Systematically Analyzing Vulnerabilities in the Connection Establishment Phase of Wi-Fi Systems

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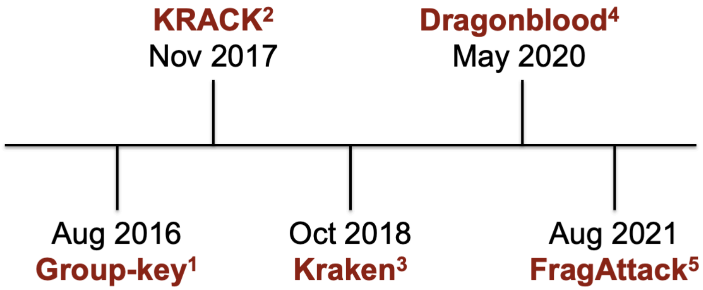
Connection Establishment Phase

- ❑ Currently not protected
    - ❑ Pre-authentication phase → infeasible to protect by WPA2/3
    - ❑ Exploited by several compound attacks
        - ❑ *Multi-channel man-in-the-middle (MitM)*



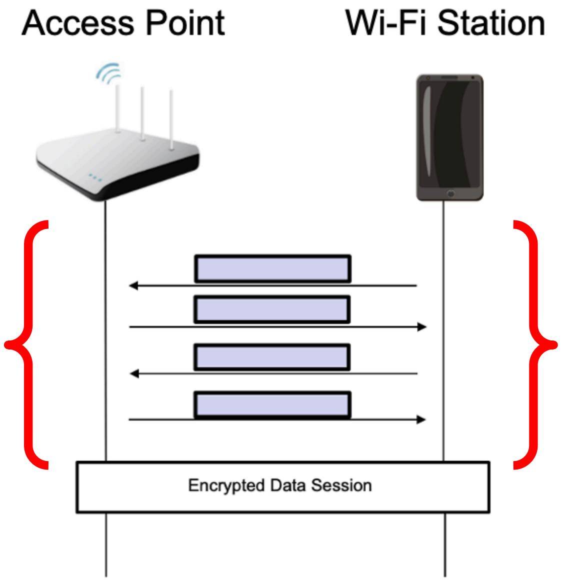
KRACK[2]
Nov 2017

Dragonblood[4]
May 2020

Aug 2016
Group-key[1]

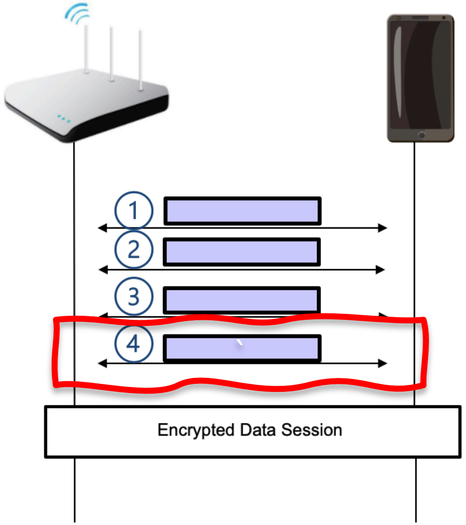
Oct 2018
Kraken[3]

Aug 2021
FragAttack[5]

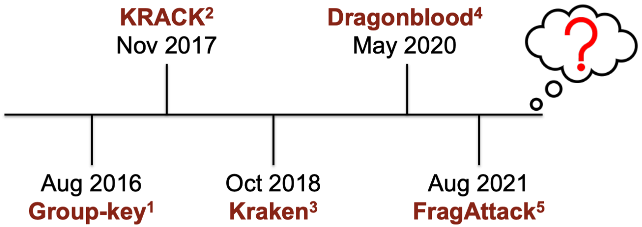


Possibility of More Attacks?

- □ Connection establishment (CE) phase
  - □ Formal analysis by Cremers *et al.*[6]
    - □ 4-way handshake and session key
    - □ Concluded no vulnerability beyond KRACK
    - □ Could not capture Multi-channel MitM
- □ Our contribution: Formal analysis of CE



① Network discovery
② Authentication & association
③ (EAP authentication)
④ 4-way handshake



