Dragonblood: Analyzing the Dragonfly Handshake of WPA3 and EAP-pwd

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Background: Wi-Fi Security

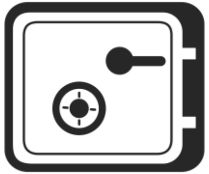
- 1999: Wired Equivalent Privacy (WEP)
  - **Broken** in 2001 [FMS01]
- 2003: Wi-Fi Protected Access (WPA)
- 2004: Wi-Fi Protected Access 2 (WPA2)
  - Allows **offline password brute-force**
  - KRACK and Kraken attack [VP][2017-8]

Background: Dragonfly in WPA3 and EAP-pwd

= Password Authenticated Key Exchange (PAKE)

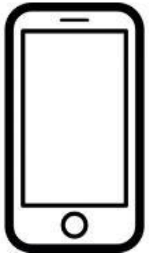
Provide mutual authentication

Negotiate session key



Prevent offline dictionary attacks

Dragonfly



Pick random r_A and m_A

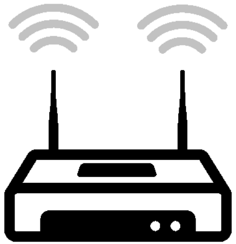
$s_A = (r_A + m_A) \bmod q$

$E_A = -m_A \boxed{P}$

Pick random r_B and m_B

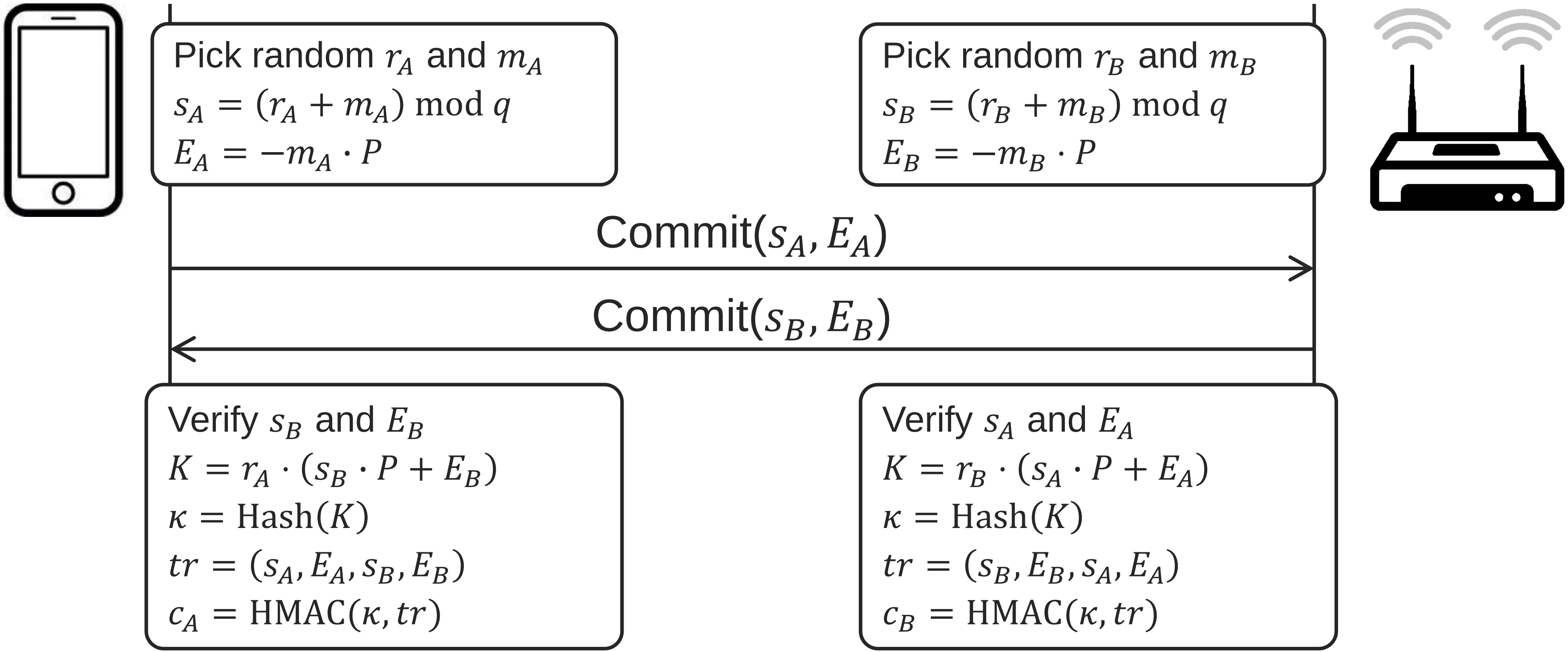
$s_B = (r_B + m_B) \bmod q$

$E_B = -m_B \boxed{P}$



Convert password to group element P

Dragonfly



Pick random r_A and m_A
$s_A = (r_A + m_A) \bmod q$
$E_A = -m_A \cdot P$
Pick random r_B and m_B
$s_B = (r_B + m_B) \bmod q$
$E_B = -m_B \cdot P$
Commit(s_A, E_A)
Commit(s_B, E_B)
Verify s_B and E_B
$K = r_A \cdot (s_B \cdot P + E_B)$
$\kappa = \mathrm{Hash}(K)$
$tr = (s_A, E_A, s_B, E_B)$
$c_A = \mathrm{HMAC}(\kappa, tr)$
Verify s_A and E_A
$K = r_B \cdot (s_A \cdot P + E_A)$
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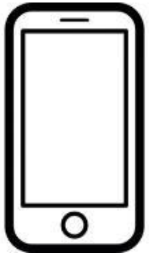
Dragonfly



Pick random r_A and m_A

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$E_A = -m_A \cdot P$

Pick random r_B and m_B

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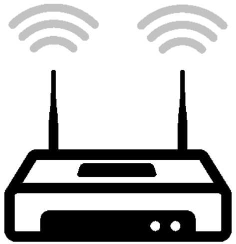

Commit(s_A, E_A)

