Breaking & Disrupting WPA2/3 Networks by Abusing Sleep Mode

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Based on our USENIX Security ’23 paper

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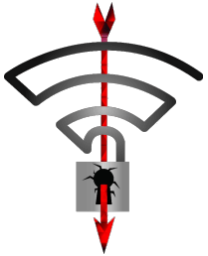
Quick Introduction

- Research: network & Wi-Fi security
- Previously discovered **KRACK**, FragAttacks, Dragonblood, …



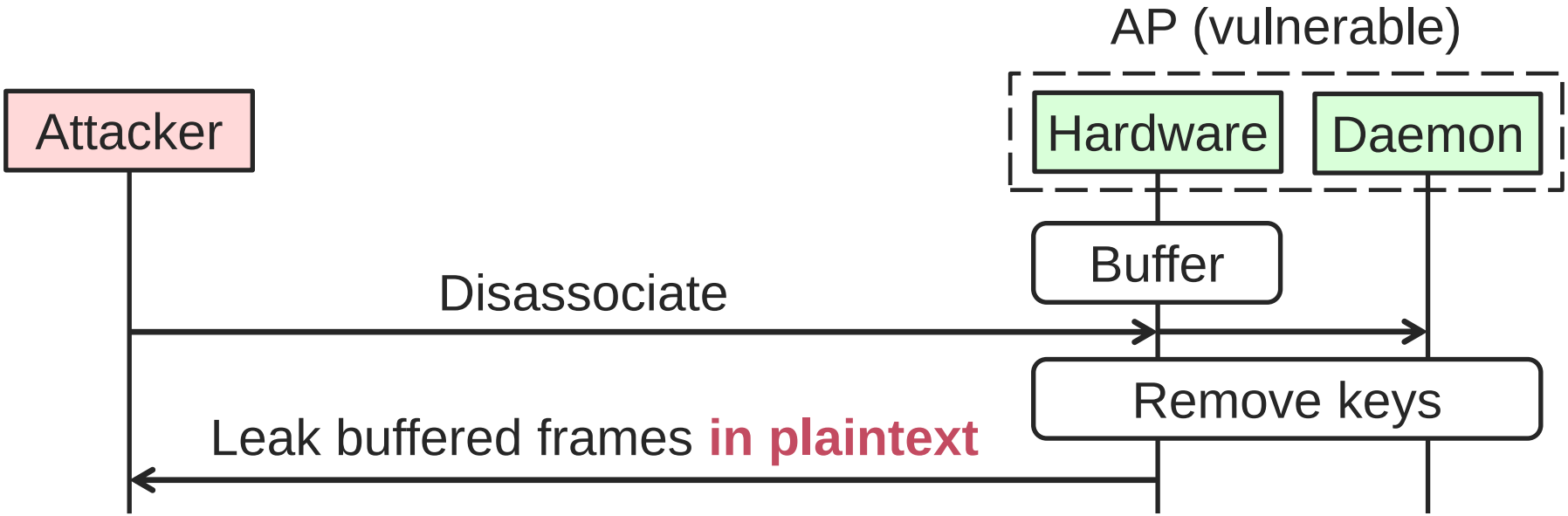
- Helped design Operating Channel Validation and **Beacon protection** (mandatory in Wi-Fi 7)
- Recently found flaws in 2/3rds of VPN clients

We collaborate with industry! ☺

History of Wi-Fi

- WEP (1999): quickly broken [FMS01]
- WPA1/2 (~2003)
  - Offline password brute-force
  - **KRACK** & **Kraken** [VP17,VP18]
- WPA3 (2018):
  - **Dragonblood** side-channels [VR20]

Background: Kr00k implementation flaw



Question: **how are “security contexts” managed**?

The Security Context

- Negotiated protocol suites, encryption keys, packet counters
- All information needed to securely communicate

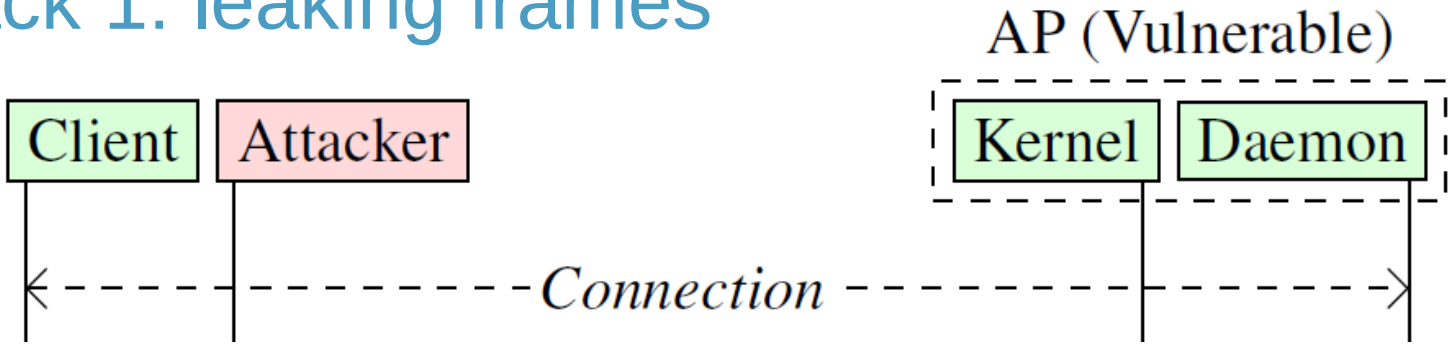
Relation between security context & sleep mode?

- When client wakes up **the security context might have changed** → what happens to queued frames?