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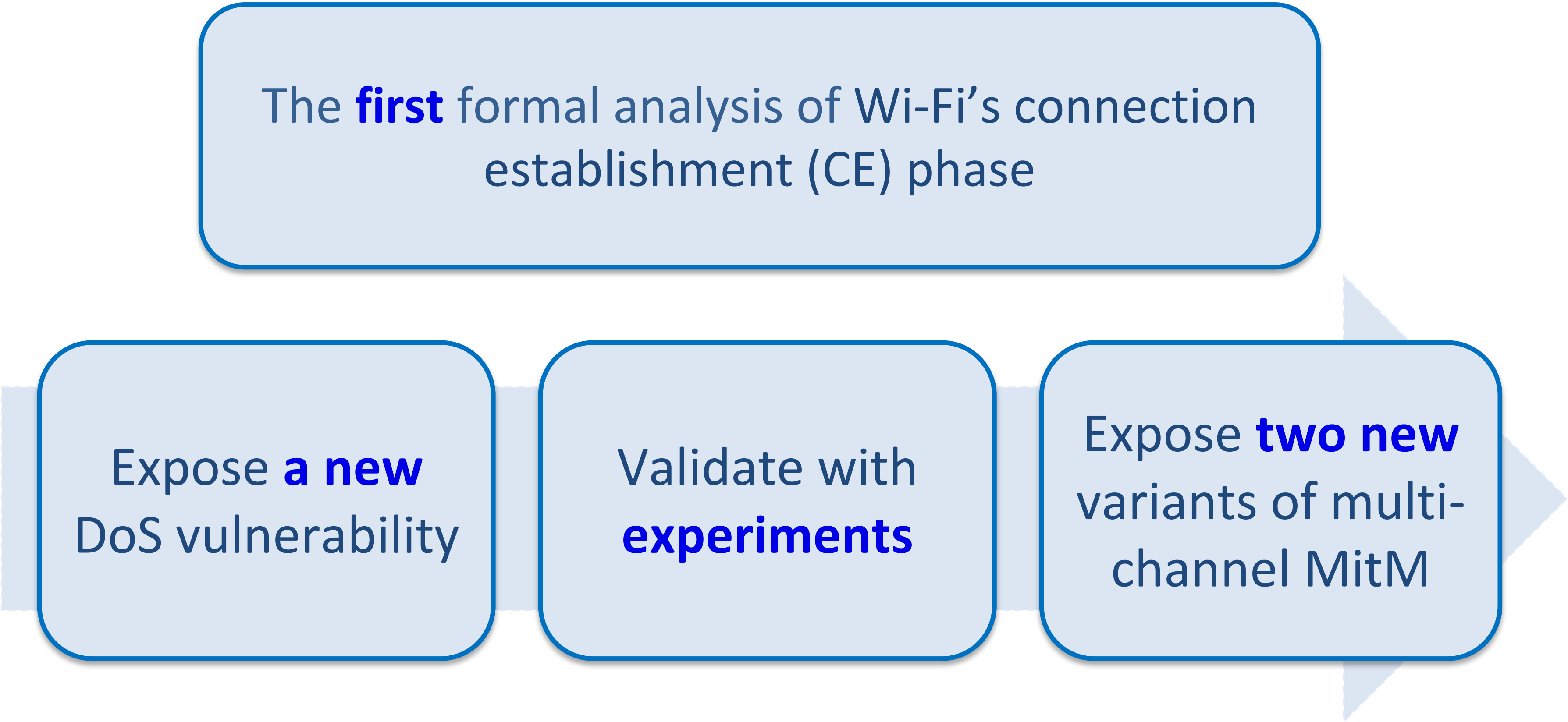
[6] C. Cremers *et al*. A formal analysis of IEEE 802.11's WPA2: Countering the kracks caused by cracking the counters. USENIX Security Symposium, 2020.

Our Contributions



The **first** formal analysis of Wi-Fi’s connection establishment (CE) phase

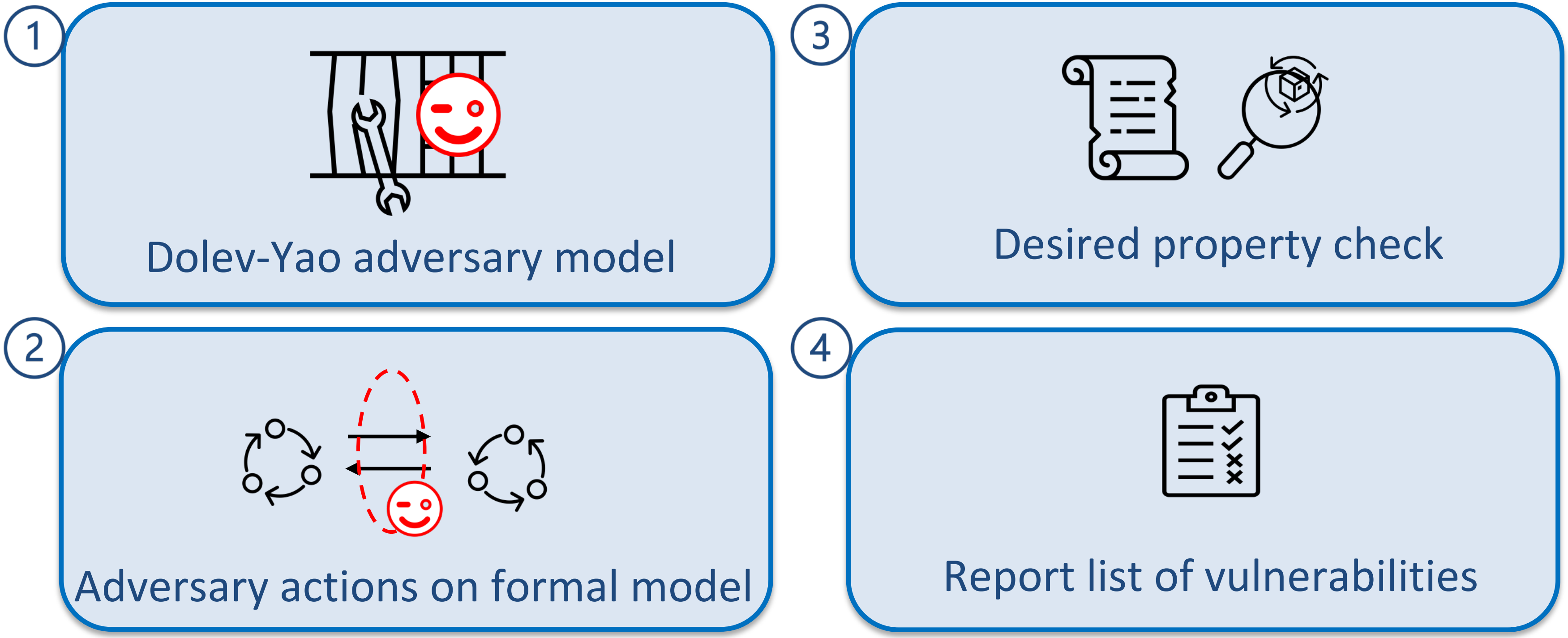
Expose **a new** DoS vulnerability

Validate with **experiments**

Expose **two new** variants of multi-channel MitM

Formal Analysis of CE

- ❑ Based on IEEE 802.11-2020 rollup
  - ❑ IEEE 802.11ax (2021) does not amend the CE components



