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

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RC4

Intriguingly simple stream cipher

WEP
WPA-TKIP

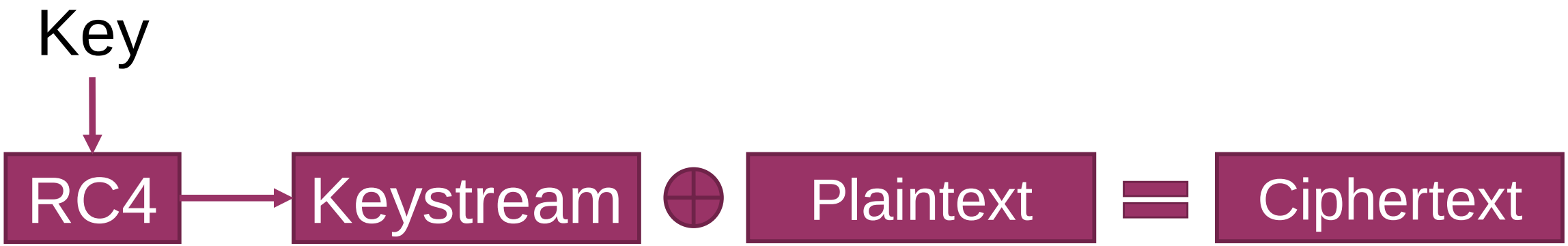
SSL / TLS

PPP/MPPE

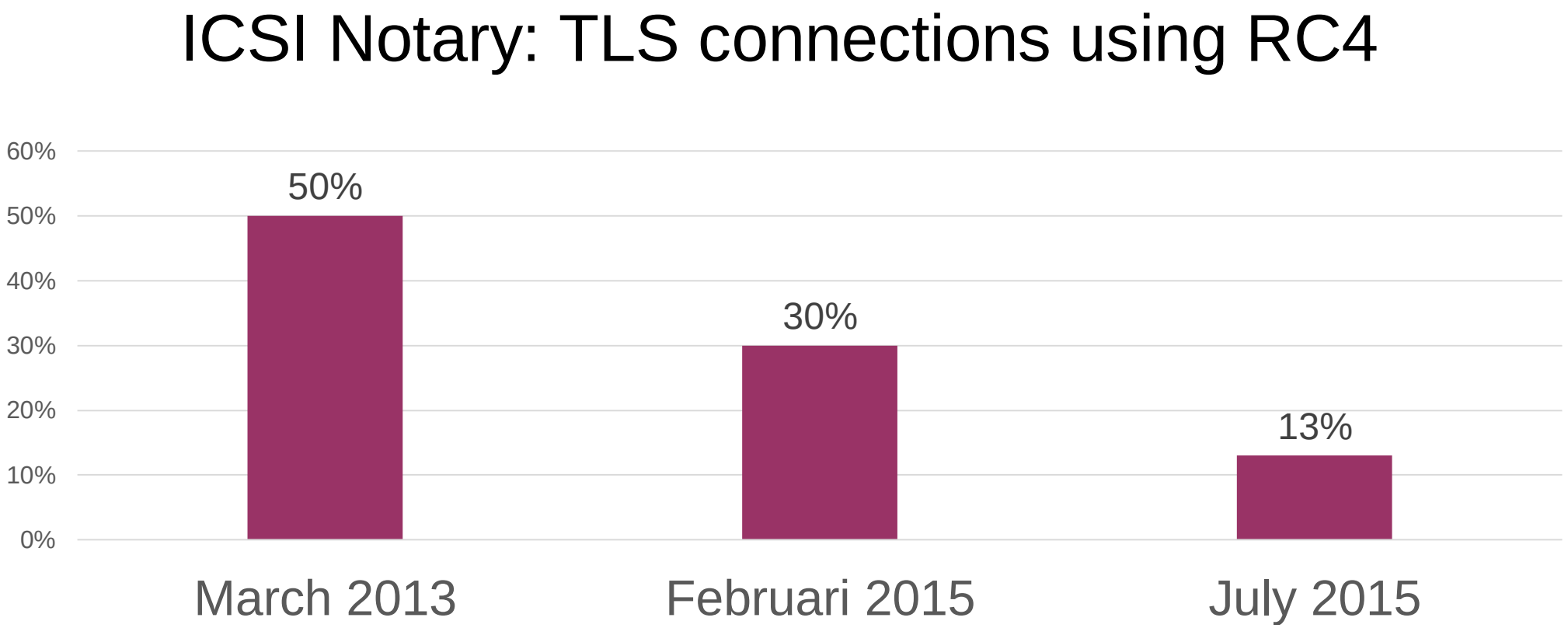
And others ...

RC4

Intriguingly simple stream cipher

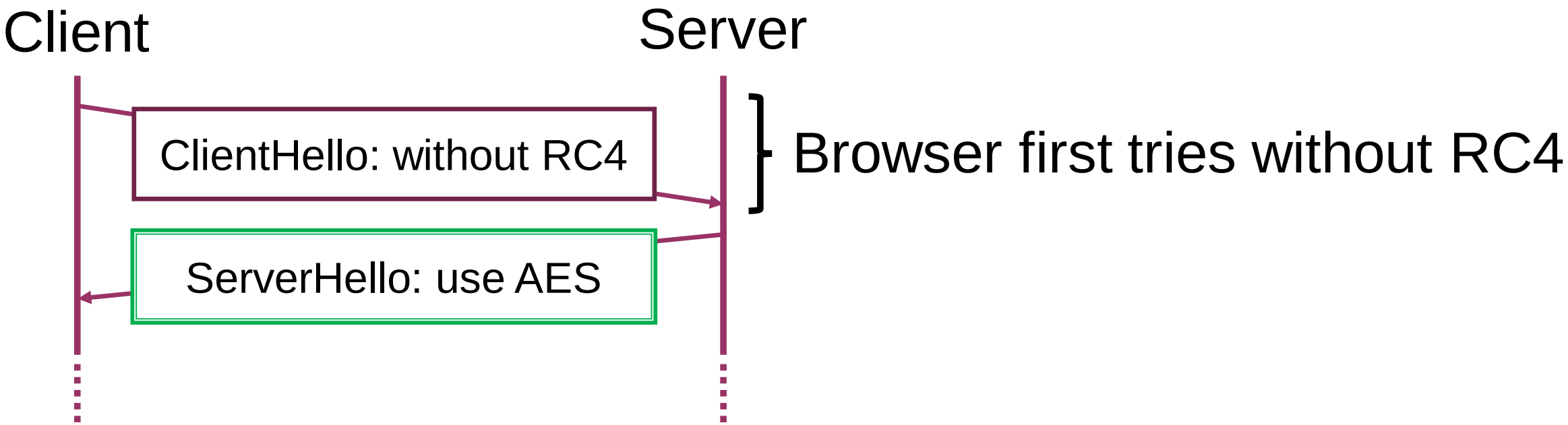


Is RC4 still used?!

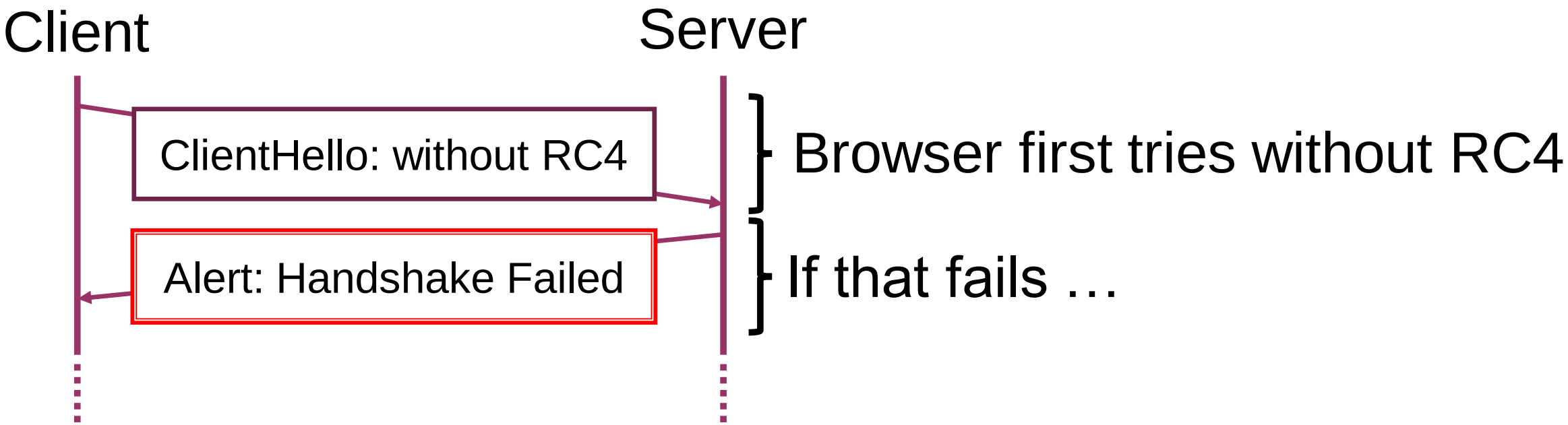


RC4 fallback not taken into account!