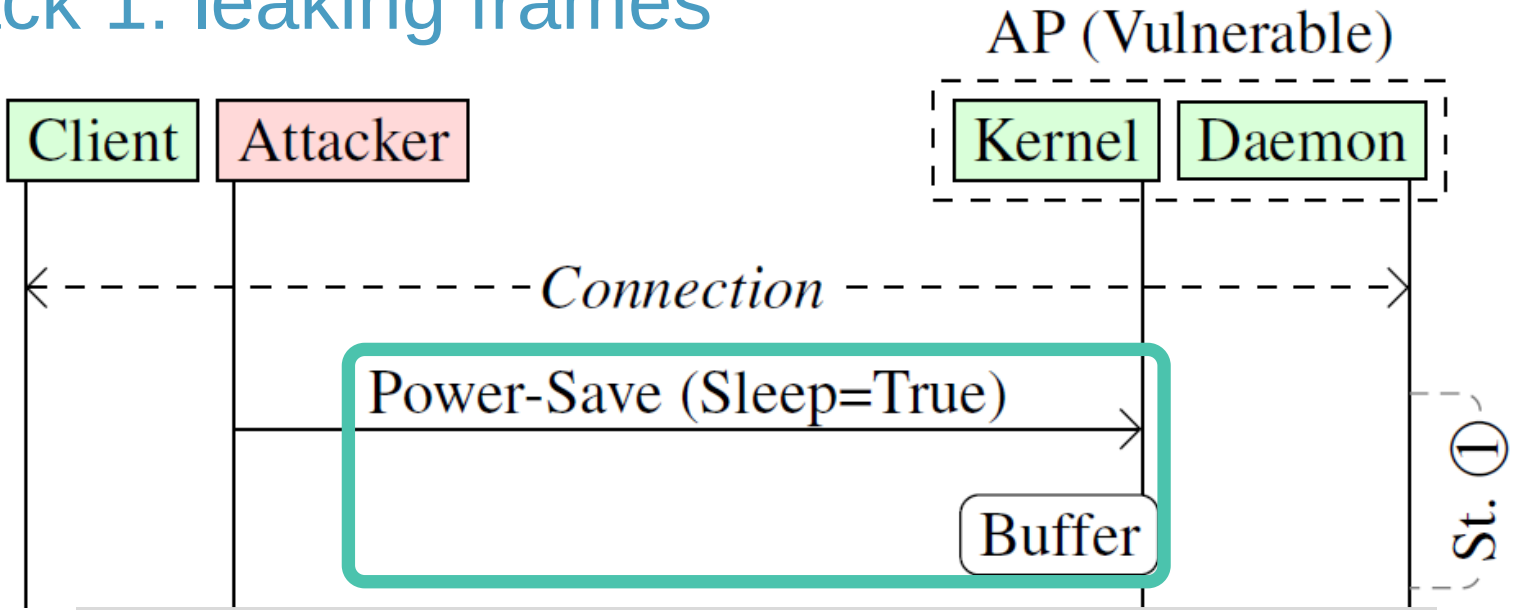
New attack 1: leaking frames

Attack 1: leaking frames

Attack 1: leaking frames

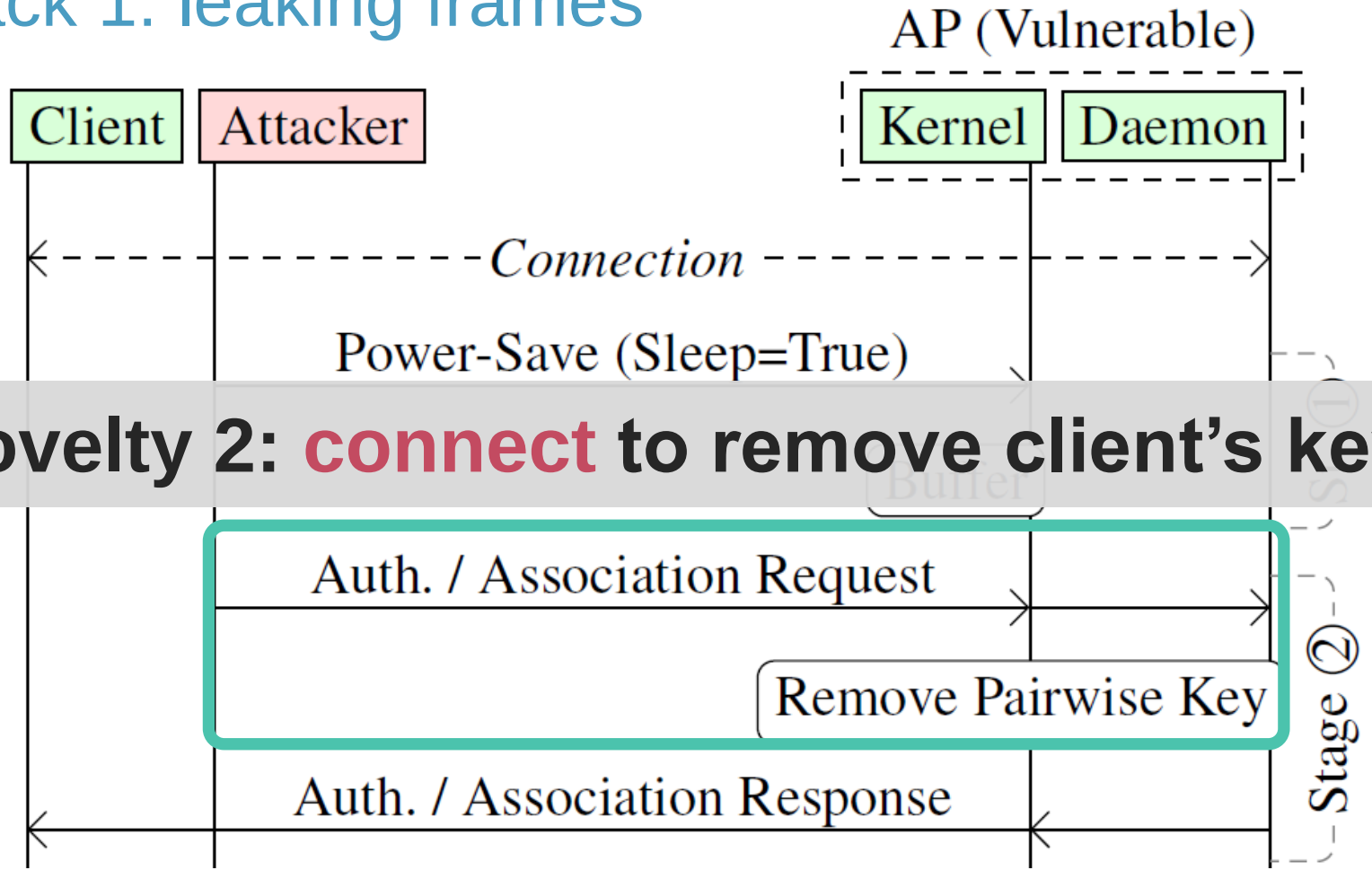


Attack 1: leaking frames



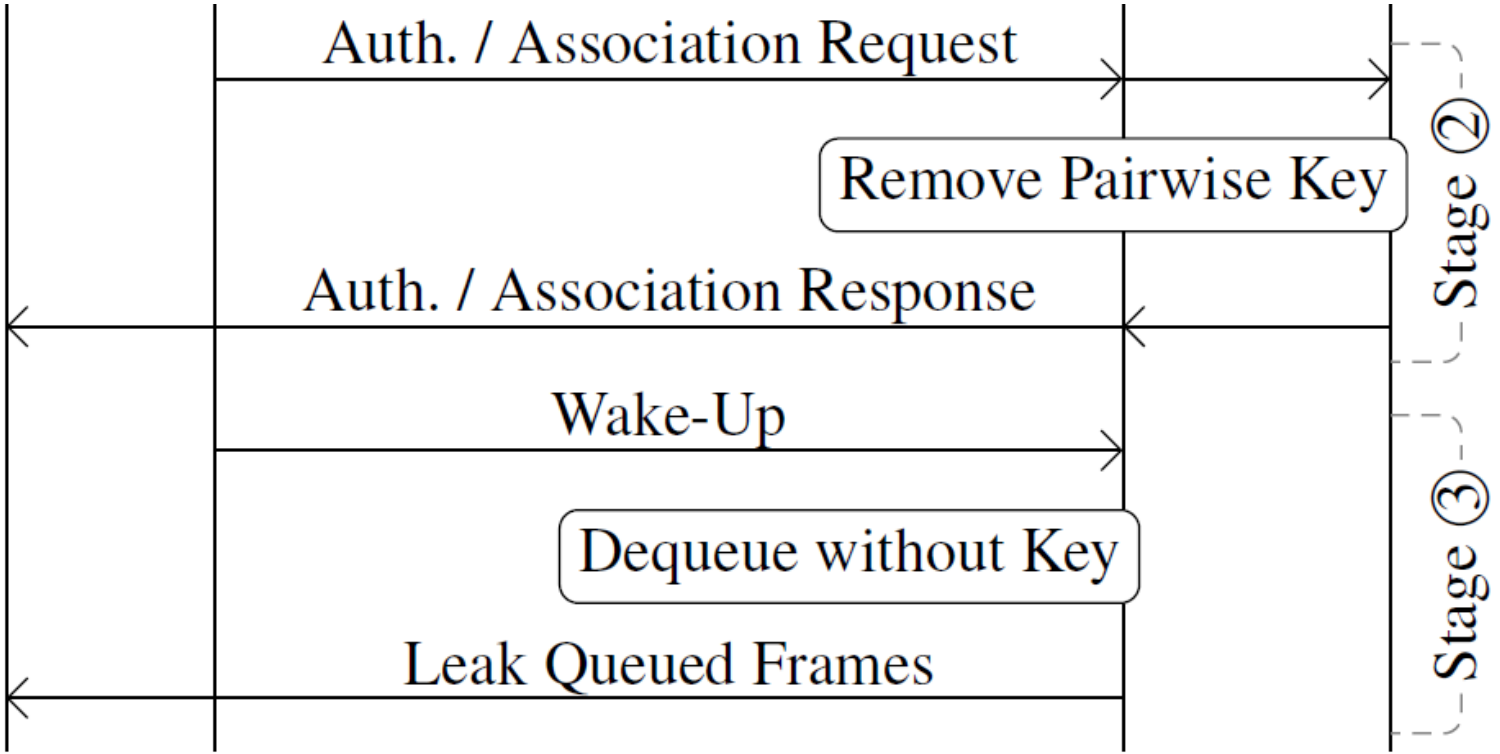
Novelty 1: controlled buffering

Attack 1: leaking frames

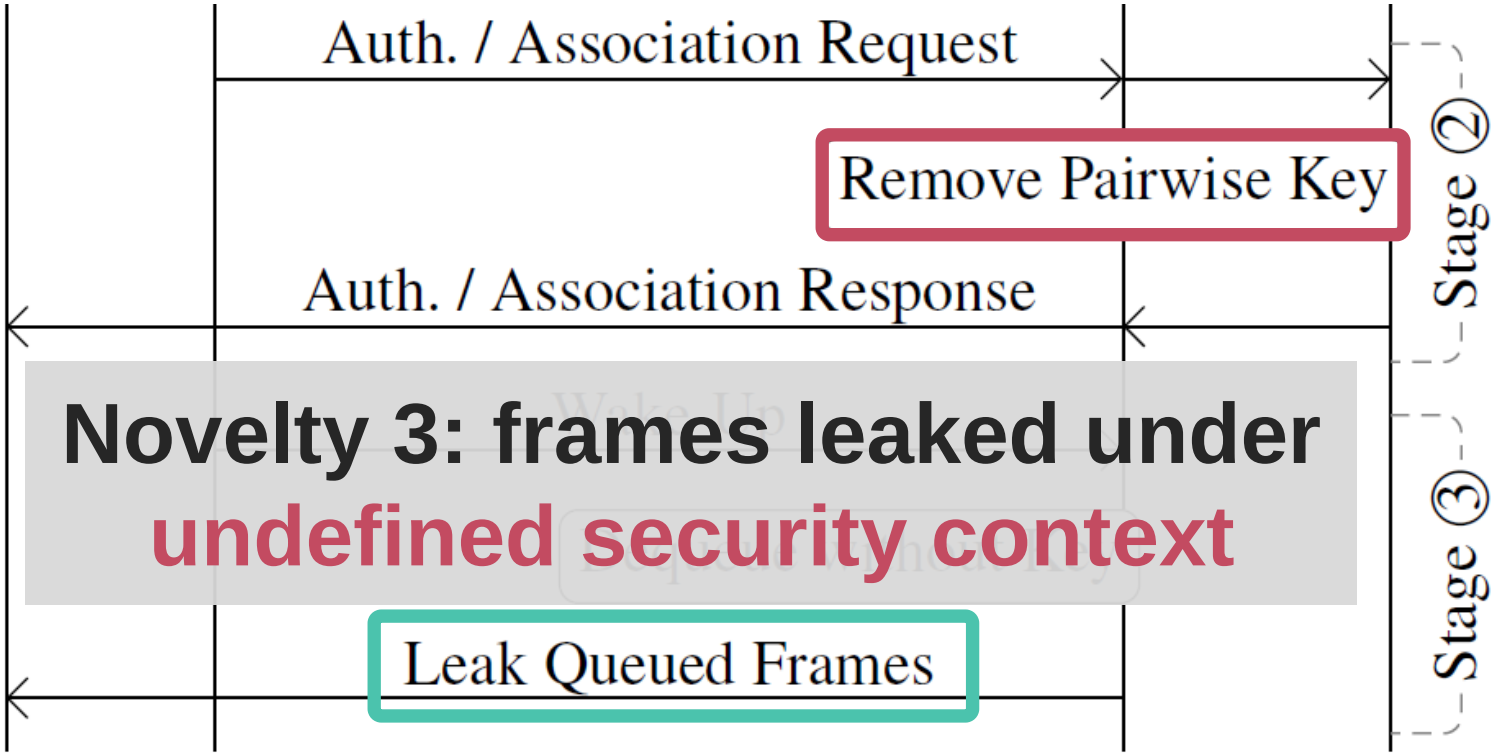


Novelty 2: connect to remove client's keys

Attack 1: leaking frames



Attack 1: leaking frames



Novelty 3: frames leaked under undefined security context

Undefined security context: FreeBSD example

How the frame is leaked depends on kernel version & driver:

Version	driver (vendor)	Leakage
13.0	run (Ralink)	Plaintext
13.1	run (Ralink)	WEP with all-zero key
13.1	rum (Ralink)	CCMP with group key
13.1	rtwn (Realtek)	CCMP with group key

- Malicious insiders know the group key!
- Linux, NetBSD, open Atheros firmware also affected

Root cause

Standard isn’t explicit on how to manage buffered frames

- Should drop buffered frames when refreshing/deleting keys

Frames are buffered in plaintext