1 Dolev-Yao adversary model

2 Adversary actions on formal model

3 Desired property check

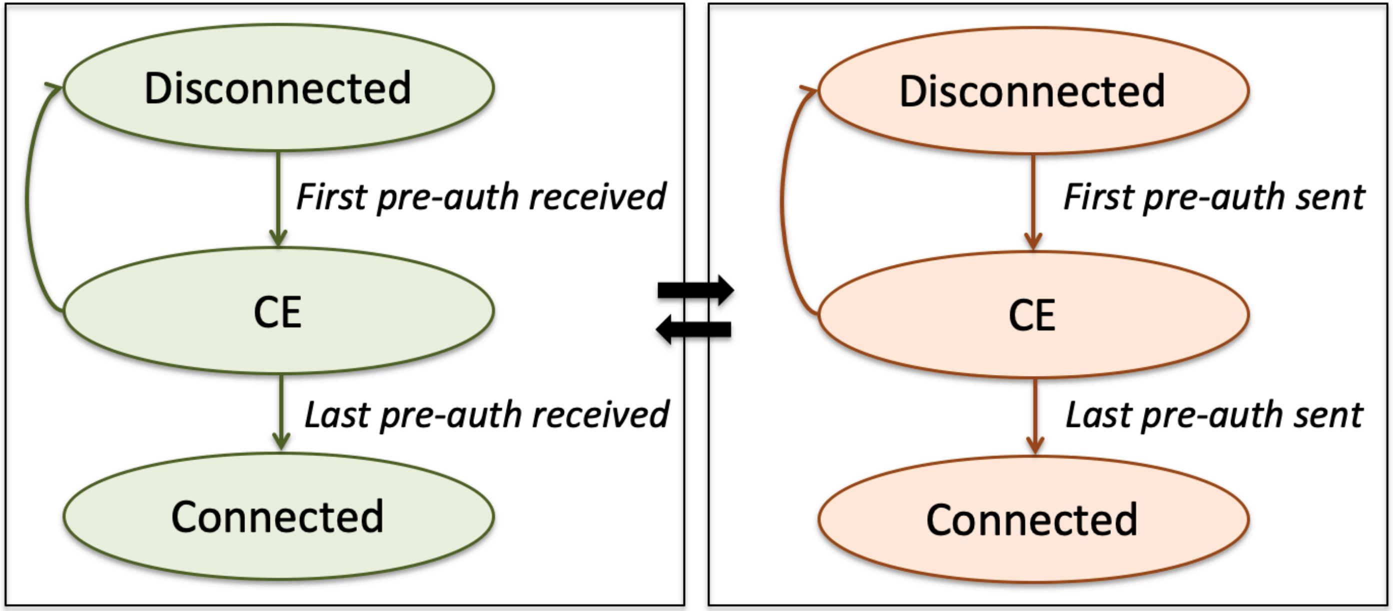
4 Report list of vulnerabilities

Threat Model

- *Dolev-Yao* adversary model
  - Can eavesdrop, drop, inject, and modify
  - Cannot encrypt/decrypt
- System model
  - Personal, enterprise, and public Wi-Fi systems
  - Assume latest security protocol
    - WPA3 or WPA2+802.11w
    - 802.11w: Management frame protection, mandatory in WPA3
  - Model the optional mechanisms in IEEE 802.11-2020 rollup separately

Simplified CE Model

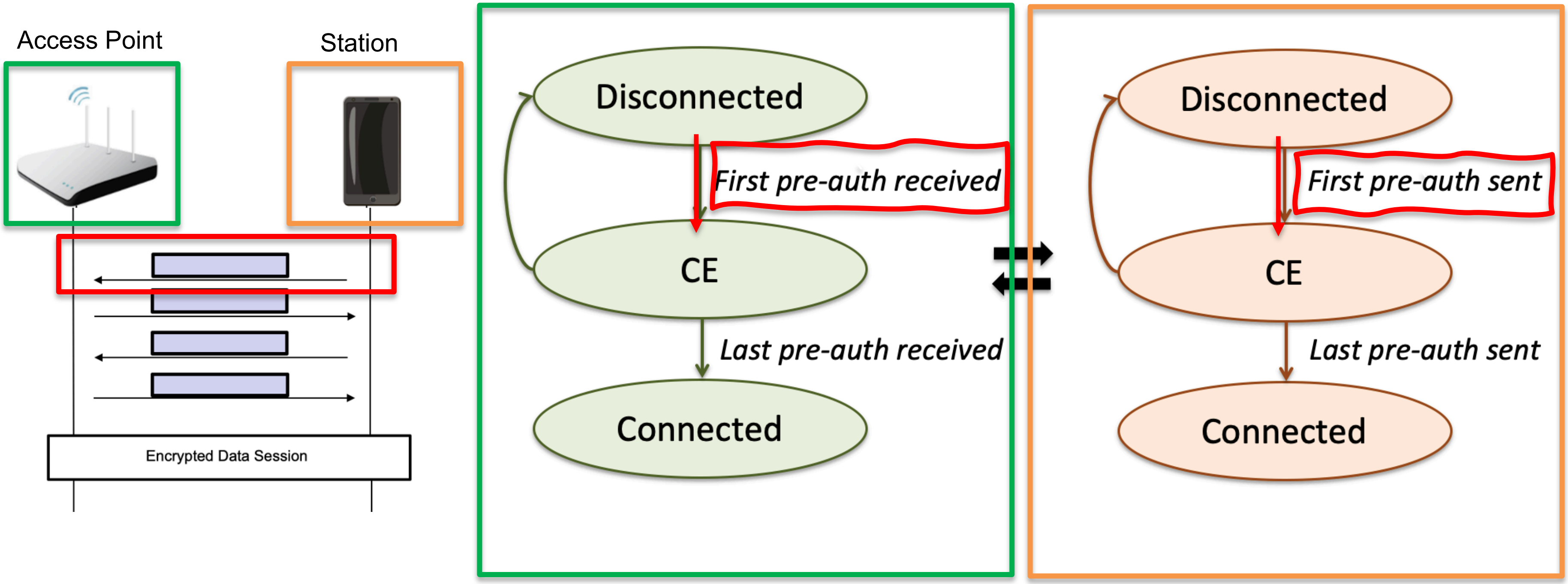
- ❑ Implemented in *NuSMV* model checker



