black hat ASIA 2023

MAY 11-12

BRIEFINGS

Sweet Dreams:

Abusing Sleep Mode to Break Wi-Fi Encryption & Disrupt WPA2/3 Networks

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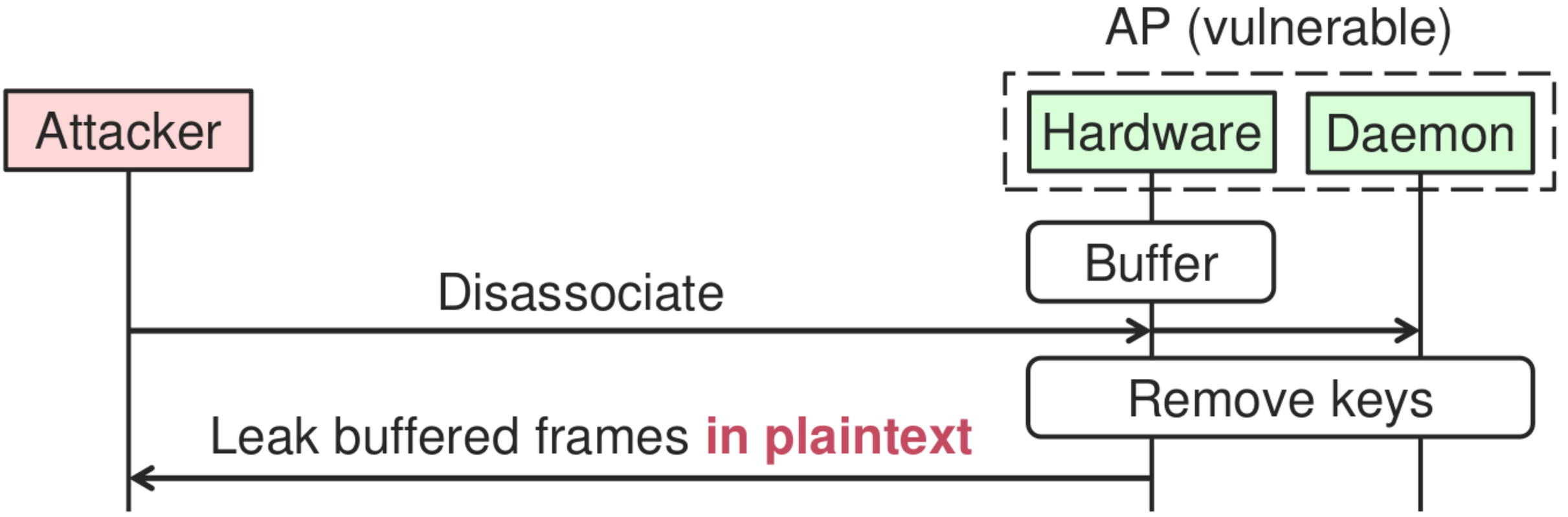
History of Wi-Fi

- 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**?

New attack 1: leaking frames

Attack 1: leaking frames

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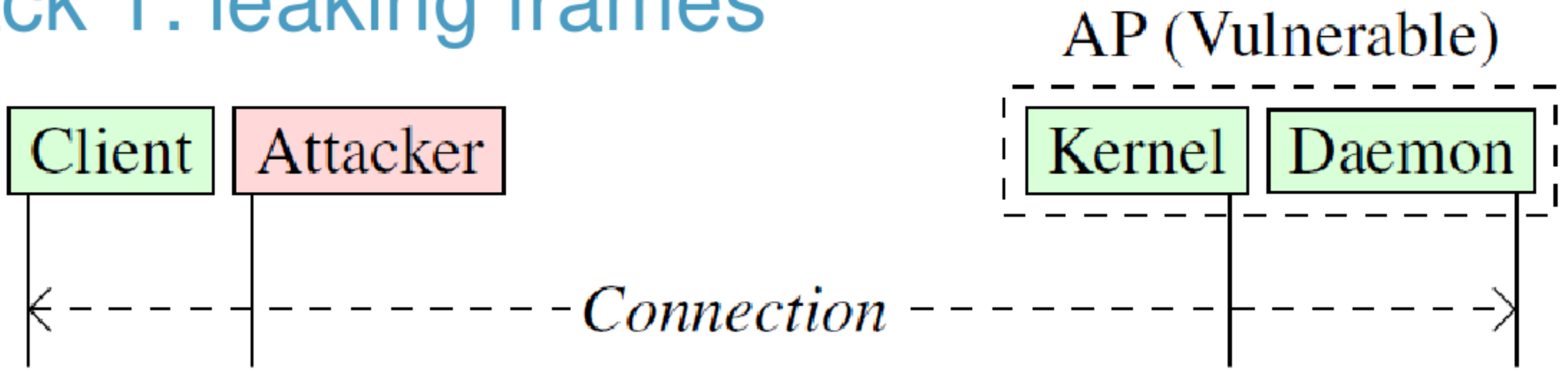
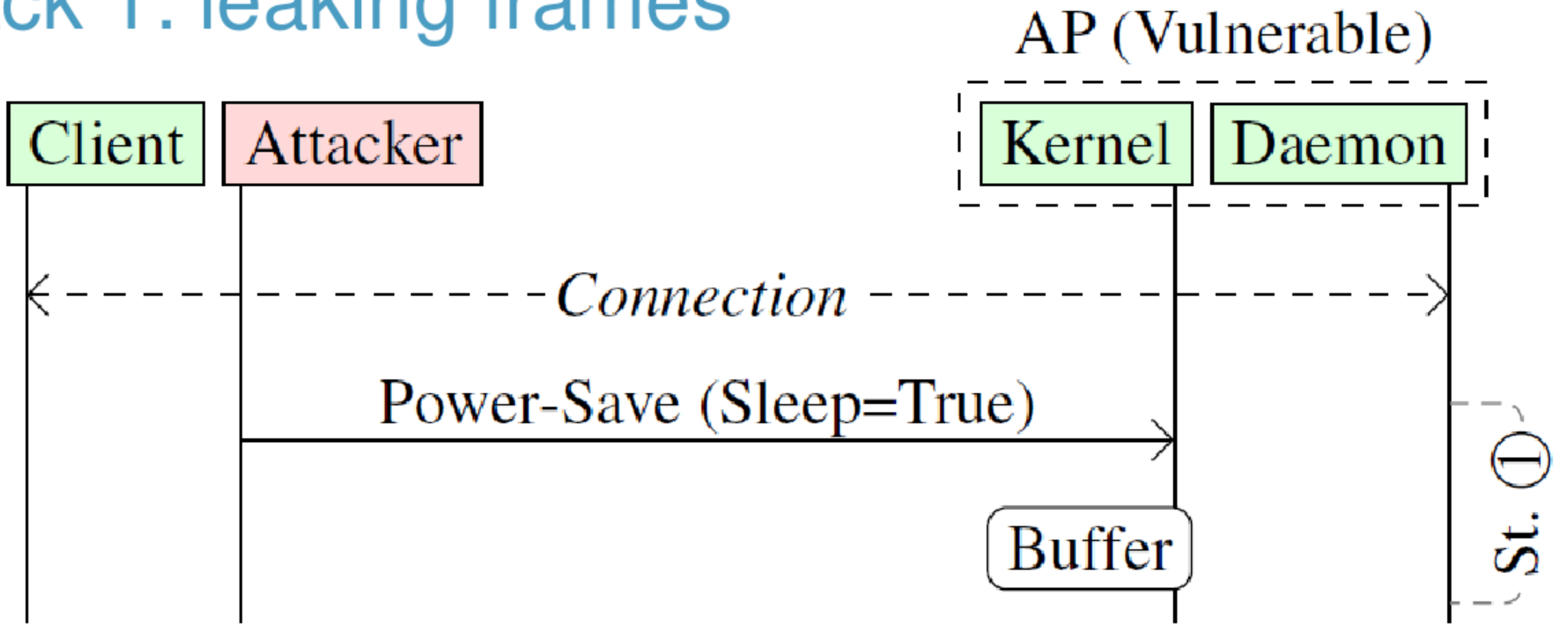