- Alternative: encrypt frames *before* buffering them (like TLS)

New attack 2:

Network Disruptions

Background: DoS attacks

Well-known DoS attacks:

- Deauthentication: spoof “disconnect” frames
- Association: spoof “I want to connect” frames

Both remove connection state of the victim

Defense:

- **M**anagement **F**rame **P**rotection (**MFP** = 802.11w)
- This defense is required in WPA3

Management Frame Protection

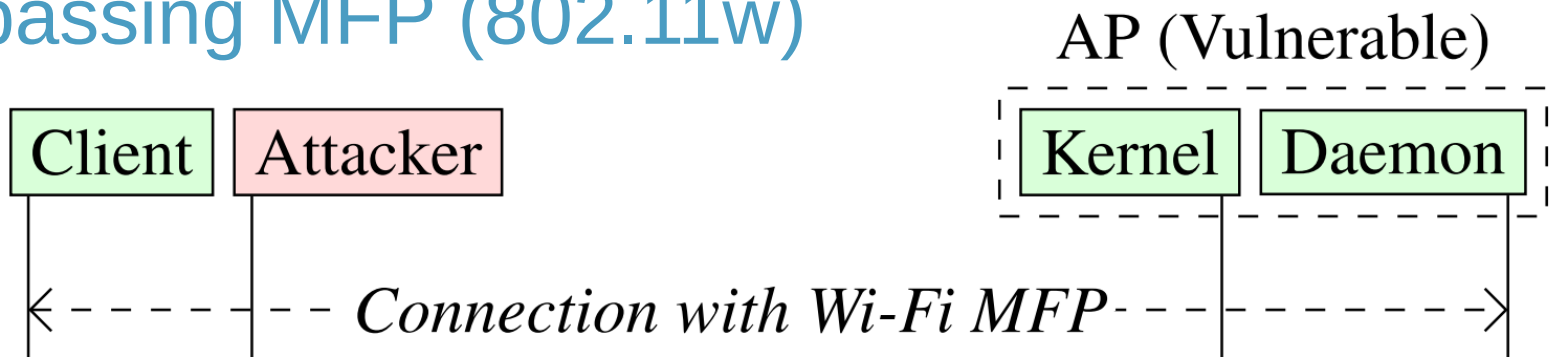
Wi-Fi has three frame types:

1. **Management**: network scanning, disconnecting,…
2. **Control**: acknowledgements, request to send,…
3. **Data**: transporting higher-layer data

New Wi-Fi-certified devices must support MFP

- Can no longer trivially **deauthenticate** (disconnect) clients
- Late 2021: close to 5% of networks supported MFP [SRV21]

Bypassing MFP (802.11w)



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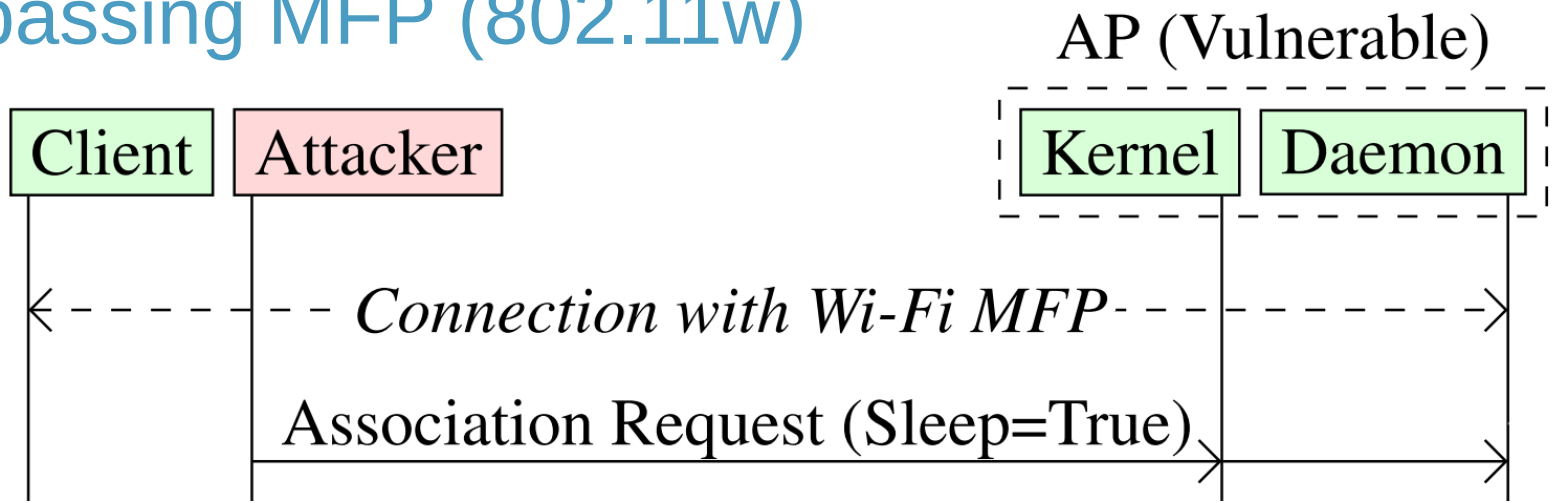

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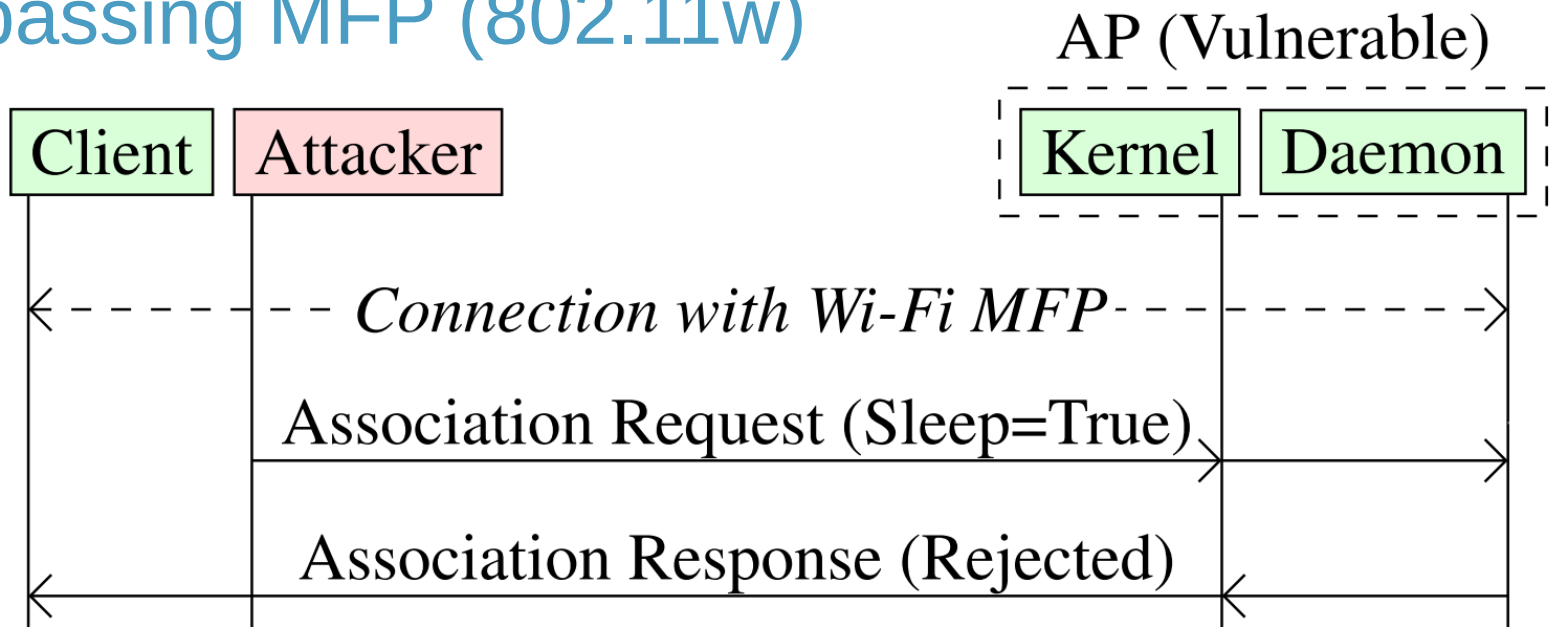