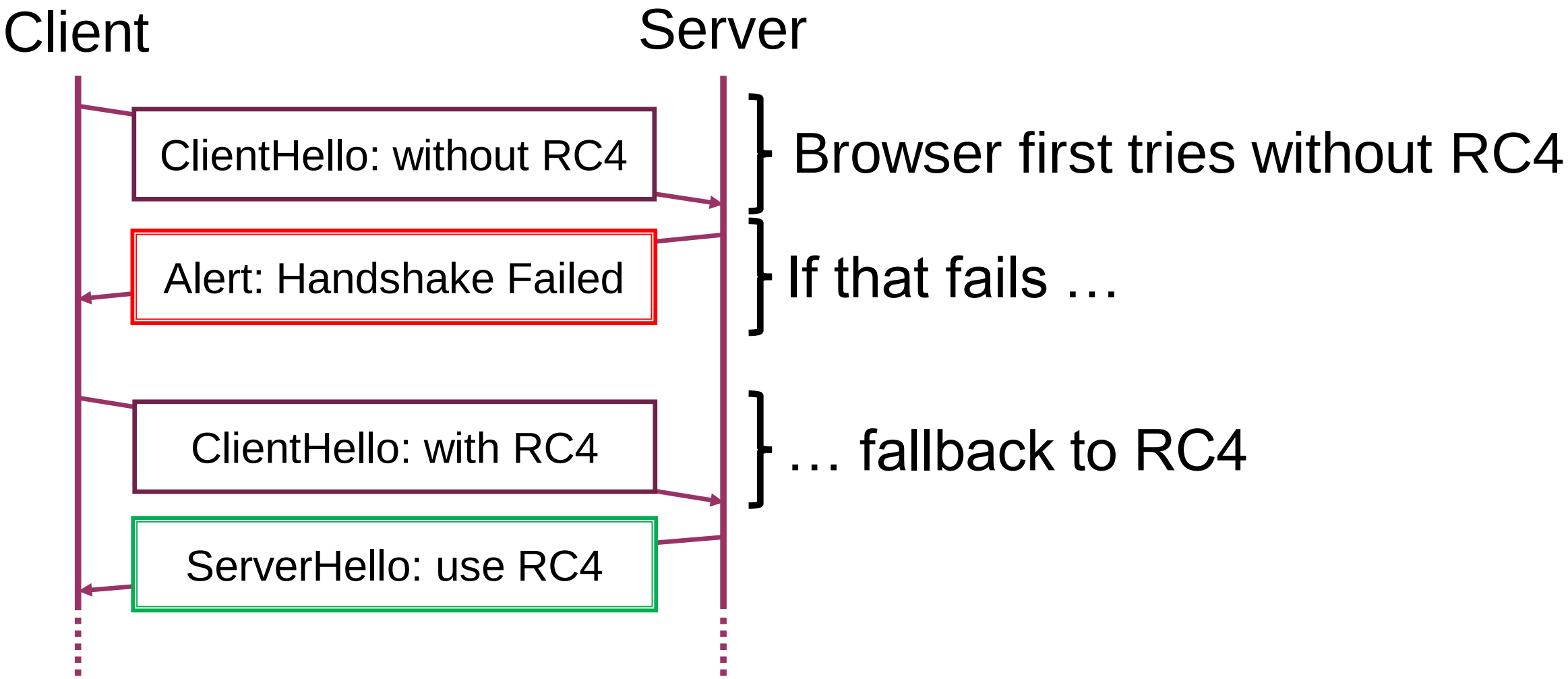
RC4 Fallback



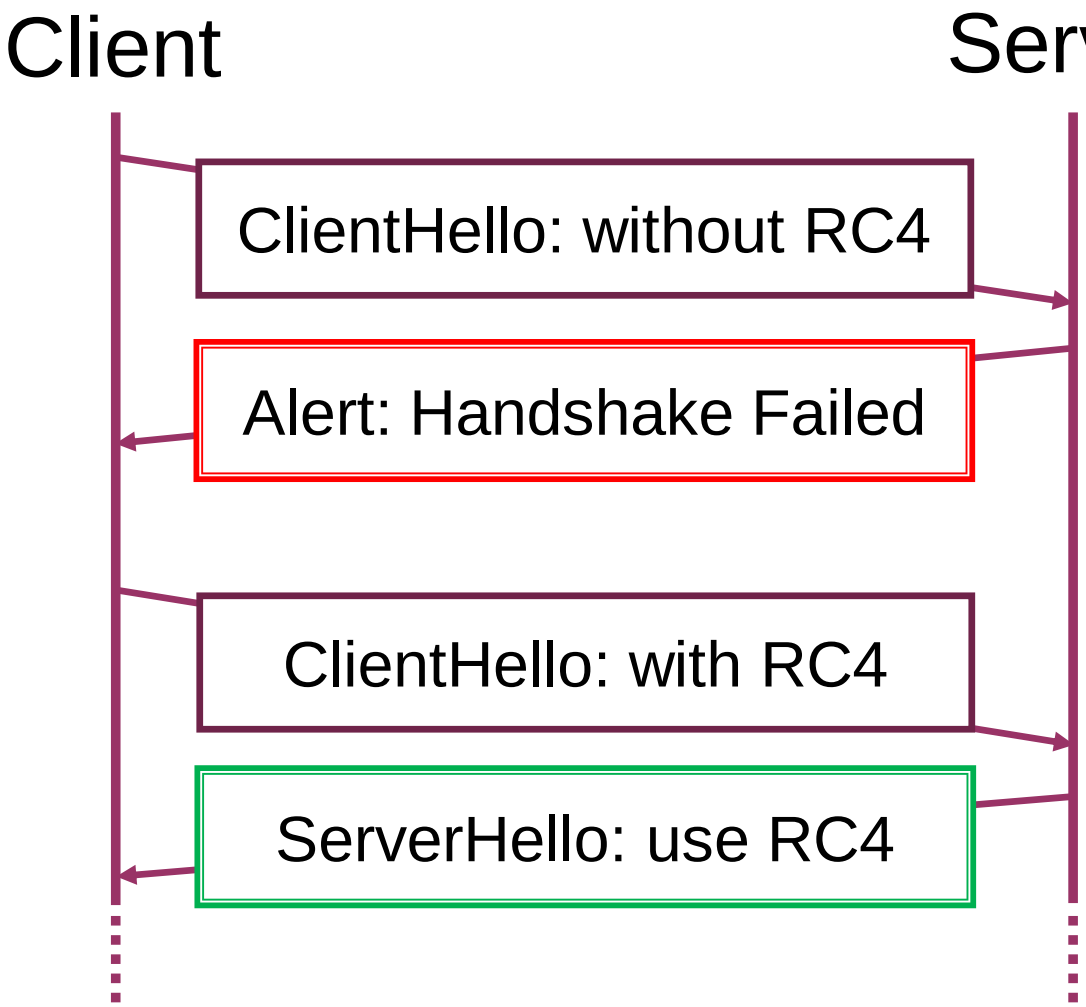
RC4 Fallback



RC4 Fallback



RC4 Fallback



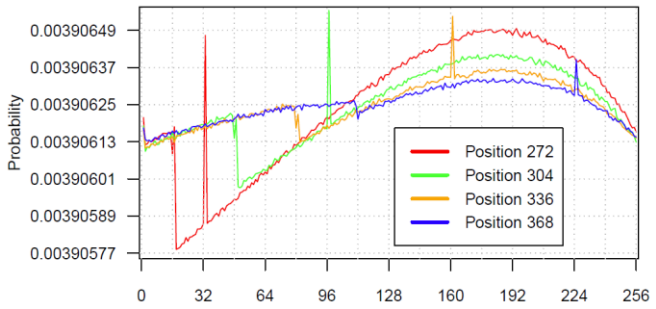
Browser first tries without RC4

Forgeable by attacker!

… fallback to RC4

- **13%** estimate is a **lower bound**
- Force connection (which we assumed secure) to use RC4

Our Goal: further kill RC4



New Biases

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

Plaintext Recovery

Break WPA-TKIP

Attack HTTPS

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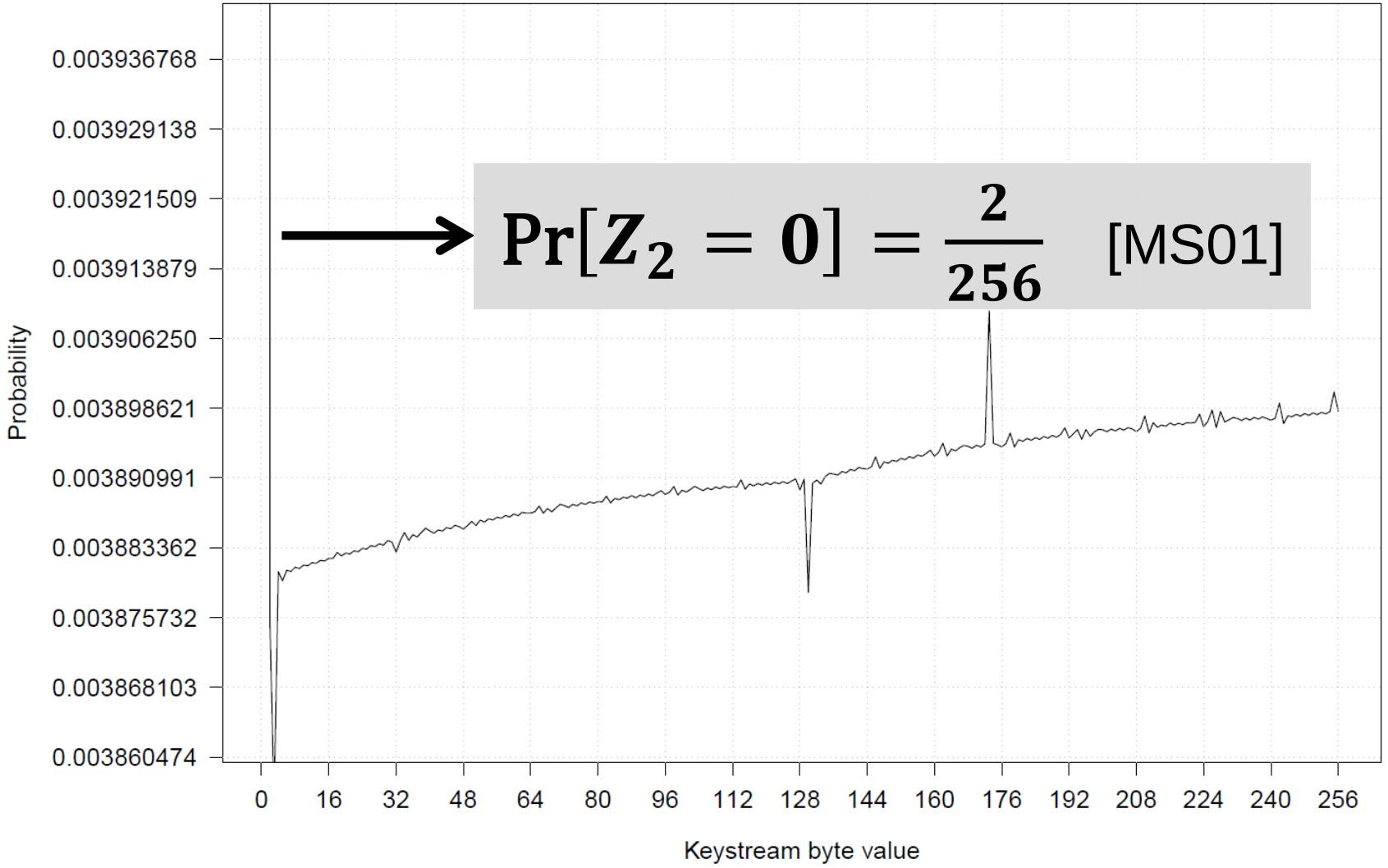
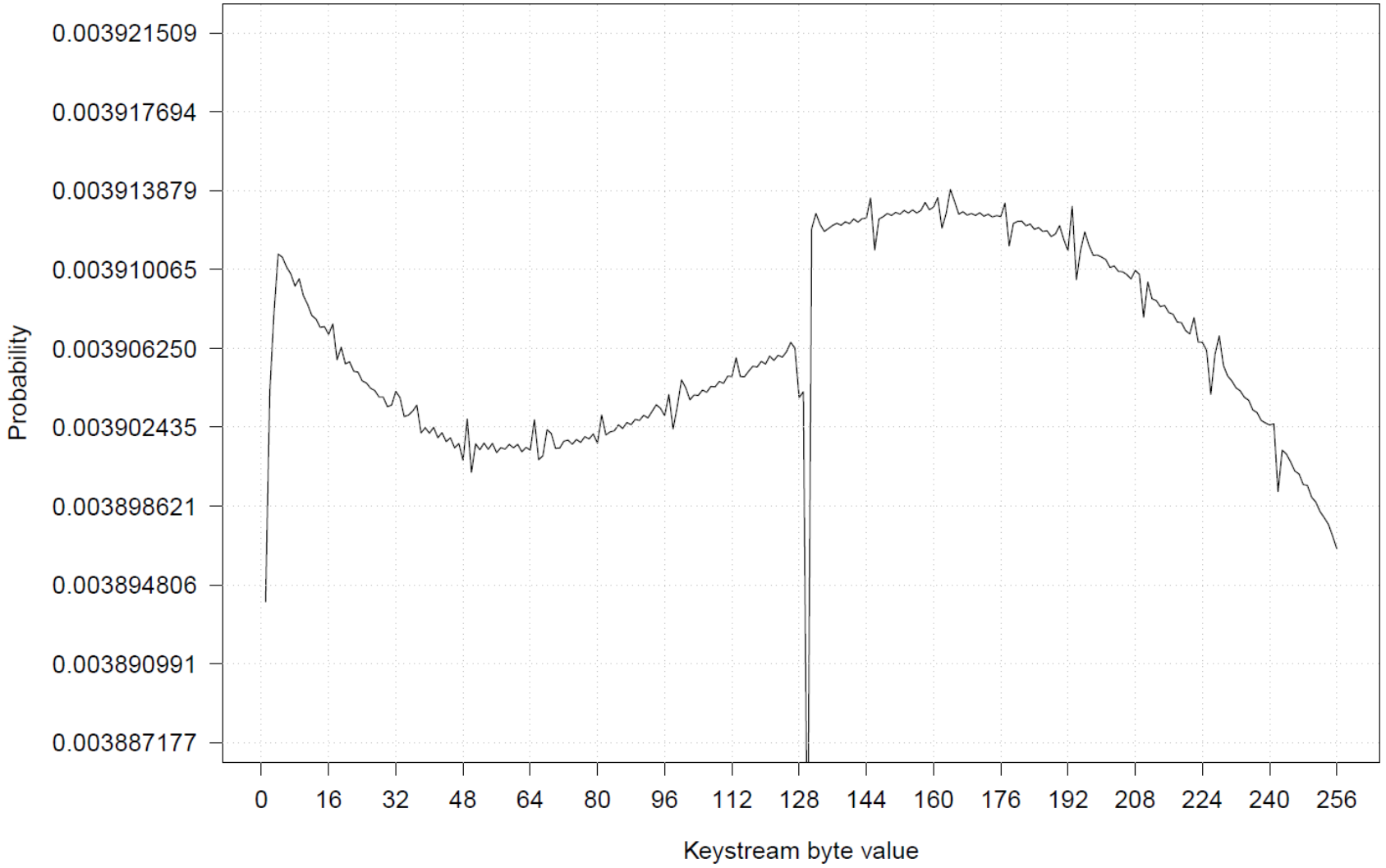
First: Existing Biases