AP’s FSM Station’s FSM

Our more detailed model can be found in the paper.

Interaction between FSMs



Property to Check

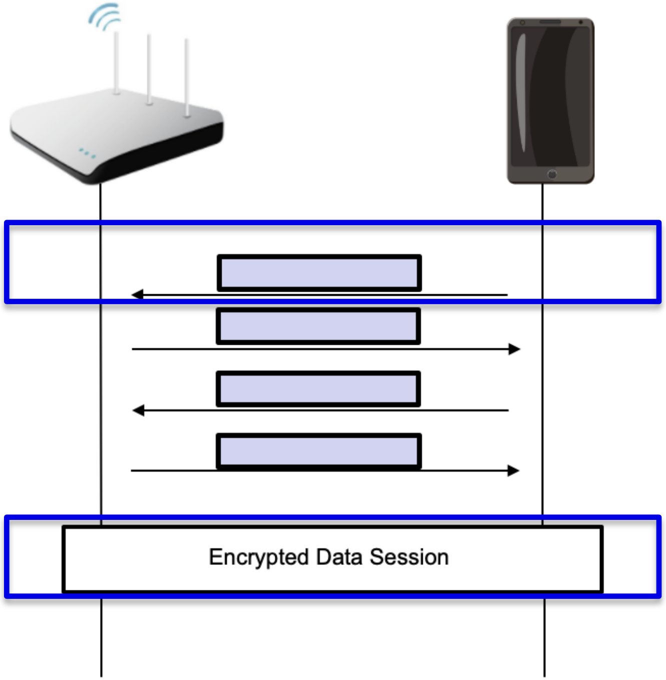
(1) It is always the case that a station and an AP will eventually move to the connected state *(checks for DoS vulnerability),*

and

(2) There does not exist a case when they connect to each other over two different channels *(checks for multi-channel MitM)*