Negotiate shared key

Verify s_B and E_B

$K = r_A \cdot (s_B \cdot P + E_B)$

$\kappa = \text{Hash}(K)$

$tr = (s_A, E_A, s_B, E_B)$

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Verify s_A and E_A

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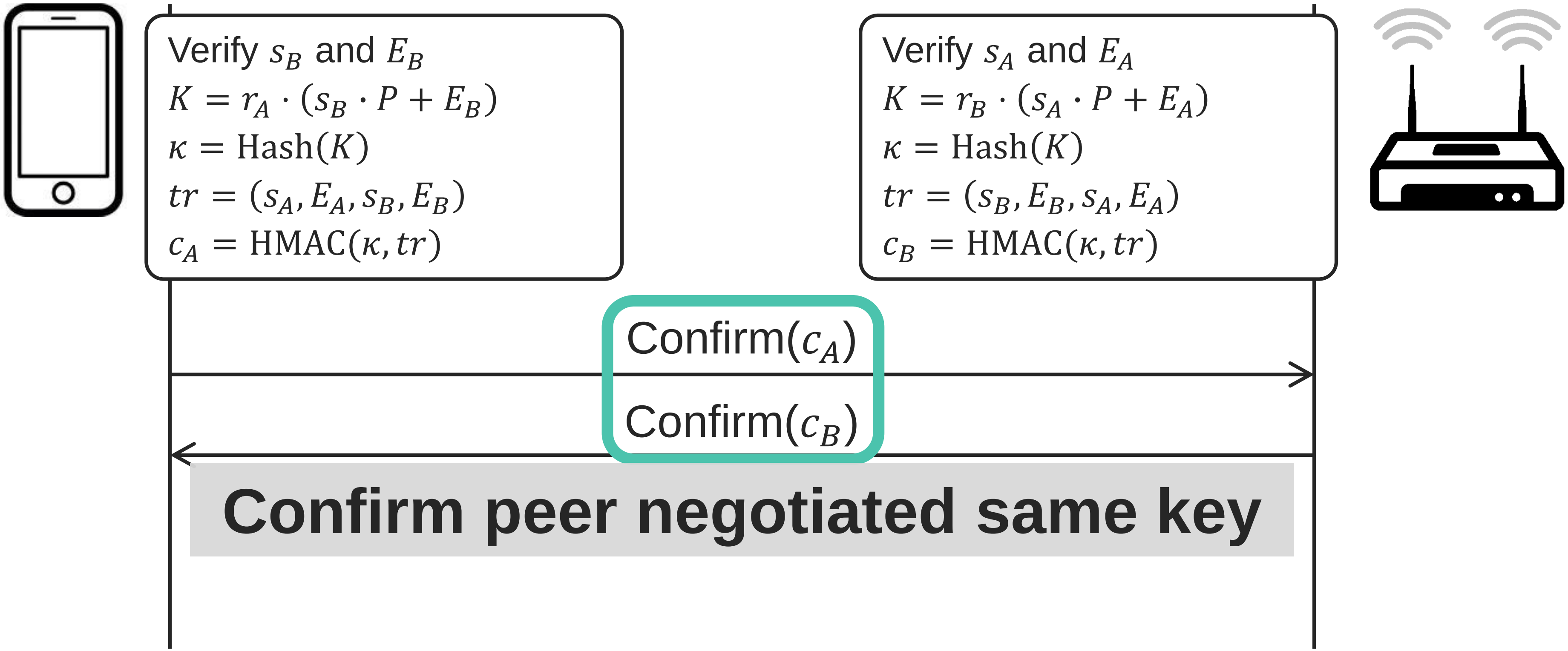
Dragonfly



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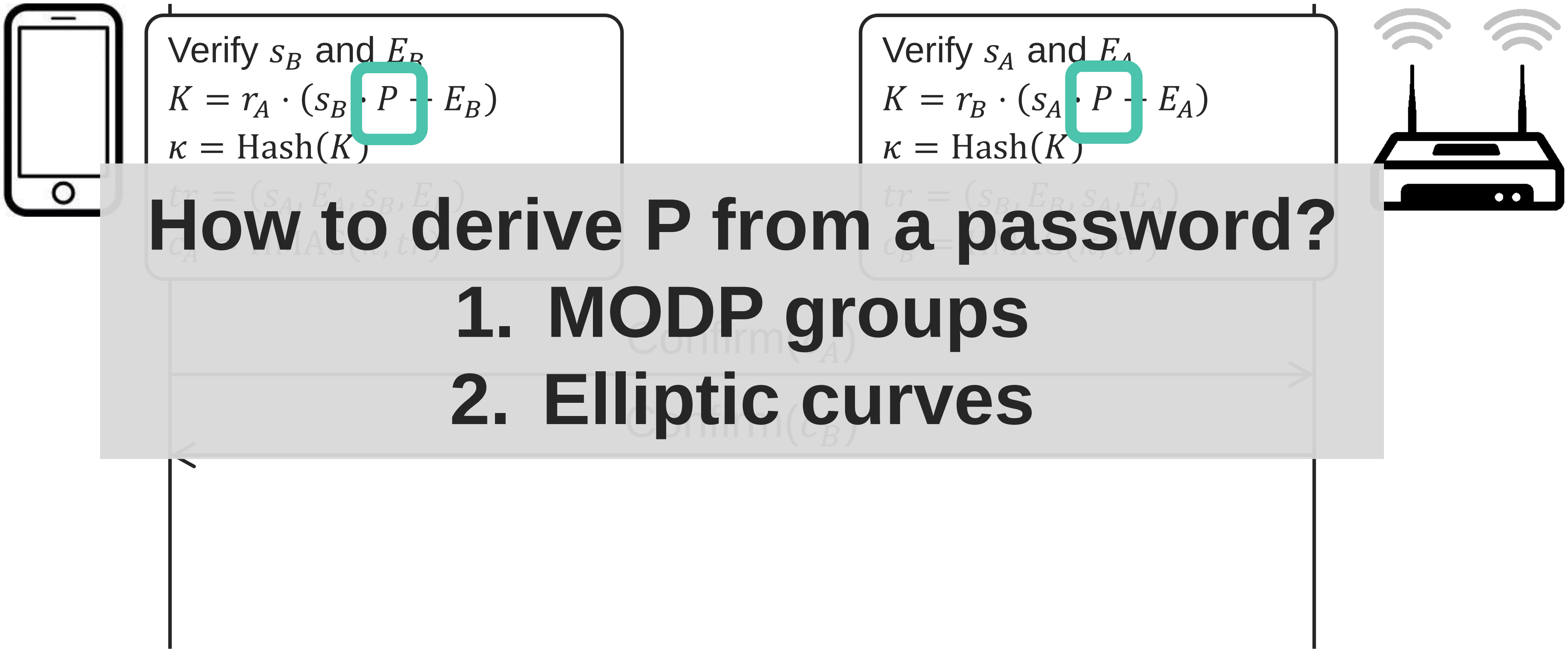
Verify s_A and E_A
$K = r_B \cdot (s_A \cdot P + E_A)$
$\kappa = \mathrm{Hash}(K)$
$tr = (s_B, E_B, s_A, E_A)$
$c_B = \mathrm{HMAC}(\kappa, tr)$
Confirm(c_A)
Confirm(c_B)
Confirm peer negotiated same key

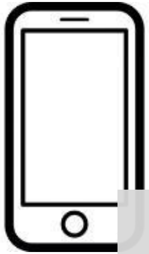
Dragonfly



How to derive P from a password?

1. **MODP groups**
2. **Elliptic curves**

Dragonfly



Verify s_B and E_B

$K = r_A \cdot (s_B \cdot \boxed{P} + E_B)$

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$c_A = \text{HMAC}(\kappa, tr)$

Verify s_A and E_A

$K = r_B \cdot (s_A \cdot \boxed{P} + E_A)$

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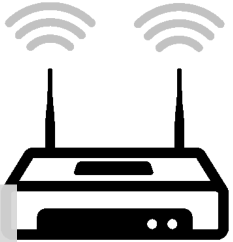

Confirm(c_A)

Confirm(c_B)

How to derive P from a password?

1. **MODP groups**
2. **Elliptic curves**

Hash-to-curve: EAP-pwd

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, addr1, addr2, counter)
    if x >= p: continue
    if square_root_exists(x) and not P:
        return (x, √(x³ + ax + b))
```

$$\text{return }\left(x, \sqrt{x^3 + ax + b}\right)$$

Hash-to-curve: EAP-pwd

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```

$$\boxed{\sqrt{x^3 + ax + b}}$$

Half of x values aren't on the curve

Hash-to-curve: EAP-pwd

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for (counter = 1; counter < 40; counter++)
    x = hash(pw, addr1, addr2, counter)
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        return (x, $\sqrt{x^3 + ax + b}$)

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#iterations depends on password

(and public MAC addresses)

Hash-to-curve: EAP-pwd

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for (counter = 1; counter < 40; counter++)
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        return (x, √(x³ + ax + b))
```