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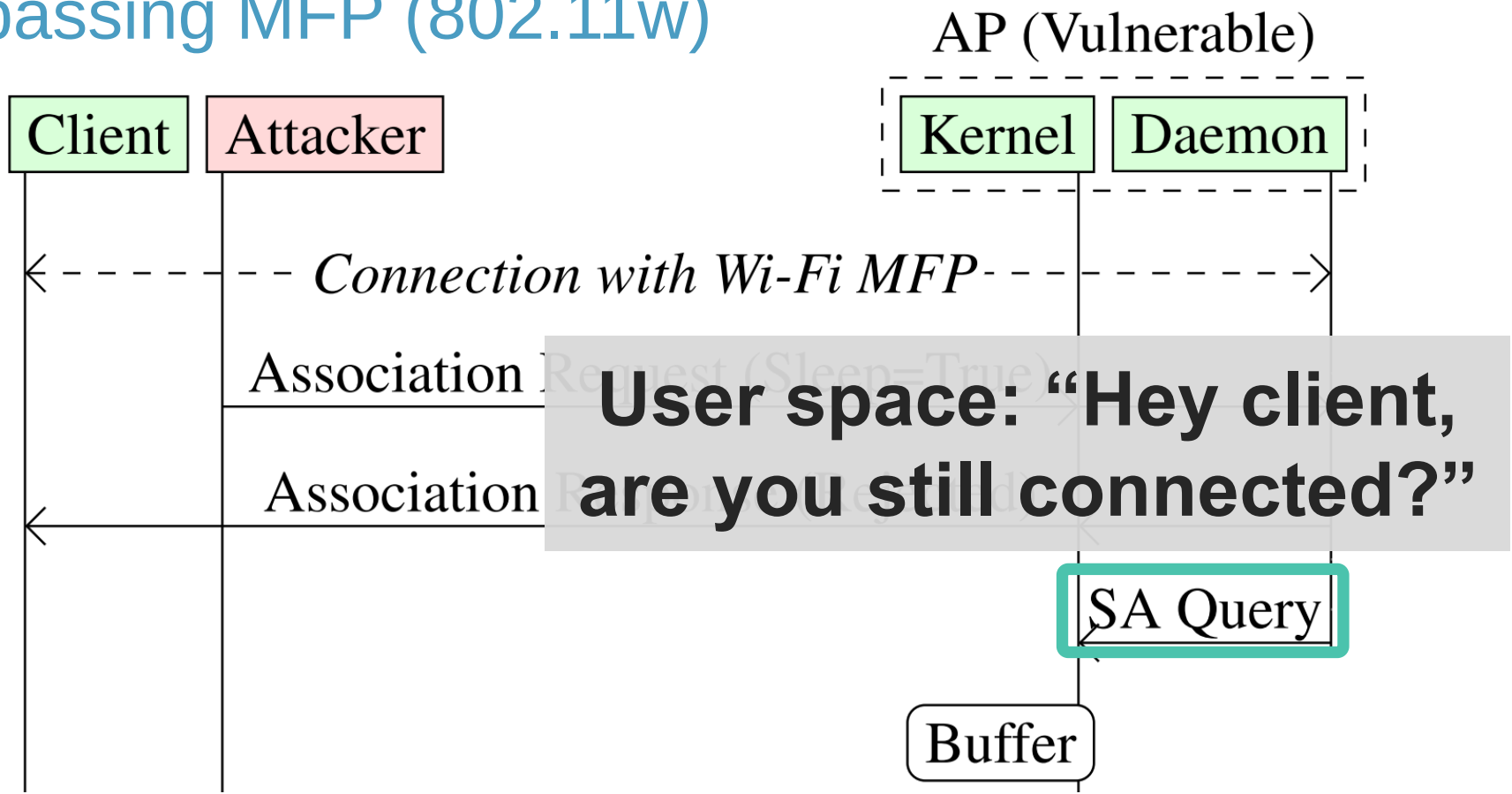

User space: "Hey client, are you still connected?"