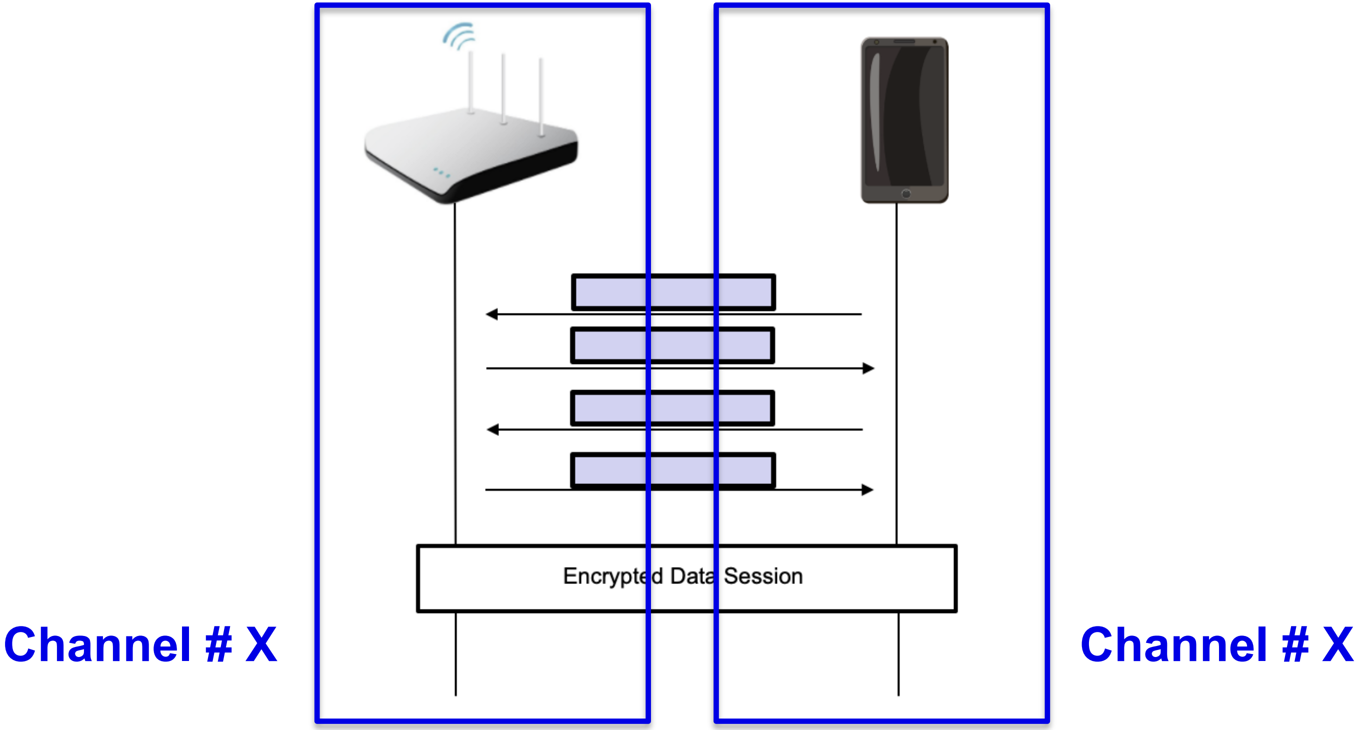
Property to Check

(1) It is always the case that a station and an AP will eventually move to the connected state



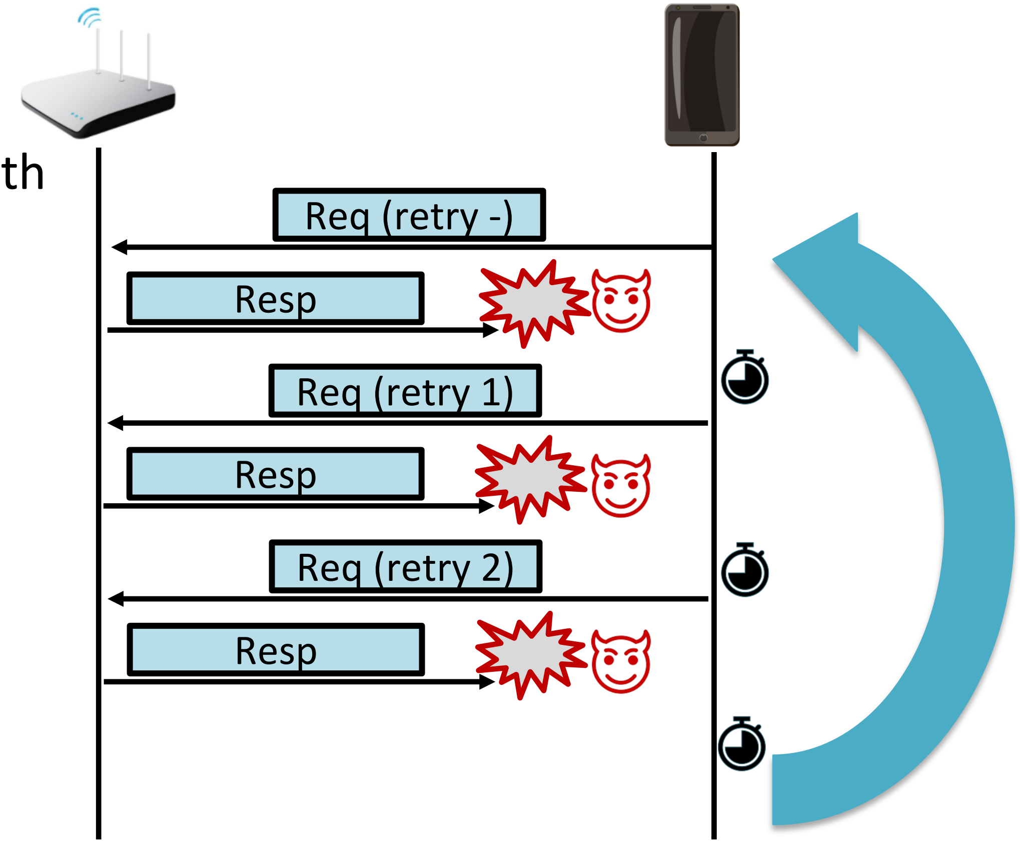
Property to Check

(2) There does not exist a case when they connect to each other over two different channels



Formal Analysis – New DoS Finding

- ❑ Continuous resetting
    - ❑ Exhaust retransmissions
    - ❑ Same AP, same signal strength
- ❑ Potential consequences
    - ❑ Denial-of-service
    - ❑ Battery depletion
    - ❑ User frustration
        - ❑ Can end up connecting with a rogue AP

