Securely Implementing Network Protocols: Detecting and Preventing Logical Flaws

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DistriNet

Introduction

Many protocols have been affected by **logical** bugs

	Design flaws	Implementation flaws
TLS	BEAST[11] POODLE[12] Lucky 13[13] …	Early CCS attack[5] FREAK[8] Logjam[10] …
Wi-Fi	WEP Protected setup[7] Key reinstallations[1] …	Bad state machine[4] No downgrade check[4] Bad randomness[6,7] …
SSH	CBC plaintext recovery[2]	Bad state machine[3]

Introduction

Many protocols have been affected by **logical** bugs

We focus on logical **implementation flaws**

Implementation flaws
Early CCS attack[5] FREAK[8] Logjam[10] …
Bad state machine[4] No downgrade check[4] Bad randomness[6,7] …
Bad state machine[3]

How were TLS flaws detected?

Several works audited state machines:

2014
- Kikuchi discovered the early CCS attack[5]
- Manual inspection of CCS transitions in implementations

2015
- Beurdouche et al: manually define state machine of TLS[8]
- Use state machine to generate invalid handshakes

2016
- de Ruiter and Poll: extract state machine automatically[9]
- Manually inspect state machine for anomalies

Lesson: use model-based testing!

→ Model-based testing!

- Test if program behaves according to some abstract model
- Proved successful against TLS

- We applied model-based approach on the Wi-Fi handshake
- Our technique can be used to test other protocols!

Background: the Wi-Fi handshake

Main purposes:

- Network discovery
- Mutual authentication & negotiation of pairwise session key
- Securely select cipher to encrypt data frames