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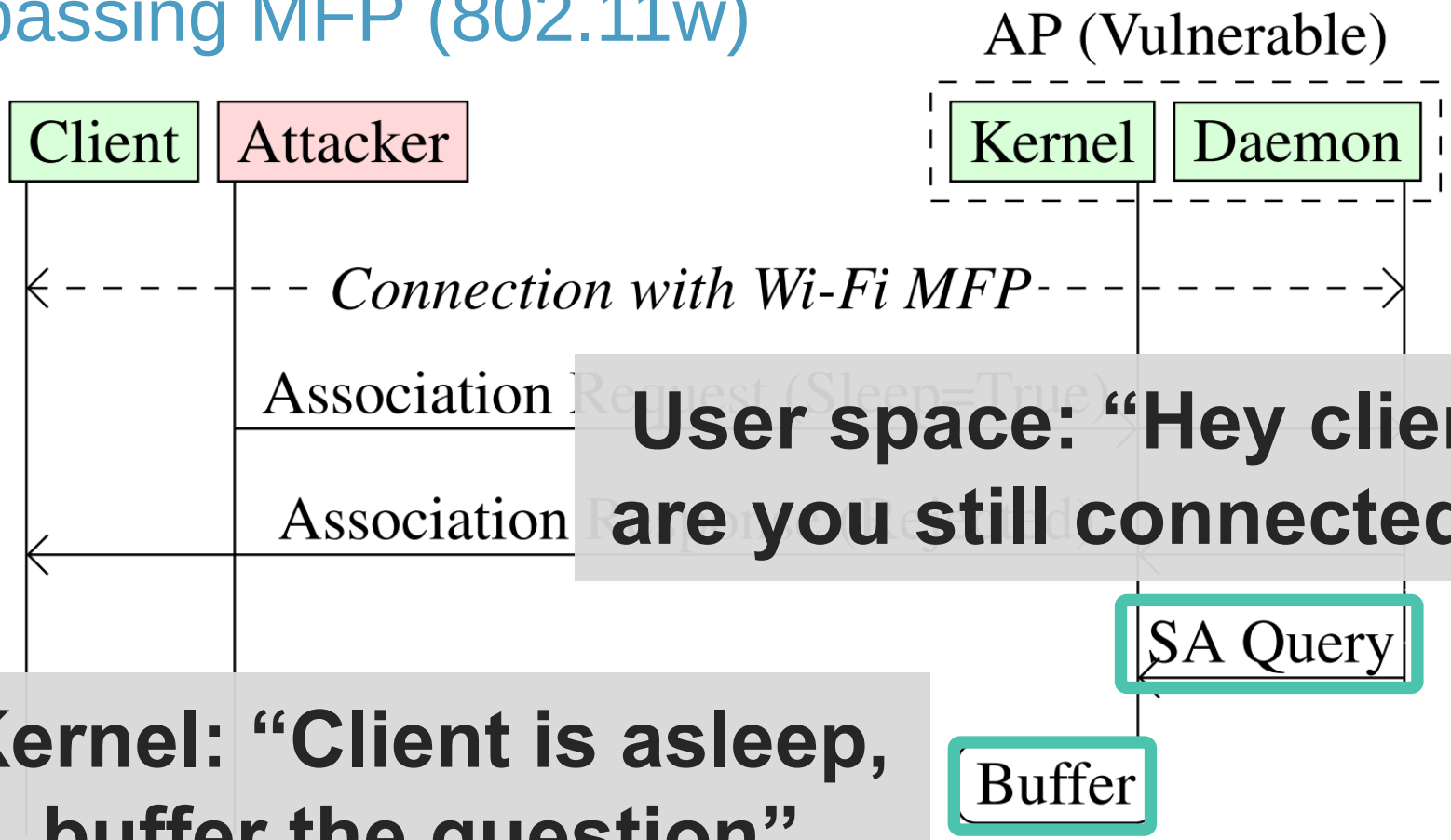
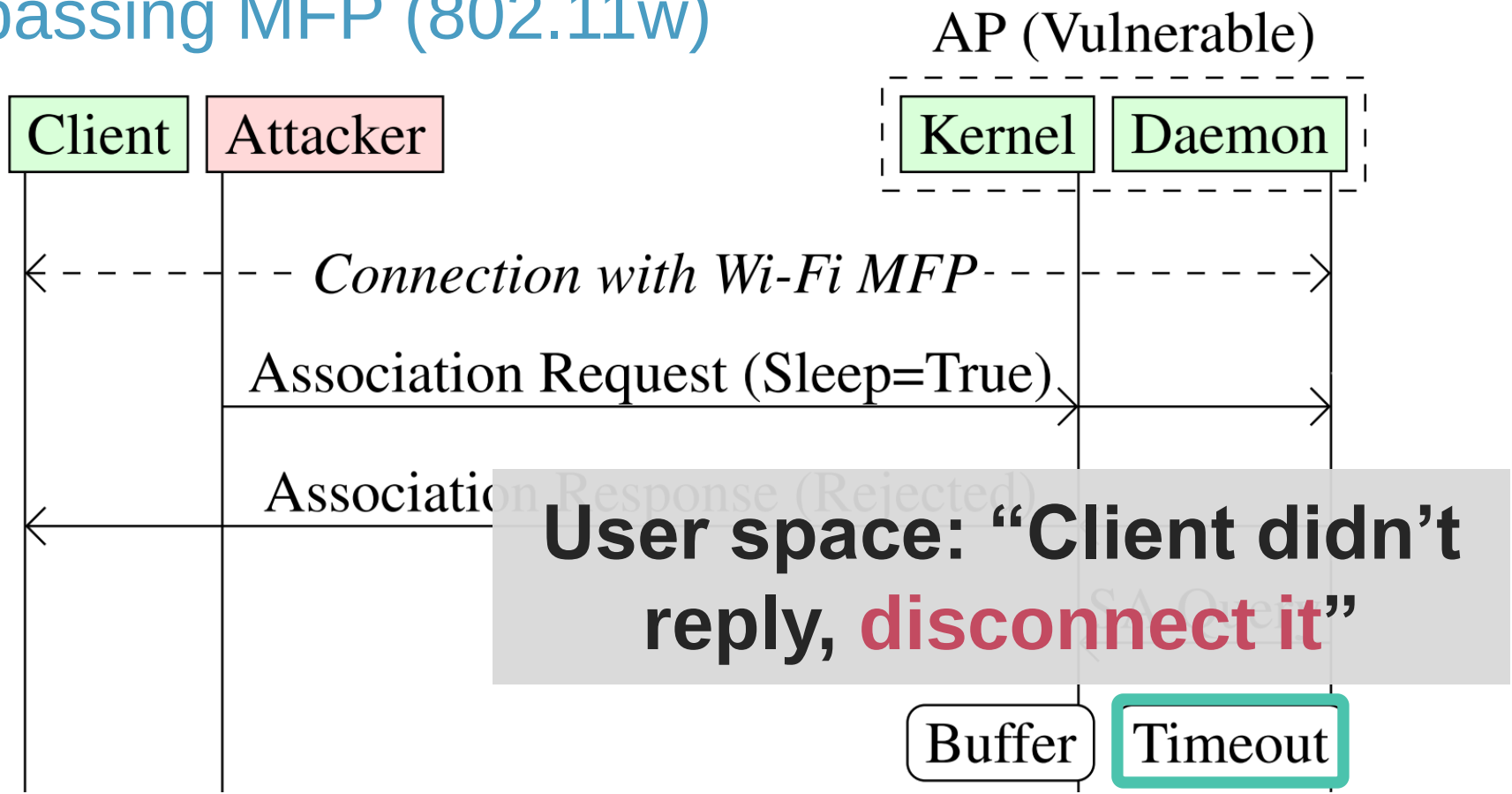


User space: "Hey client, are you still connected?"

Kernel: "Client is asleep, buffer the question"

Bypassing MFP (802.11w)



User space: “Client didn’t reply, disconnect it”

Other Attacks & Defenses

Can also **force buffering of Fine Timing Measurements** frames

- Used to measure distance to AP and localize device
- For details, see our USENIX Security ‘23 paper “Framing Frames”

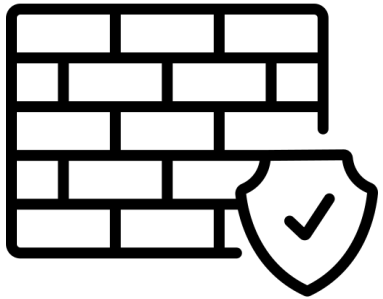
Defenses:

- Never buffer “are you still connected?” frames
- Authenticate the sleep bit in the header of Wi-Fi frames

New attack 3:

Bypassing client isolation

What is client isolation?



Blocks traffic between clients:

- Clients **cannot attack each other**
- ARP spoofing is not possible

All clients have unique encryption keys:

- Prevents “Hole 196” attack (Black Hat ’10)

→ **Defends against malicious insiders**

Attack 2: bypassing Wi-Fi client isolation

Attack targets networks that use **client isolation**:

- Defense against malicious or compromised internal clients
- Used by networks on large organizations, universities, hotspots,…

→ Attacker can connect to the network. But can't communicate with, or attack, others…

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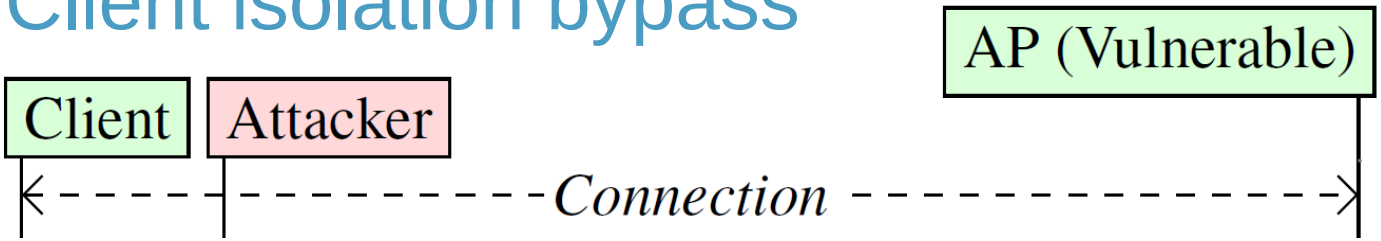
- Defense against malicious or compromised internal clients
- Used by networks on large organizations, universities, hotspots,…

→ Attacker can connect to the network. But can't communicate with, or attack, others… unless we manipulate the security context!

Client isolation bypass



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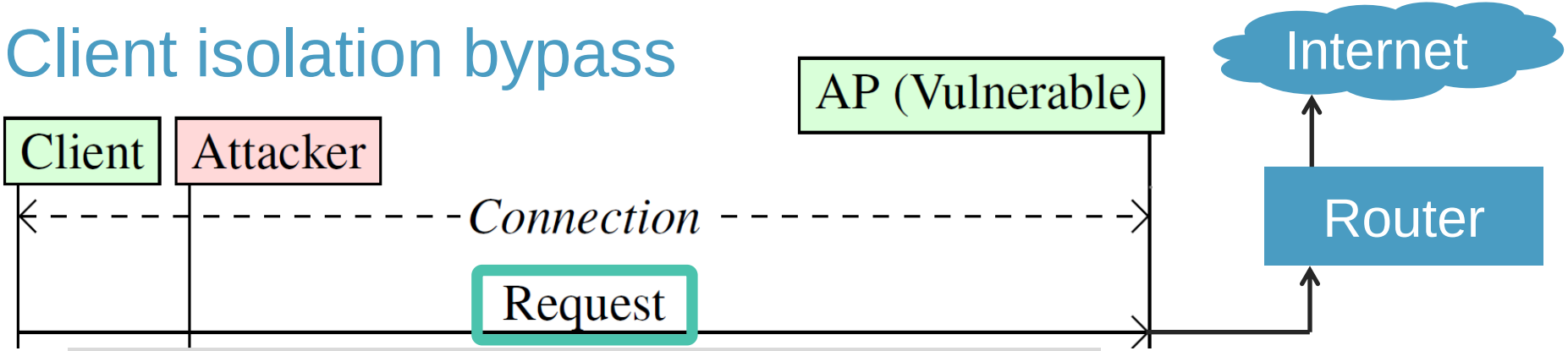
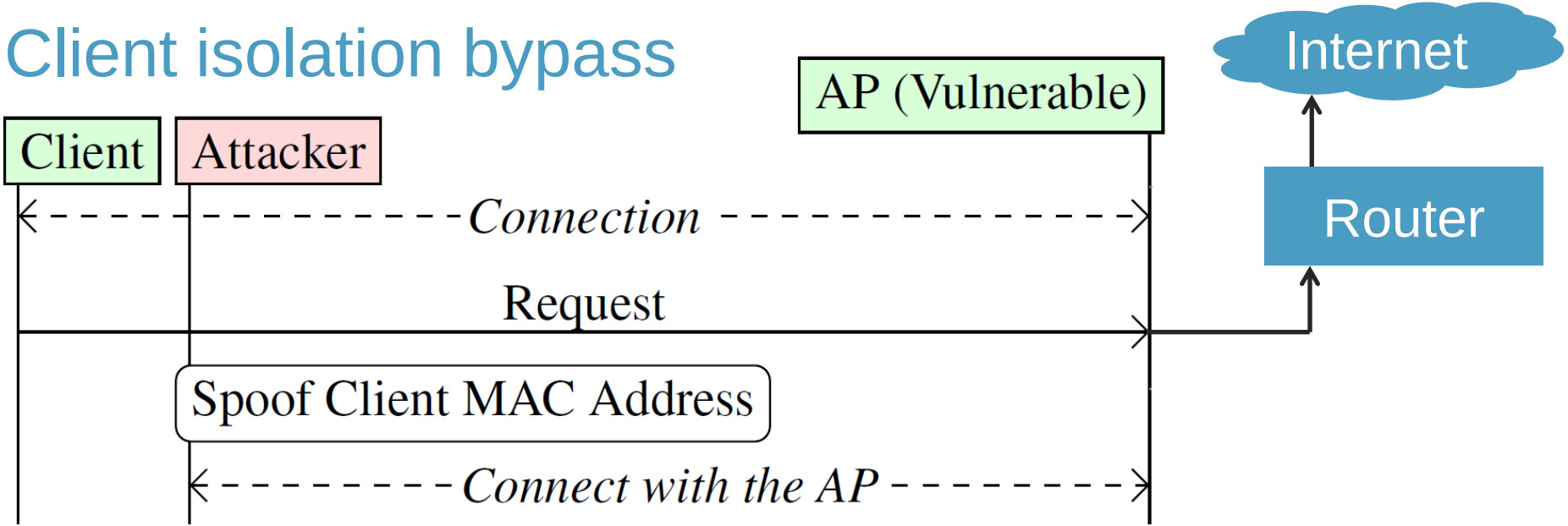