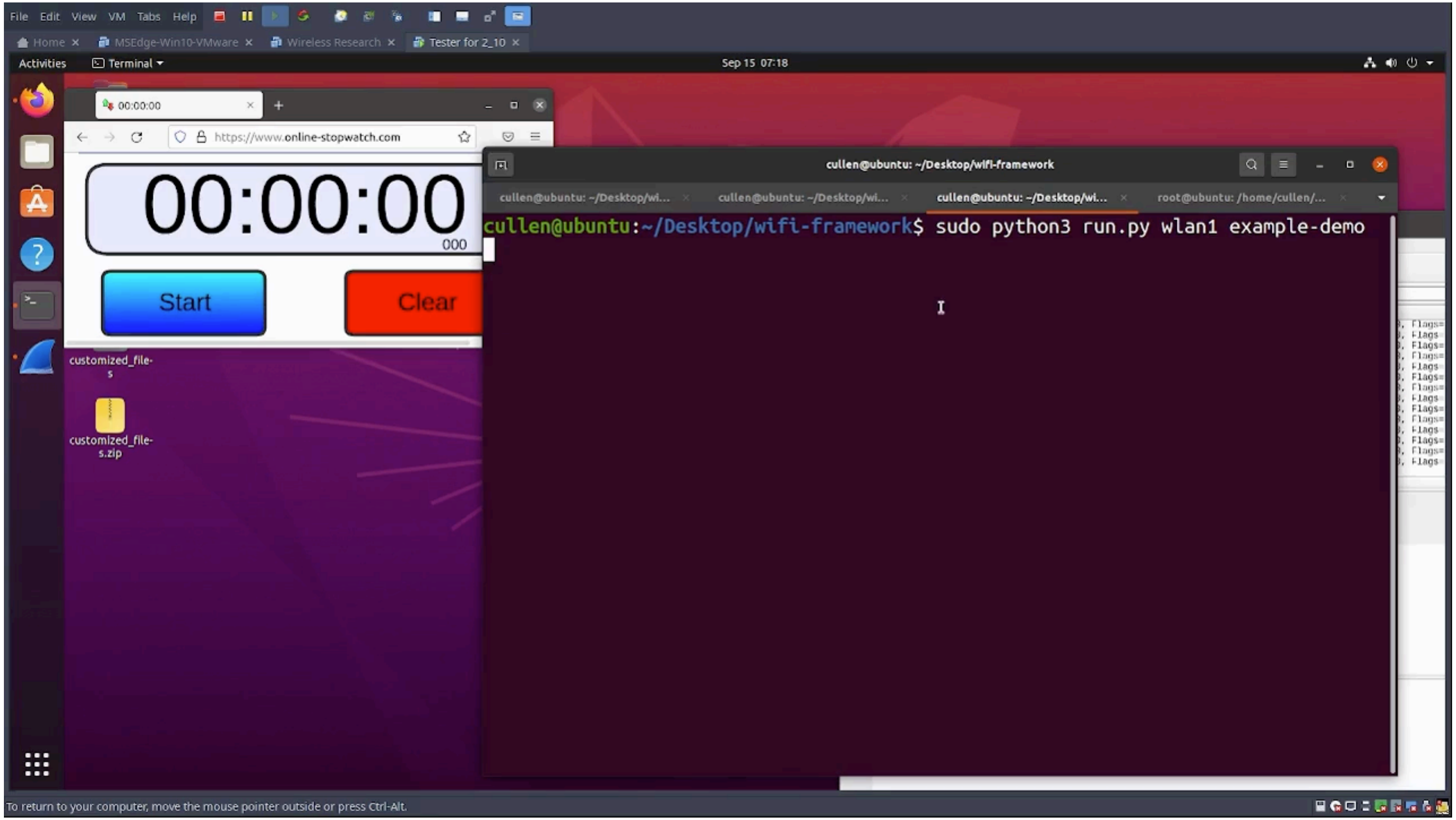


Experimental Validation

- ❑ Based on *hostapd* and *wpa_supplicant* (latest 2022 update)
  - ❑ Wi-Fi framework[7]
- ❑ WPA3-Personal
- ❑ Experimental scenario
  - ❑ Blocking pre-authentication frame sent by AP
  - ❑ Observe behavior at the station
- ❑ Responsible and timely disclosure to Wi-Fi Alliance

[7] D. Schepers *et al*. A framework to test and Fuzz Wi-Fi devices. In Proc. of the ACM Conference on Security and Privacy in Wireless and Mobile Networks (WiSec). 2021.