Attack 1: leaking frames



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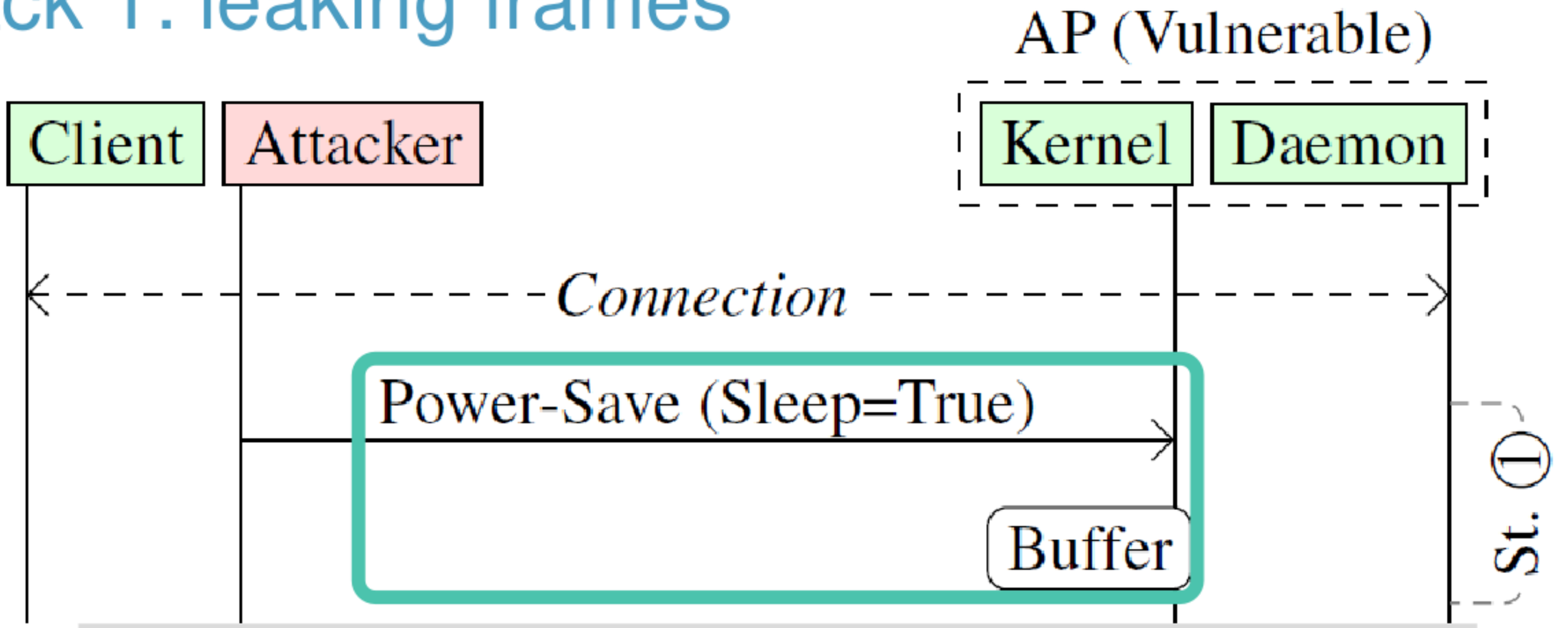
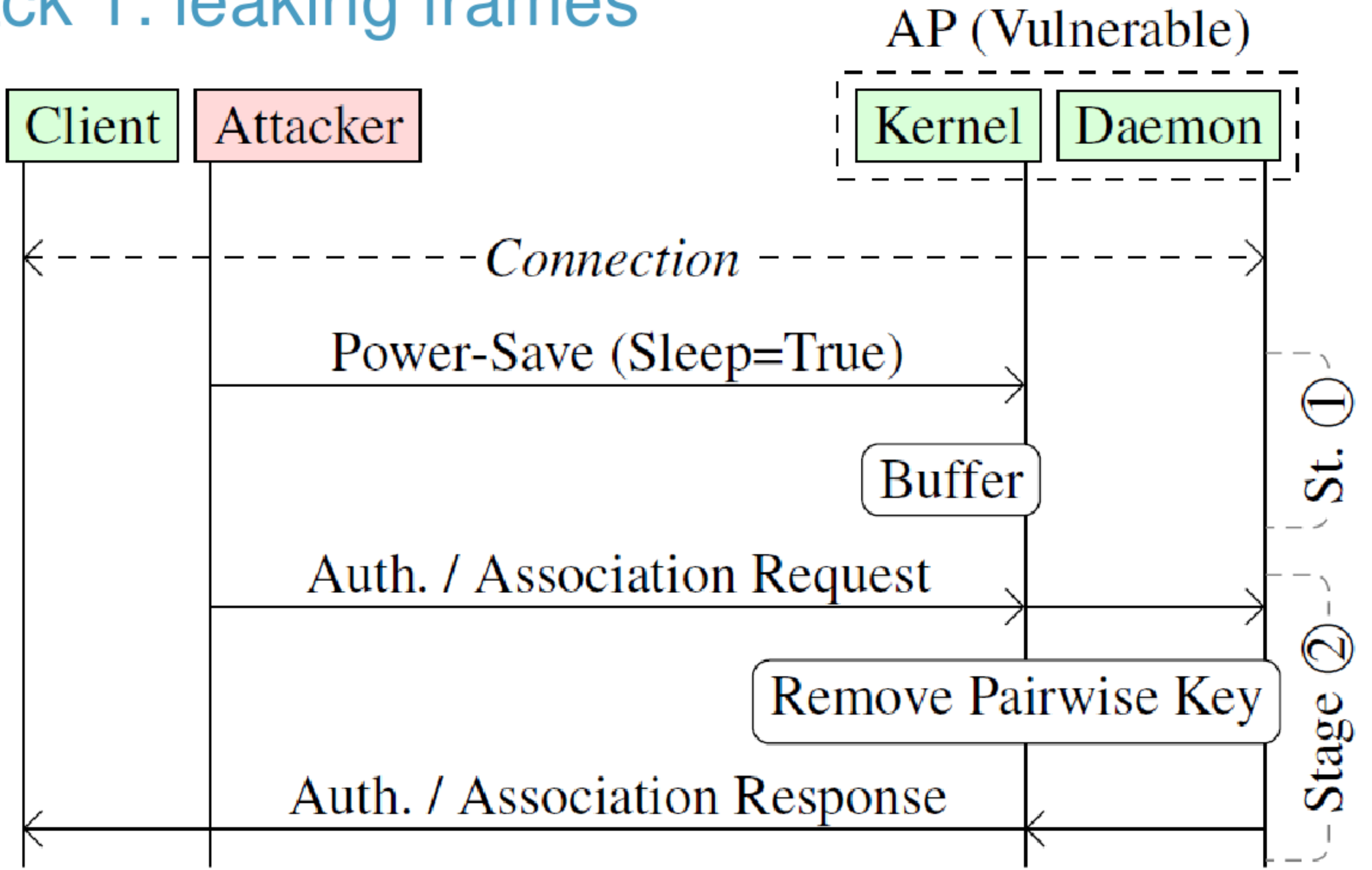