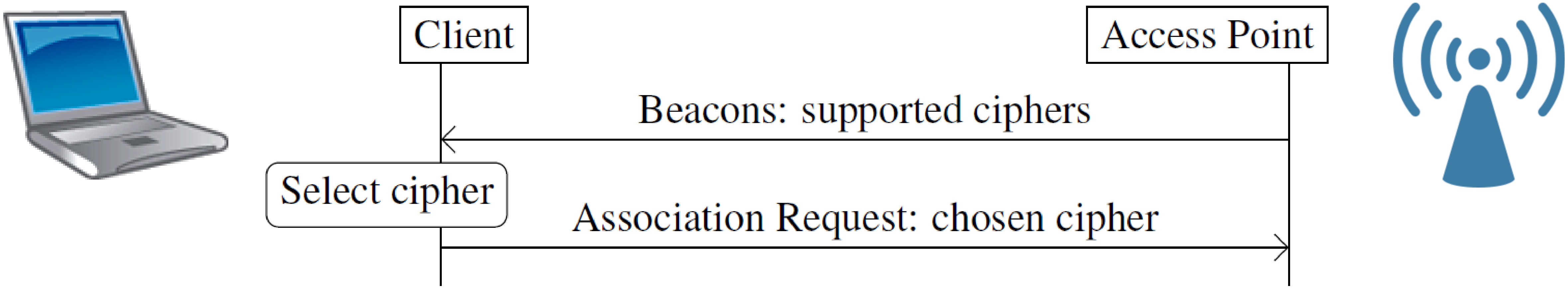
WPA-TKIP

Short-term solution: reduced security so it could run on old hardware

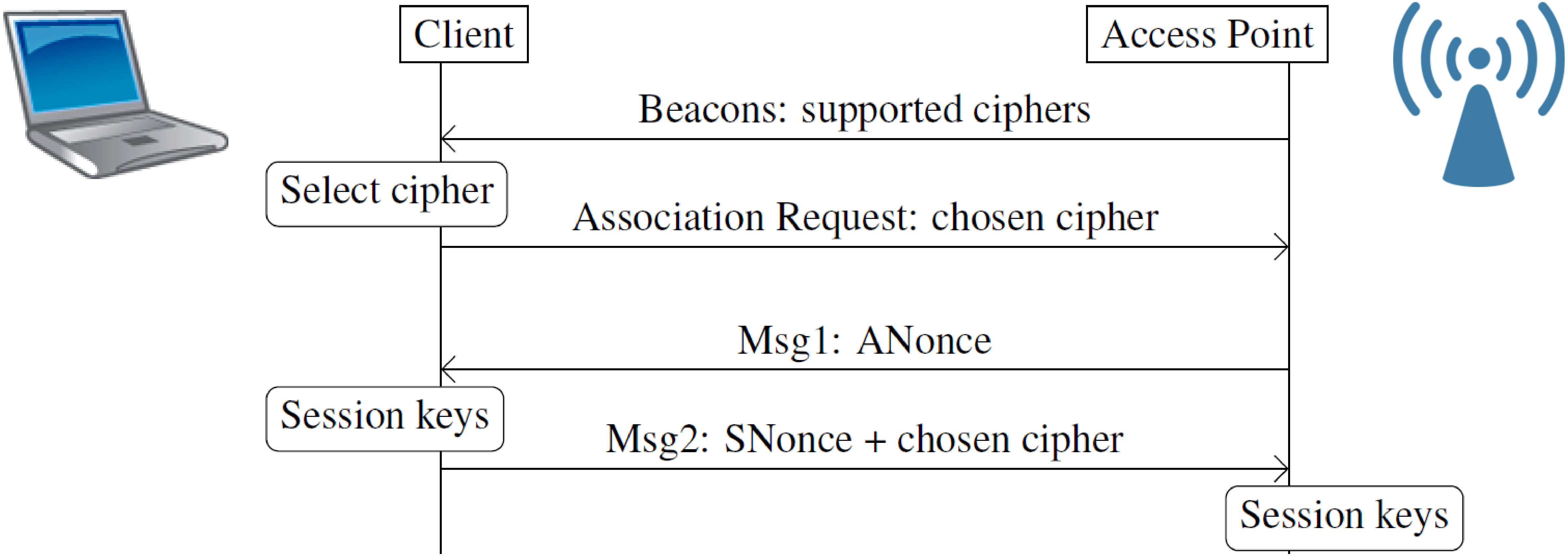
AES-CCMP

Long-term solution based on modern cryptographic primitives

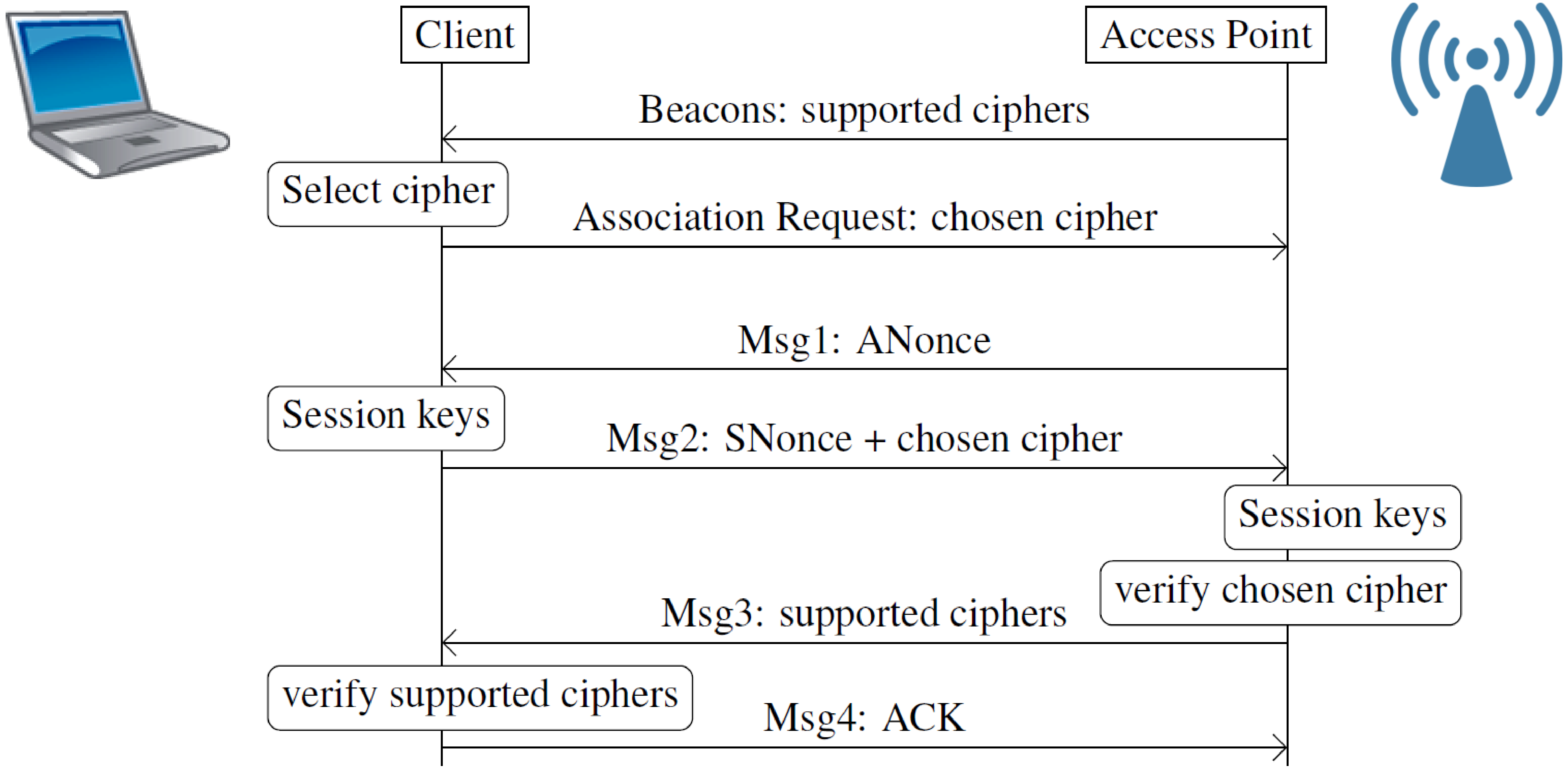
Wi-Fi handshake (simplified)



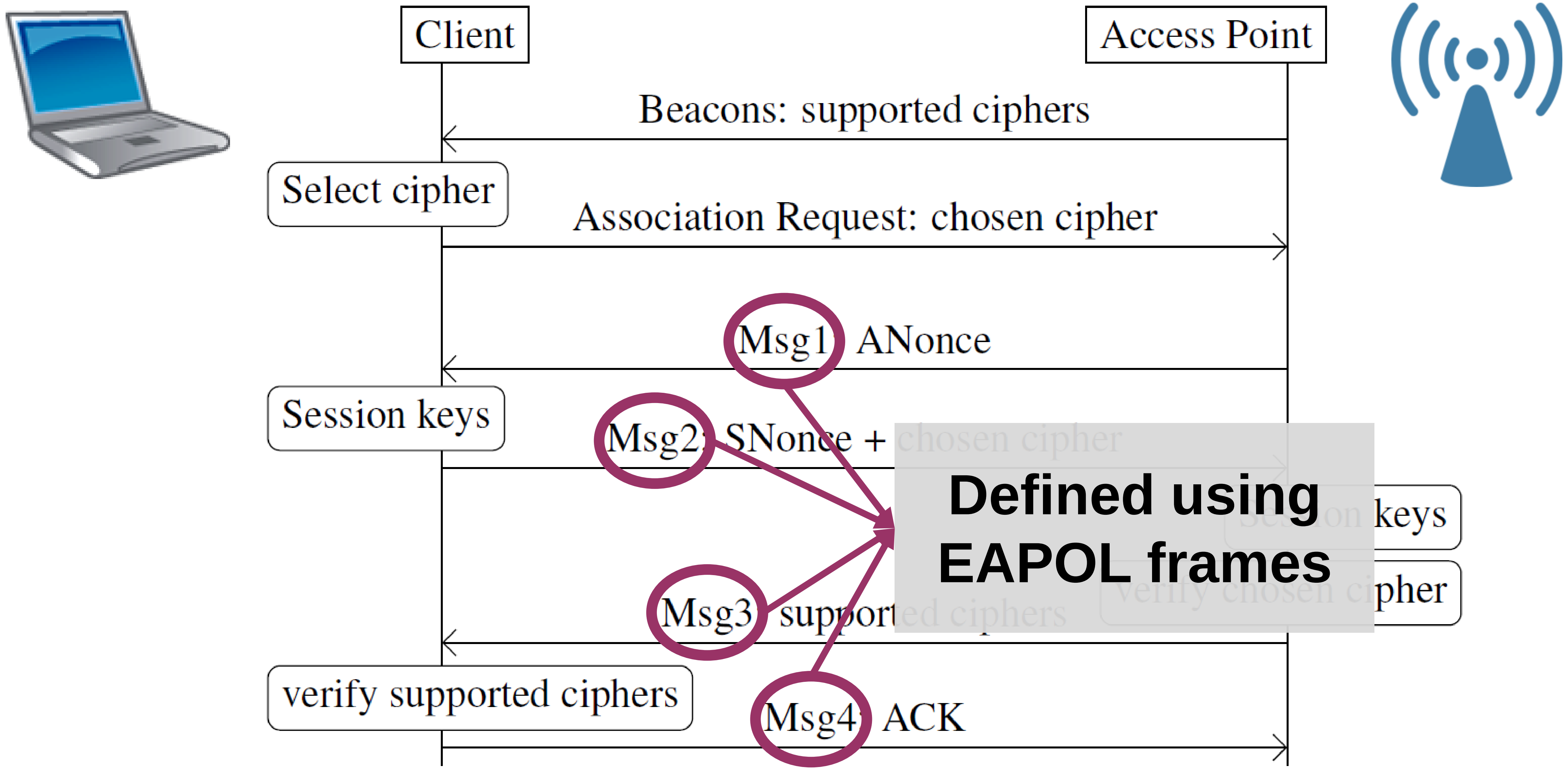
Wi-Fi handshake (simplified)