Demonstration

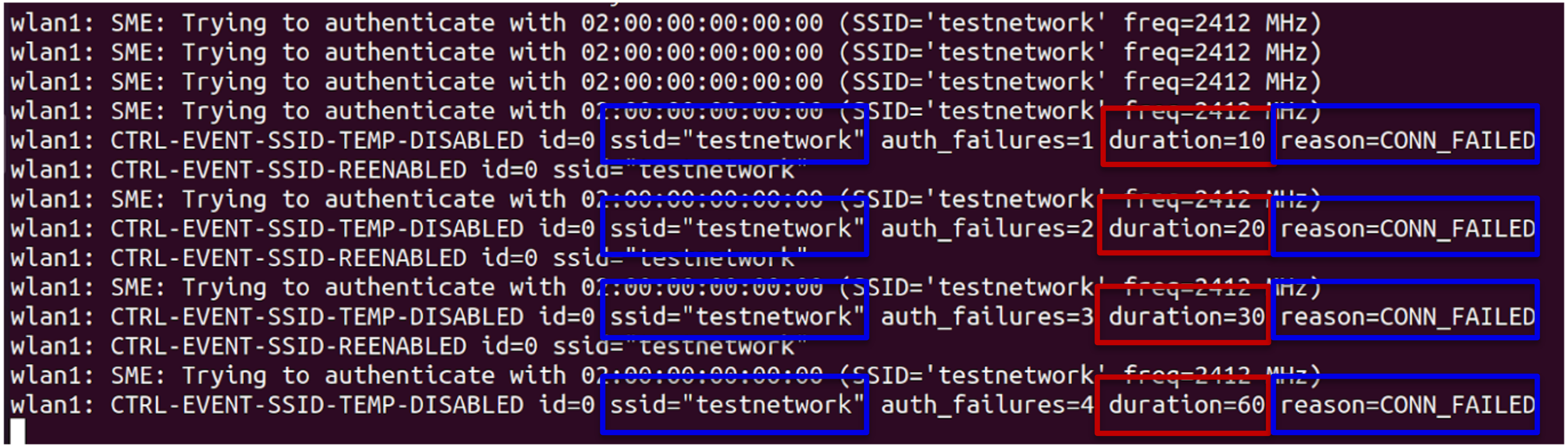

File Edit View VM Tabs Help
Home
MSEdge-Win10-VMware
Wireless Research
Tester for 2_10
Activities
Terminal
Sep 15 07:18
00:00:00
https://www.online-stopwatch.com
00:00:00
000
Start
Clear
customized_files
customized_files.zip
cullen@ubuntu: ~/Desktop/wifi-framework
cullen@ubuntu: ~/Desktop/wi...
cullen@ubuntu: ~/Desktop/wi...
cullen@ubuntu: ~/Desktop/wi...
root@ubuntu: /home/cullen/...

```
cullen@ubuntu:~/Desktop/wifi-framework$ sudo python3 run.py wlan1 example-demo
```

To return to your computer, move the mouse pointer outside or press Ctrl-Alt.

Experimental Result

- ❑ DoS vulnerability validated
  - ❑ Continuous resetting with the same AP
- ❑ Duration (?)



```
wlan1: SME: Trying to authenticate with 02:00:00:00:00:00 (SSID='testnetwork' freq=2412 MHz)
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wlan1: CTRL-EVENT-SSID-TEMP-DISABLED id=0 ssid="testnetwork" auth_failures=1 duration=10 reason=CONN_FAILED
wlan1: CTRL-EVENT-SSID-REENABLED id=0 ssid="testnetwork"
wlan1: SME: Trying to authenticate with 02:00:00:00:00:00 (SSID='testnetwork' freq=2412 MHz)
wlan1: CTRL-EVENT-SSID-TEMP-DISABLED id=0 ssid="testnetwork" auth_failures=2 duration=20 reason=CONN_FAILED
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wlan1: CTRL-EVENT-SSID-TEMP-DISABLED id=0 ssid="testnetwork" auth_failures=3 duration=30 reason=CONN_FAILED
wlan1: CTRL-EVENT-SSID-REENABLED id=0 ssid="testnetwork"
wlan1: SME: Trying to authenticate with 02:00:00:00:00:00 (SSID='testnetwork' freq=2412 MHz)
wlan1: CTRL-EVENT-SSID-TEMP-DISABLED id=0 ssid="testnetwork" auth_failures=4 duration=60 reason=CONN_FAILED
```
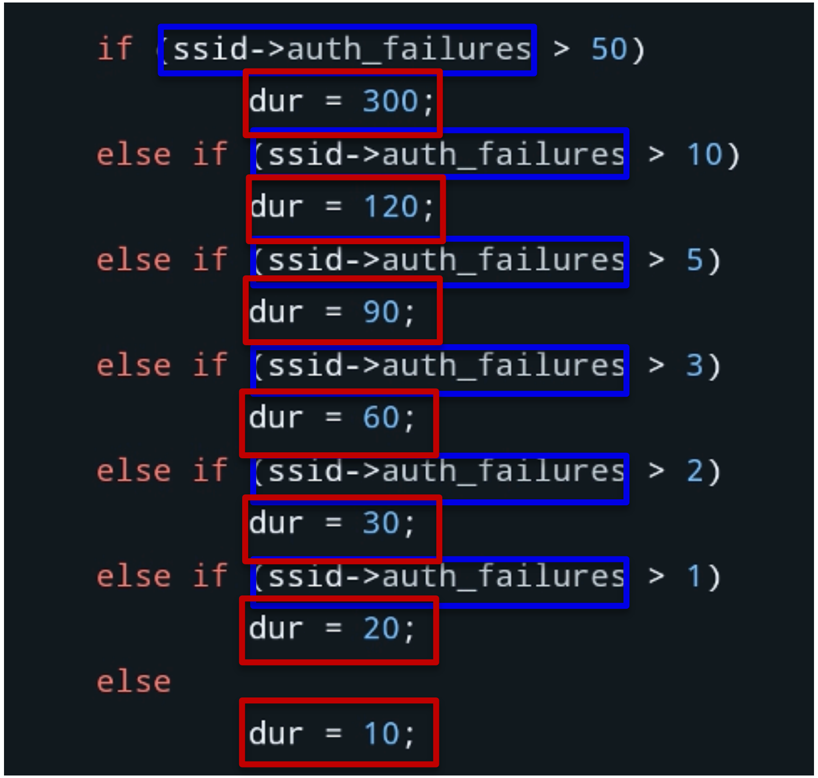

Code Snippet - *wpa_supplicant*

- ❑ *wpa_supplicant*
  - ❑ Retransmission limit exhaust
    - ❑ One failure
  - ❑ Defines a delay between resets
  - ❑ Documentation – unexplained
  - ❑ Conjecture – waiting time for better channel condition, etc.
  - ❑ Problem? – known and accumulated delay



```
if (ssid->auth_failures > 50)
        dur = 300;
else if (ssid->auth_failures > 10)
        dur = 120;
else if (ssid->auth_failures > 5)
        dur = 90;
else if (ssid->auth_failures > 3)
        dur = 60;
else if (ssid->auth_failures > 2)
        dur = 30;
else if (ssid->auth_failures > 1)
        dur = 20;
else
        dur = 10;
```