Distribution keystream byte 2



First: Existing Biases

Distribution keystream byte 1



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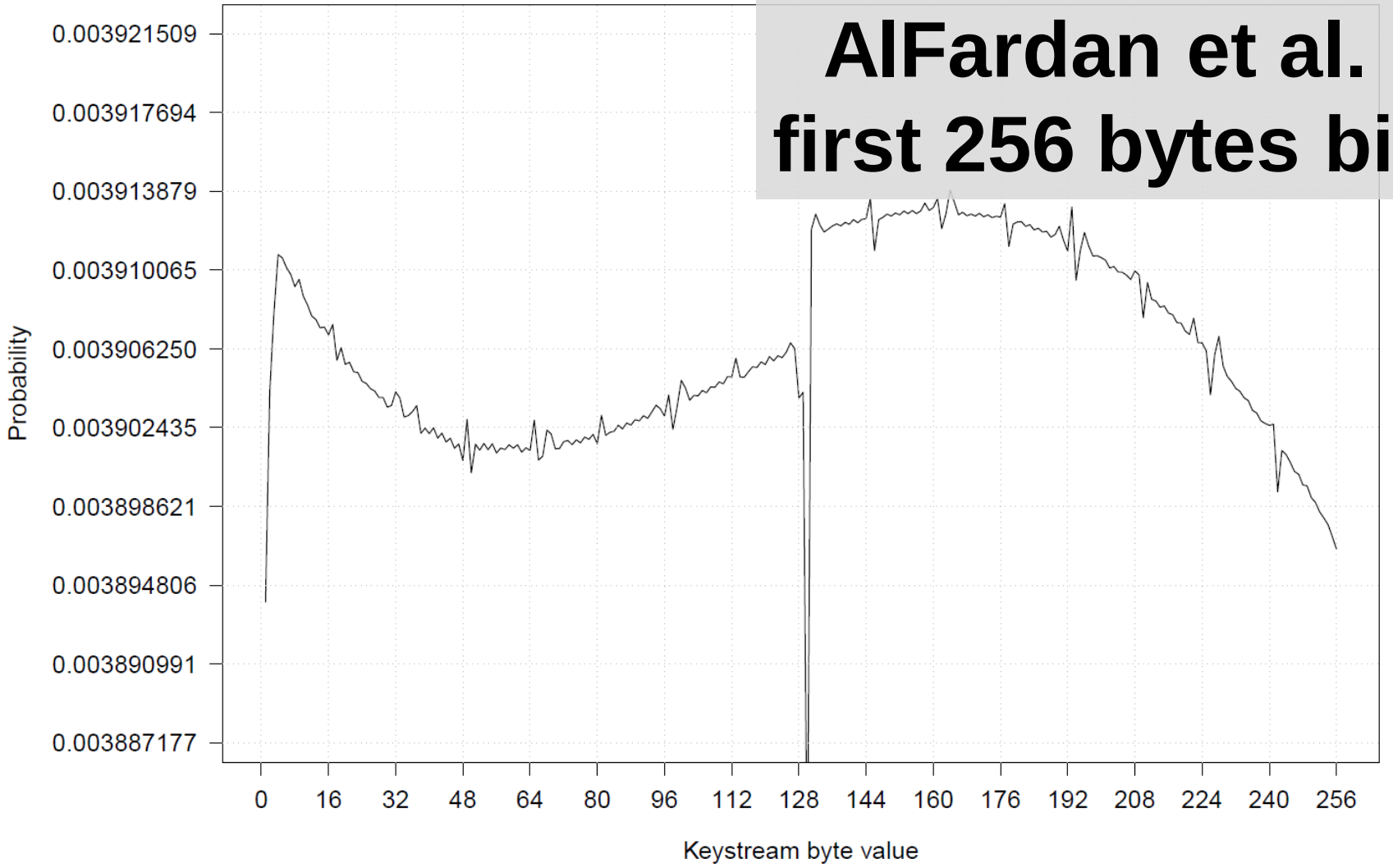
First: Existing Biases

Short-term biases

Distribution keystream byte 1 (to 256)



AlFardan et al. '13: first 256 bytes biased

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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

Search for new biases

Traditional emperical approach:

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

Fluhrer-McGrew: only 8 out 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

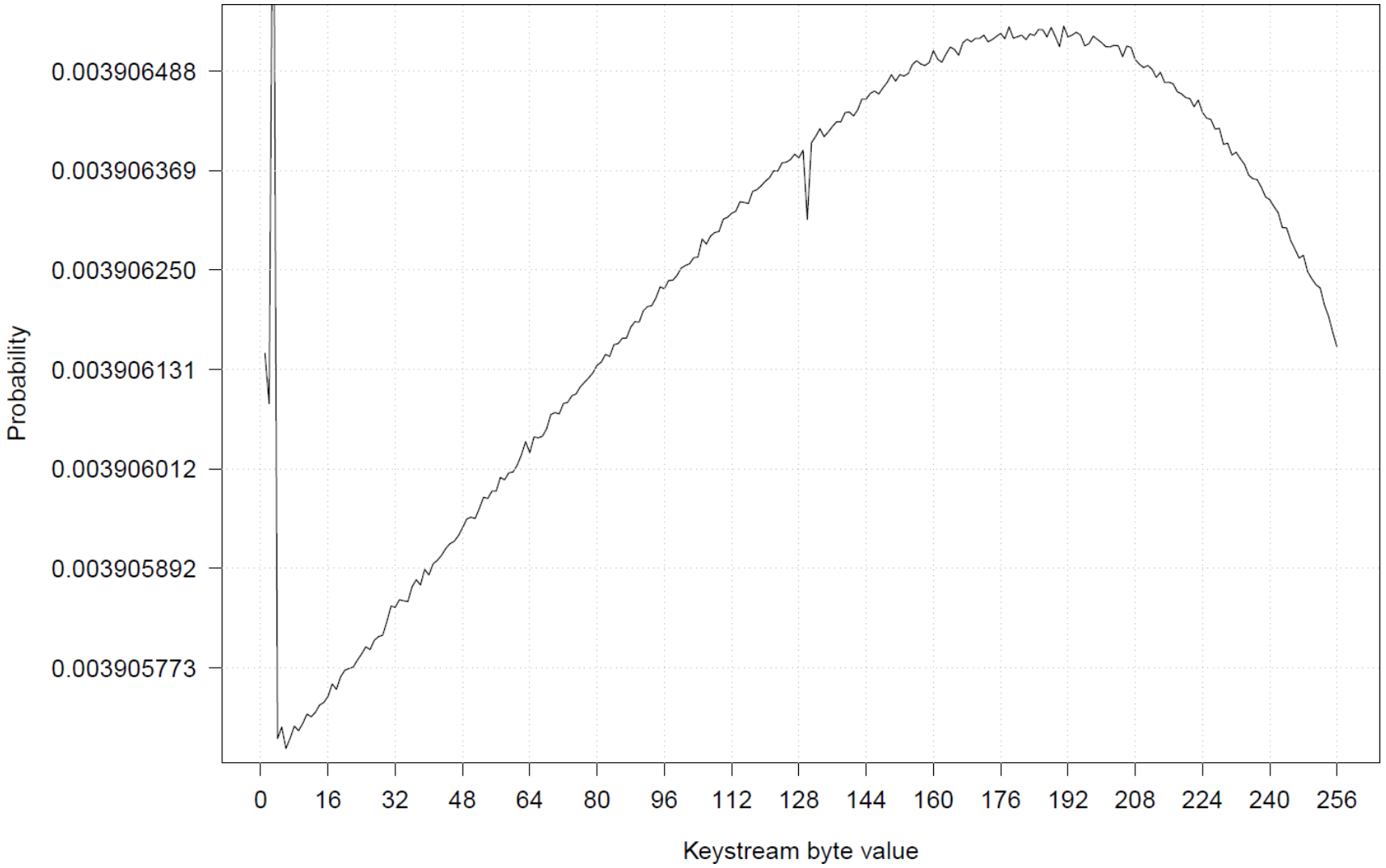
Hypothesis tests!