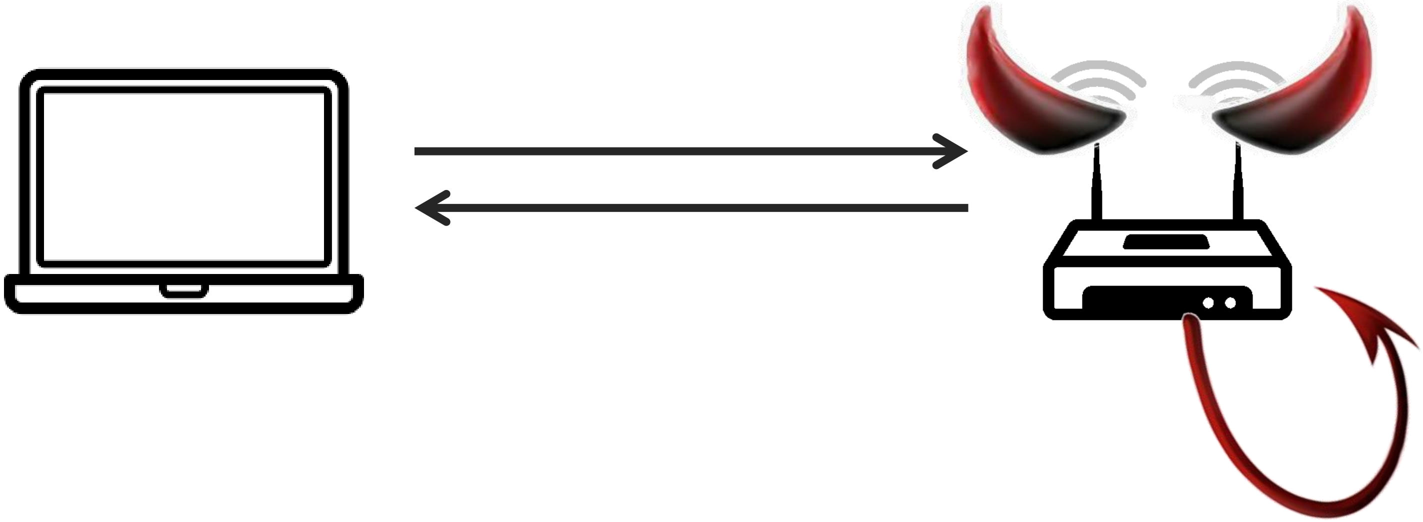
#iterations depends on password

(and public MAC addresses)

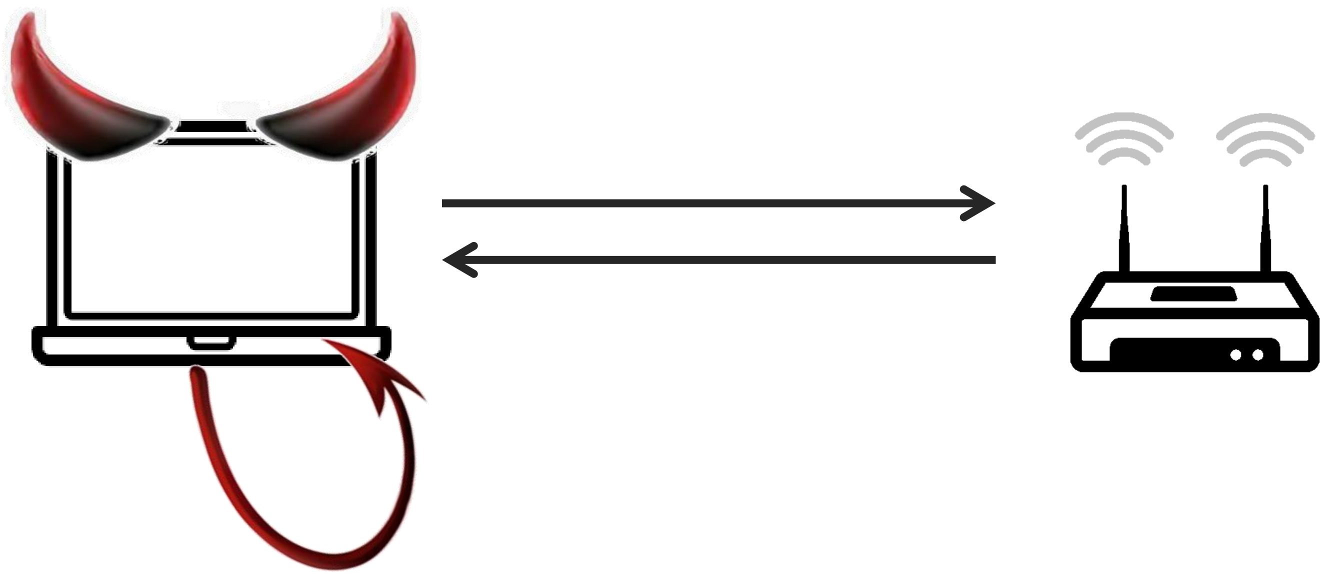
No timing leak countermeasures,

despite warnings by IETF & CFRG!

Attacking Clients



Attacking Access Points

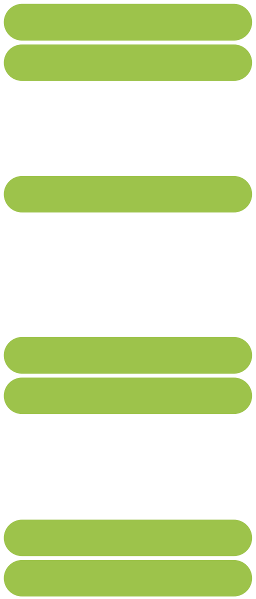


Leaked information: #iterations needed

Client address	addrA
Measured	

Leaked information: #iterations needed

Client address	addrA
Measured	
Password 1	
Password 2	
Password 3	



Leaked information: #iterations needed

Client address	addrA
Measured	
~~Password 1~~	
Password 2	
Password 3	

What information is leaked?