Failures and Accumulated Delay

Number of failures (num_f)	Delay between retries (t_d)	Accumulated delay (sec)
1	10	10
2	20	30
3	30	60
$4\ or\ 5$	60	$120\ (num_f = 4)$
$5 < num_f \leq 10$	90	$270\ (num_f = 6)$
$10 < num_f \leq 50$	120	$750\ (num_f = 11)$
$num_f > 51$	300	$\boxed{5370}\ (num_f = 51)$

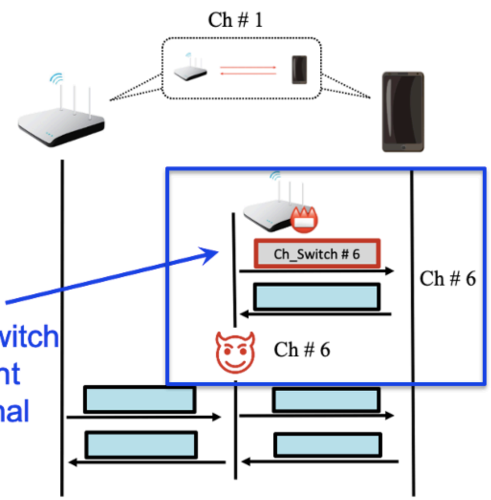
~ 90 minutes!!

Possible Mitigation Technique

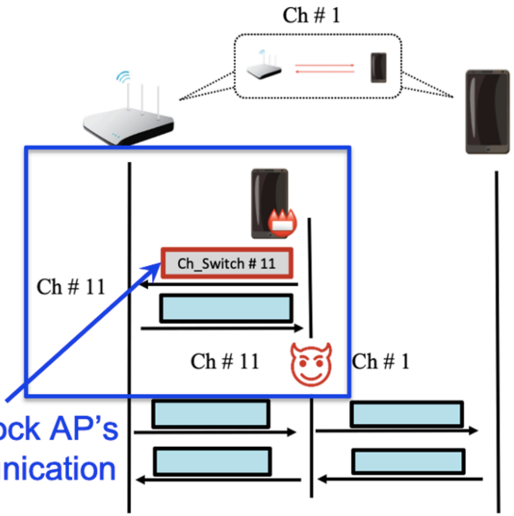
- ❑ The problem: Fixed delay values
  - ❑ Long (and fixed) waiting time between retries
  - ❑ Predictable to an adversary
  - ❑ Allows selectively and stealthily activate DoS
- ❑ Mitigation: Random delay values
  - ❑ Between 5 and 60 seconds
  - ❑ Reduces the accumulated delay
  - ❑ Forces costly (consistent) jamming

Formal Analysis – MitM Finding

- ❑ Multi-channel MitM
  - ❑ Three variants (two new)
    - ❑ (1) Target: station, (2) Target: AP, and (3) Target: both



1. Channel switch announcement
2. Higher signal strength

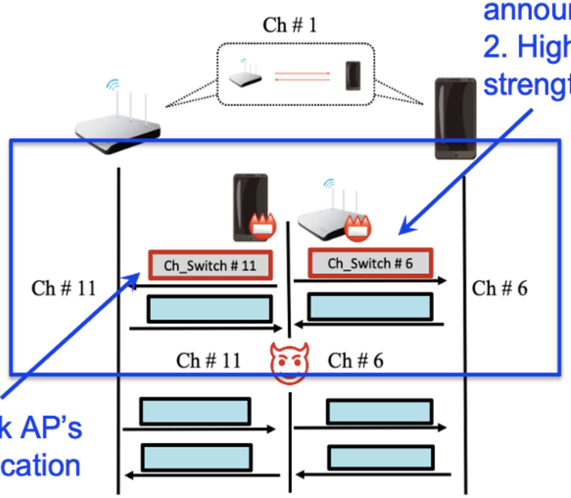


Jam/block AP's communication

New variant # 1

Formal Analysis – MitM Finding

- ❑ Multi-channel MitM
  - ❑ Three variants (two new)
    - ❑ (1) Target: station, (2) Target: AP, and (3) Target: both



1. Channel switch announcement
2. Higher signal strength

Jam/block AP's communication

New variant # 2

Conclusion & Future Work

- ❑ Existing formal analysis efforts
  - ❑ 4-way handshake
  - ❑ But not CE/pre-authentication phase
- ❑ Findings
  - ❑ One new DOS vulnerability
    - ❑ 90-minutes with additional 5-minute
  - ❑ Two new variants of multi-channel MitM
- ❑ Future work

References

[1] M. Vanhoef and F. Piessens, “Predicting, decrypting, and abusing WPA2/802.11 group keys”. in USENIX Security Symposium, 2016.

[2] M. Vanhoef and Frank Piessens. Key reinstallation attacks: Forcing nonce reuse in WPA2. In Proc. of the ACM Conference on Computer and Communications Security (CCS), 2017.

[3] M. Vanhoef and F. Piessens. Release the Kraken: New KRACKs in the 802.11 Standard. In Proc. of the ACM Conference on Computer and Communication Security (CCS), 2018.

[4] M. Vanhoef and Eyal Ronen. Dragonblood: analyzing the Dragonfly handshake of WPA3 and EAP-pwd. In Proc. of the IEEE Symposium on Security & Privacy (S&P), 2020.

[5] M. Vanhoef. Fragment and Forge: Breaking Wi-Fi Through Frame Aggregation and Fragmentation. In USENIX Security Symposium, 2021.

[6] C. Cremers. A formal analysis of IEEE 802.11’s WPA2: Countering the kracks caused by cracking the counters. In USENIX Security Symposium, 2020.

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Questions..?

https://www.rit.edu/wisplab/

GitHub Link: