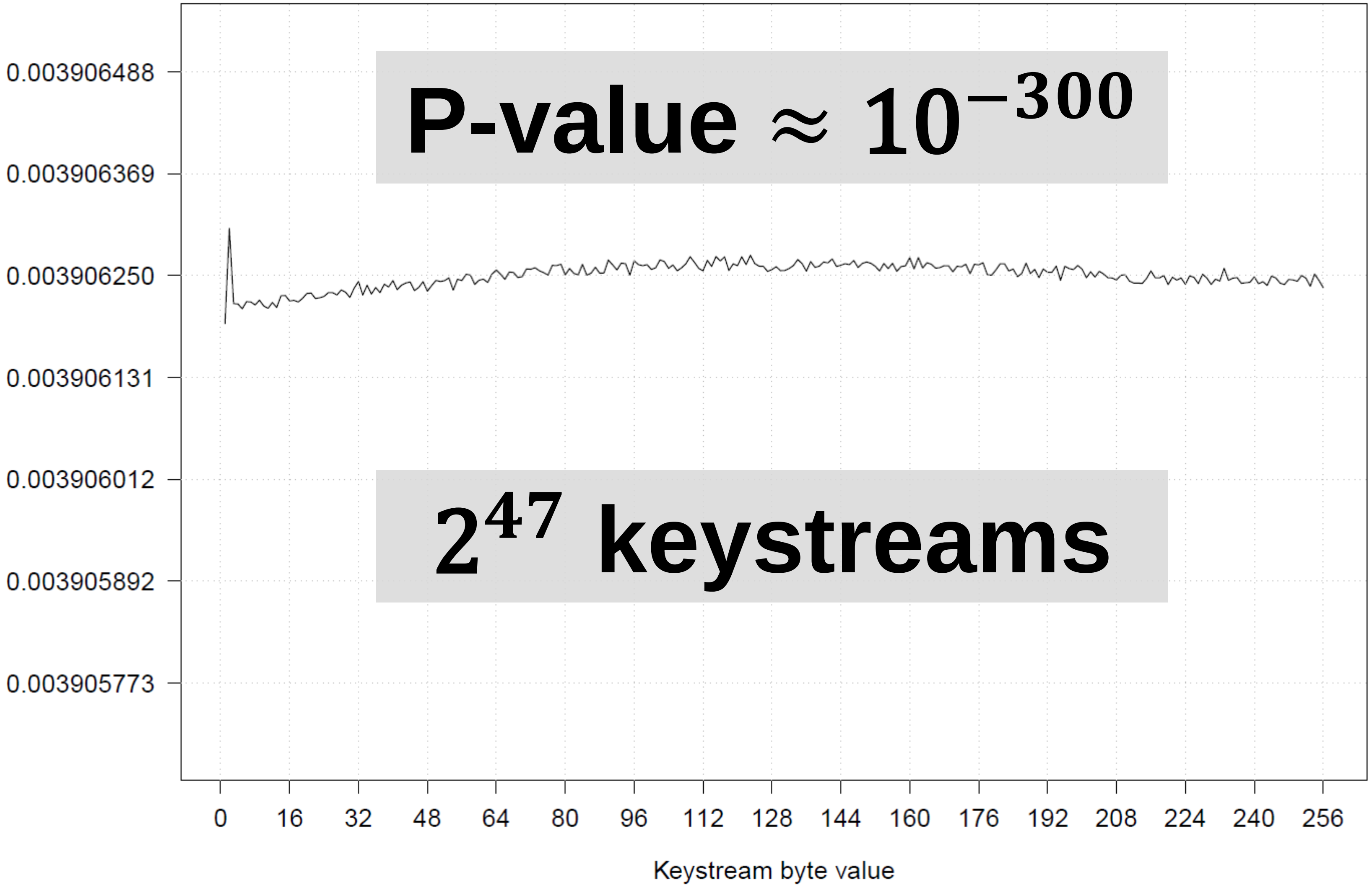
Forgeable by attacker!

… fallback to RC4

- **Fallback provides no security**
- But useful to determine how many servers require RC4

Biases in Bytes 257-513

Distribution keystream byte 513



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Additional Biases

Short-Term:

- Z_1 and Z_2 influence initial 256 bytes
- Consecutive bytes likely (in)equal

Long-term Biases:

- Byte value “likely” reappears

See paper!