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, addr1, addr2, counter)
    if x >= p: continue
    if square_root_exists(x):
```

return $(x, \sqrt{x^3 + ax + b})$

Spoof client address to obtain different execution & leak new data

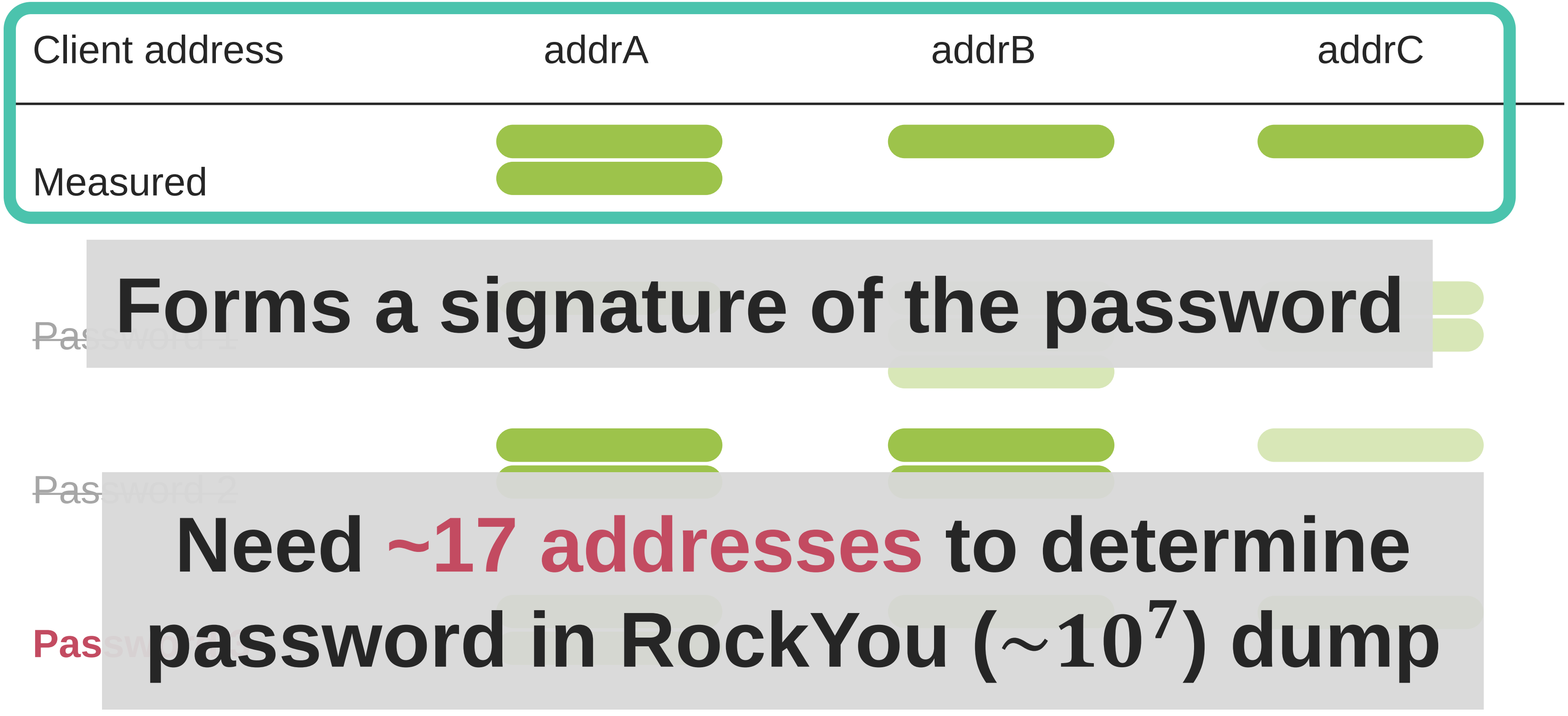
Leaked information: #iterations needed

Leaked information: #iterations needed

Client address	addrA	addrB
Measured		
~~Password 1~~		
~~Password 2~~		
Password 3		

Leaked information: #iterations needed

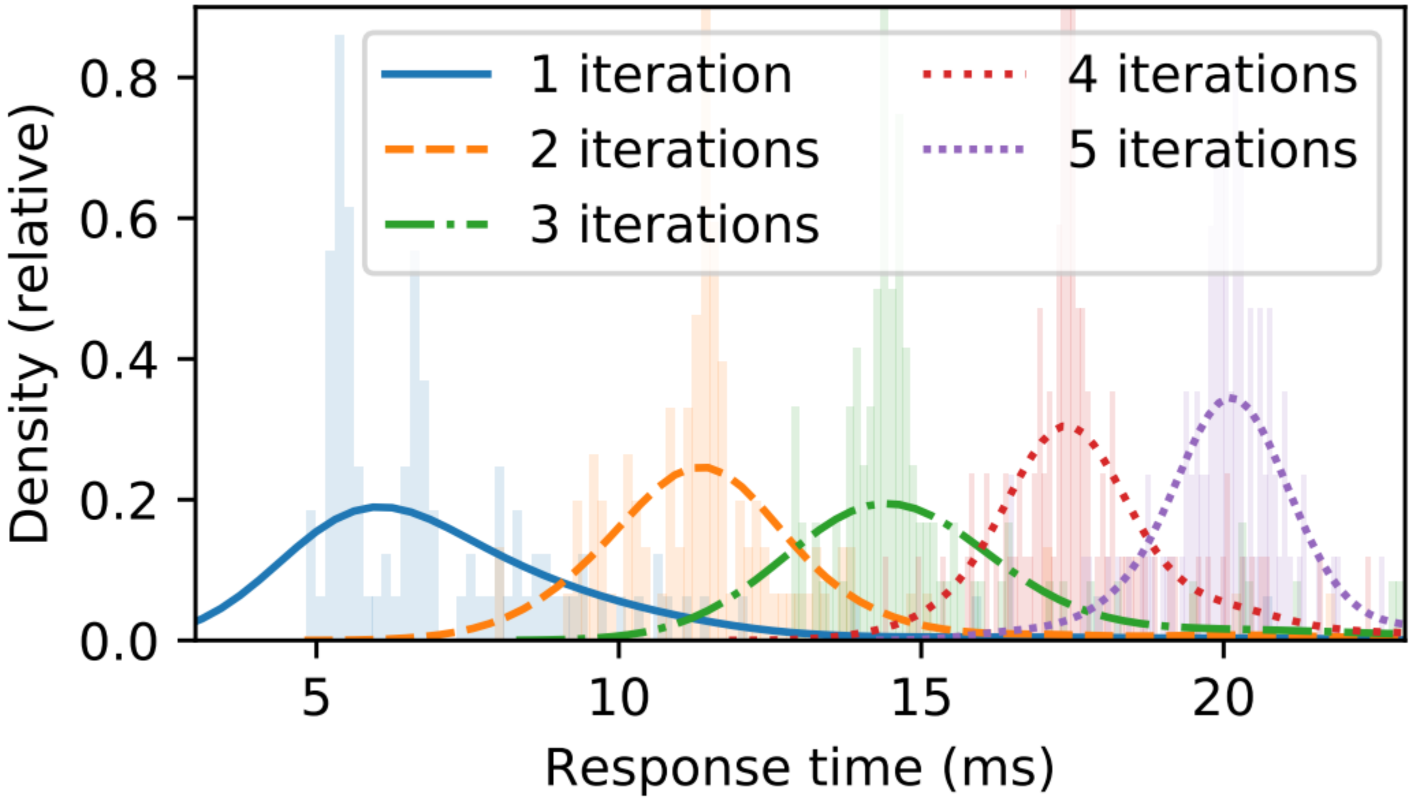
Leaked information: #iterations needed



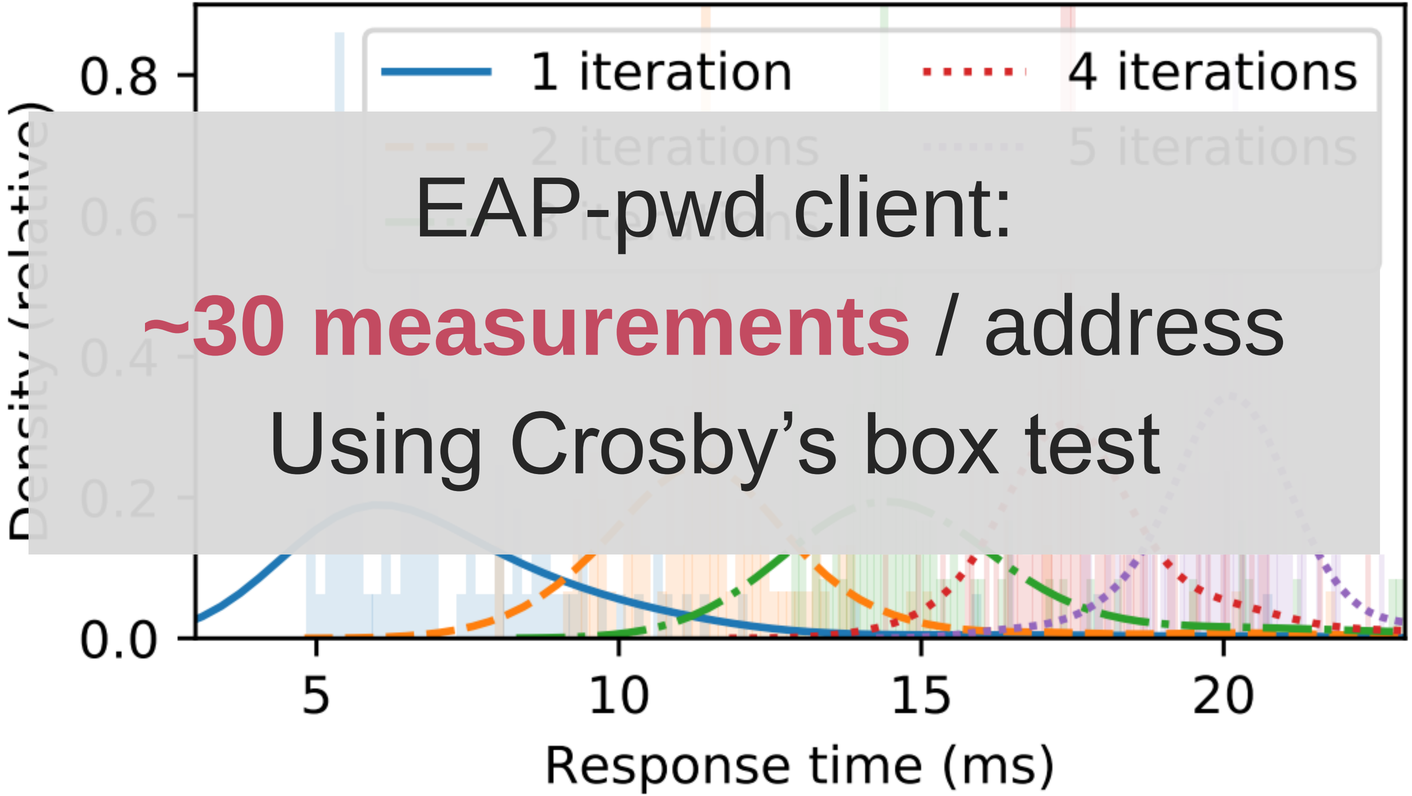
Forms a signature of the password

Need ~17 addresses to determine password in RockYou ($\sim 10^7$) dump

Raspberry Pi 1 B+: differences are measurable



Raspberry Pi 1 B+: differences are measurable



EAP-pwd client:

~30 measurements / address

Using Crosby's box test

Hash-to-curve: EAP-pwd

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
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```

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, √(x³ + ax + b))
        pw = rand()
return P
```