- 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



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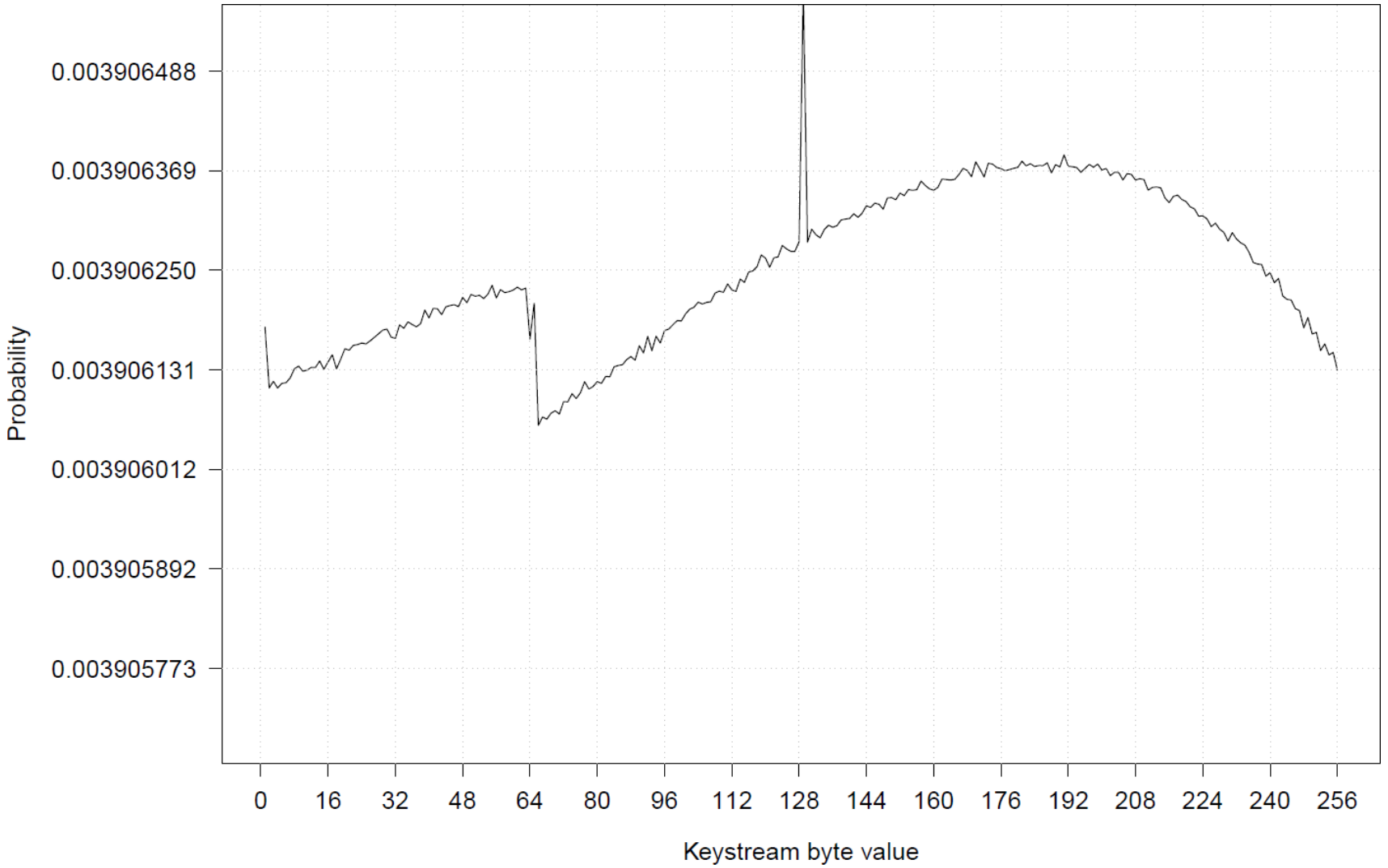
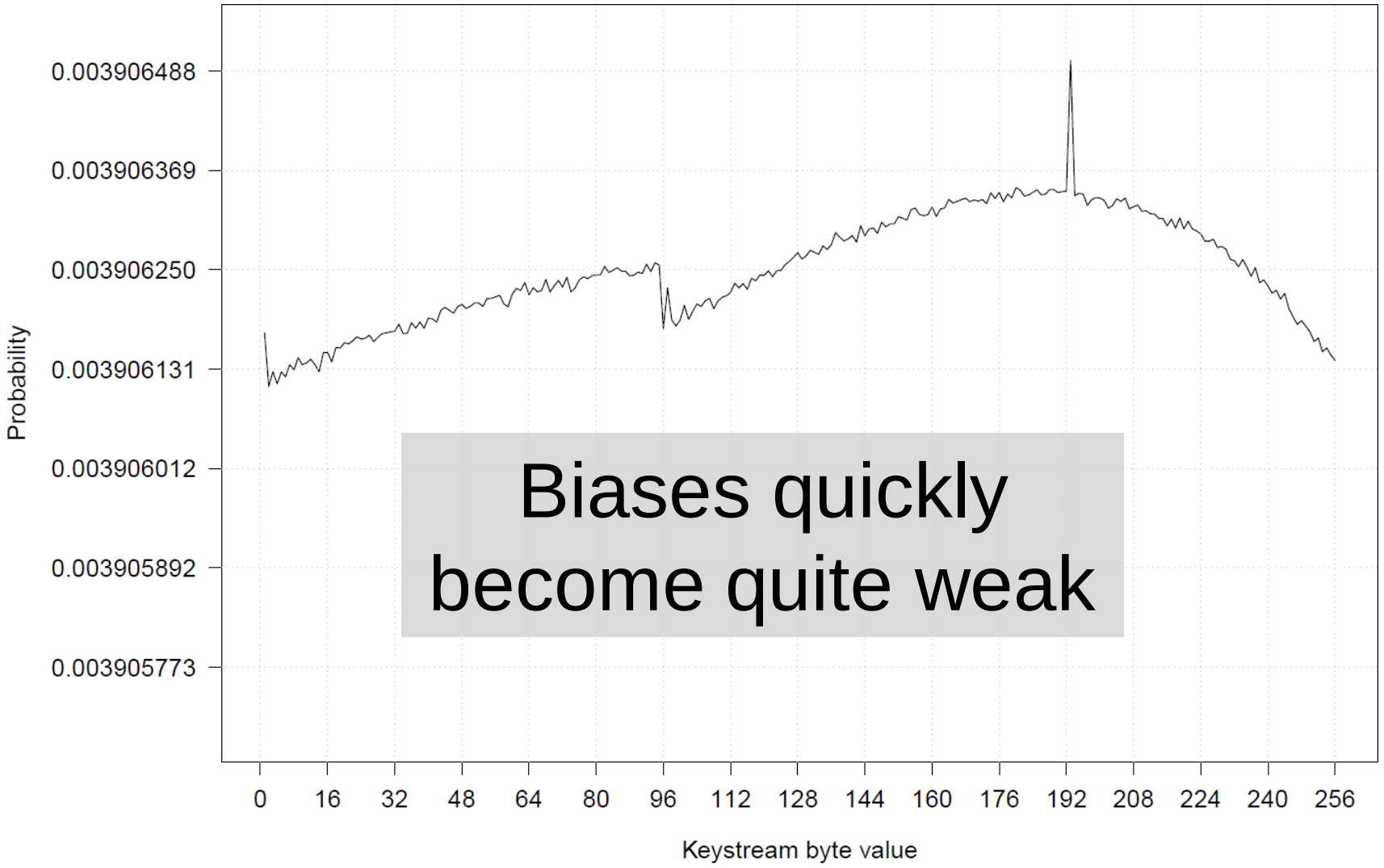
Biases in Bytes 258-513

Example: keystream byte 320



Biases in Bytes 258-513

Example: keystream byte 352



New Long-term Bias

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

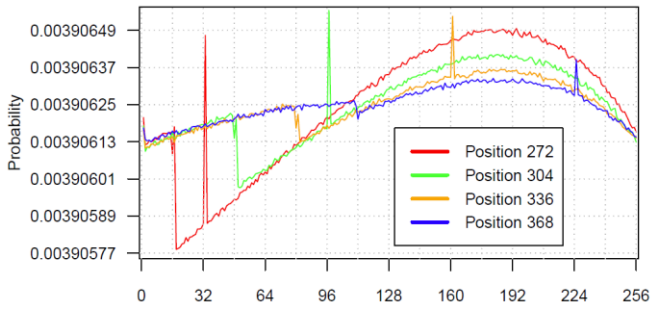
with probability $2^{-16}(1 + 2^{-8})$

Every block of 256 bytes

Additional Biases

See paper!

Our Goal: further kill RC4



New Biases

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

Plaintext Recovery

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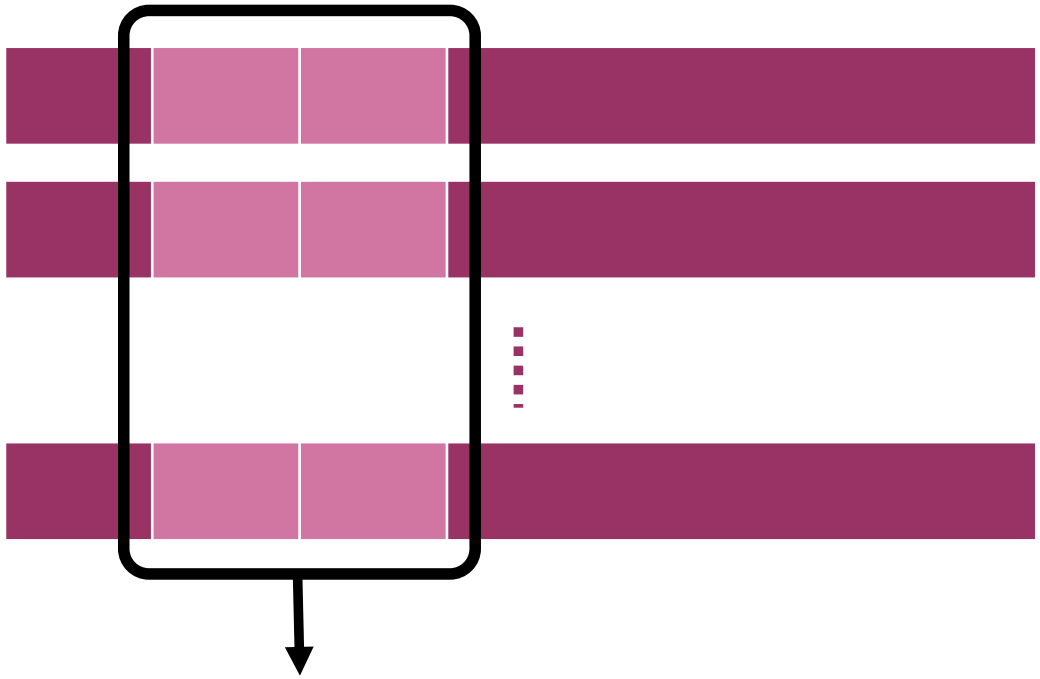
Existing Methods [AlFardan et al. '13]

Plaintext encrypted under several keystreams



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

Verify guess: how close to real keystream distribution?