Keystream bytes Z_1 and Z_2

Z_1 and Z_2 influence all initial 256 bytes

- $Z_1 = 257 - i \rightarrow Z_i = 0$

Keystream bytes Z_1 and Z_2

Z_1 and Z_2 influence all initial 256 bytes

- $Z_1 = 257 - i \;\rightarrow\; Z_i = 0$
- $Z_1 = 257 - i \;\rightarrow\; Z_i = i$

Keystream bytes Z_1 and Z_2

Z_1 and Z_2 influence all initial 256 bytes

- $Z_1 = 257 - i \;\rightarrow Z_i = 0$
- $Z_1 = 257 - i \;\rightarrow Z_i = i$
- $Z_2 = 0 \qquad\qquad\quad \rightarrow Z_i \neq i$

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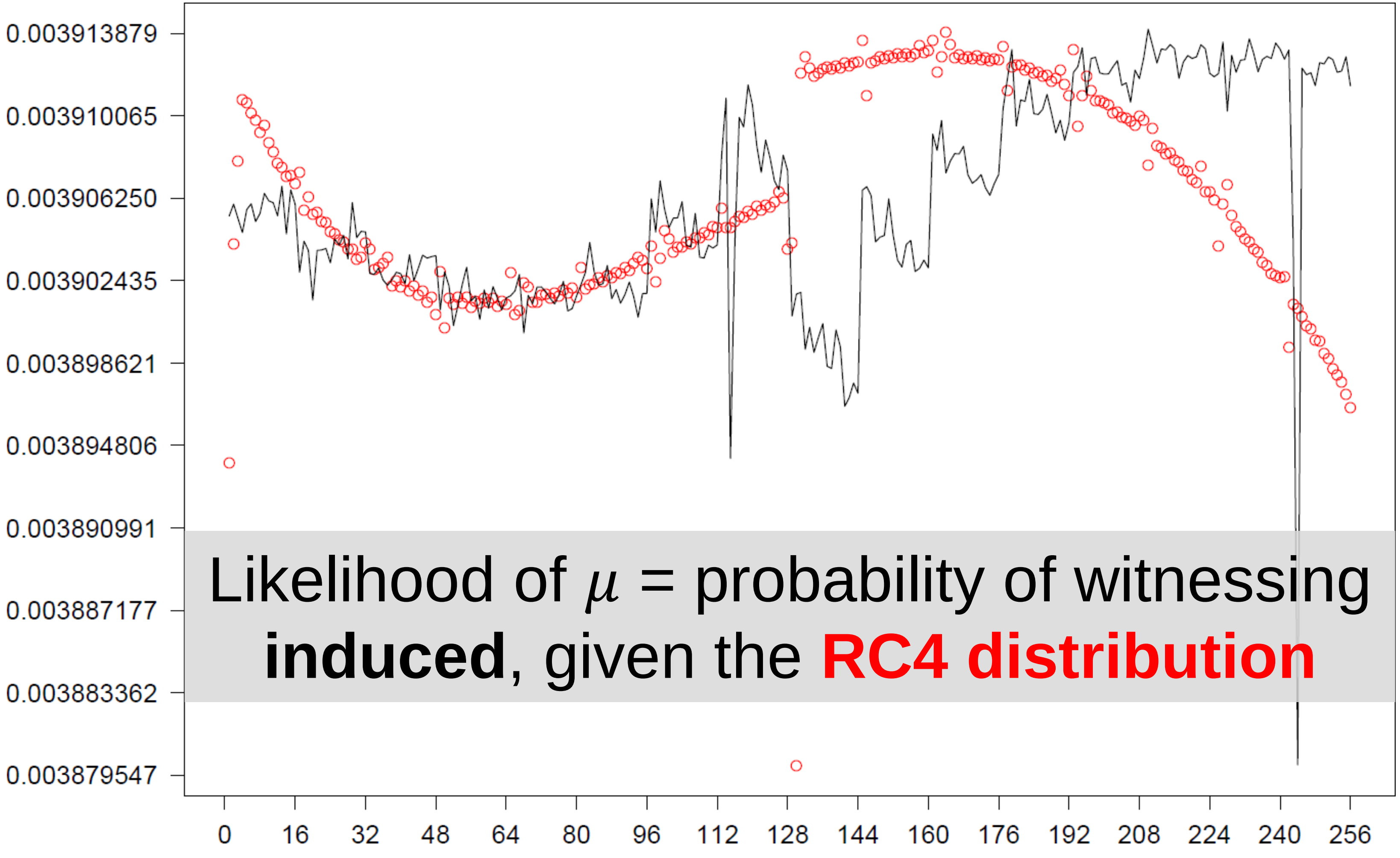
Keystream bytes Z_1 and Z_2

Z_1 and Z_2 influence all initial 256 bytes

- $Z_1 = 257 - i \rightarrow Z_i = 0$
- $Z_1 = 257 - i \rightarrow Z_i = i$
- $Z_2 = 0 \rightarrow Z_i \neq i$
- And others

Example: Decrypt byte 1

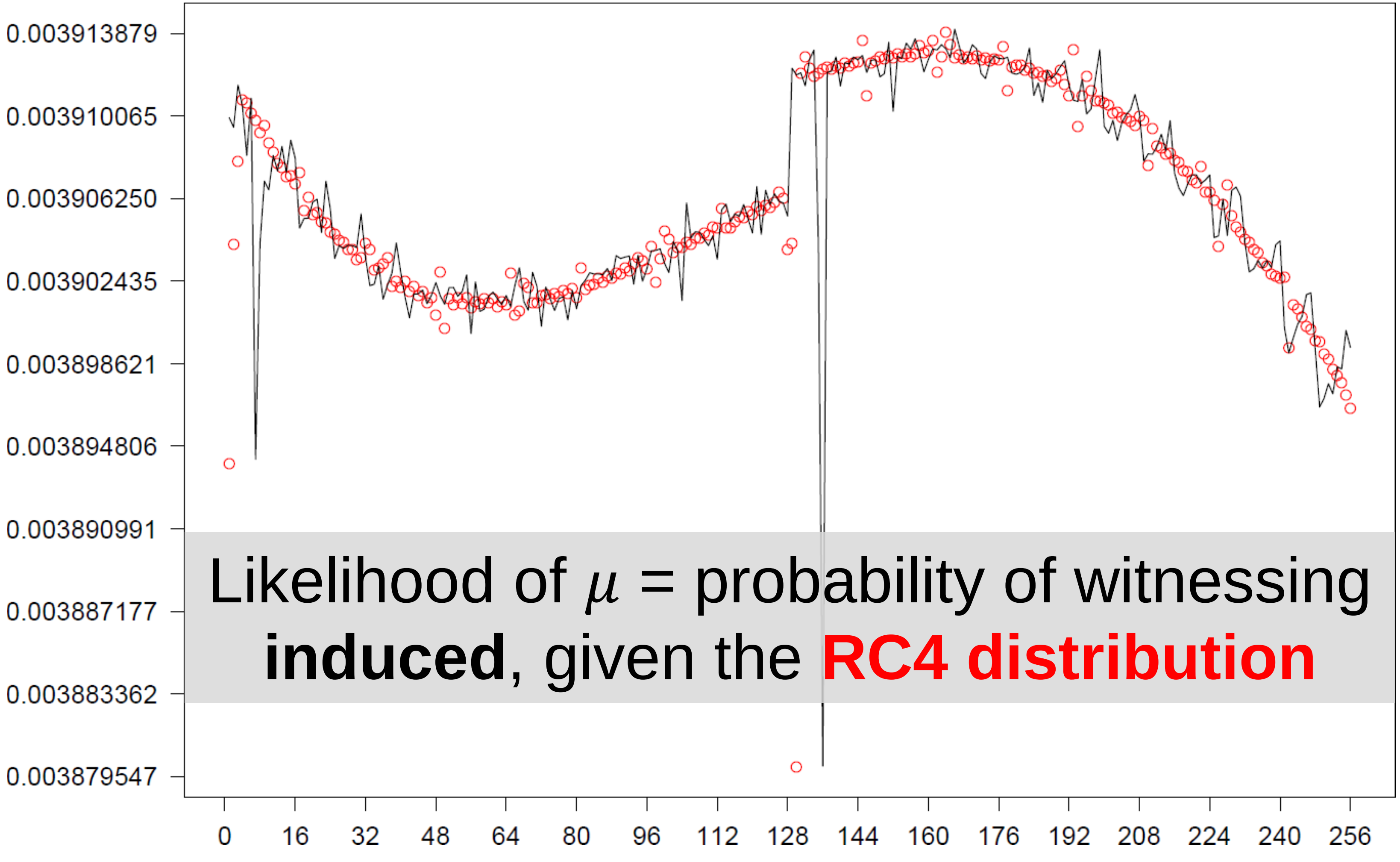
If plaintext byte $\mu = 0x28$: **RC4** & **Induced**



Likelihood of μ = probability of witnessing **induced**, given the **RC4 distribution**

Example: Decrypt byte 1

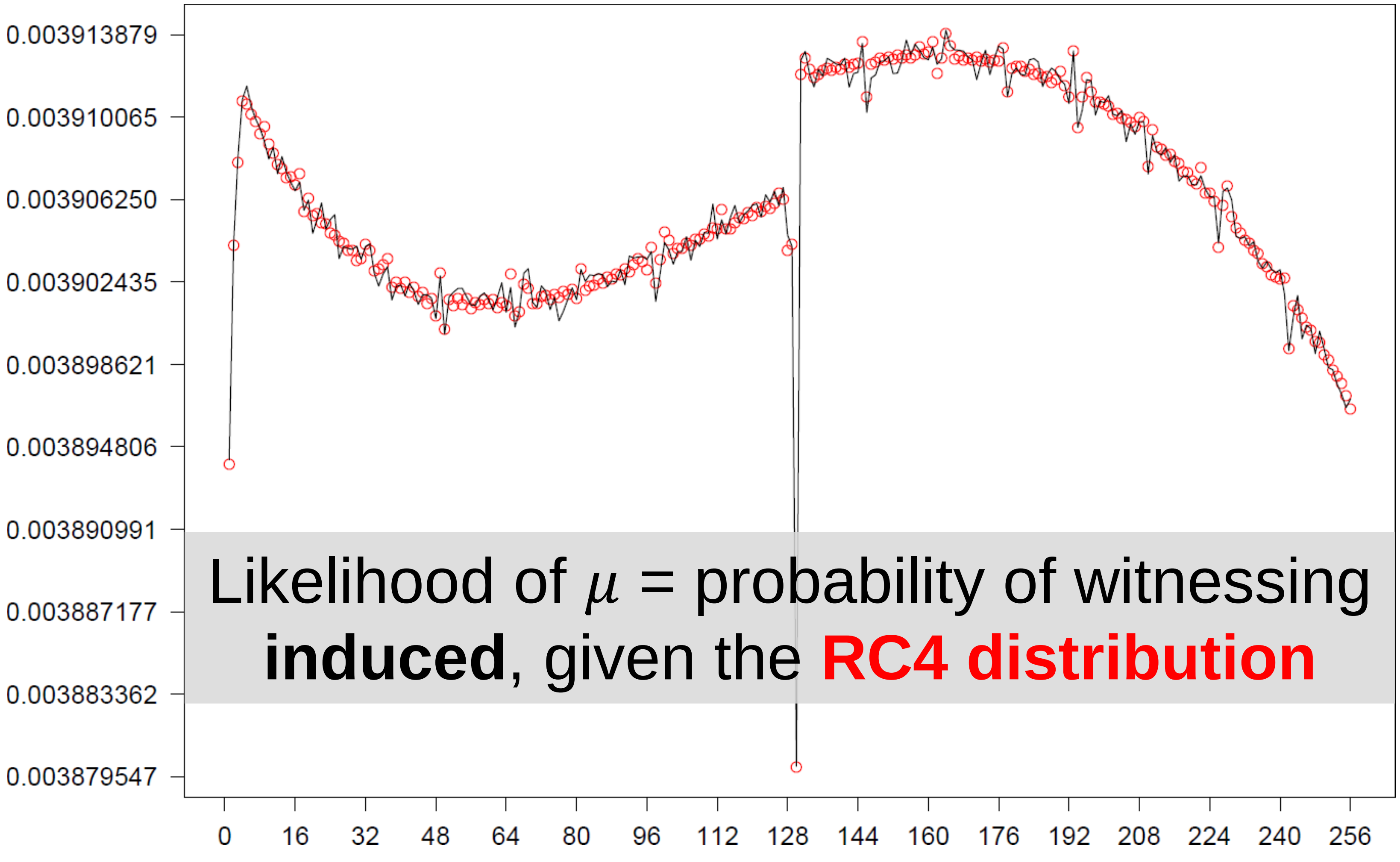
If plaintext byte $\mu = \mathrm{0x5C}$: **RC4** & **Induced**



Likelihood of μ = probability of witnessing **induced**, given the **RC4 distribution**

Example: Decrypt byte 1

If plaintext byte $\mu = \mathrm{0x5A}$: **RC4** & **Induced**



Likelihood of μ = probability of witnessing **induced**, given the **RC4 distribution**

Evaluation

Simulations with 2^{30} candidates:

- Need $\approx 2^{24}$ captures to decrypt with high success rates

Emperical tests:

- Server can inject 2 500 packets per second
- Roughly one hour to capture sufficient traffic
- **Successfully decrypted packet & found MIC key!**

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