$P = (x, \sqrt{x^3 + ax + b})$

WPA3: always do 40 loops & return first P

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
```

Blinded constant time
square root test

```
return P
```

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, √(x³ + ax + b))
        pw = rand()
return P
```

Extra iterations based on random password

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
```

$$P = (x, \sqrt{x^3 + ax + b})$$

```
        pw = rand()
return P
```

Truncate to size of prime p

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, √(x^3 + ax + b))
        pw = rand()
return P
```

Brainpool: $p = \mathrm{0xA9FB57DBA1EEA9BC}\ldots$

→ **High chance that x >= p**

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, sqrt(x^3 + ax + b))
        pw = rand()
return P
```

$$P = \left(x, \sqrt{x^3 + ax + b}\right)$$

= rejection sampling

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, $\sqrt{x^3 + ax + b}$)
        pw = rand()
return P
```

Code may be skipped

Hash-to-curve: WPA3

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for (counter = 1; counter < 40; counter++)
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return P
```

$$P = \left(x, \sqrt{x^3 + ax + b}\right)$$

#Times skipped depends on password

Hash-to-curve: WPA3

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
```

$$P = (x, \sqrt{x^3 + ax + b})$$

```
        pw = rand()
return P
```

#Times skipped depends on password
& random password in extra itreations

Hash-to-curve: WPA3

`for (counter = 1; counter < 40; counter++)`
    `x = hash(pw, counter, addr1, addr2)`
    `if x >= p: continue`
    `if square_root_exists(x) and not P:`
        `P = (x,` $\sqrt{x^3 + ax + b}$`)`
        `pw = rand()`
`return P`

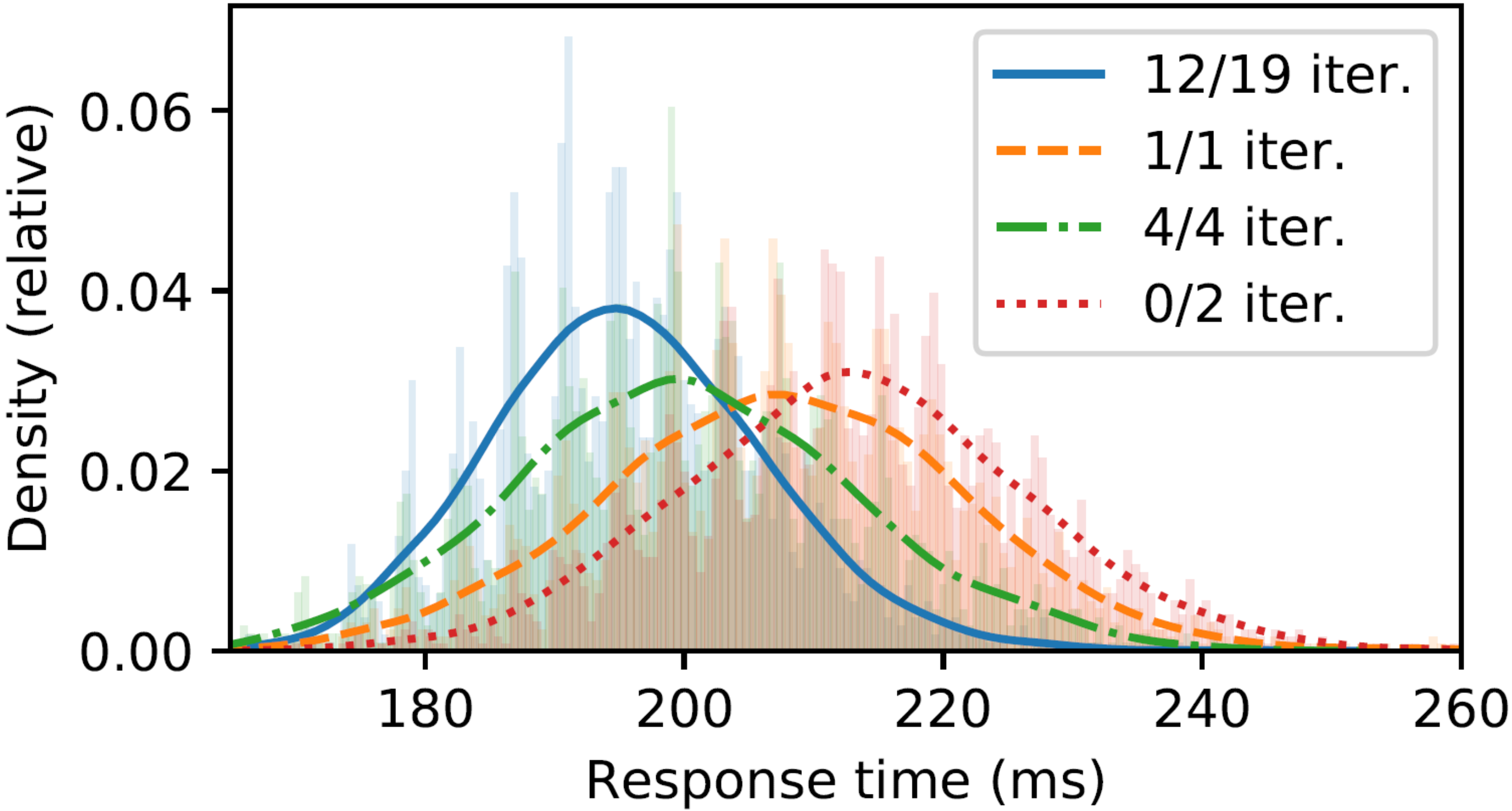
Variance ~ when password element was found

Hash-to-curve: WPA3

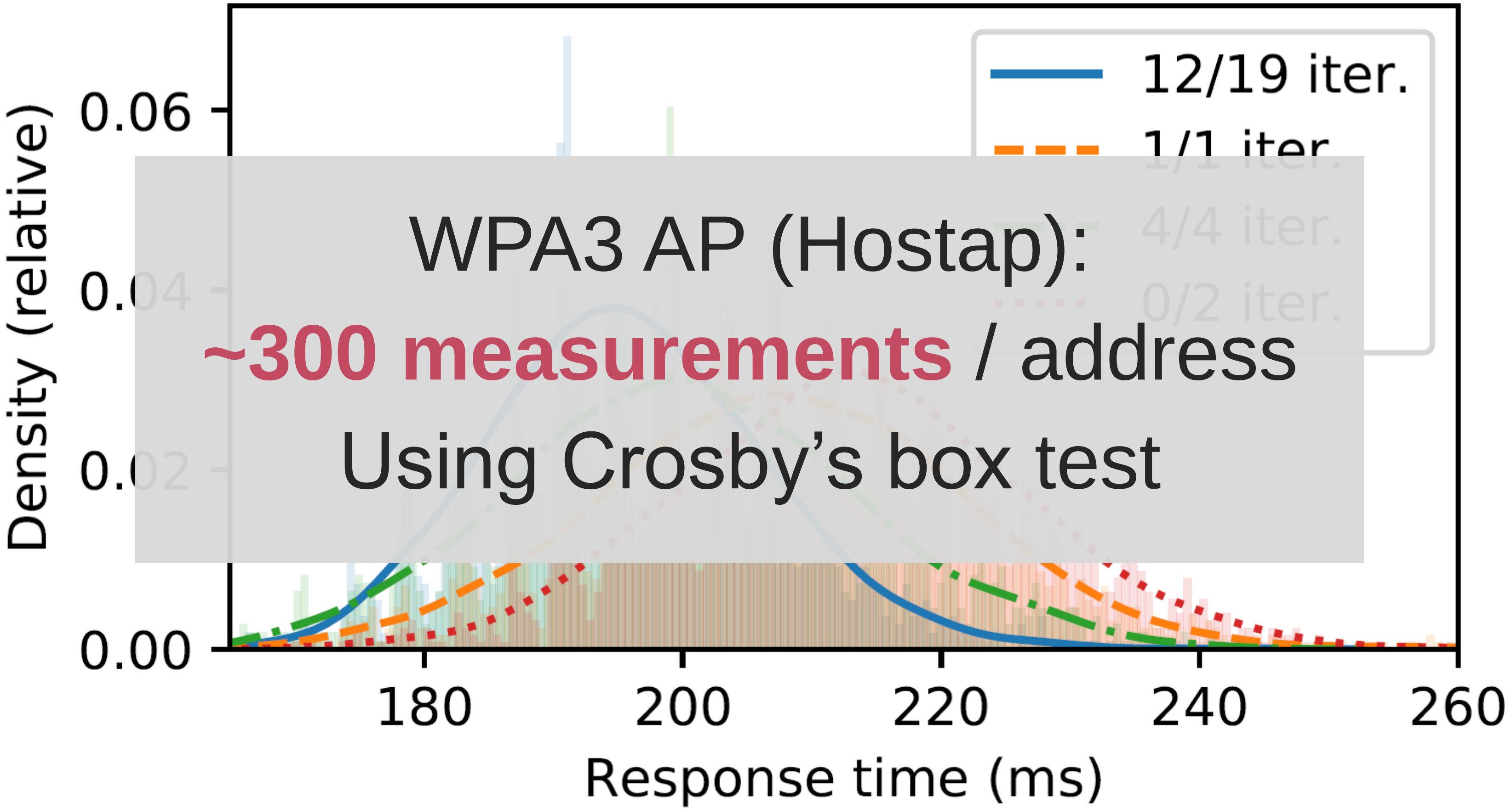
```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, $\sqrt{x^3 + ax + b}$)
        pw = rand()
return P
```

Variance ~ when password element was found
Average ~ when found & #iterations code skipped

Raspberry Pi 1 B+



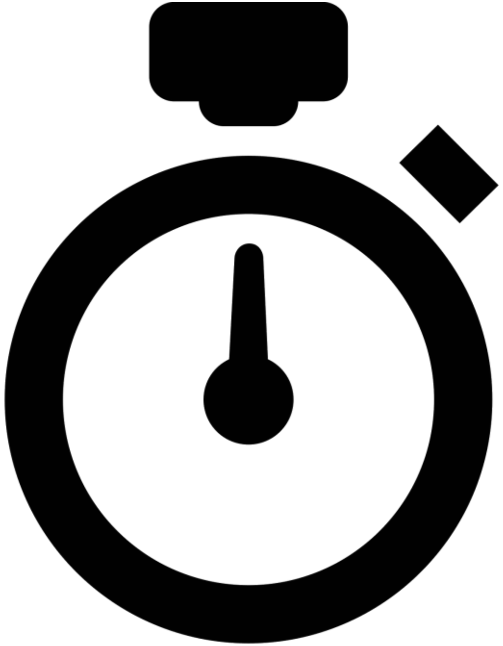
Raspberry Pi 1 B+



WPA3 AP (Hostap):

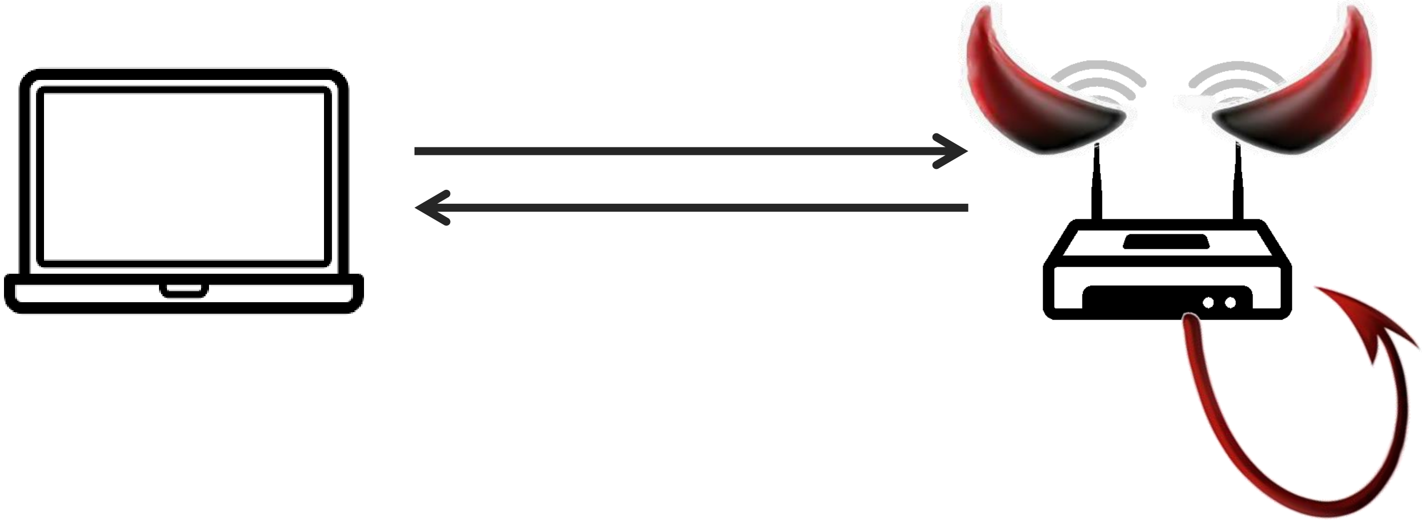
~300 measurements / address

Using Crosby’s box test

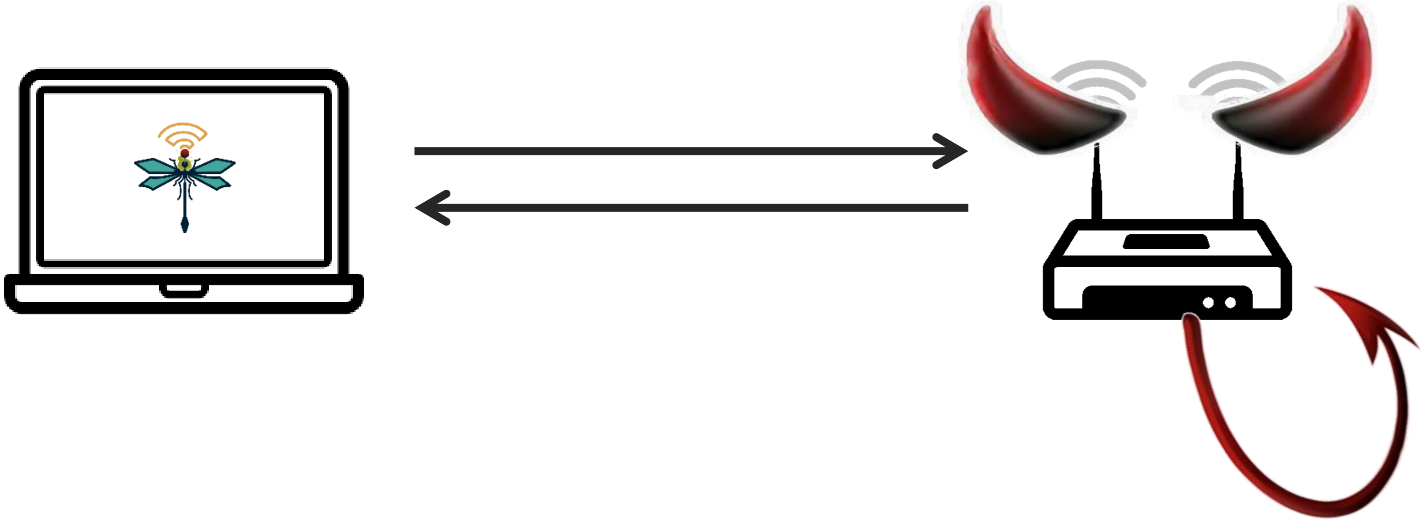


Cache Attacks

Threat Model



Threat Model



Cache attack on NIST curves

```
for (counter = 1; counter < 40; counter++)
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    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, √(x^3 + ax + b))
        pw = rand()
return P
```

NIST: $p = $ 0x0xFFFFFFFF00000001000…

→ **Negligible chance that x >= p**

Cache attack on NIST curves

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
```

$$\boxed{P = (x, \sqrt{x^3 + ax + b})}$$

```
        pw = rand()
return P
```

NIST curves: use Flush+Reload to detect when code is executed

Cache attack on NIST curves