E.g., DNS or HTTP request

Client isolation bypass



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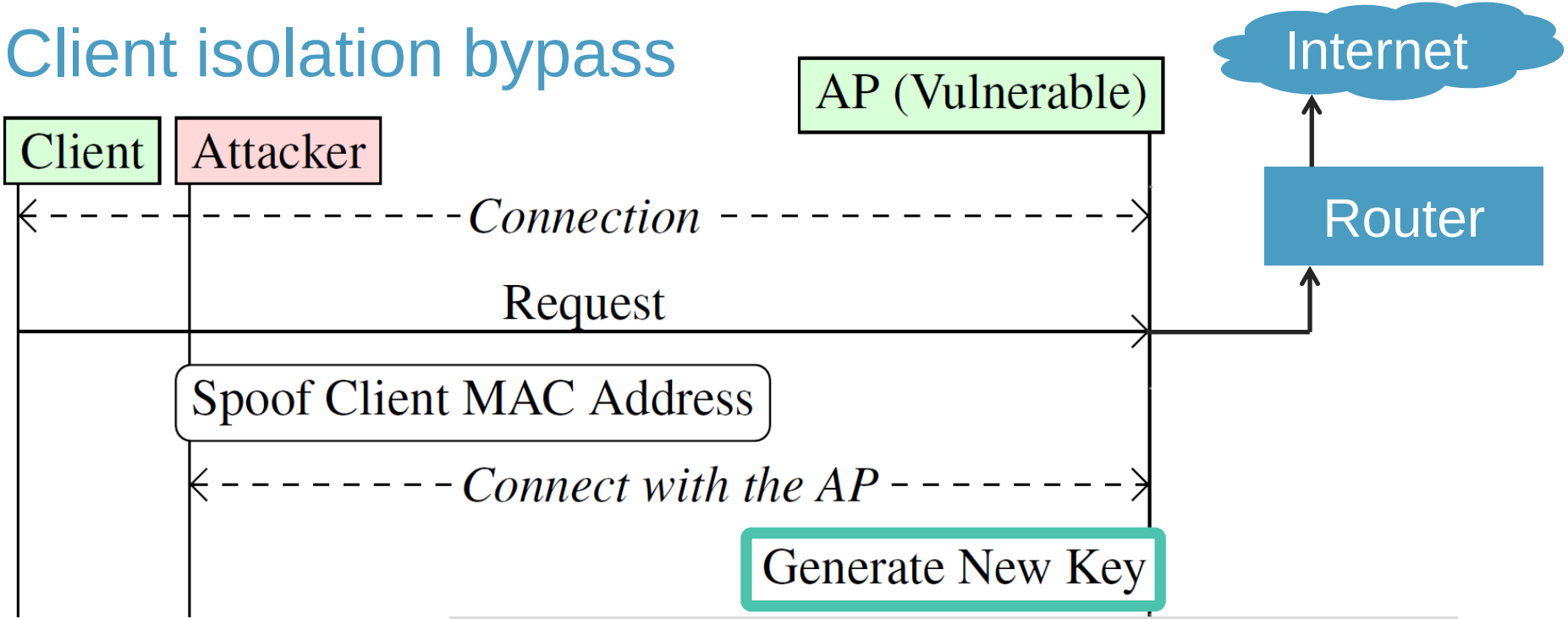
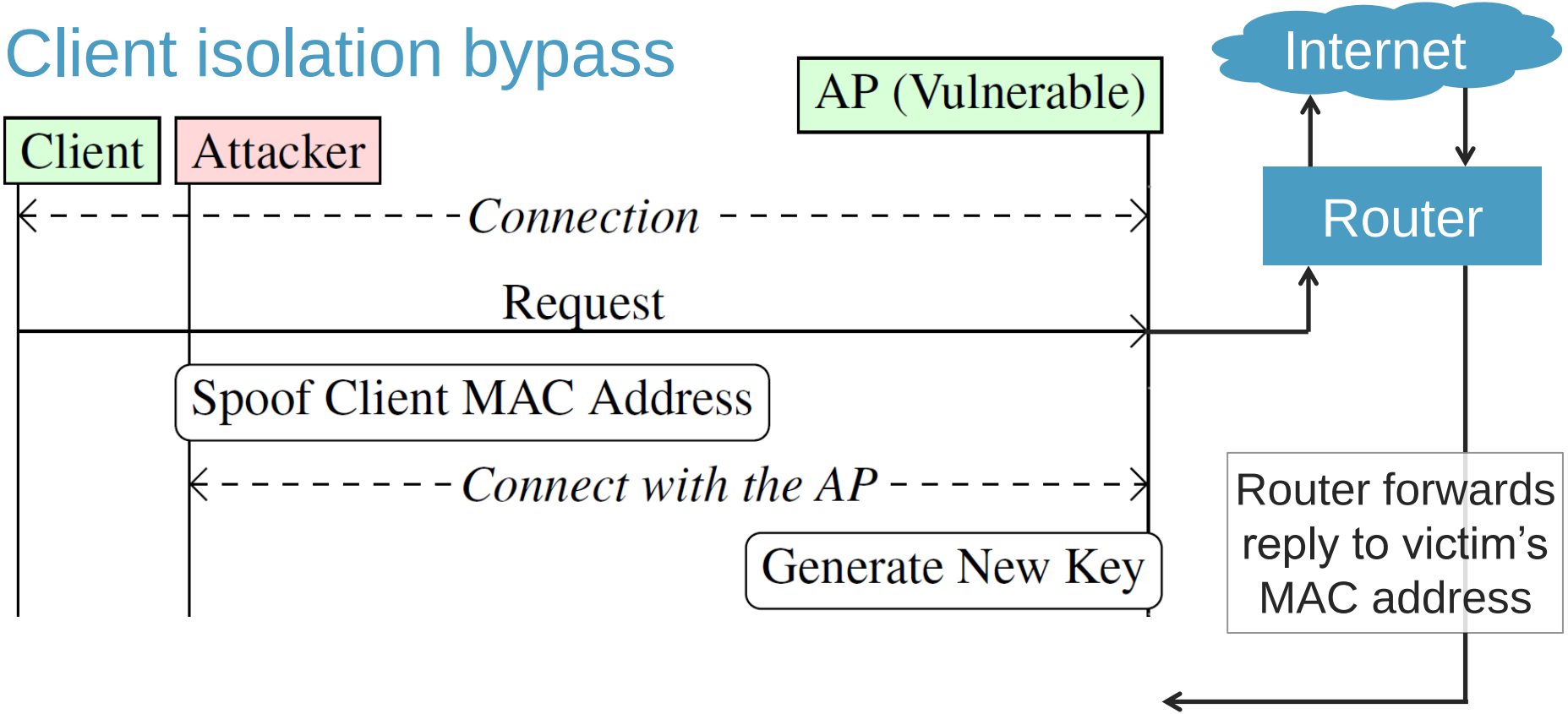