Novelty 1: controlled buffering

Attack 1: leaking frames



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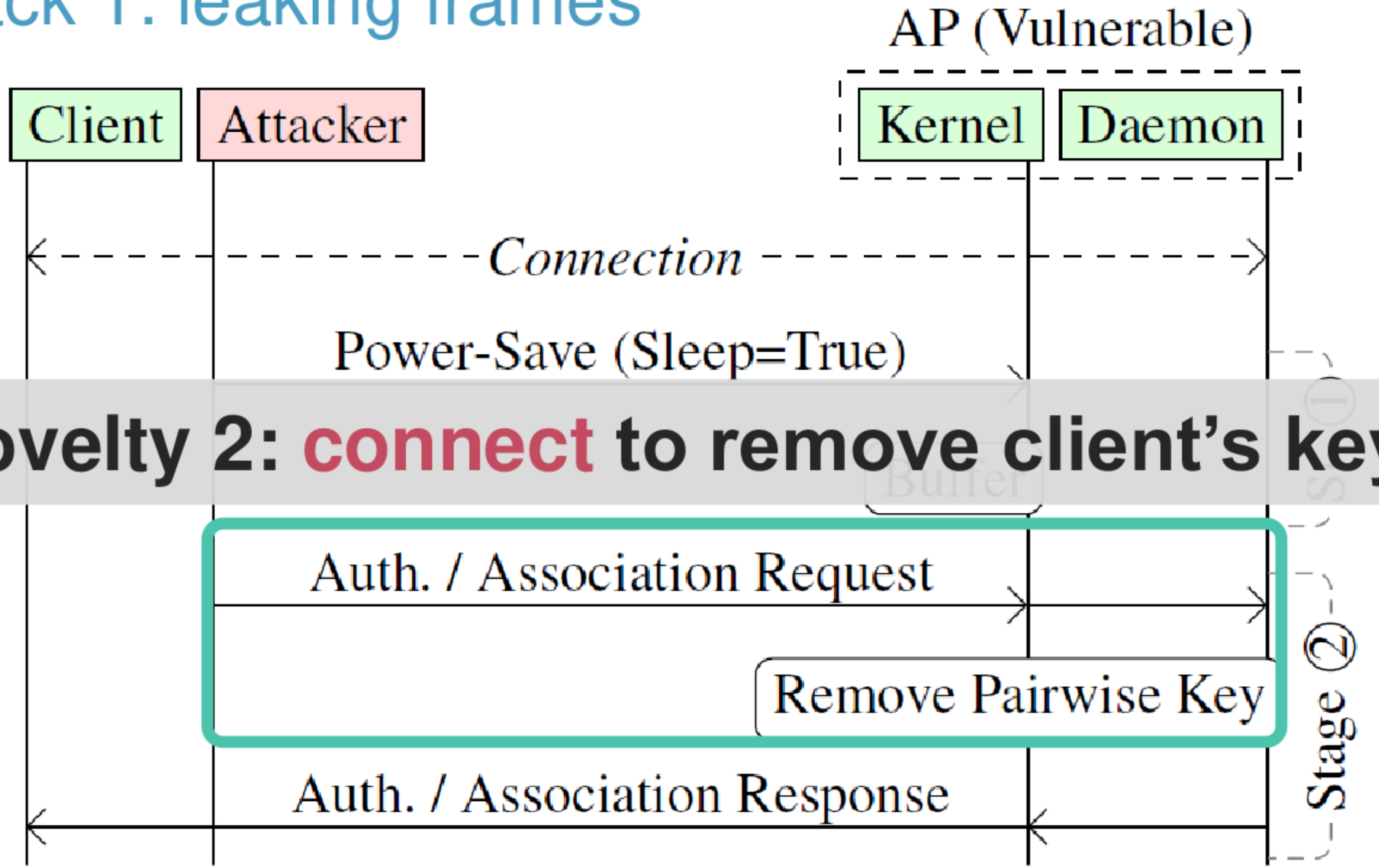
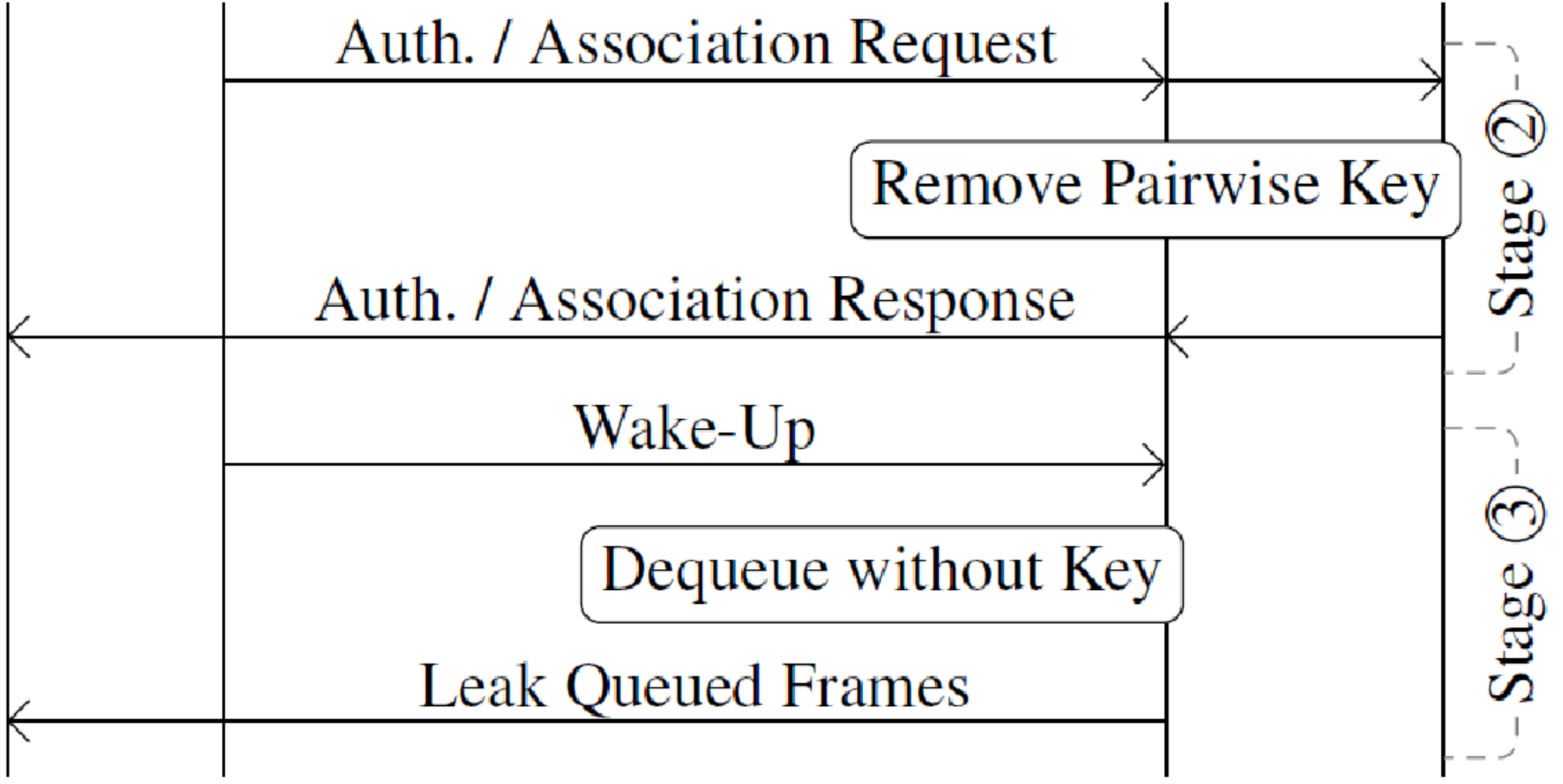
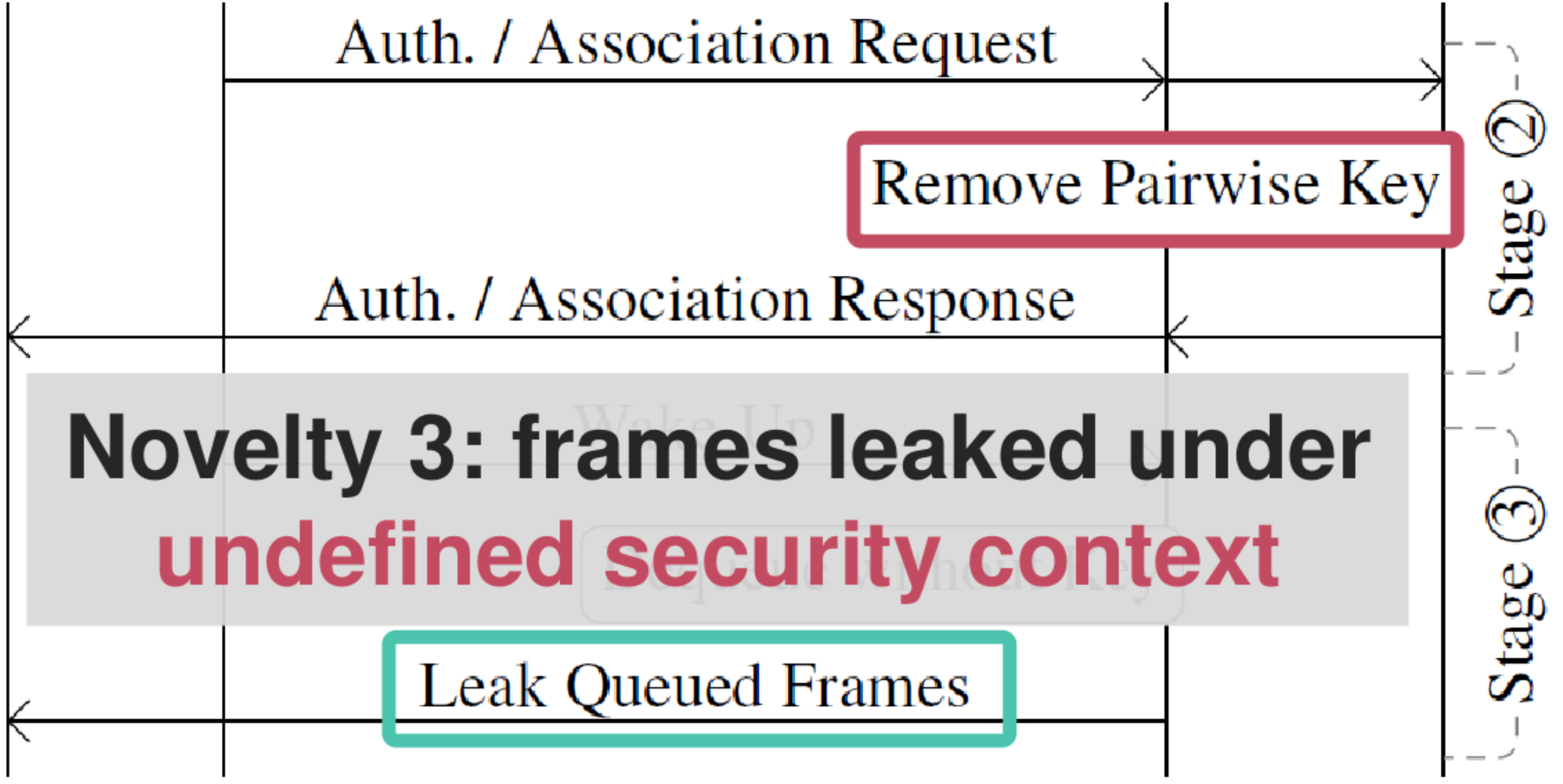


Novelty 2: connect to remove client's keys

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:

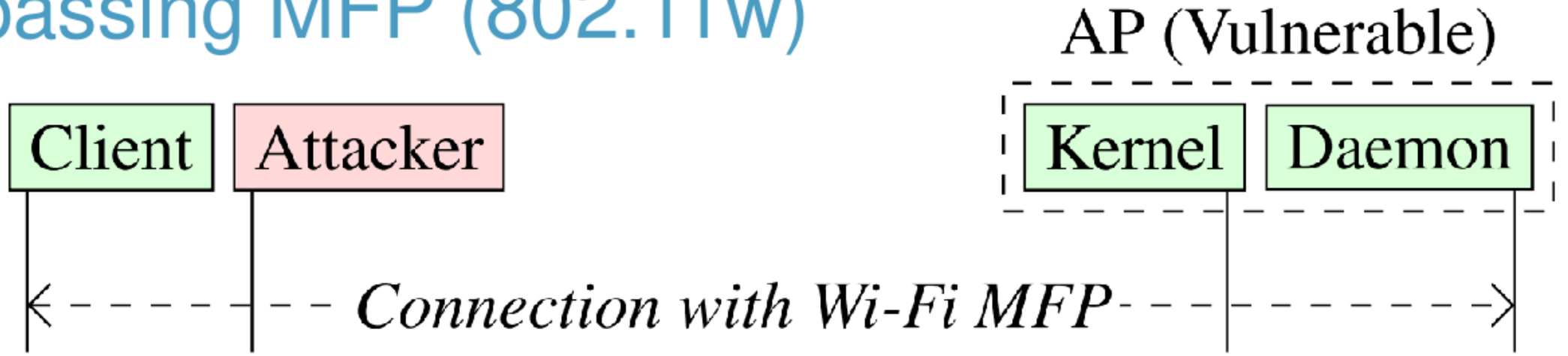
- Deauthentication: spoof “disconnect” frames
- Association: spoof “I want to connect” frames

Both remove connection state of the victim

Defense:

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

Bypassing MFP (802.11w)



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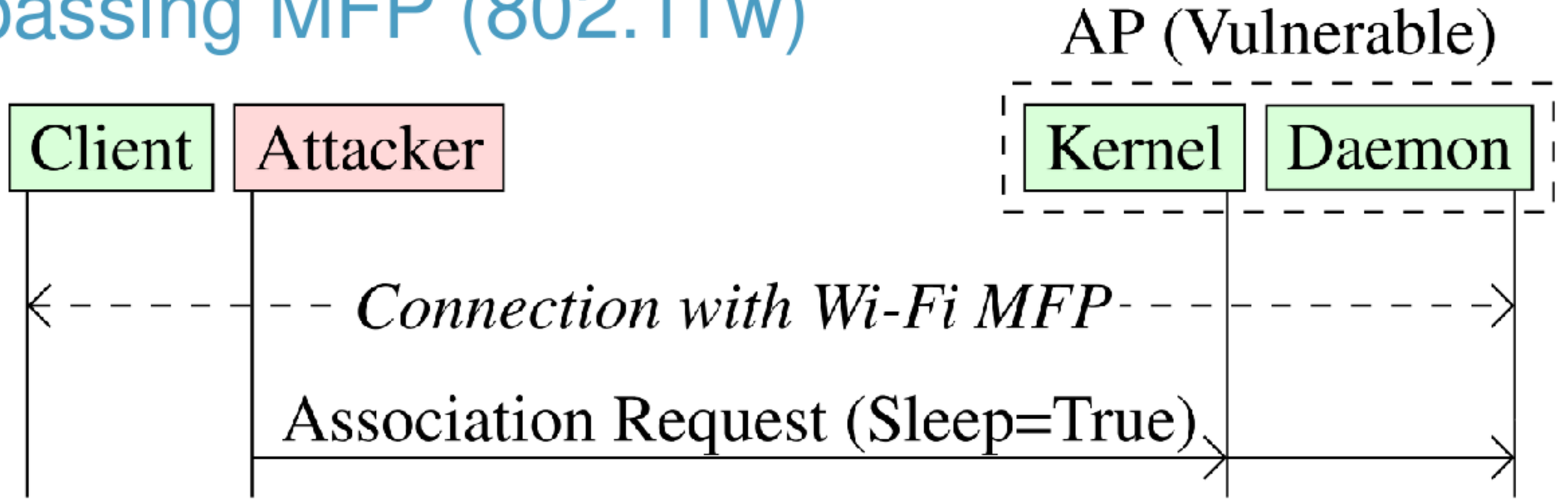