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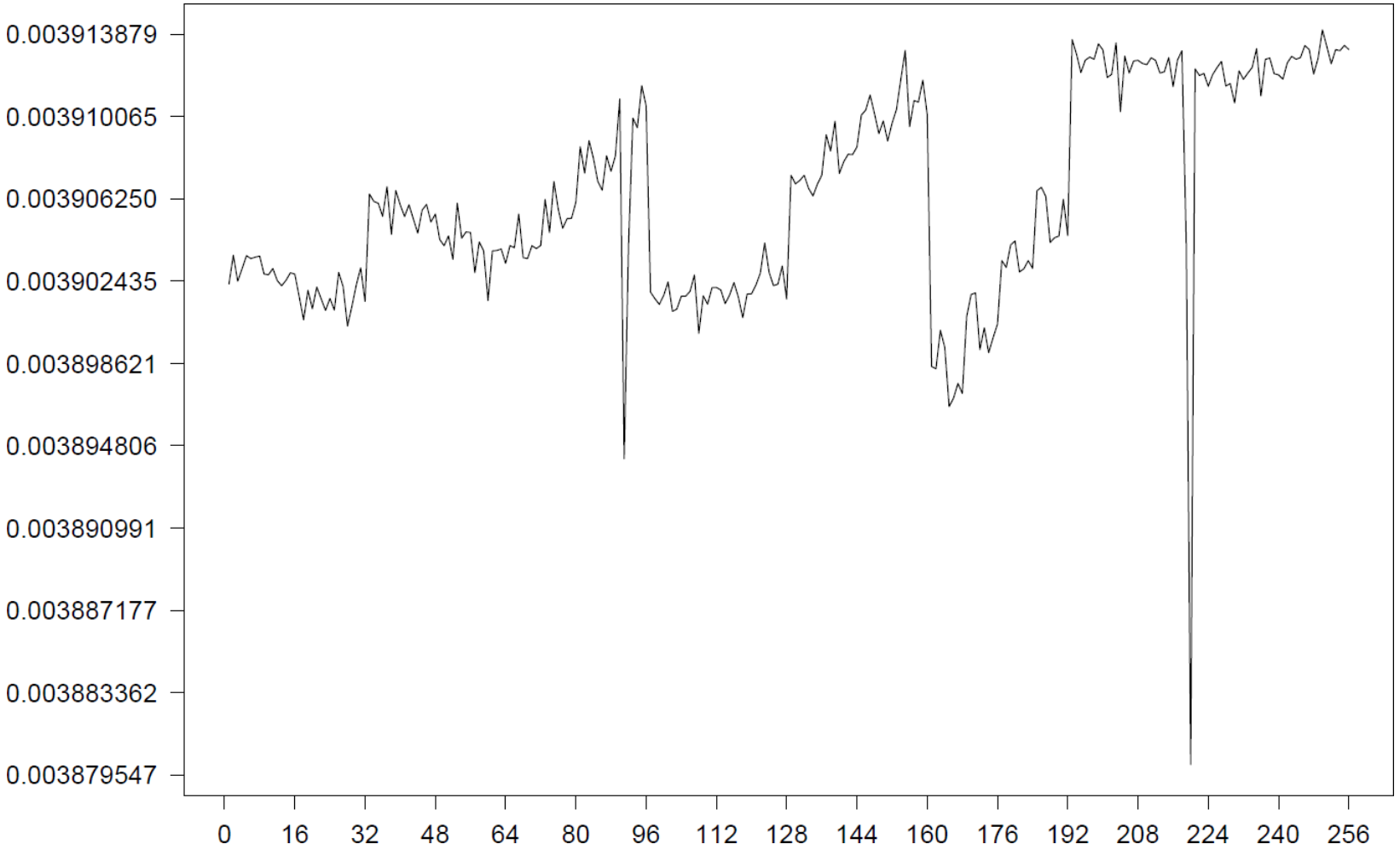
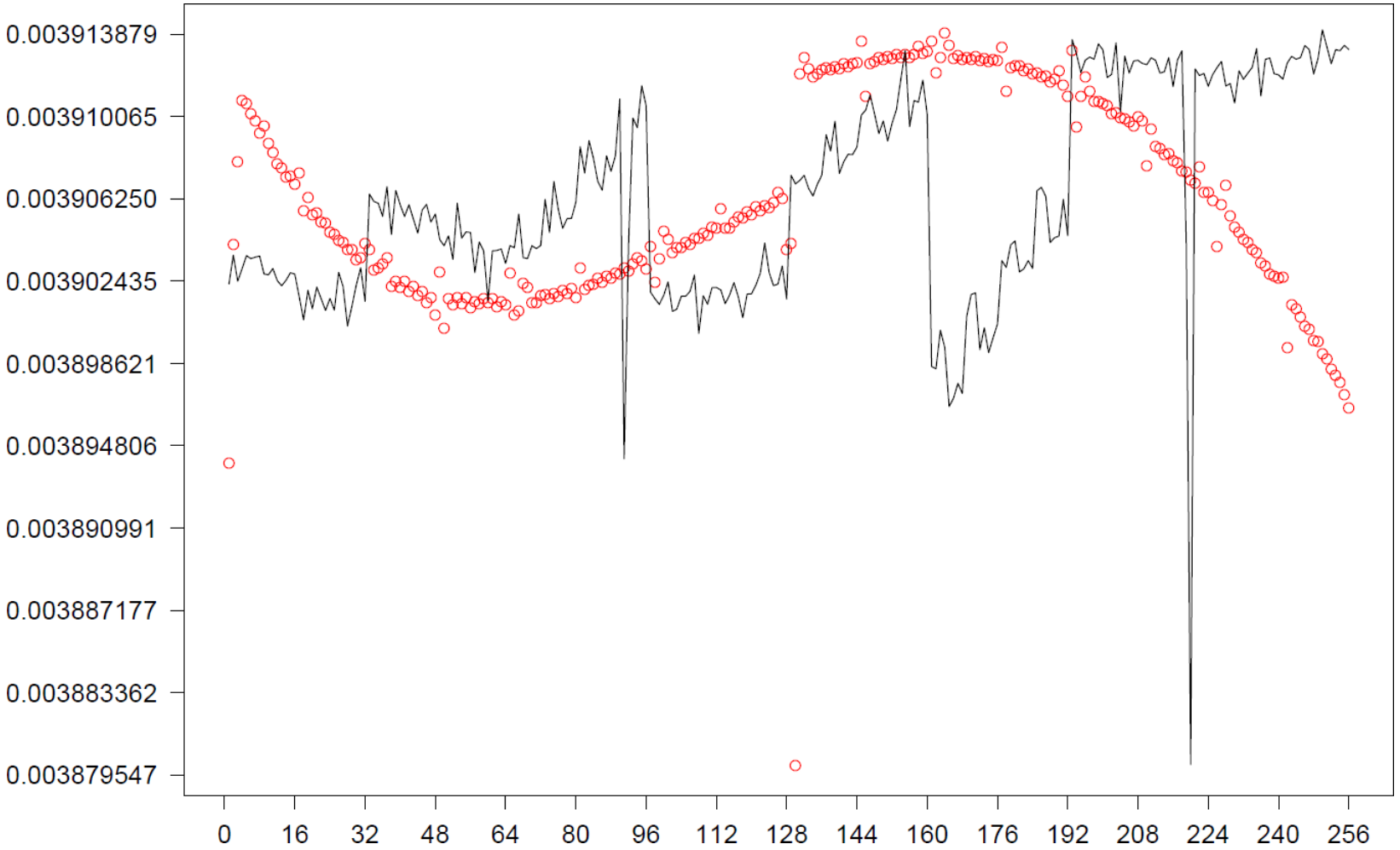
Example: Decrypt byte 1

Ciphertext Distribution



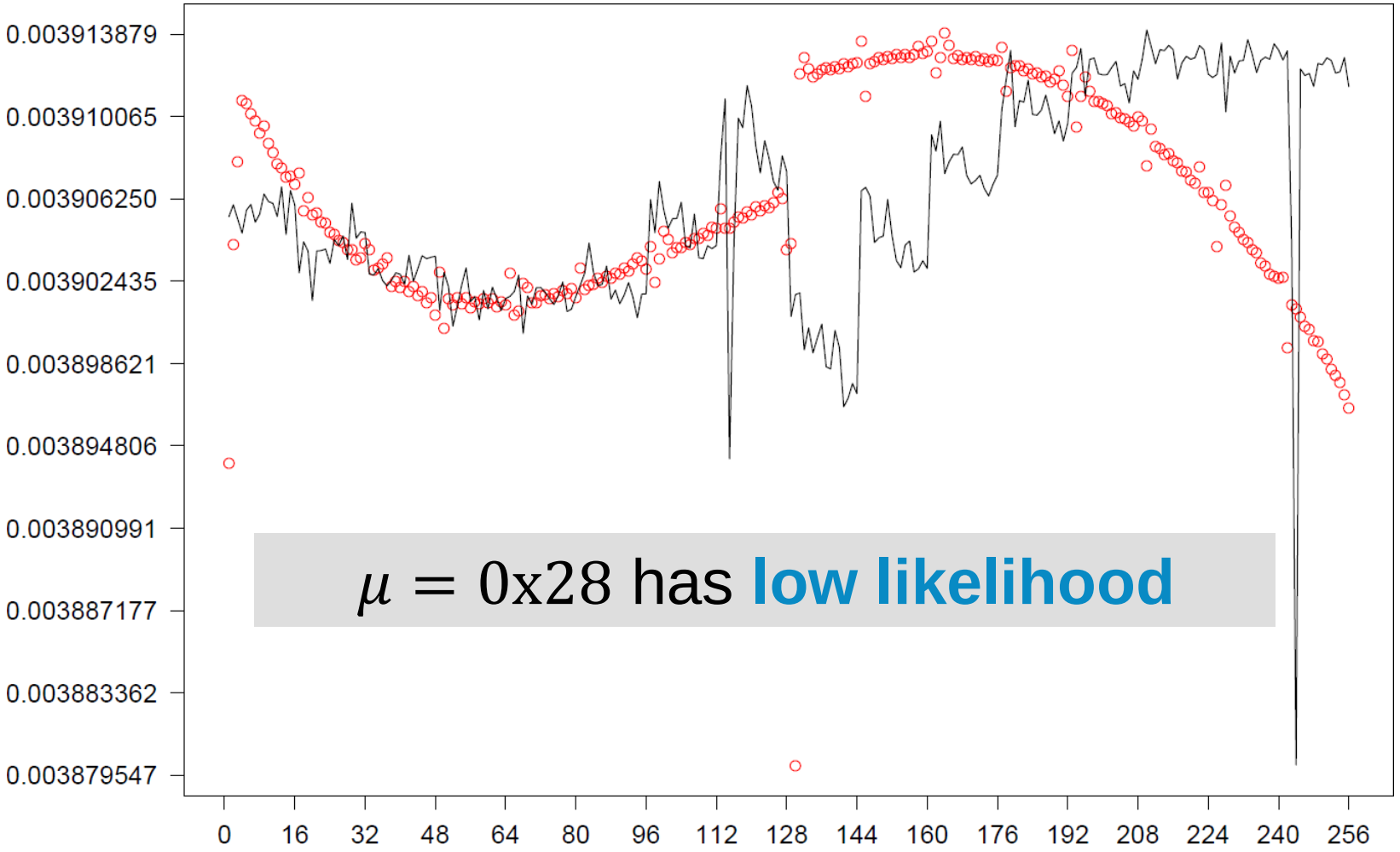
Example: Decrypt byte 1

RC4 & **Ciphertext** distribution



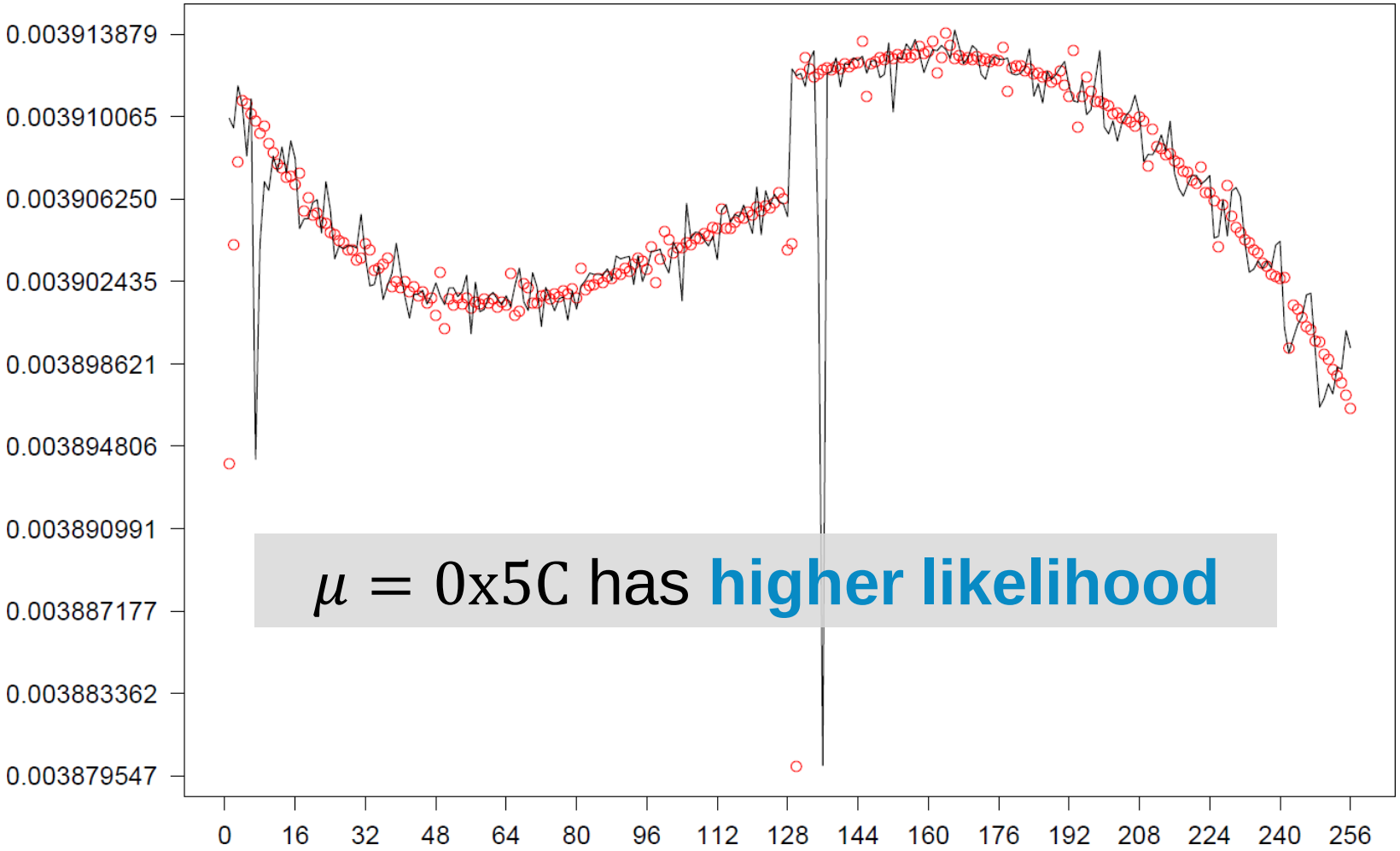
Example: Decrypt byte 1

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



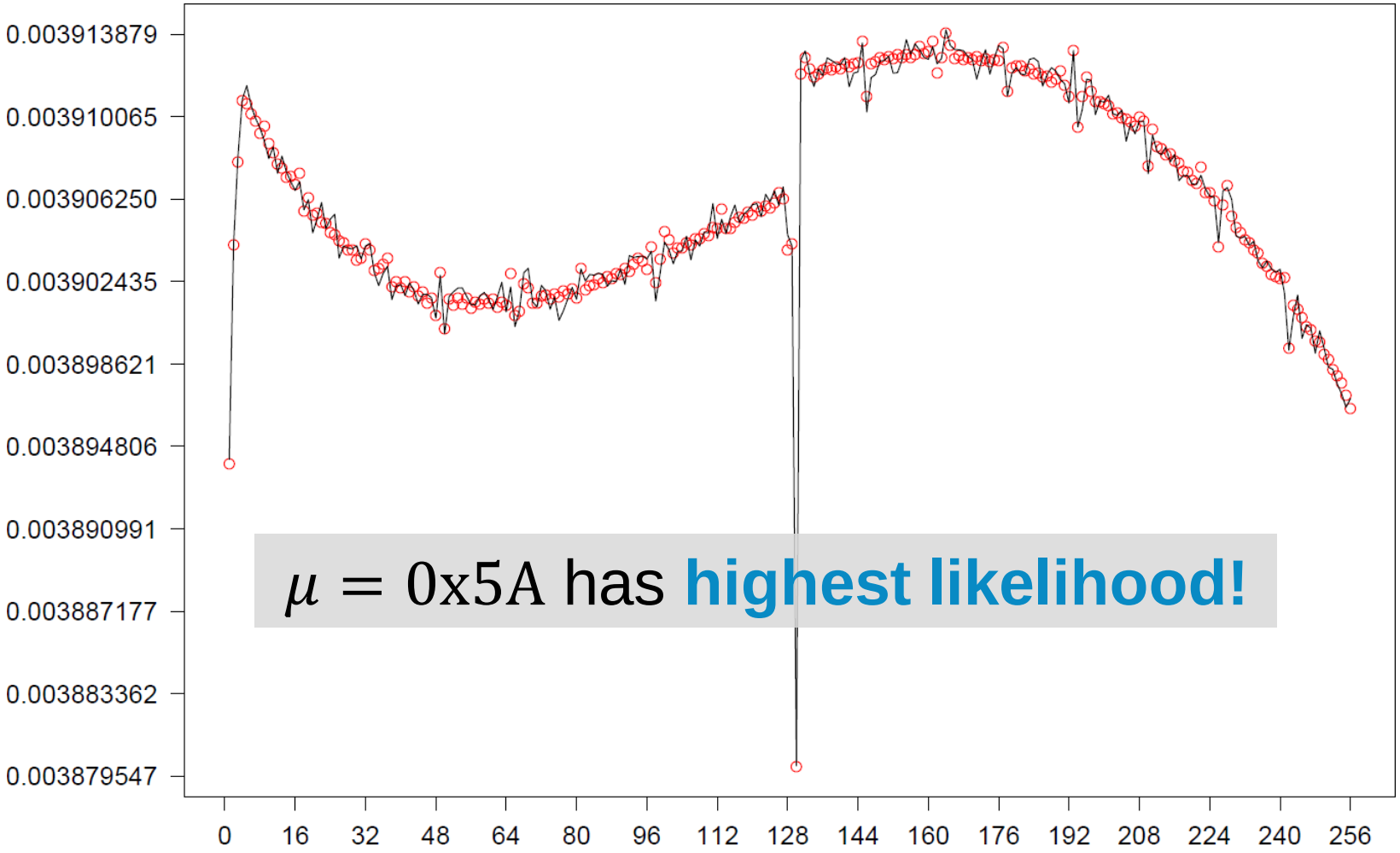
Example: Decrypt byte 1

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



Example: Decrypt byte 1

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



Types of likelihood estimates

Previous works: pick value with highest likelihood.

Better idea: list of candidates in decreasing likelihood:

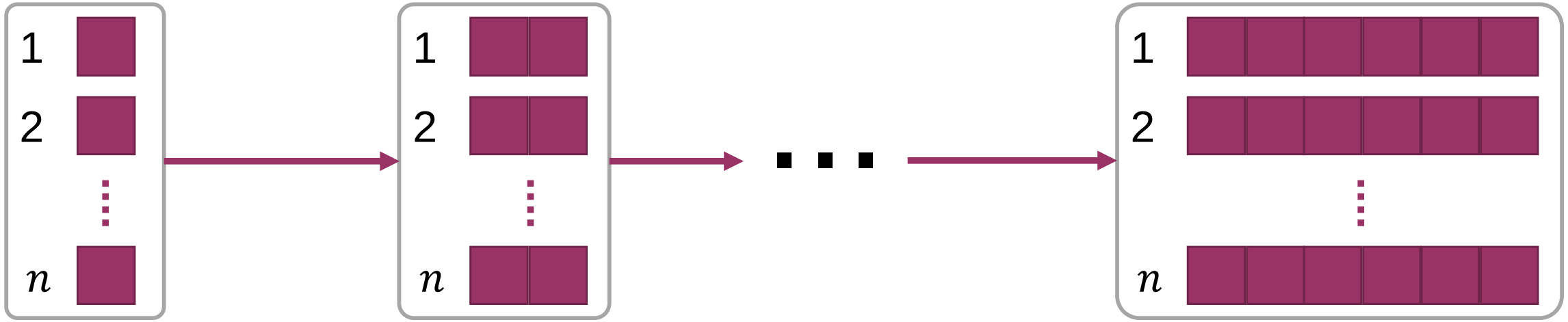
- Most likely one may not be correct!
- Prune bad candidates (e.g. bad CRC)
- Brute force cookies or passwords

How to calculate list of candidates?

1st idea: Generate List of Candidatess

Gist of the Algorithm: Incremental approach

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



2nd 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: $\lambda_{\widehat{\mu}} = (1-\alpha(g))^{|\mathcal{C}|-|\widehat{\mu}|} \cdot \alpha(g)^{|\widehat{\mu}|}$

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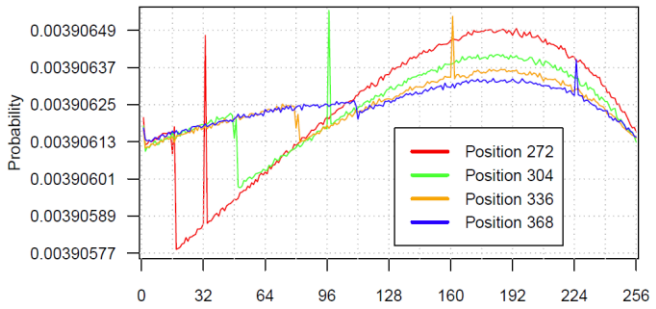
Our Goal: further kill RC4



New Biases

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Plaintext Recovery

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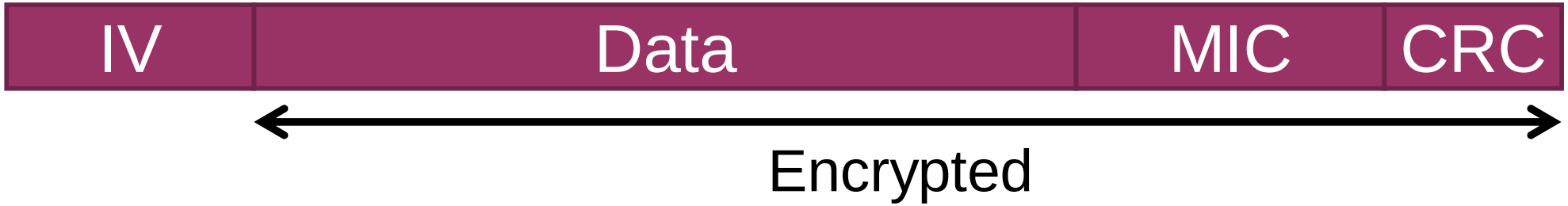
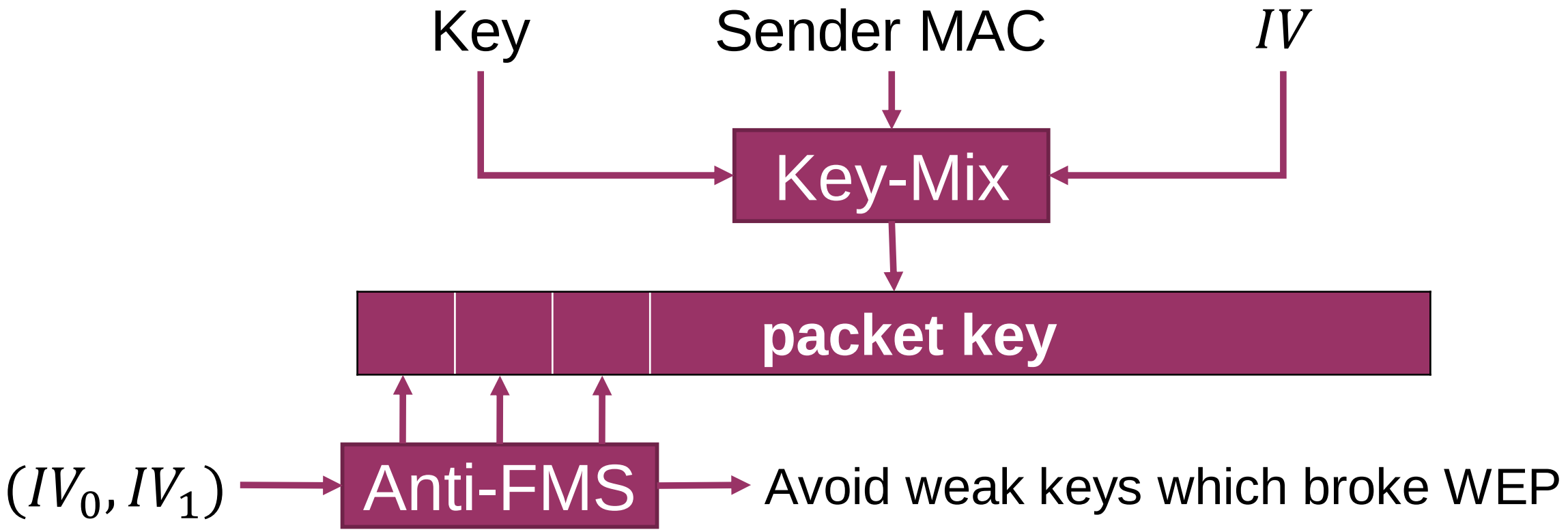
TKIP Background

How are packets sent/received?



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



→ 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

If decrypted, reveals MIC key

Generate identical packets (otherwise MIC changes):

- Assume victim connects to server of attacker
- Retransmit identical TCP packet
- List of plaintext candidates (unknown MIC and CRC)
- Prune bad candidates based on CRC

Evaluation

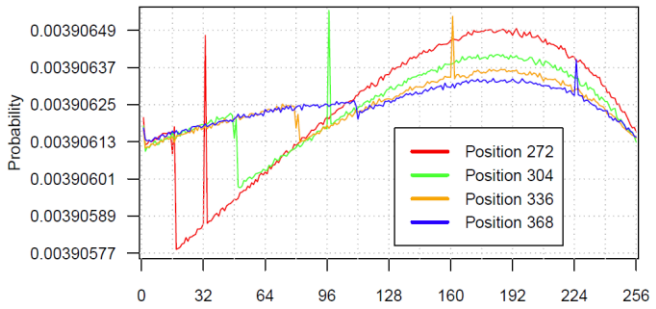
Simulations with 2^{30} candidates:

- 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!**

Our Goal: further kill RC4



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TLS Background

Client

Negotiate keys

Handshake protocol

Record protocol

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 bias with the AB*S*AB bias

Must surround cookie with known plaintext

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

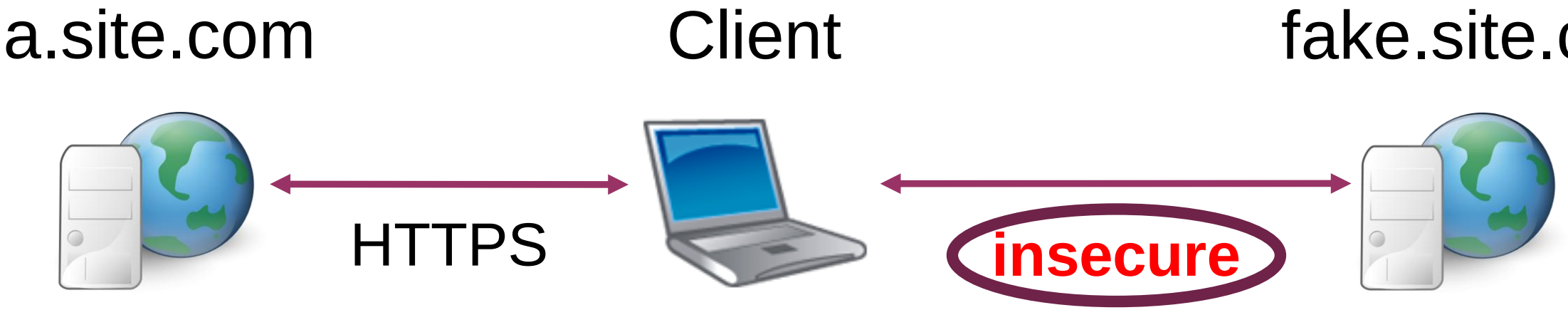
Example: manipulated HTTP request

```
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

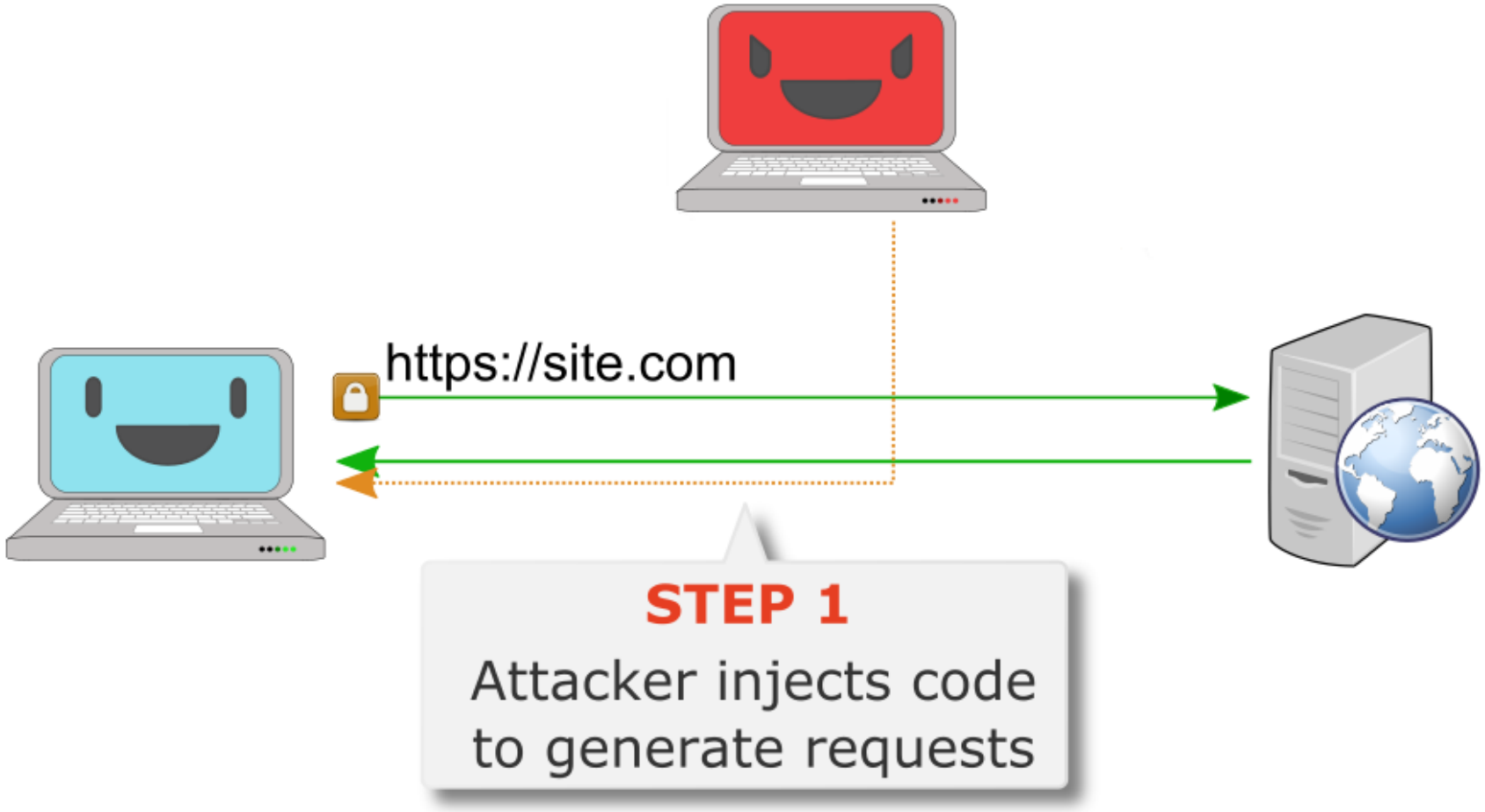
Surrounded by known plaintext at both sides

Preparation: manipulating cookies

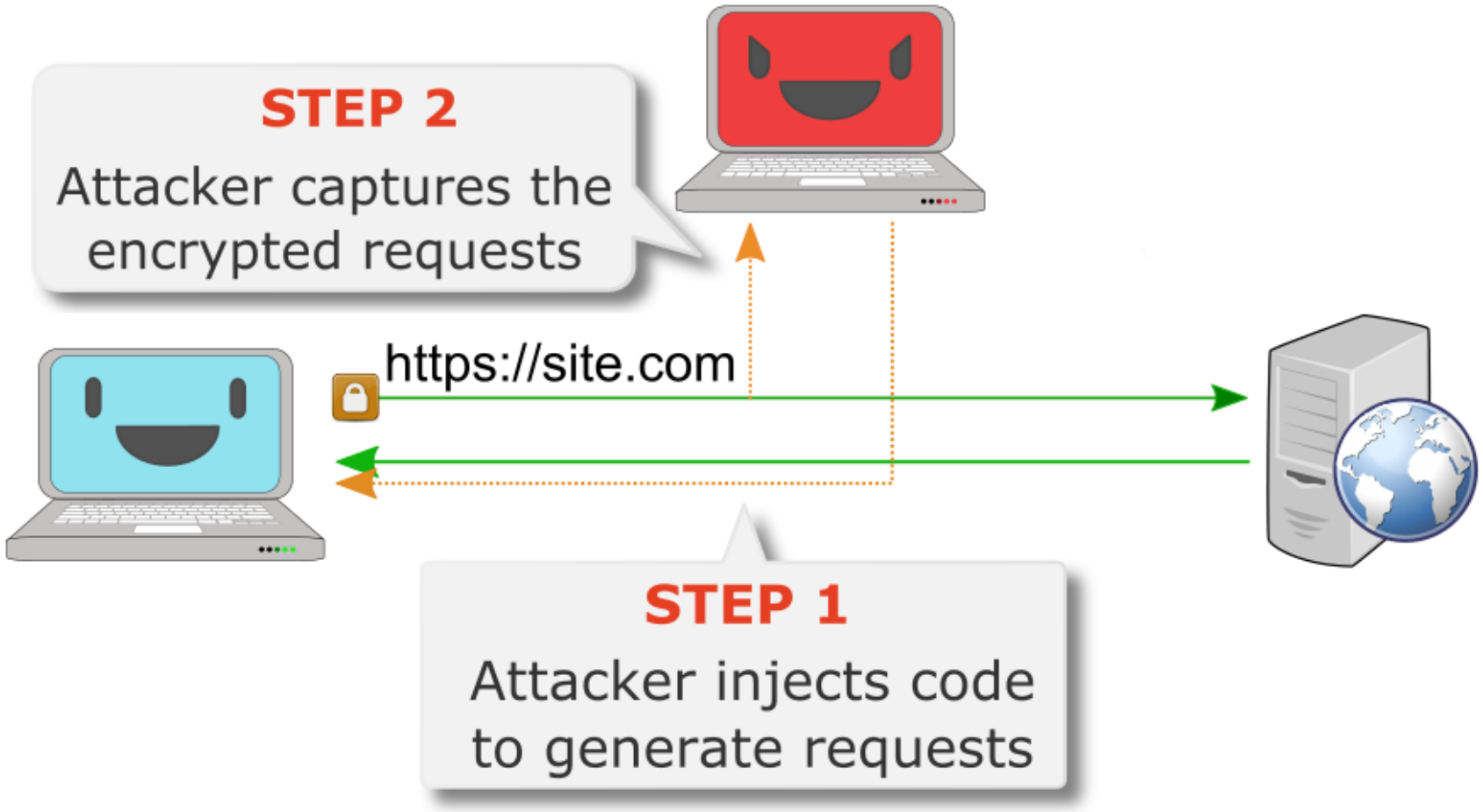


Remove & inject *secure* cookies!

Performing the attack!

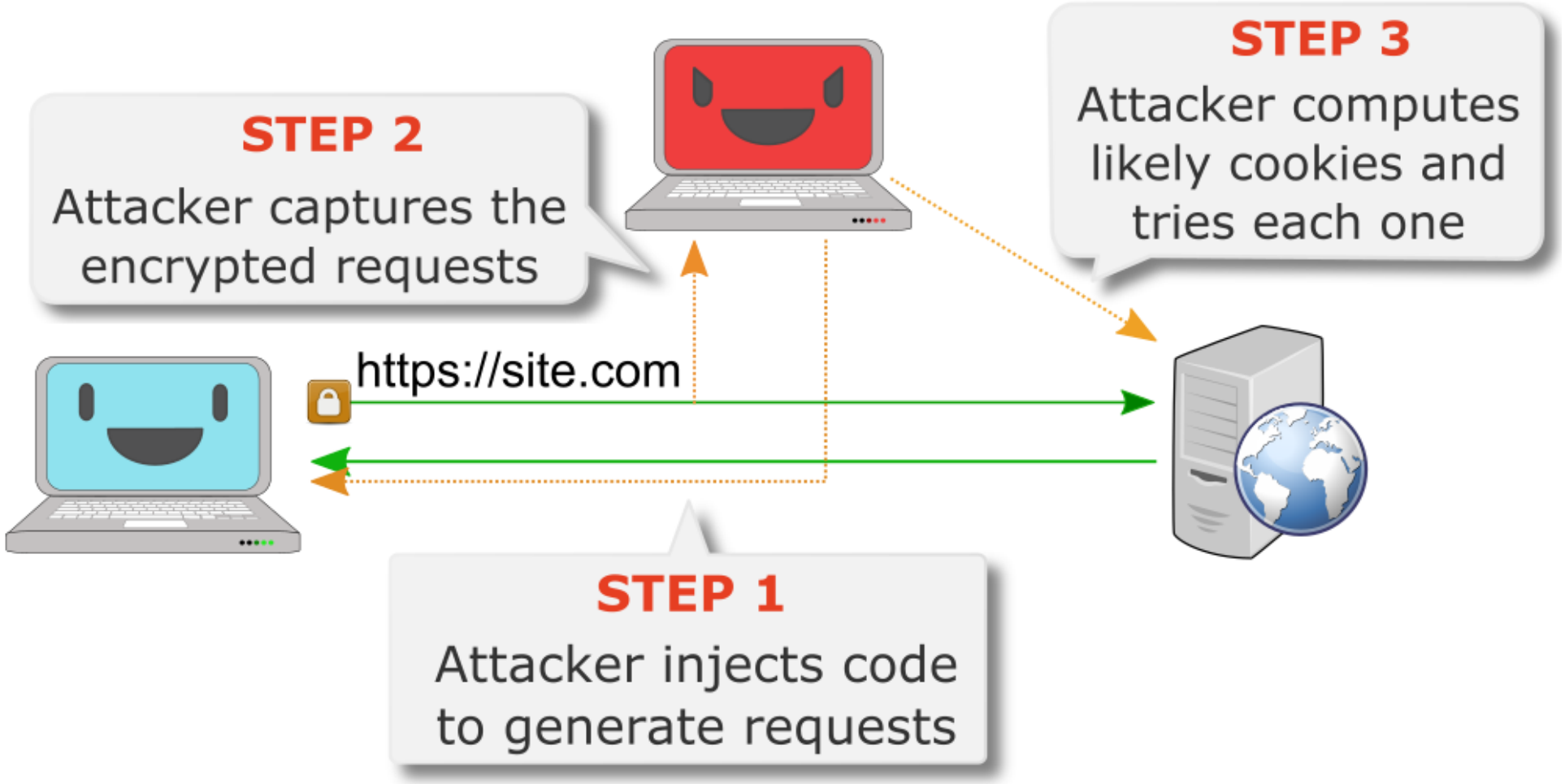


Performing the attack!



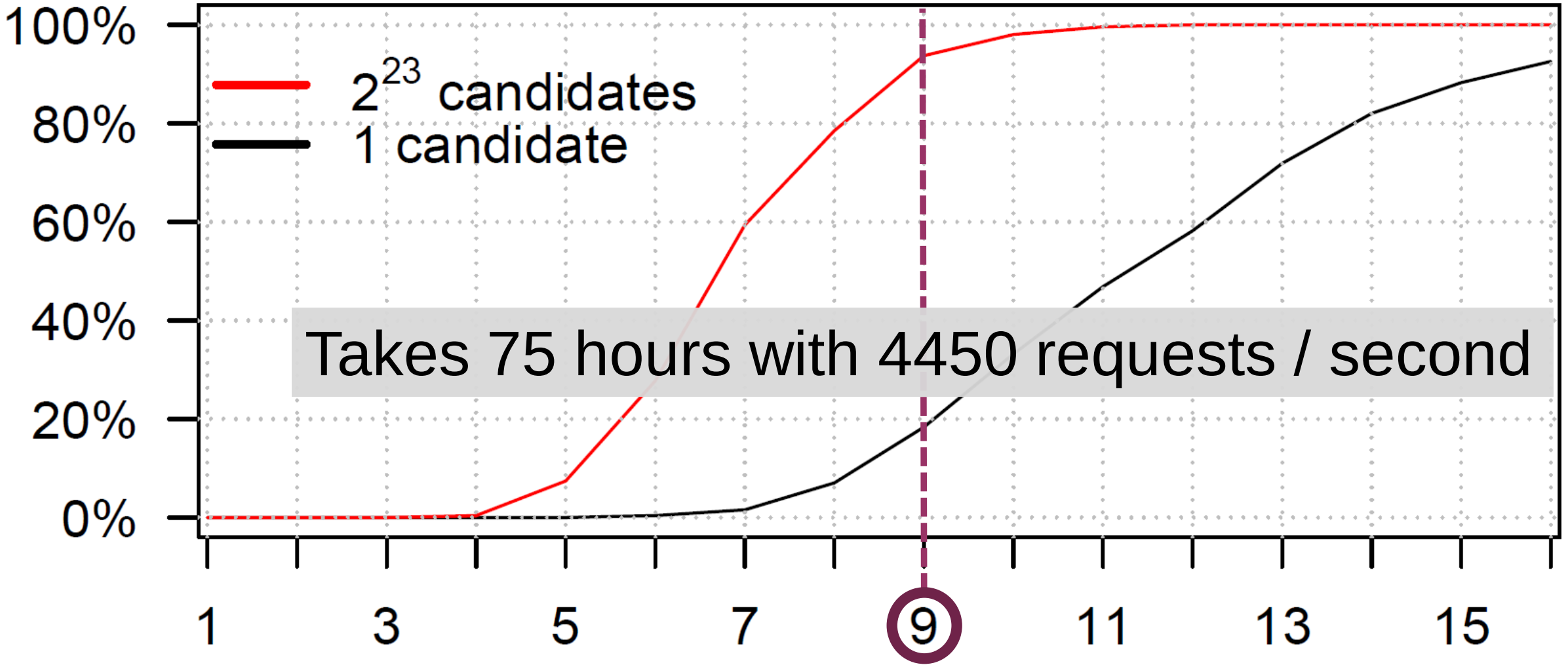
Keep-Alive connection to generate them fast

Performing the attack!



Combine Fluhrer-McGrew and ABSAB biases

Decrypting 16-character cookie



Ciphertext copies times 2^{27}

Decrypting 16-character cookie

DEMO!

rc4nomore.com

Questions?

May the bias be ever in your favor