Wi-Fi handshake (simplified)



Wi-Fi handshake (simplified)

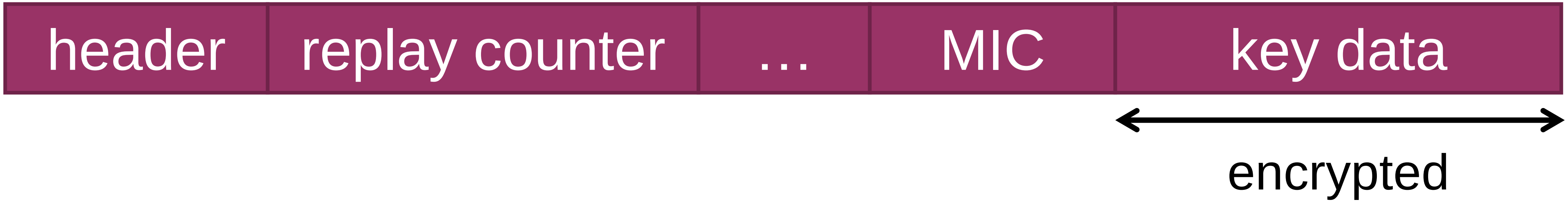


EAPOL frame layout

```
⌄ 802.1X Authentication
    Version: 802.1X-2004 (2)
    Type: Key (3)
    Length: 117
    Key Descriptor Type: EAPOL RSN Key (2)
  › Key Information: 0x008a
    Key Length: 16
    Replay Counter: 0
    WPA Key Nonce: 3e8e967dacd960324cac5b6aa721235bf57b949771c86798...
    Key IV: 00000000000000000000000000000000
    WPA Key RSC: 0000000000000000
    WPA Key ID: 0000000000000000
    WPA Key MIC: 00000000000000000000000000000000
    WPA Key Data Length: 22
  › WPA Key Data: dd14000fac04592da88096c461da246c69001e877f3d
```

EAPOL frame layout

≈



Model-based testing: our approach

Model: normal handshake $\xrightarrow{\text{Test generation rules: (in)correct modifications}}$ Set of test cases

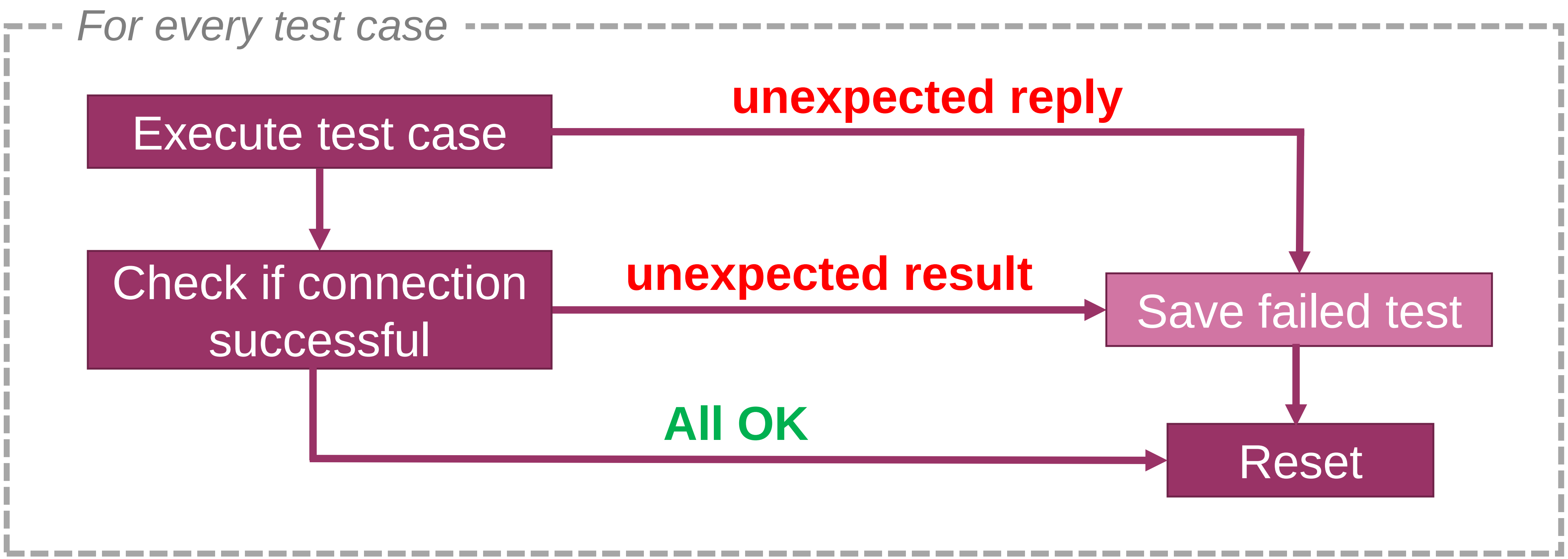
Test generation rules:

- Test various edge cases, allows some creativity
- Are assumed to be independent (avoid state explosion)

A test case defines:

1. Messages to send & expected replies
2. Results in successful connection?

Executing test cases



Afterwards inspect <u>failed</u> test cases

- Experts determines impact and exploitability

Test generation rules

Test generation rules manipulating messages as a whole:

1. Drop a message
2. Inject/repeat a message

Test generation rules that modify fields in messages:

1. Bad EAPOL replay counter
2. Bad EAPOL header (e.g. message ID)
3. Bad EAPOL Message Integrity Check (MIC)
4. Mismatch in selected cipher suite
5. …

Evaluation

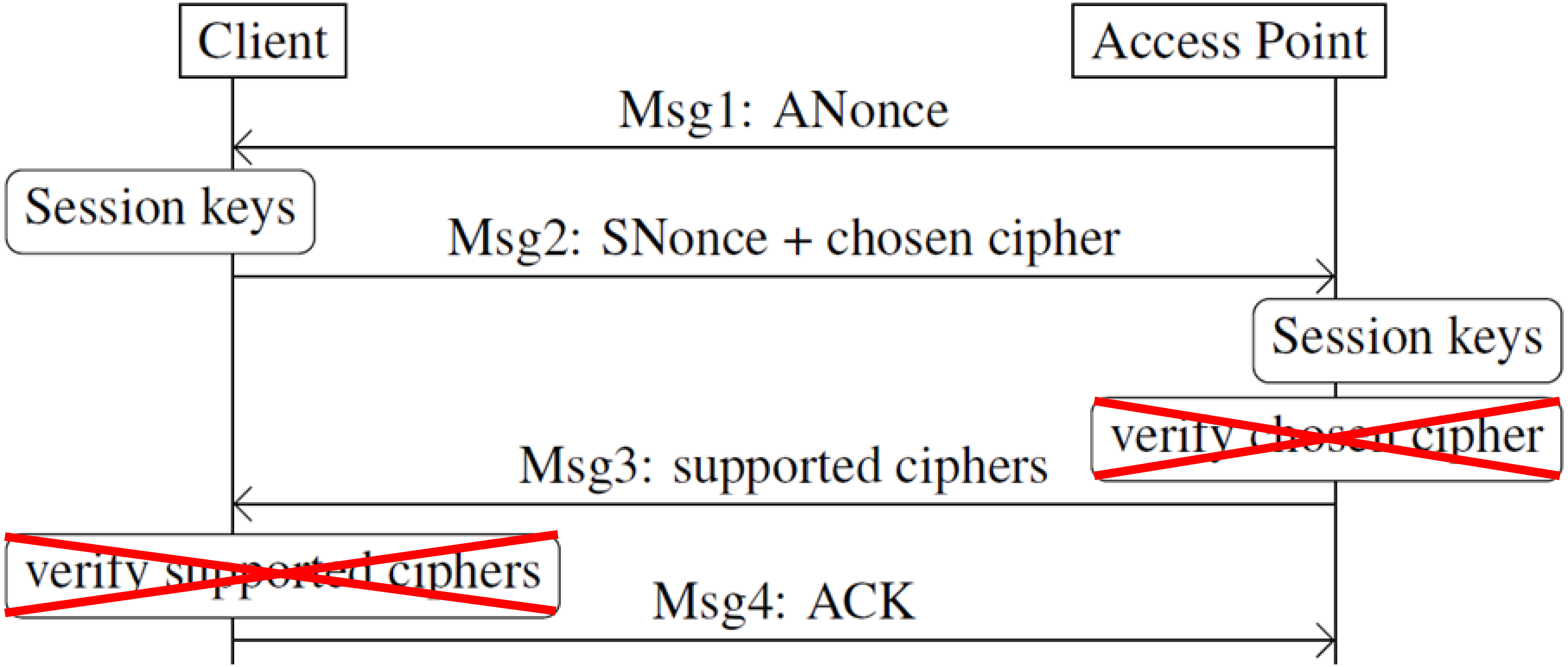
We tested 12 access points:

- Open source: OpenBSD, Linux’s Hostapd
- Leaked source: Broadcom, MediaTek (home routers)
- Closed source: Windows, Apple, …
- Professional equipment: Aerohive, Aironet

Discovered several issues!

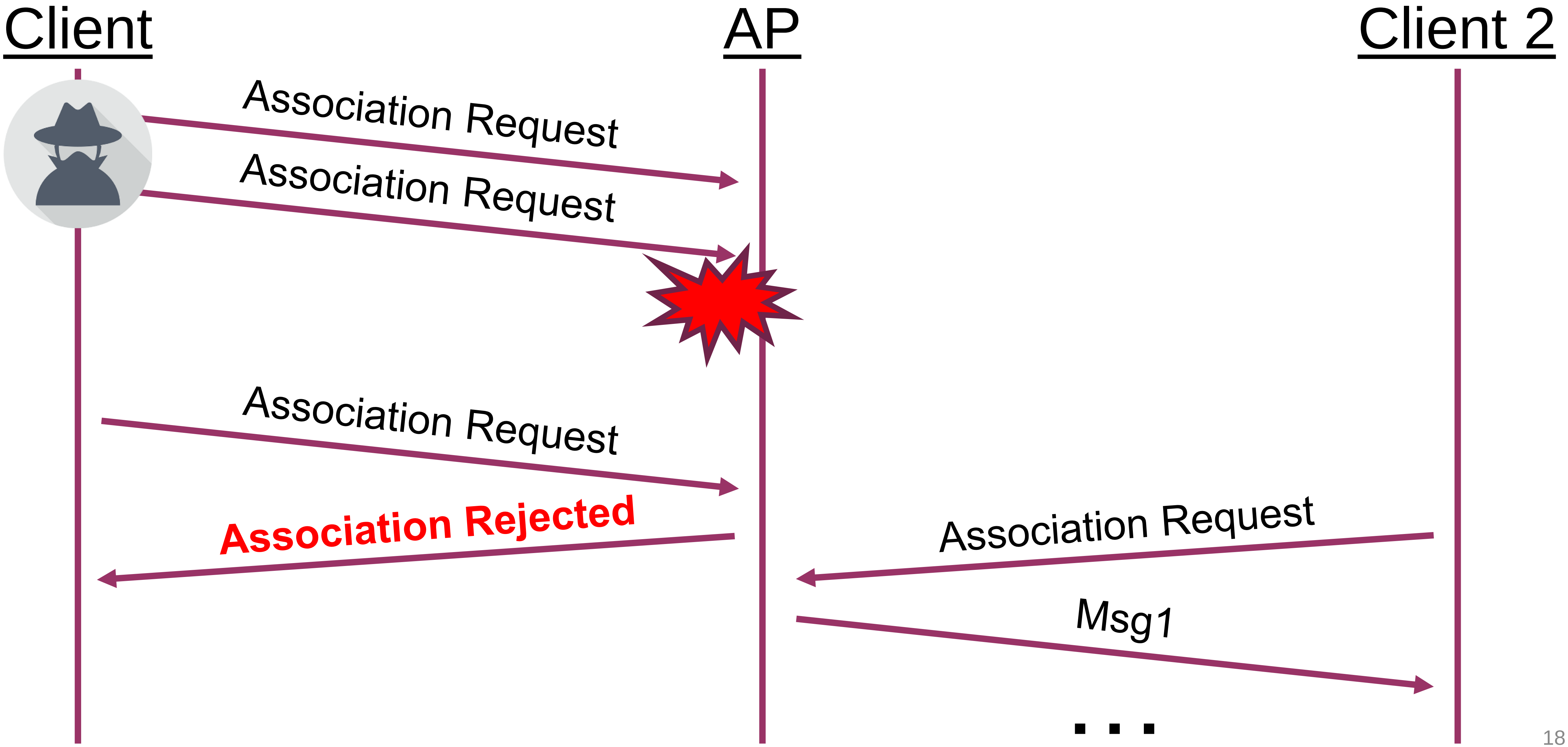
Missing downgrade checks

1. MediaTek & Telenet don't verify selected cipher in message 2
2. MediaTek also ignores supported ciphers in message 3

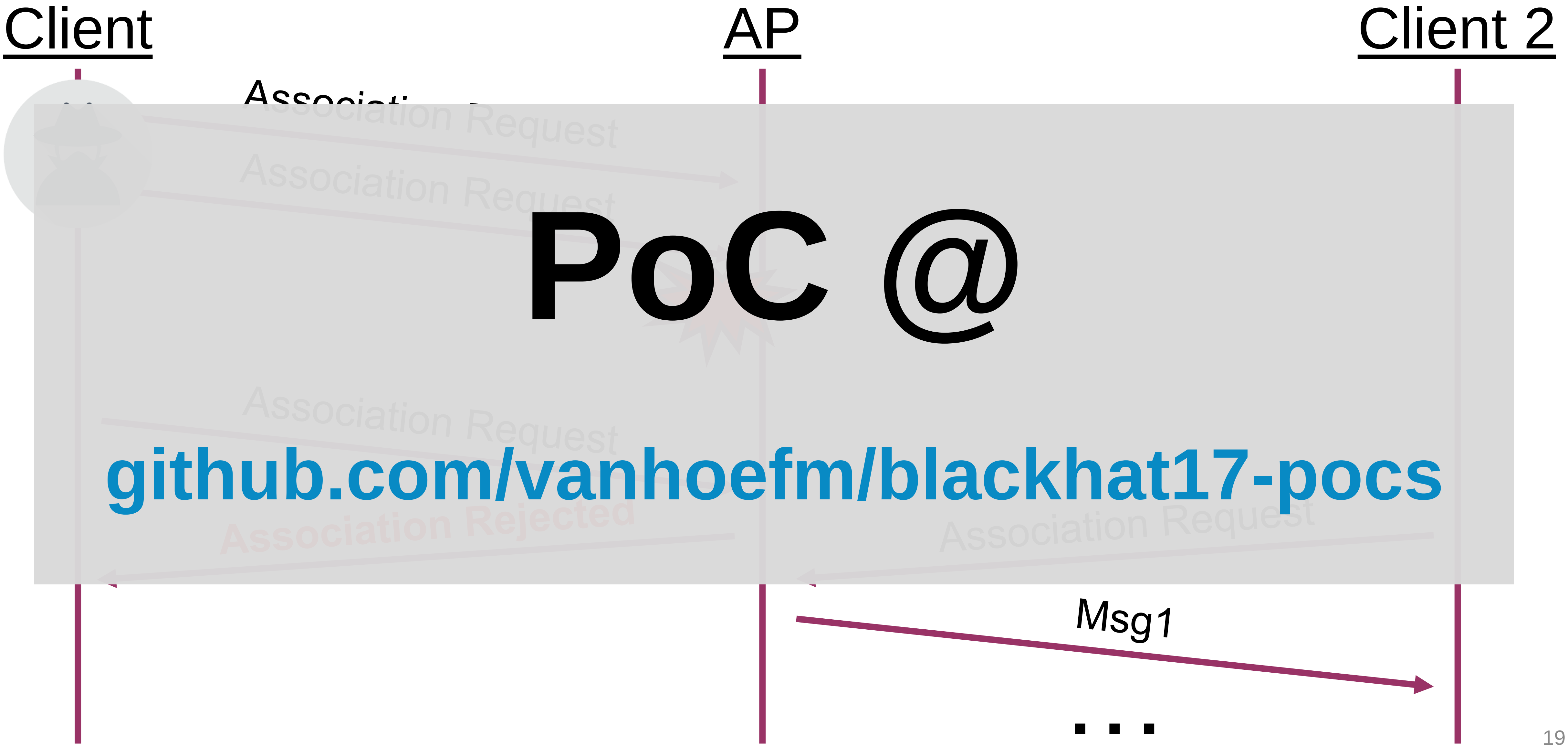


→ Trivial downgrade attack against MediaTek clients

Windows 7 targeted DoS



Windows 7 targeted DoS



PoC @

github.com/vanhoefm/blackhat17-pocs

Broadcom downgrade

Broadcom cannot distinguish message 2 and 4

- Can be abused to downgrade the AP to TKIP

Hence message 4 is essential in preventing downgrade attacks

- This highlights incorrect claims in the 802.11 standard:

> "**While Message 4 serves no cryptographic purpose**, it serves as an acknowledgment to Message 3. **It is required to ensure reliability** and to inform the Authenticator that the Supplicant has installed the PTK and GTK and hence can receive encrypted frames."

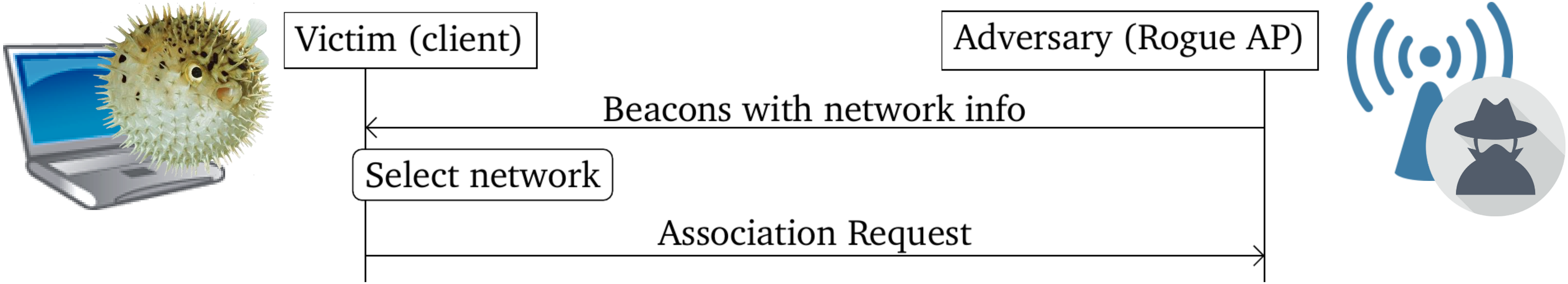
OpenBSD: client man-in-the-middle

Bug in state machine of AP → we also inspected client:

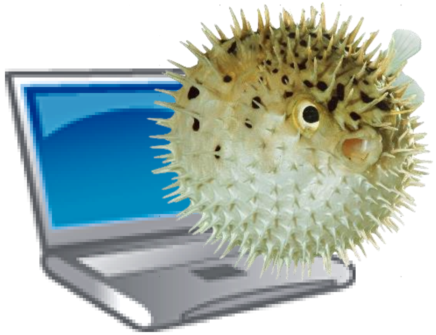
State machine missing!

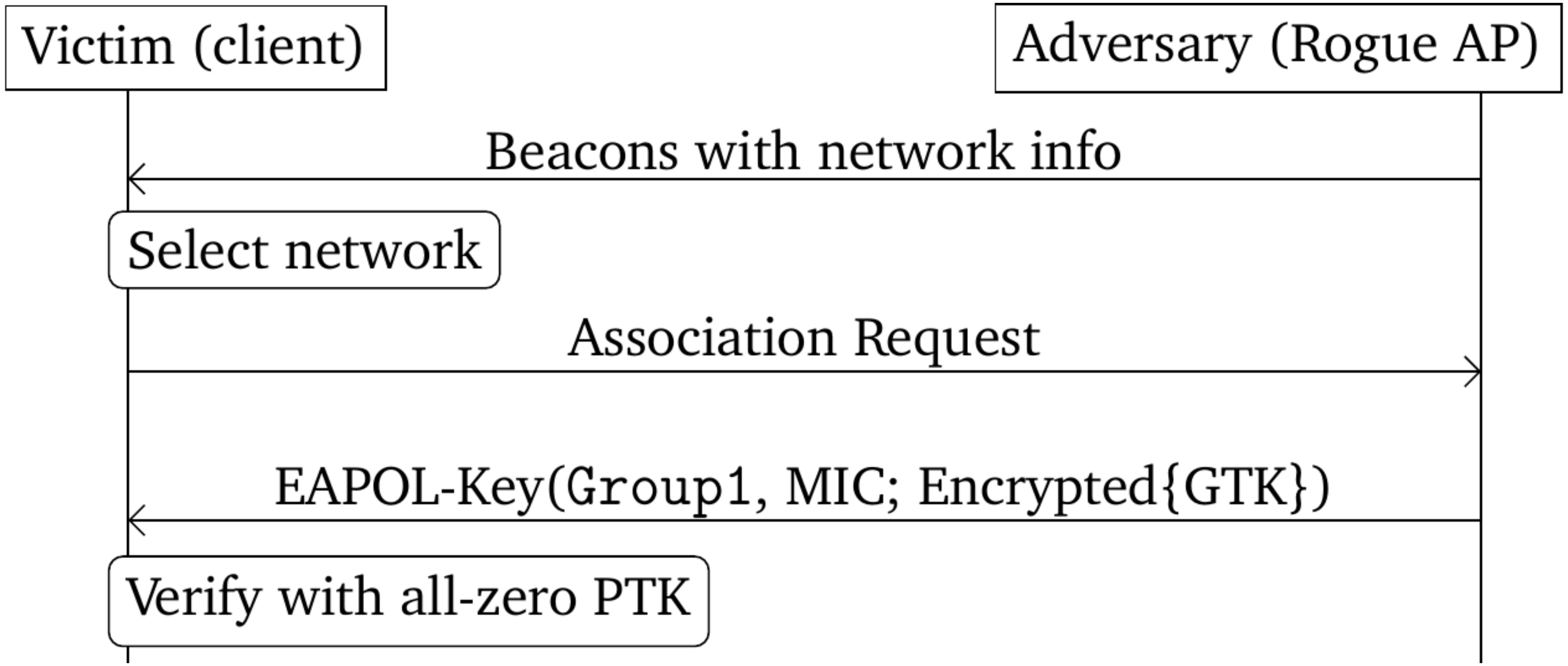
→ Man-in-the-middle against client

OpenBSD: client man-in-the-middle



OpenBSD: client man-in-the-middle





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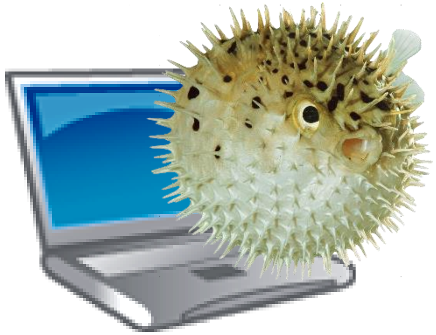

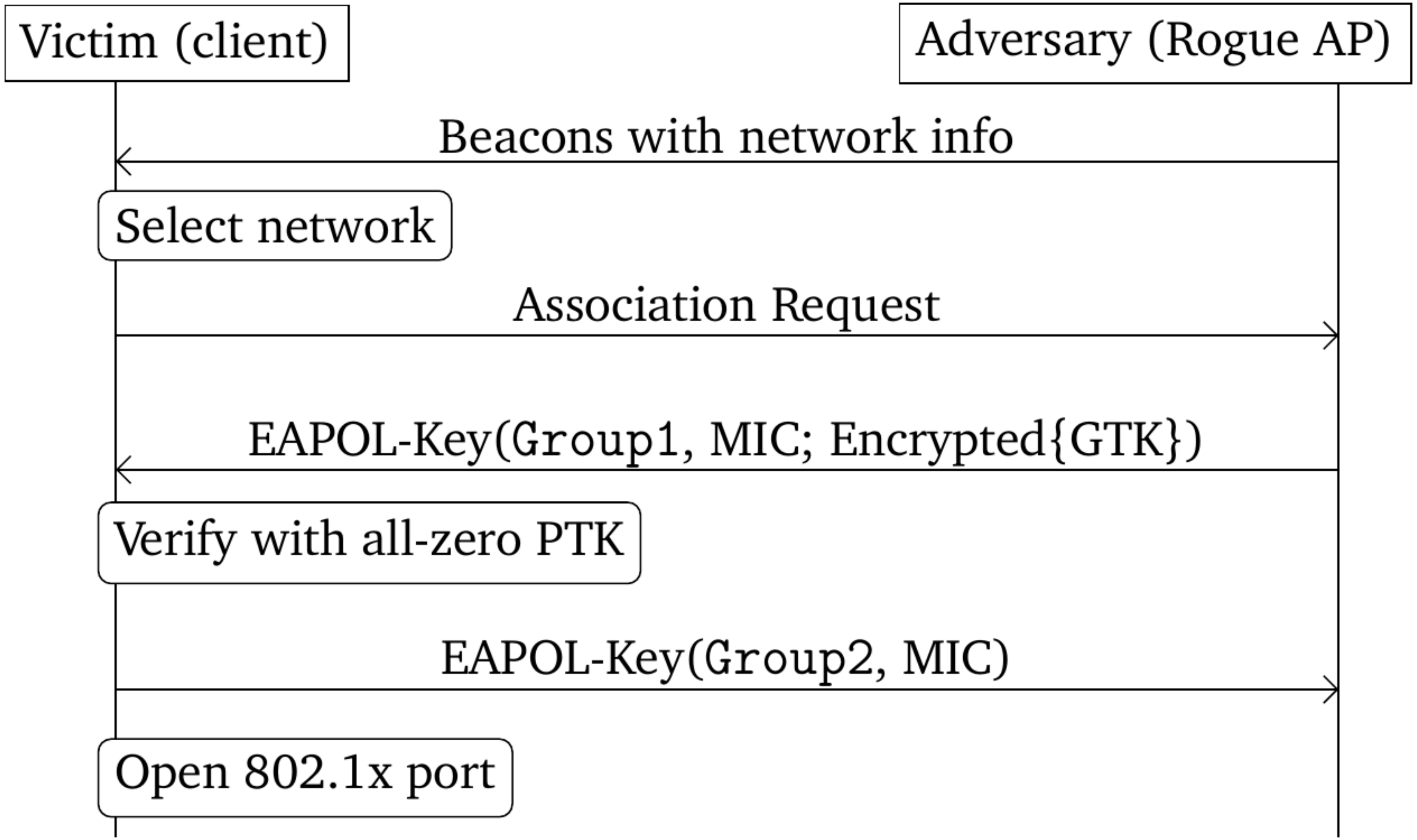

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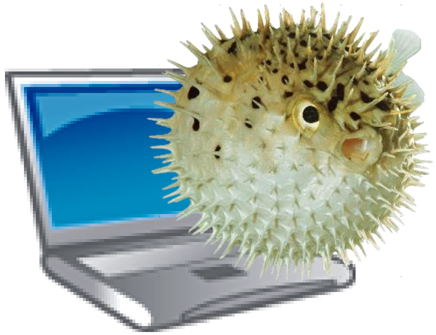

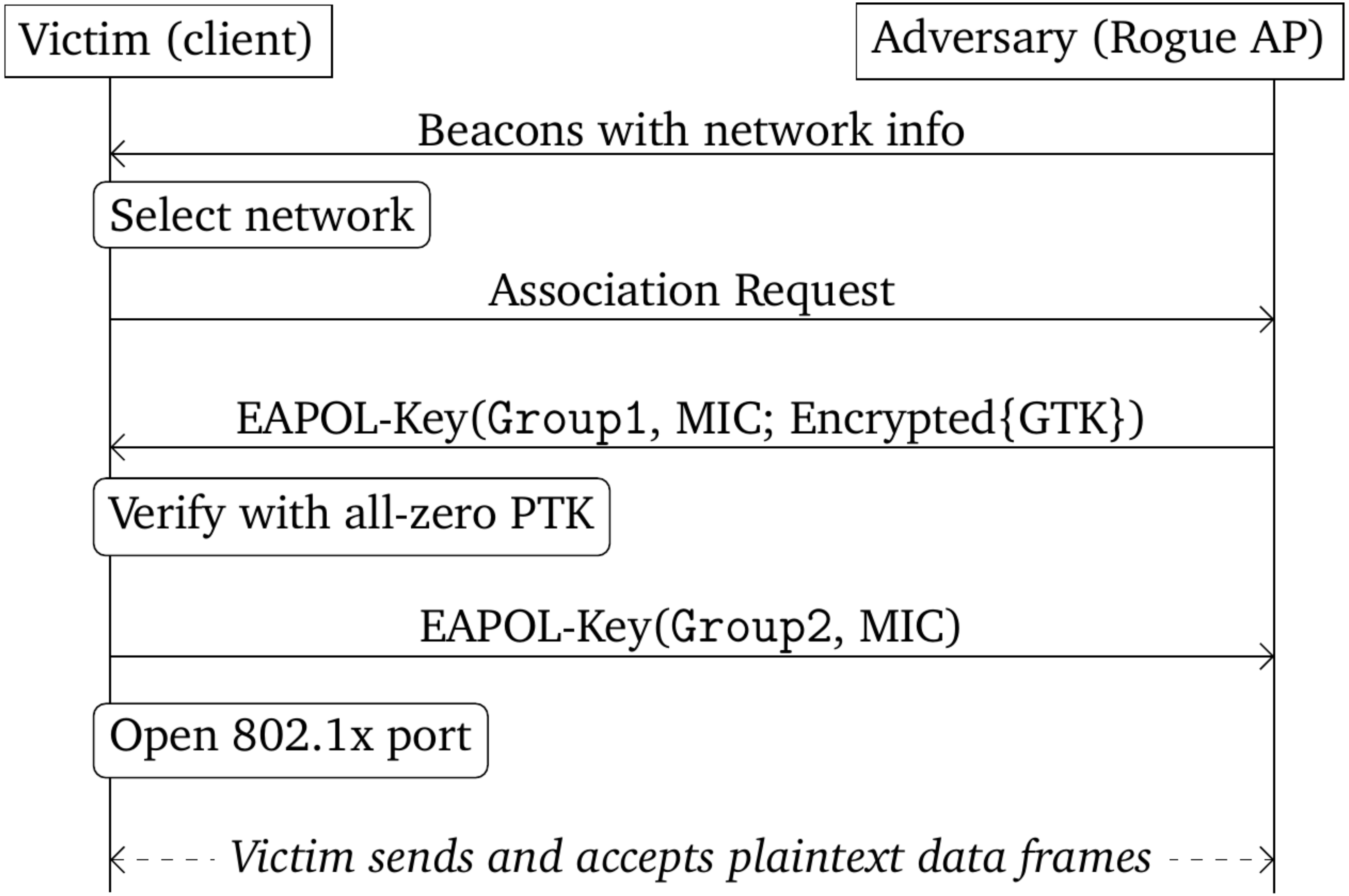

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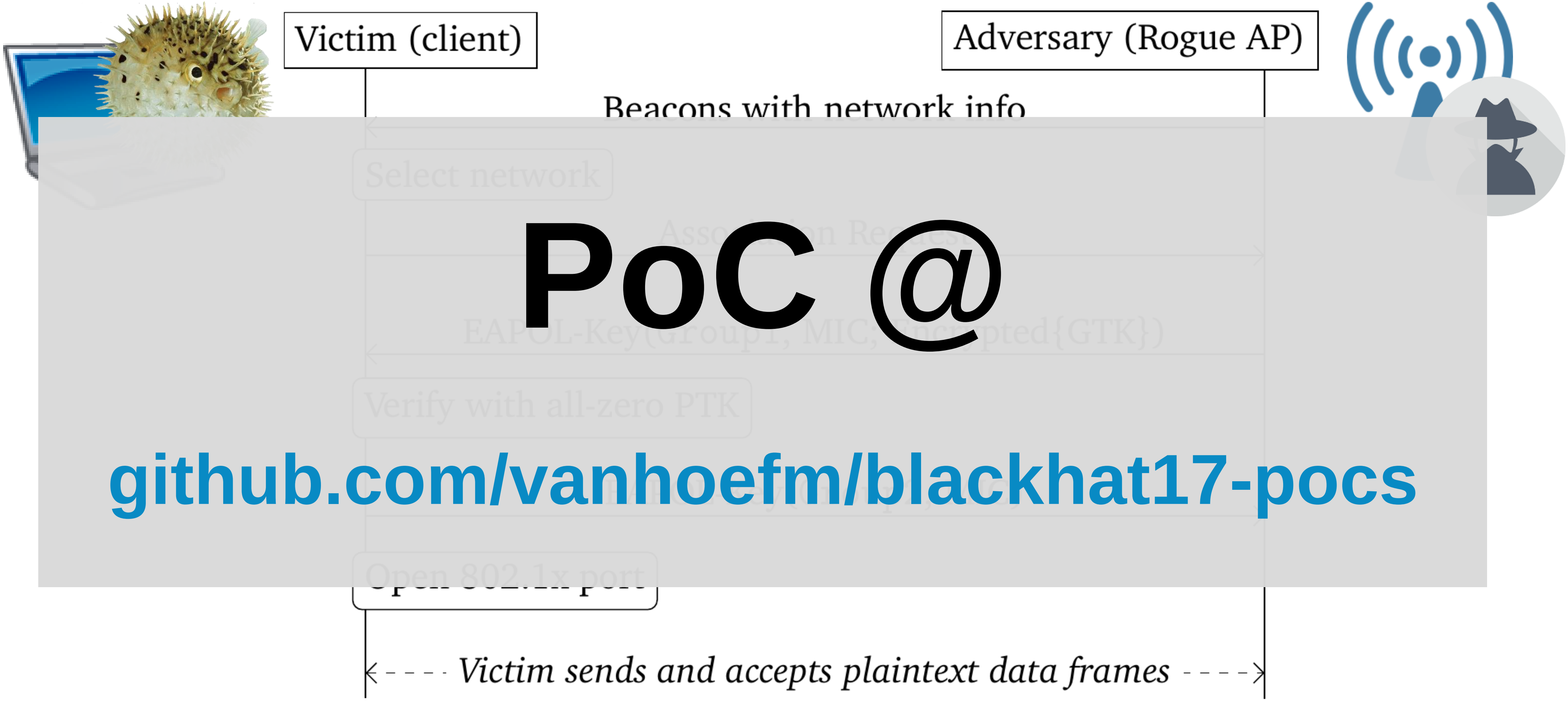

PoC @

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More results

See Black Hat & AsiaCCS paper[4]:

- Benign irregularities → fingerprint
- Permanent DoS attack against Broadcom and OpenBSD
- DoS attack against Windows 10, Broadcom, Aerohive
- Inconsistent parsing of supported cipher suite list
- …

Future work!

Current limitations:

- Amount of code coverage is unknown
- Only used well-formed (albeit invalid) packets
- Test generation rules applied independently

But already a promising technique

- ✓ Black-box testing mechanism: no source code needed
- ✓ Fairly simple handshake, but still several logical bugs!

Conclusion: avoiding logical bugs

What helps:

- Try to generalize known bugs (in your/other products)
- Model-based testing (e.g. this presentation)
- Write rigorous requirements (specification) and review them
- Detailed code reviews (e.g. by domain experts)

Does not help:

- Standard code review (only detects common mistakes)
- Traditional static or dynamic testing

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References

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