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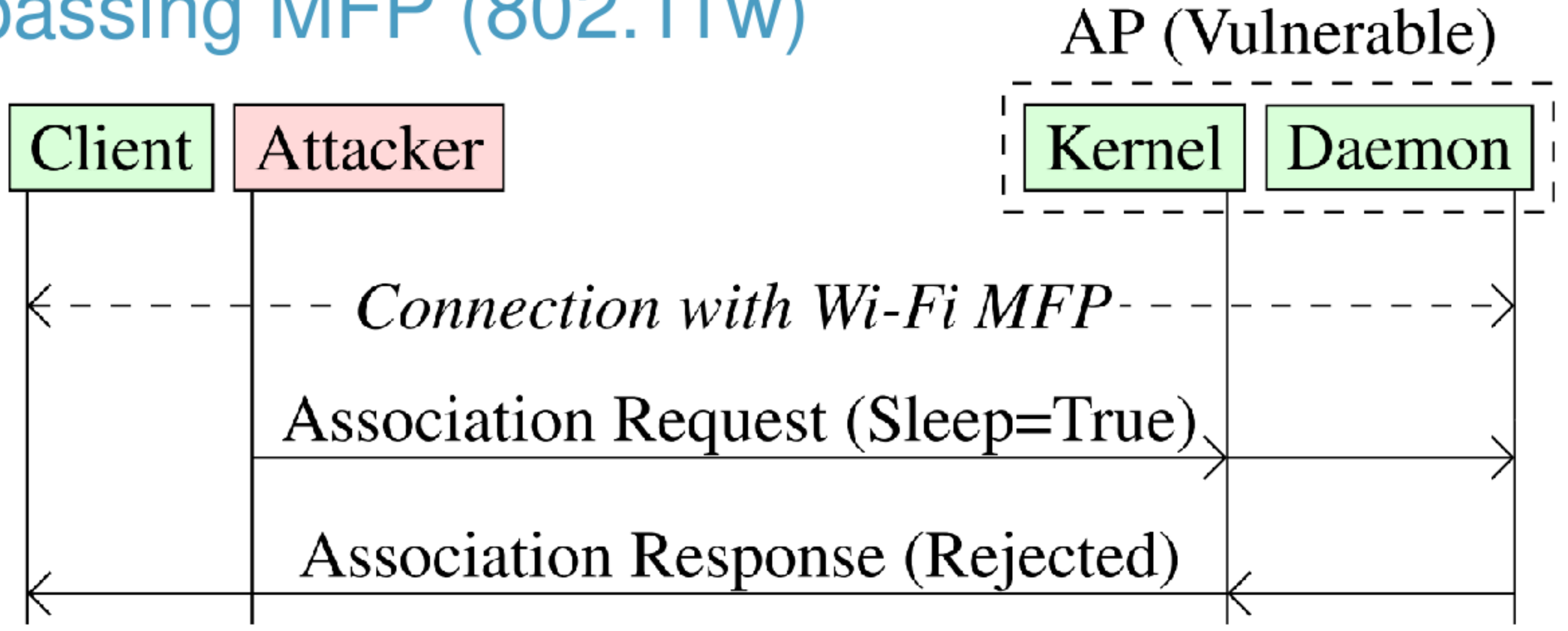

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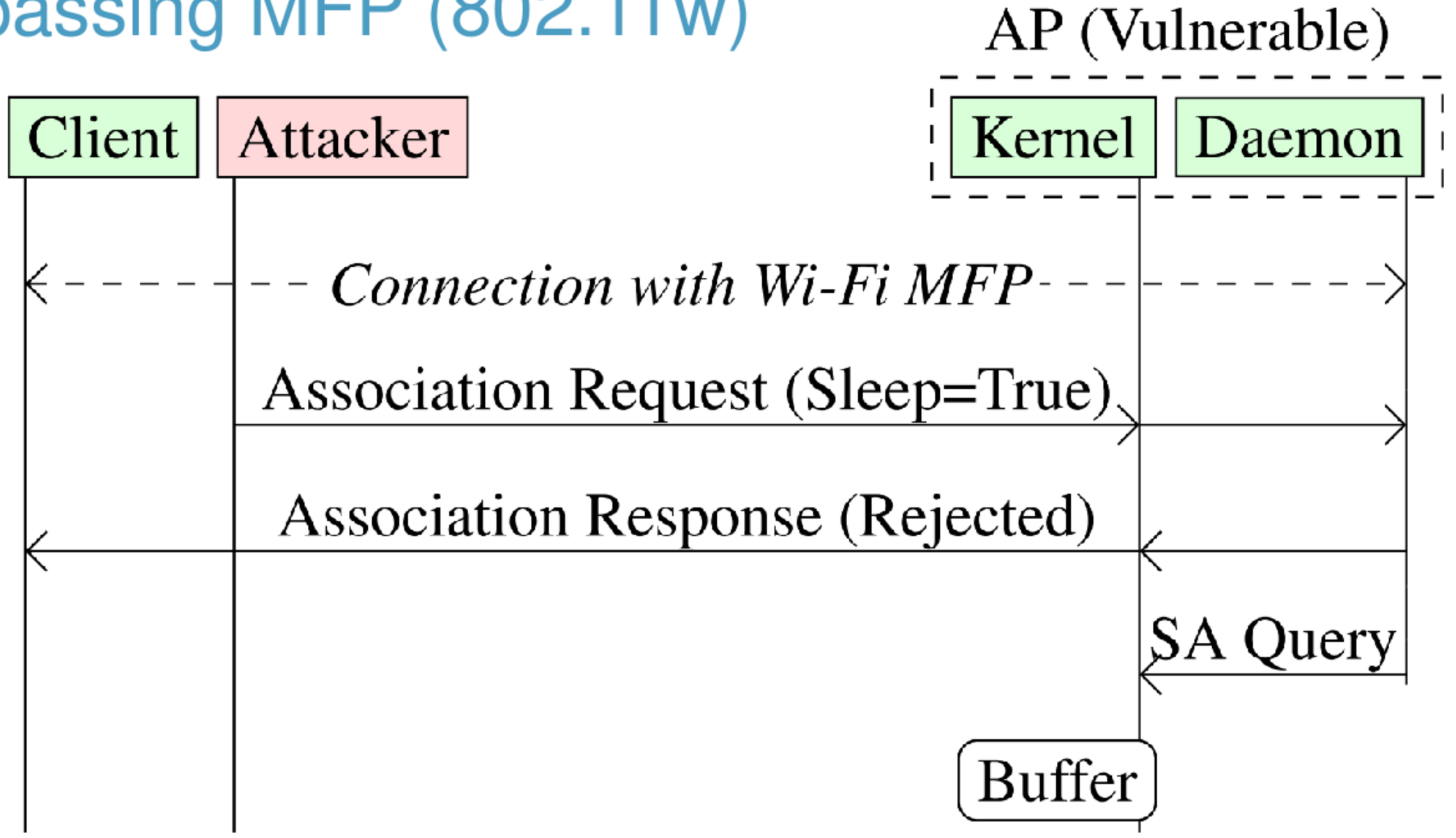

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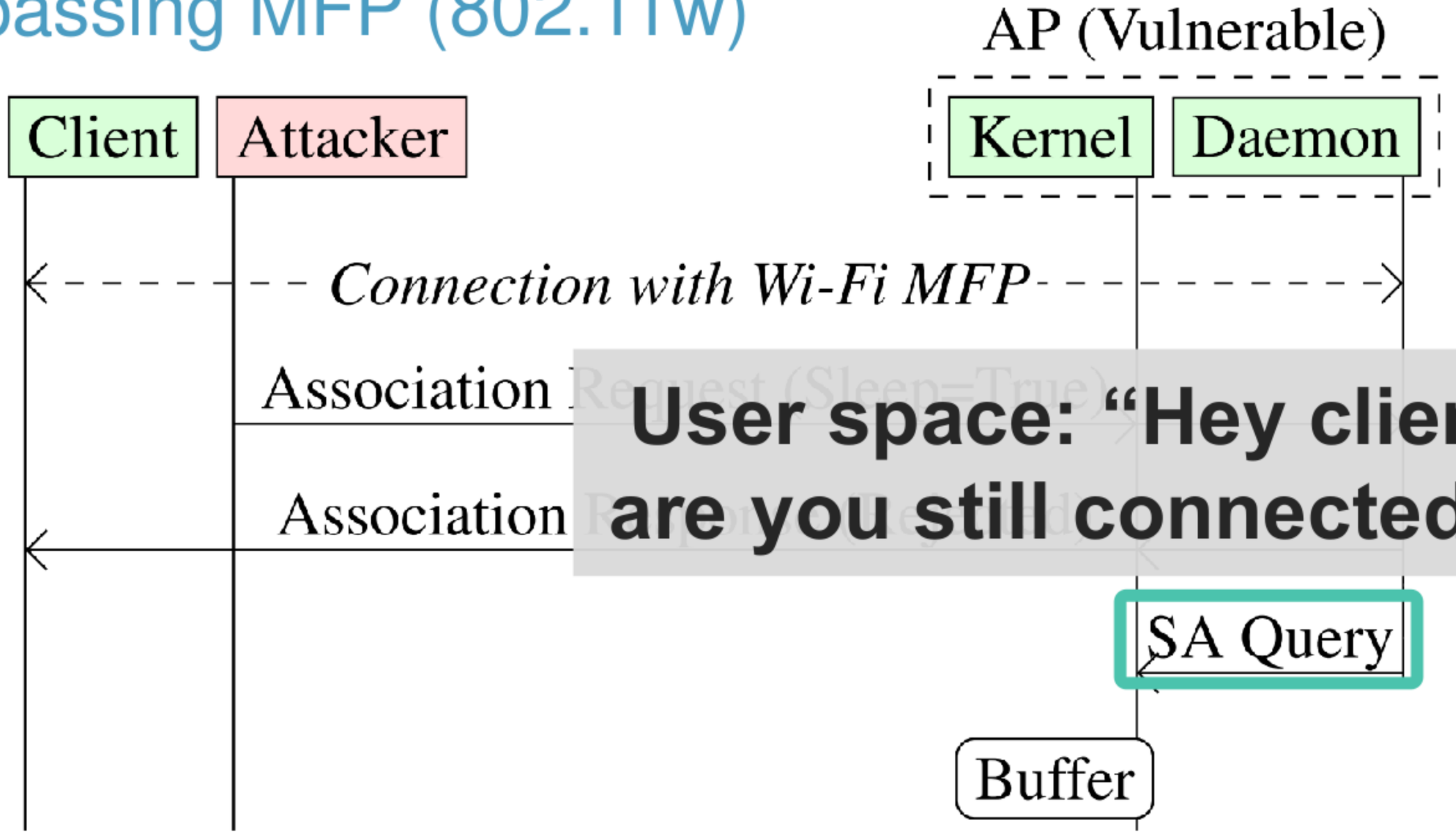
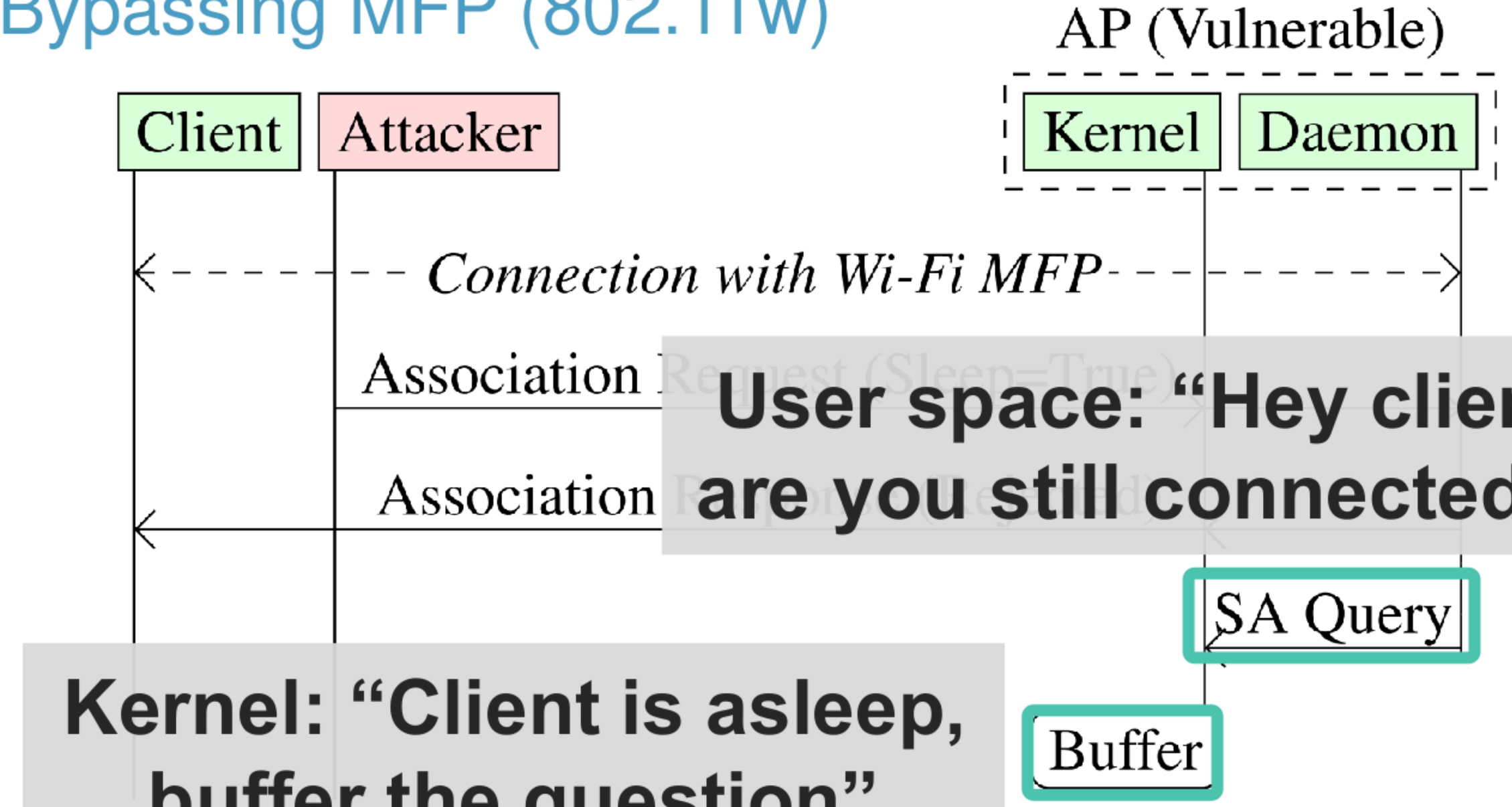


User space: “Hey client, are you still connected?”

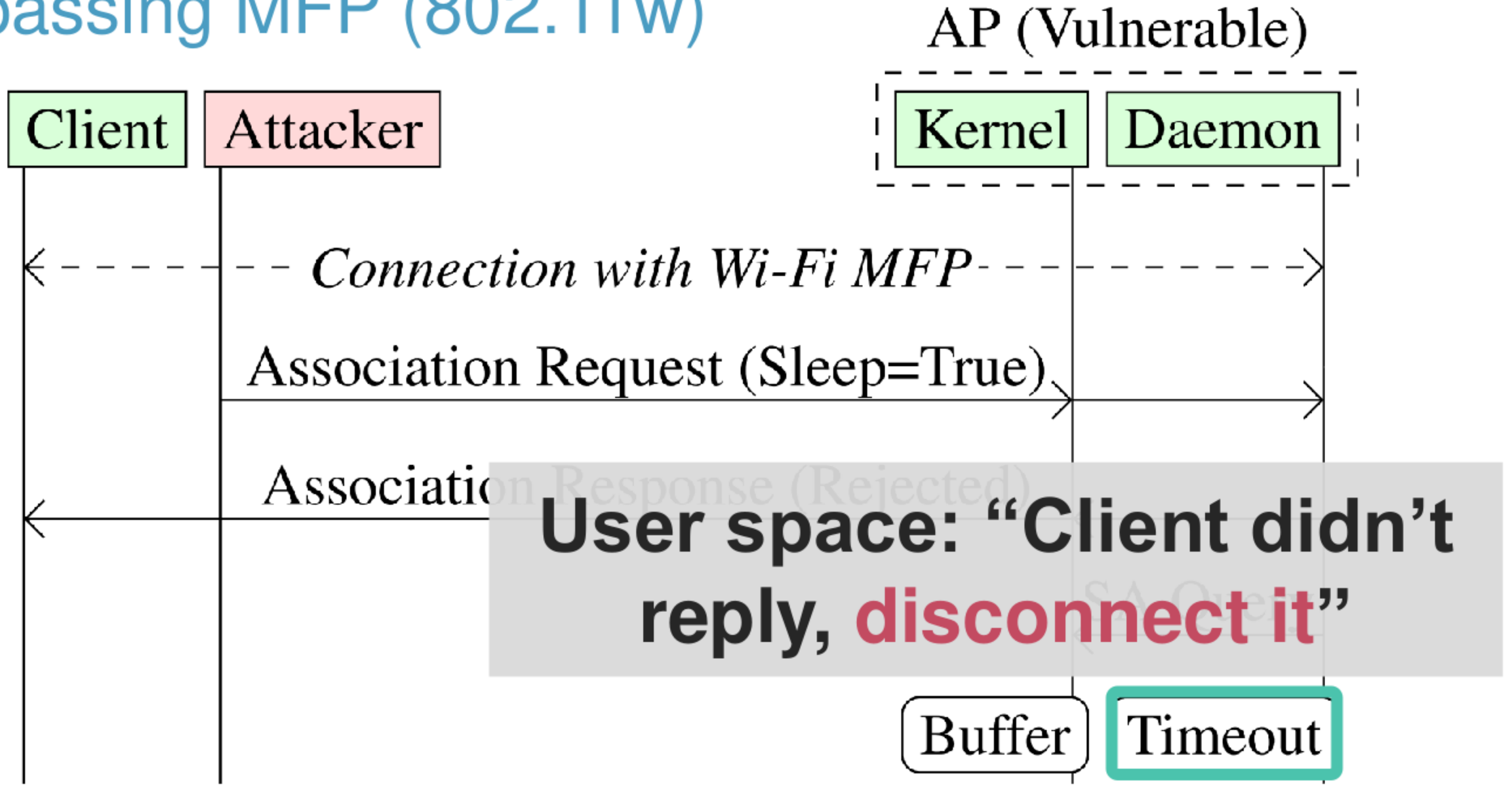
Bypassing MFP (802.11w)



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 paper “Framing Frames: Bypassing Wi-Fi Encryption by Manipulating Transmit Queues” (USENIX Security)

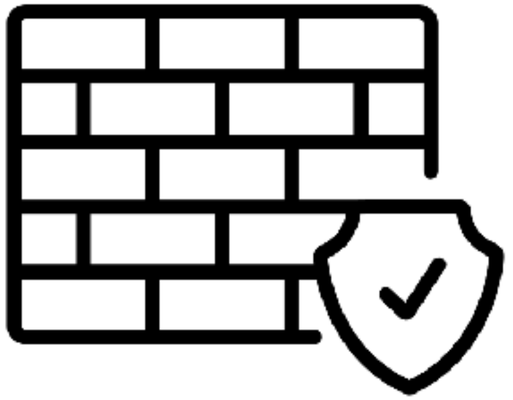
Defenses:

- Never buffer “are you still connected?” frames
- Authenticate the sleep bit in the header of Wi-Fi frames
- **Standard should be updated** with one of these defenses

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**

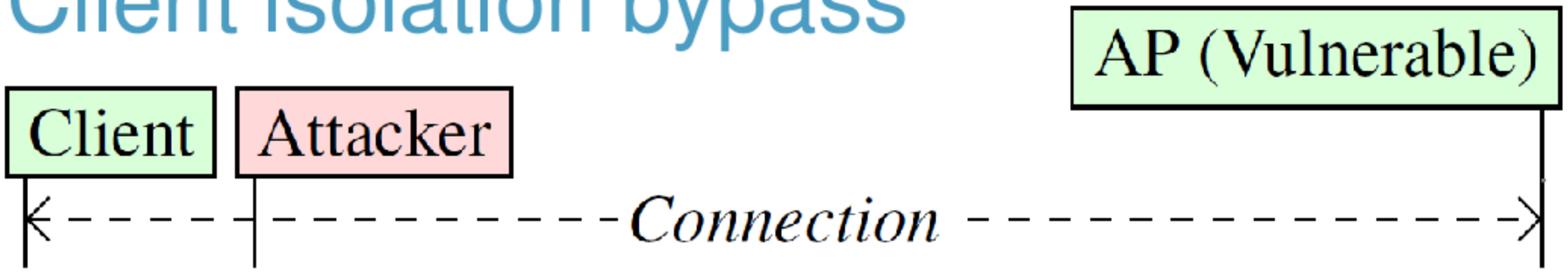
Attack 2: bypassing Wi-Fi client isolation

Target is networks that use **client isolation**. Examples:

- Company network with malicious/compromised clients
- Public hotspots that require authentication

→ Adversary can connect to the network, but can't attack others

Client isolation bypass



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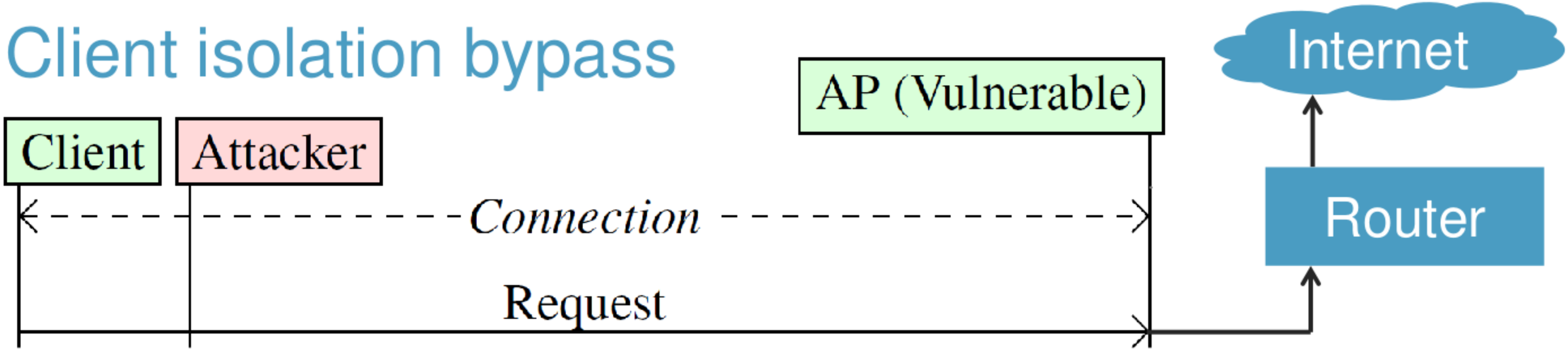

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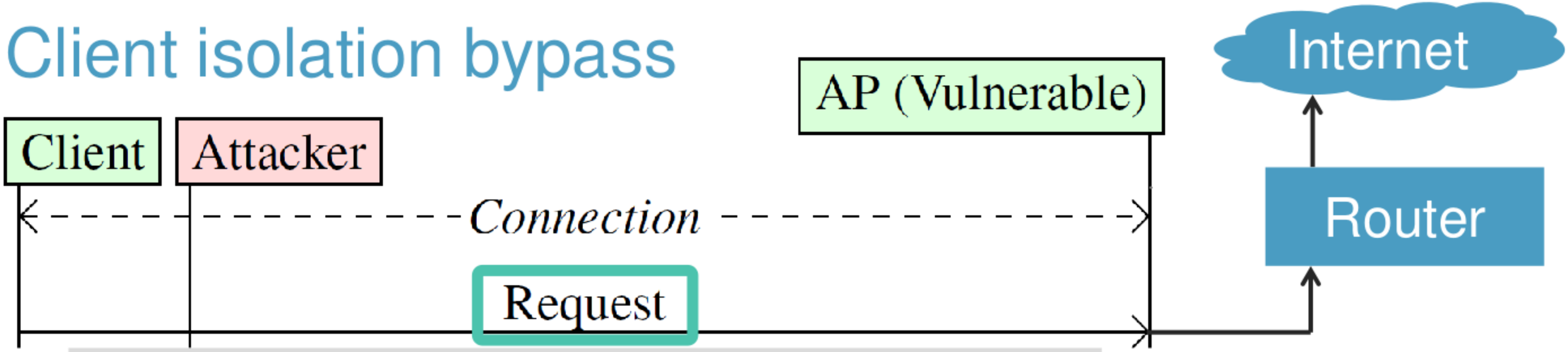
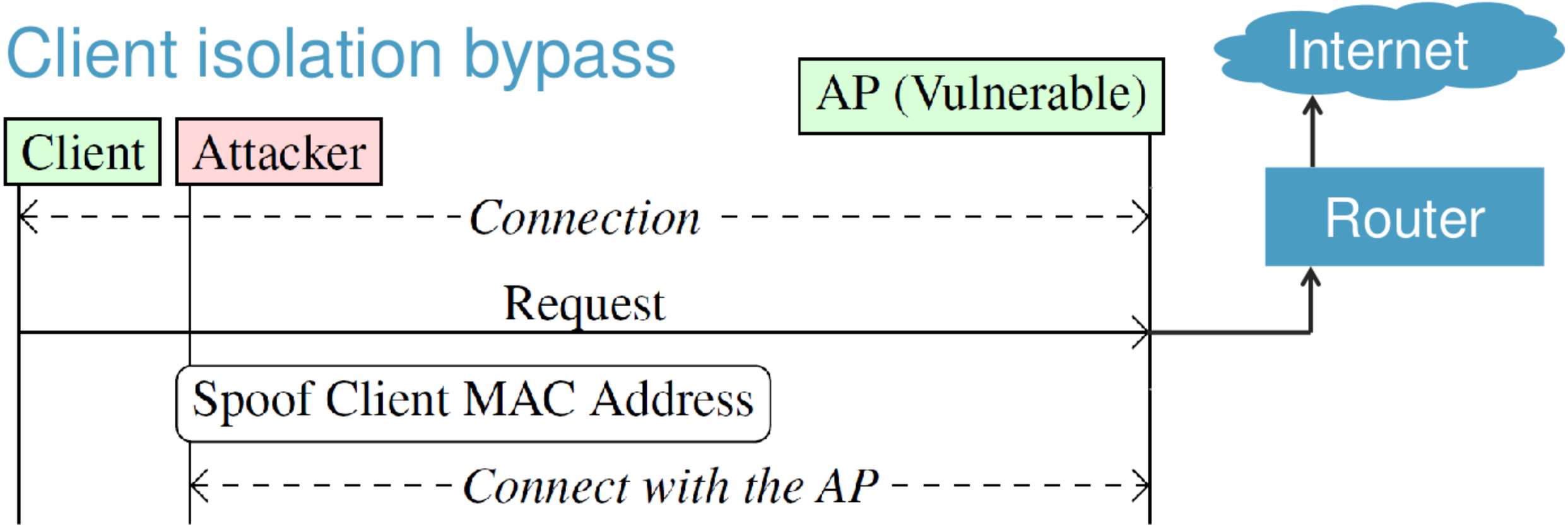
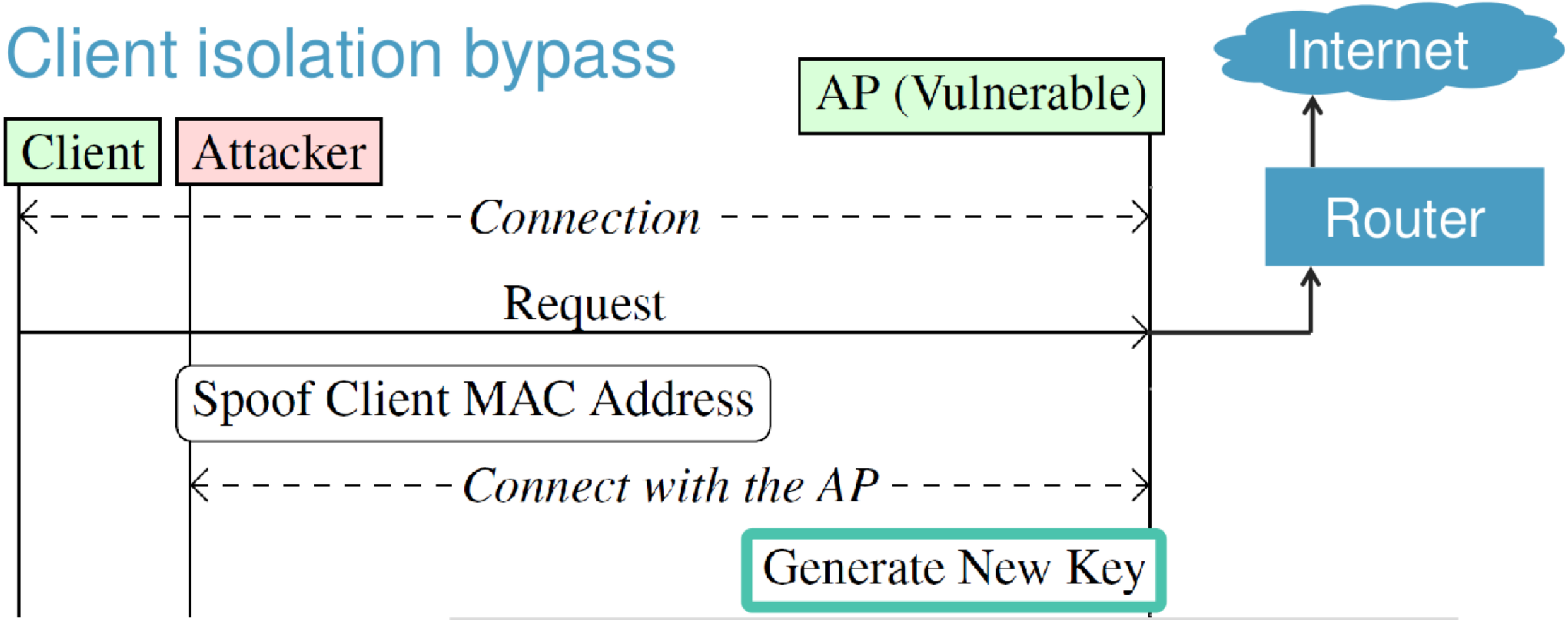


E.g., DNS or HTTP request

Client isolation bypass

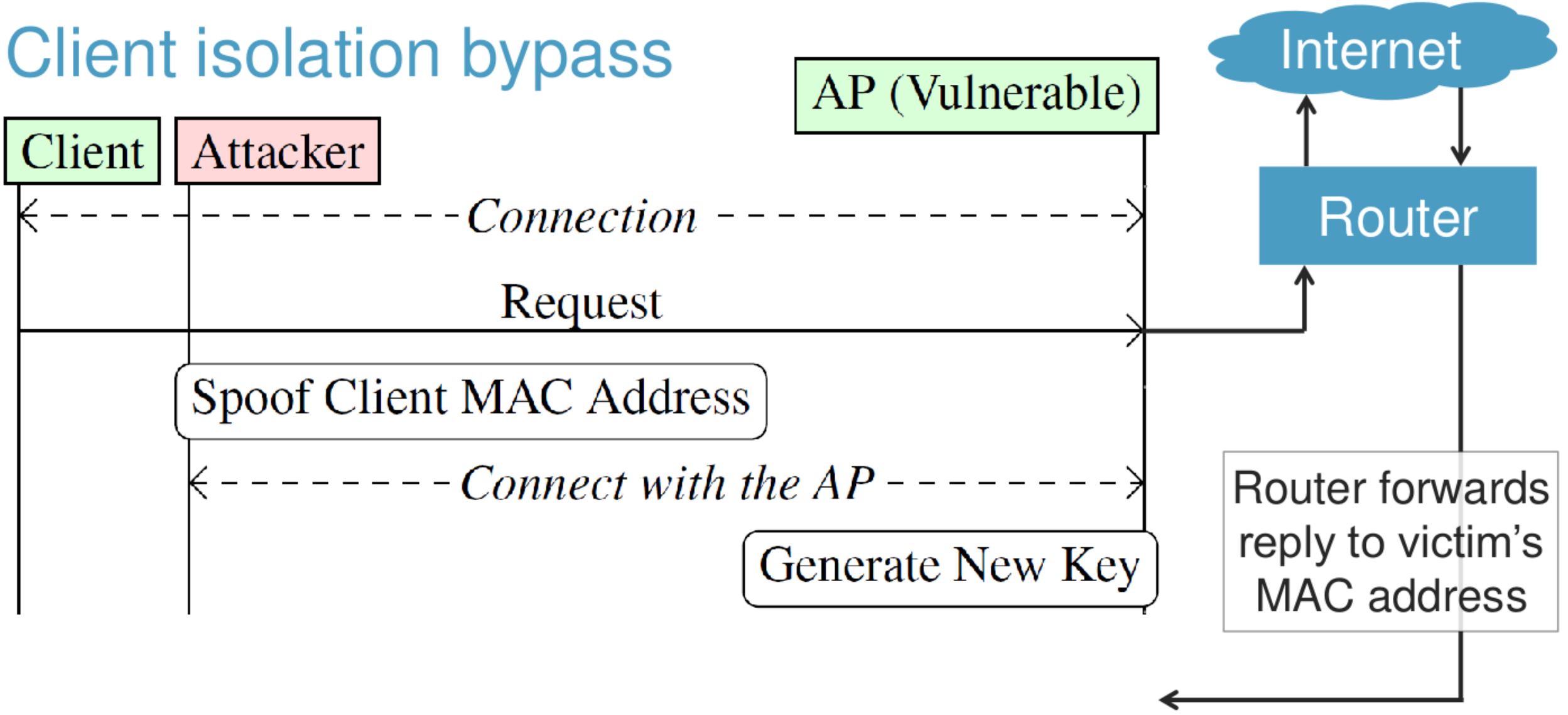


Client isolation bypass



New key is associated with the victim's MAC address

Client isolation bypass



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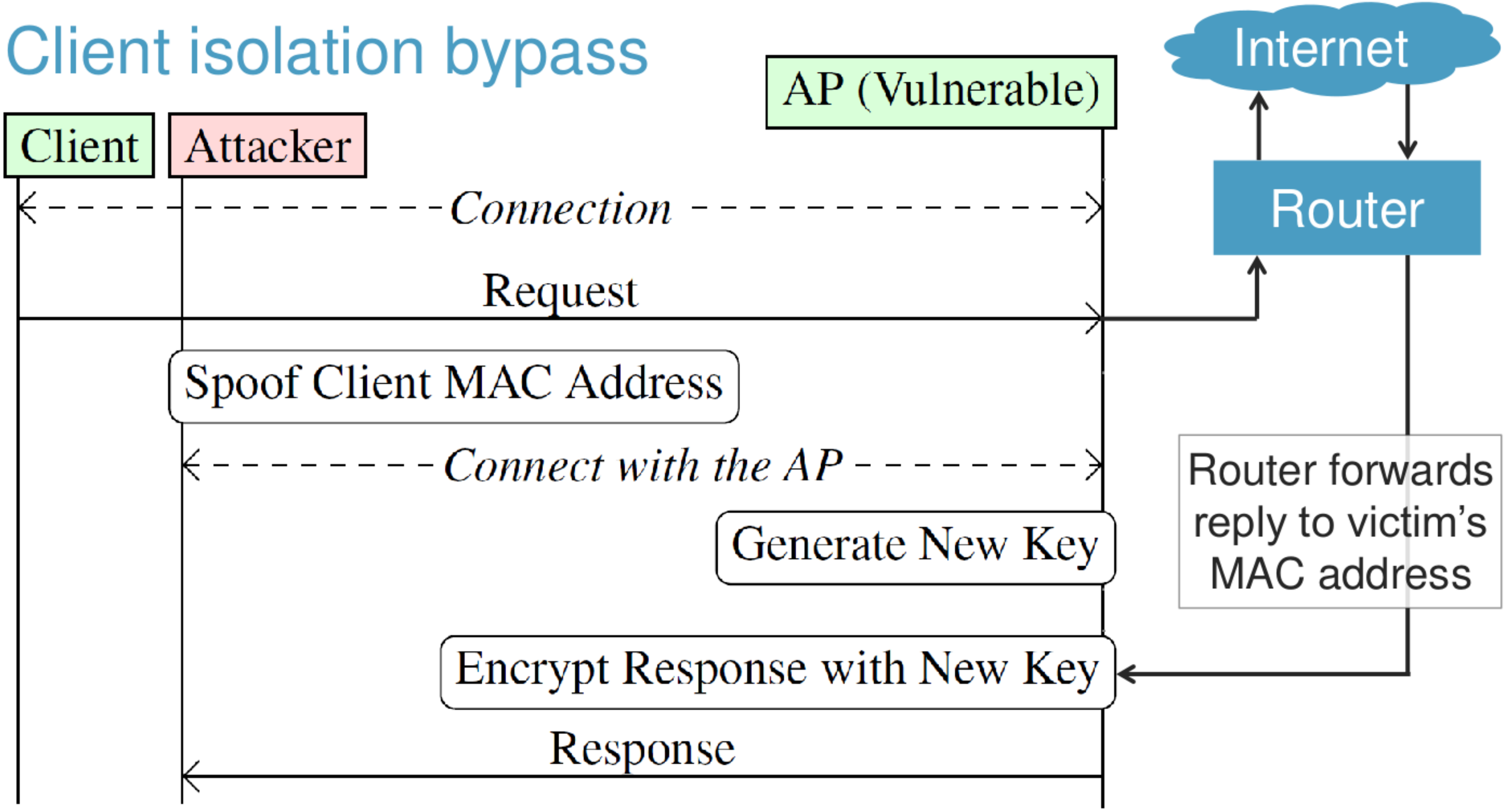

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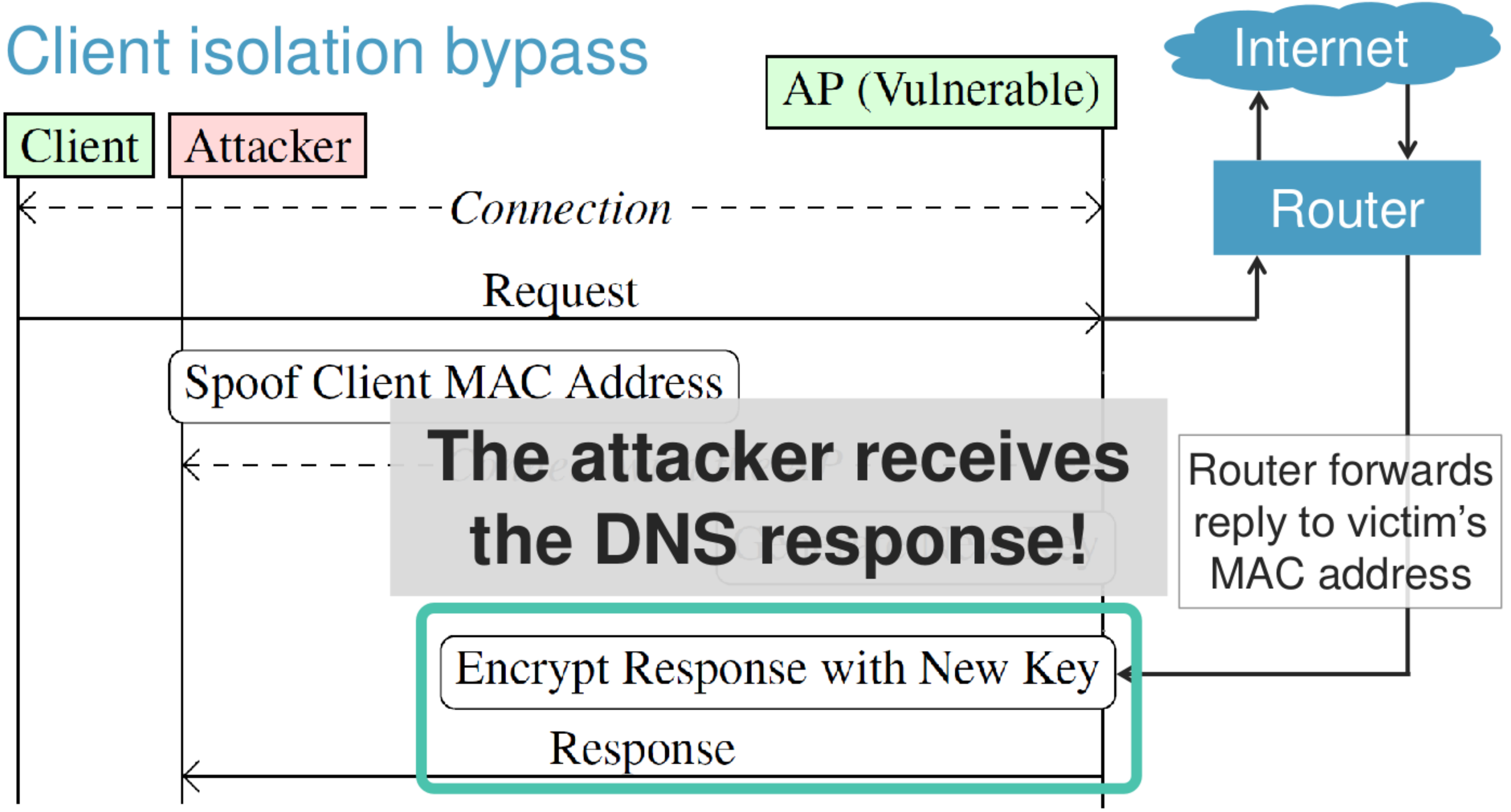

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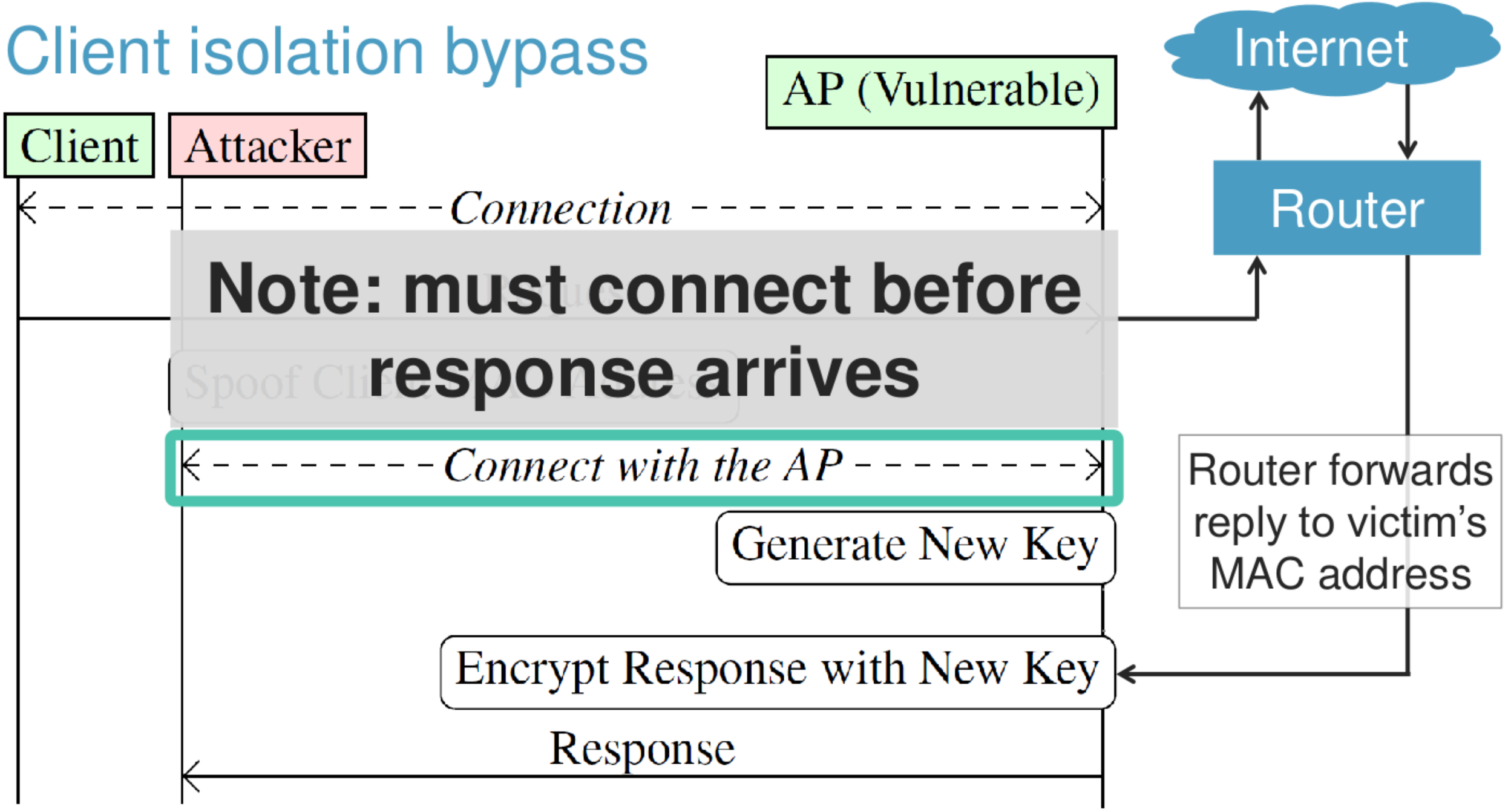


Fixing client isolation

Disallow recently-used MAC address unless:

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

Currently few vendors implemented a defense or mitigation

- Client isolation is flawed but still useful
- Alternative: use VLANs to isolate groups

Tool to test devices: MacStealer

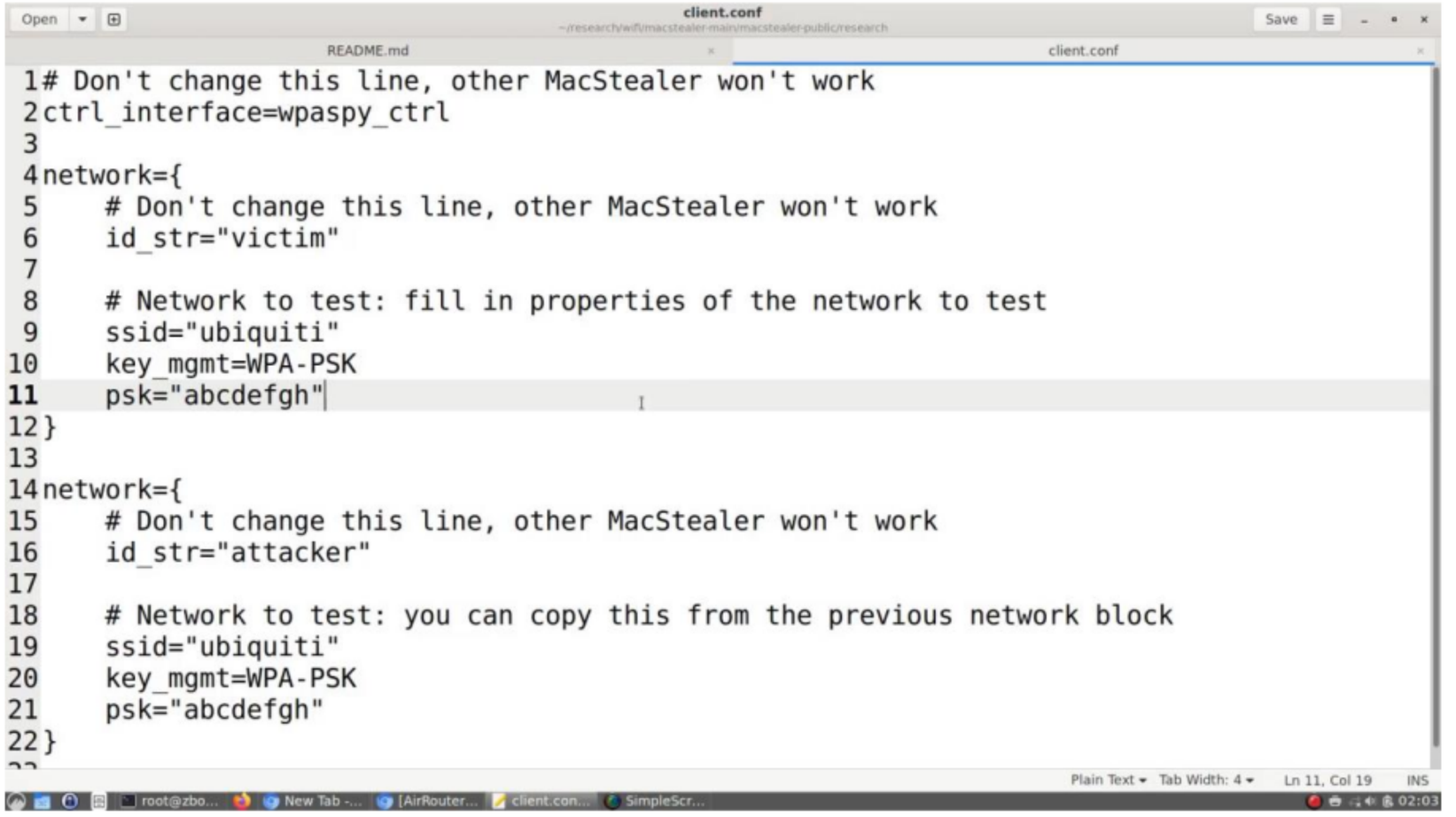
Command	Short description
Sanity checks	
`./macstealer.py wlan0 --ping`	Connect as victim & test server's retransmission behavior.
`./macstealer.py wlan0 --ping --flip`	Connect as attacker & test server's retransmission behavior.
Vulnerability tests	
`./macstealer.py wlan0`	Test the default variant of 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 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

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

Backup slide: root cause

Client identity not authenticated across the network stack:

- Wi-Fi security: 802.1X identity (username)
- Packet routing: IP/MAC addresses

} Not bound to each other

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

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

- Not part of IEEE 802.11 standard → less studied

Backup slide: 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

[Verizon] Verizon IP latency statistics