New key is associated with the victim's MAC address

Client isolation bypass



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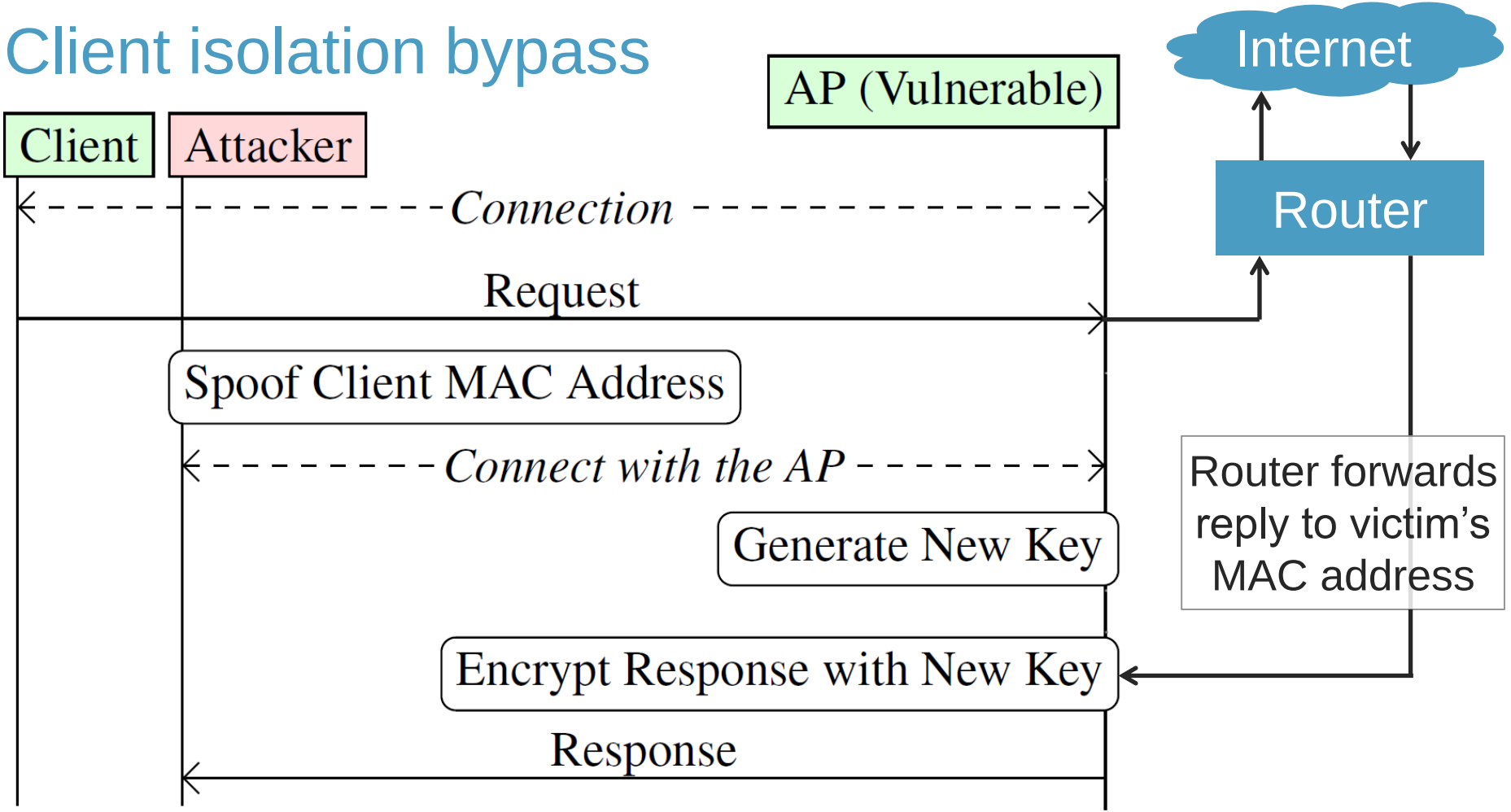
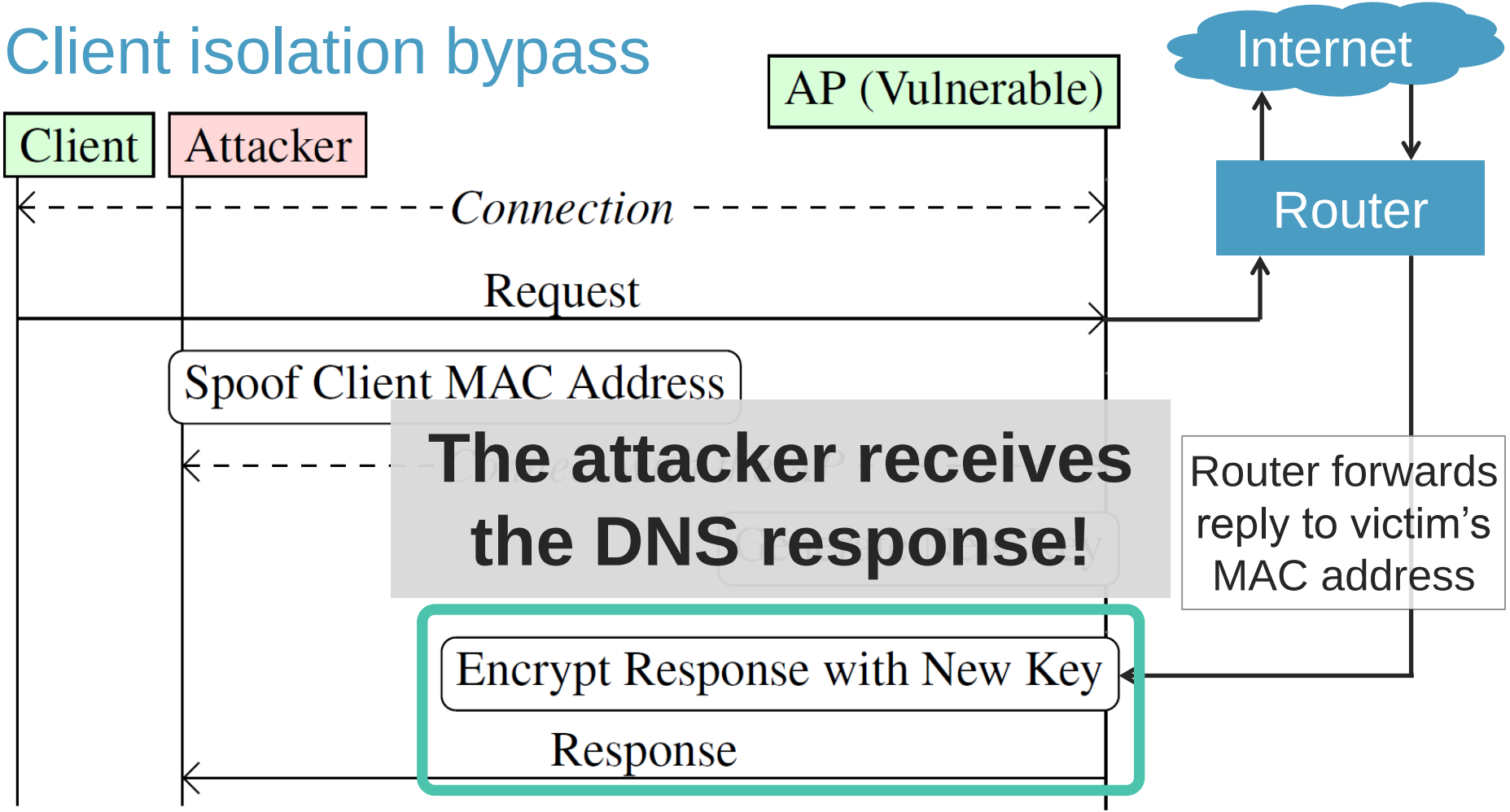


Client isolation bypass



Tool to test devices: MacStealer

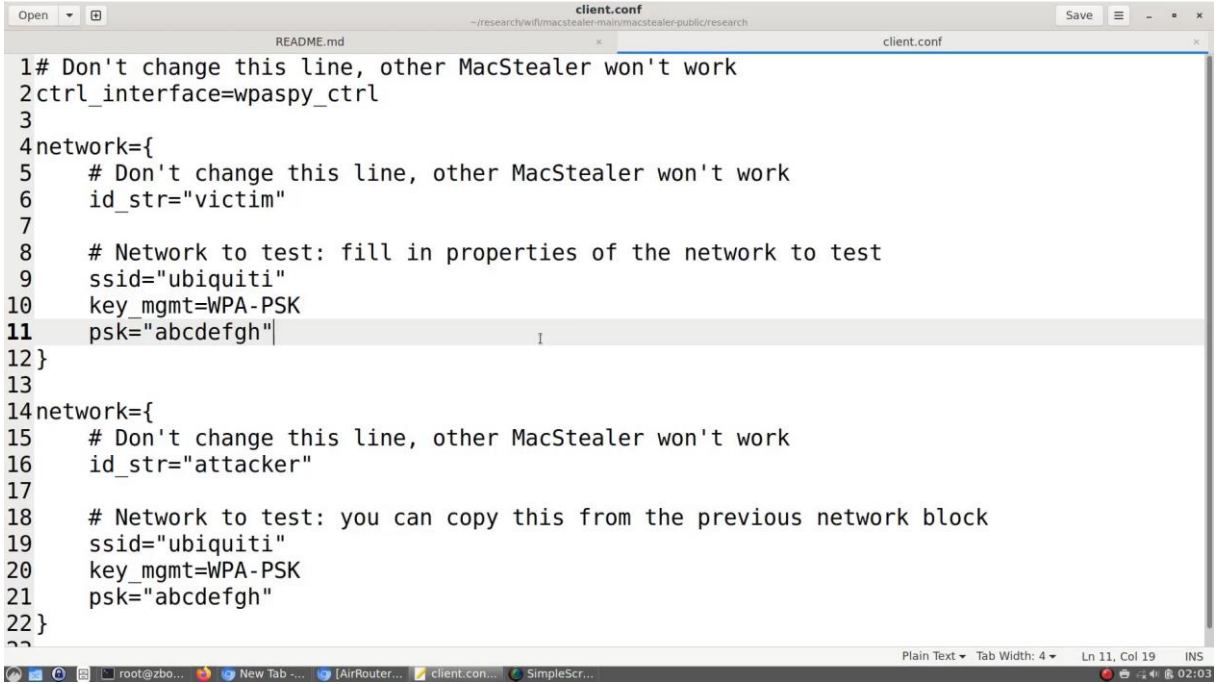
Command	Short description
Sanity checks	
`./macstealer.py wlan0 --ping`	Connect as victim & test server's retransmission behavior.
`./macstealer.py wlan0 --ping --flip`	Connect as attacker & test server's retransmission behavior.
Vulnerability tests	
`./macstealer.py wlan0`	Test the default variant of the MAC address stealing attack.
`./macstealer.py wlan0 --other-bss`	Let the attacker connect with a different AP than the victim.
Client isolation: Ethernet layer	
`./macstealer.py wlan0 --c2c wlan1`	Test client isolation on the Ethernet layer.
`./macstealer.py wlan0 --c2c-eth wlan1`	Test client isolation on the Ethernet layer (DNS).

Sanity checks

Vulnerability tests

Does the network use client isolation?

MacStealer demo



→ Ubuiqiti is one of the few vendors that implemented a mitigation!

Experiments

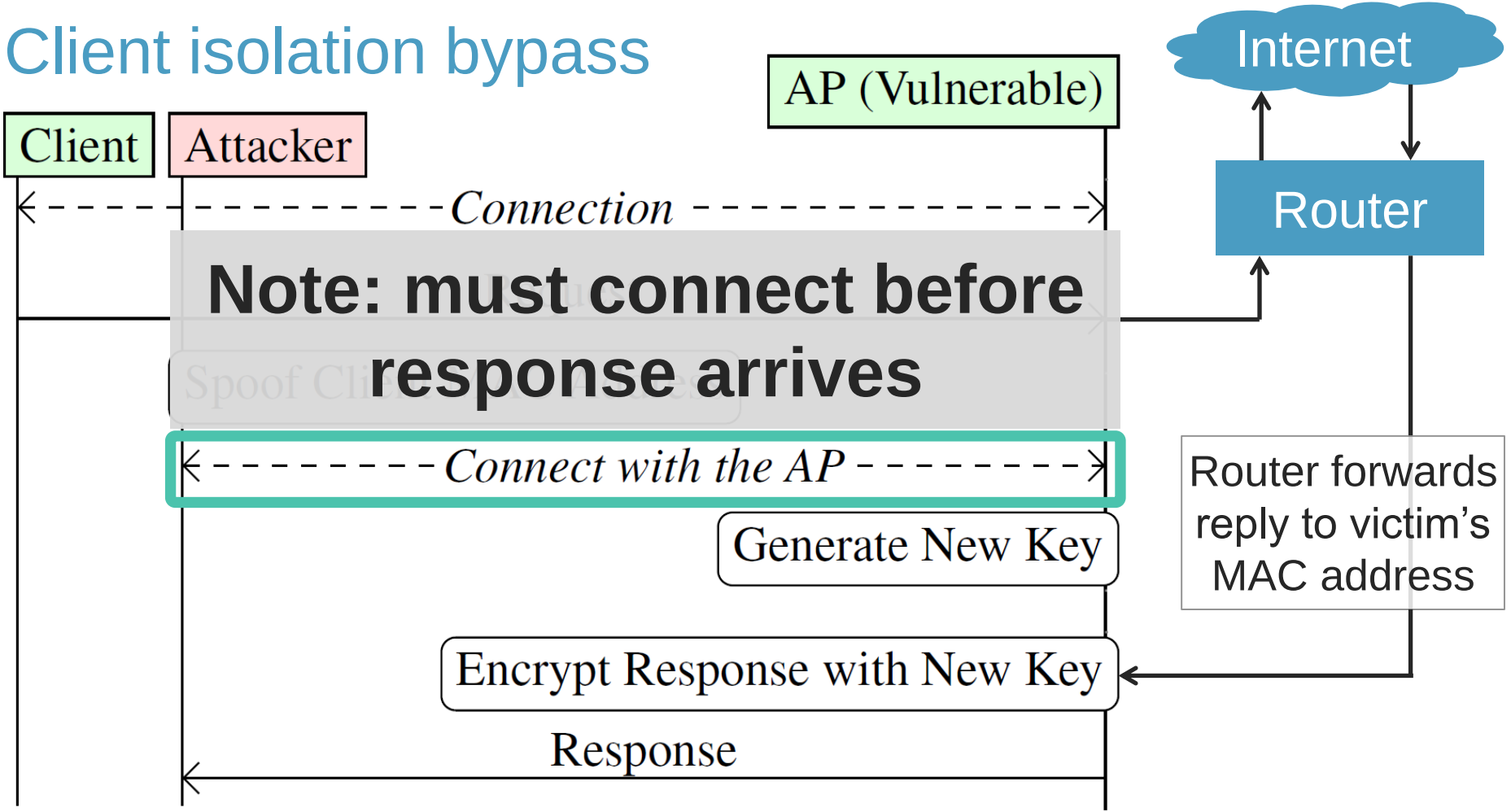
All tested professional & home APs were vulnerable

→ **Design flaw** in Wi-Fi client isolation!

→ Useful test for auditors

github.com/vanhoefm/macstealer

Client isolation bypass



Fast security context override

Technique to quickly reconnect. Experiments:

- Minimum reconnect time: ~12 ms
- Average UDP response time: [Verizon]
  - Transatlantic connections: ~70 ms
  - Connections within Europe: ~13 ms
- TCP responses are retransmitted → trivial to intercept
- Adversary can spoof MAC address of the default gateway

[Verizon] Verizon IP latency statistics

Root cause

Client identities are not bound to each other:

- Authenticated Wi-Fi 802.1X identity (username)
- But spoofable IP/MAC addresses

  → Wi-Fi attacker can spoof victim's identity on other layers

Other observation: client isolation was "bolted on" by vendors

- Not part of IEEE 802.11 standard → less studied

Fixing client isolation

One defense is disallowing recently-used MAC address, unless:

- Certain amount of time has passed (incomplete defense)
- We know it's the same user as before (complete defense)
  - Based on 802.1X identity or cached keys (not always available)

→ These aren't ideal fixes: impractical, incomplete, unreliable,…

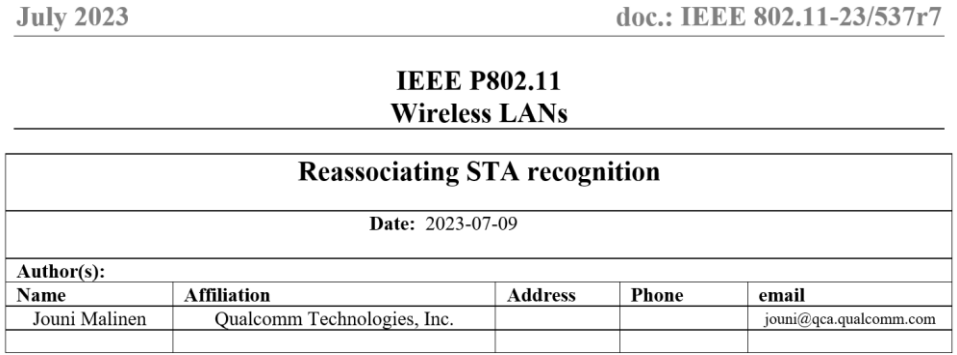
Current situation in practice

Currently few vendors implemented a defense or mitigation

- **Don’t rely on client isolation for security**
- Alternative: use VLANs to isolate groups

Accepted standard update:

- Recognize returning client
- Further updates being discussed in 802.11bh



July 2023 doc.: IEEE 802.11-23/537r7

IEEE P802.11
Wireless LANs

Reassociating STA recognition

Date: 2023-07-09

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Conclusion

Standard is vague on how to manage buffered frames

- Can **leak frames** under different security context
- Important to **model/define transmit queues**

Can partially **bypass client isolation**

- All devices vulnerable → **design flaw**
- Hard to fully prevent