```
for (counter = 1; counter < 40; counter++)
    x = hash(pw, counter, addr1, addr2)
    if x >= p: continue
    if square_root_exists(x) and not P:
        P = (x, √(x³ + ax + b))
        pw = rand()
return P
```

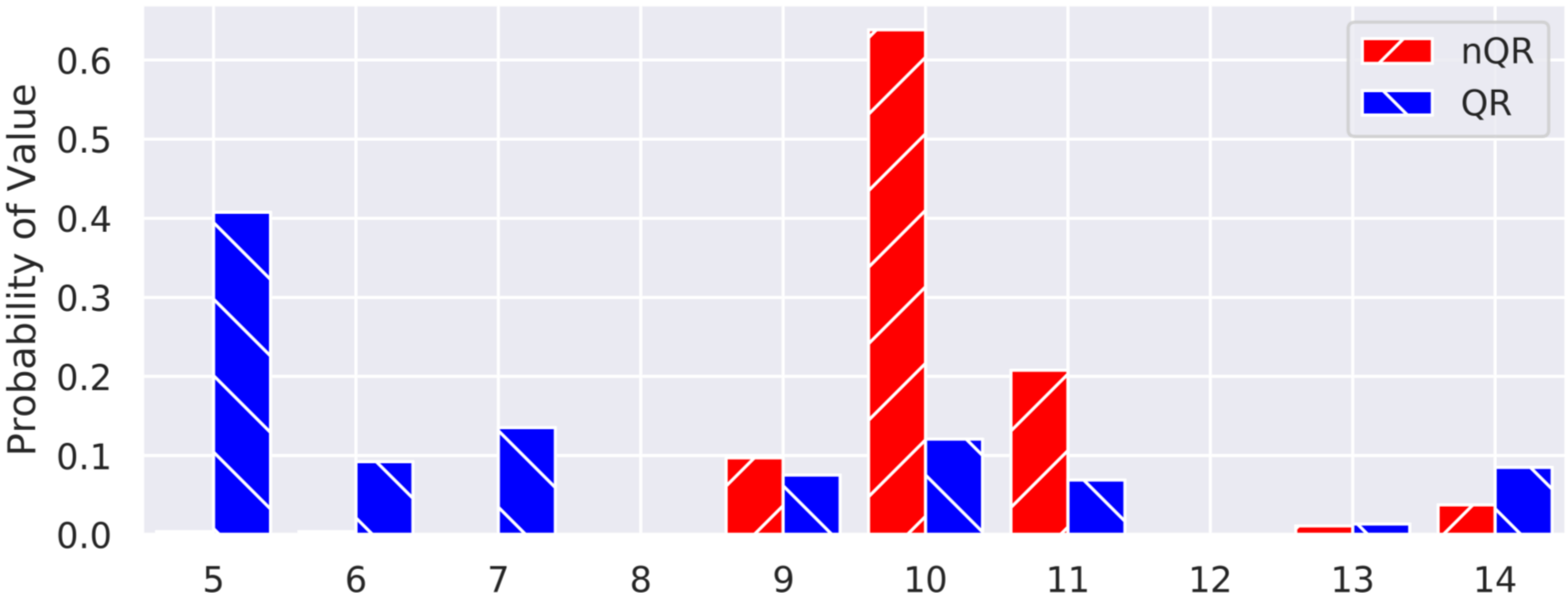
$\boxed{\texttt{hash(pw, counter, addr1, addr2)}}$

$\boxed{P = \left(x, \sqrt{x^3 + ax + b}\right)}$

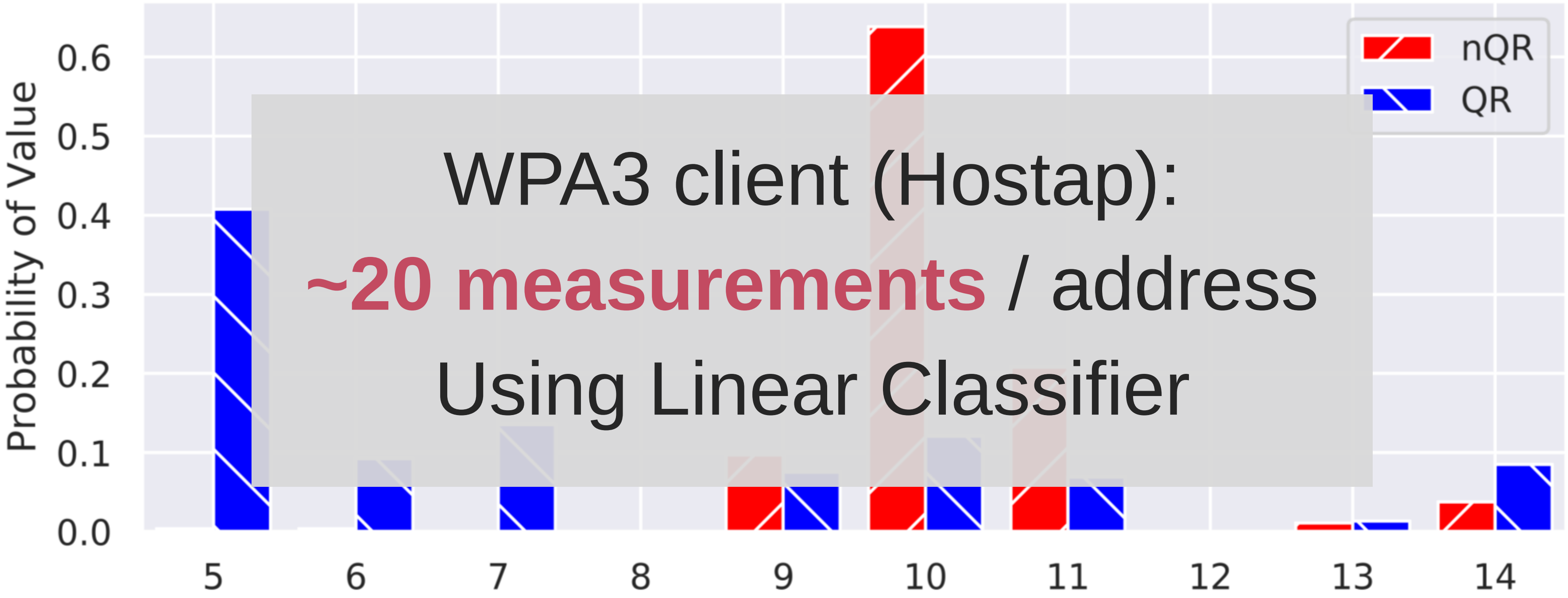
Monitor using Flush+Reload to know in which iteration we are

NIST curves: use Flush+Reload to detect when code is executed

Attacking client: Intel Core i7-7500



Attacking client: Intel Core i7-7500



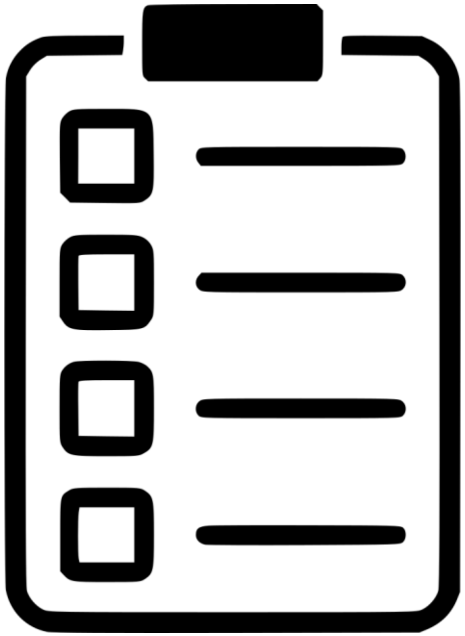
WPA3 client (Hostap):

~20 measurements / address

Using Linear Classifier

Password Brute-force Cost

Group / Dictionary	Dictionary Size	$ for MODP 22 Brainpool 28	$ for P-256
RockYou [20]	$1.4 \cdot 10^{7}$	$2.1 \cdot 10^{-6}$	$4.4 \cdot 10^{-4}$
HaveIBeenPwned [45]	$5.5 \cdot 10^{8}$	$8.0 \cdot 10^{-5}$	$1.7 \cdot 10^{-2}$
Probable Wordlists [12]	$8.0 \cdot 10^{9}$	$1.2 \cdot 10^{-3}$	$2.5 \cdot 10^{-1}$
8 Low Case	$2.1 \cdot 10^{11}$	$3.0 \cdot 10^{-2}$	6.5
8 Letters	$5.3 \cdot 10^{13}$	7.8	$1.7 \cdot 10^{3}$
8 Alphanumerics	$2.2 \cdot 10^{14}$	$3.2 \cdot 10^{1}$	$6.7 \cdot 10^{3}$
8 Symbols	$4.6 \cdot 10^{14}$	$6.7 \cdot 10^{1}$	$1.4 \cdot 10^{4}$

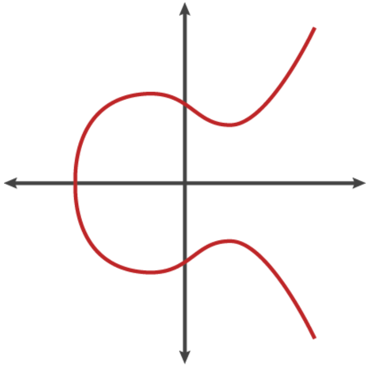


Implementation Inspection

Other Implementation Vulnerabilities

Bad randomness:

- Can recover password element P
- With WPA2 bad randomness has lower impact!

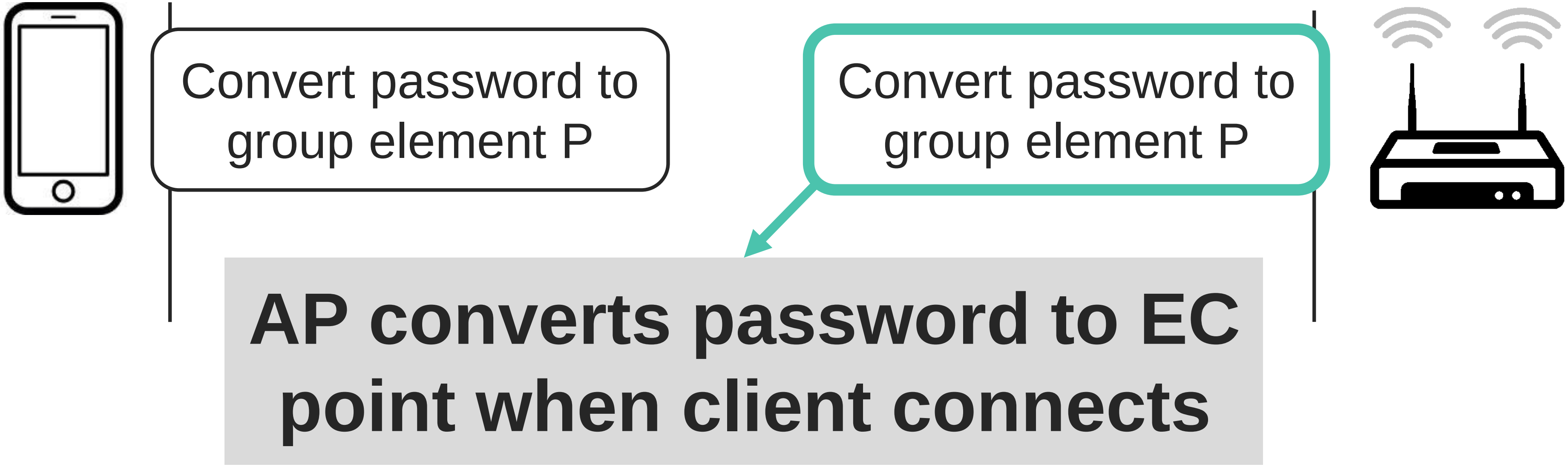


Invalid curve attack:

- Attacker sends point not on curve
- Recover session key & bypass authentication

Wi-Fi Specific Attacks

Denial-of-Service Attack



- Conversion is computationally expensive (**40 iterations**)
- Forging **8 connections/sec** saturates AP’s CPU

Downgrade Attacks

Transition mode: **WPA2/3 use the same password**

- WPA2's handshake detects downgrades
- Performing partial WPA2 handshake → **dictionary attacks**

Handshake can be performed with multiple curves

- Initiator proposes curve & responder accepts/rejects
- **Spoof reject messages to downgrade** used curve

Disclosure

Disclosure process

Notified parties early with **hope to influence WPA3**

Reaction of the Wi-Fi Alliance

- **Privately created** backwards-compatible security guidelines
- **2nd disclosure** round to address Brainpool side-channels
- **Nov 2019**: Updated guidelines now prohibit Brainpool curves

Latest Wi-Fi Alliance guidelines (Nov 2019)

- SAE implementations must avoid differences in code execution that allow side channel information collection through the cache (see Cache-Based Elliptic Curve Side-Channels).
- If WPA3-Personal Transition Mode does not meet the security requirements for a deployment, WPA3-Personal and WPA2™-Personal should be deployed on individual service set identifiers (SSIDs) using unique passwords and logically separated/isolated network segments (see WPA3-Personal Transition Mode).

Failure to implement these recommendations correctly may expose the vendor implementation to attack and/or compromise the network.

› “implementations must avoid [..] side-channels”

› If WPA3-Transition *“doesn’t meet security requirements”*, then seperate passwords

› “Failure to implement...” → how can it be checked?

Fundamental issue still unsolved

- Hard to implement in constant time
- On lightweight devices, doing **40 iterations is too costly**

Draft IEEE 802.11 standard has been updated

- Exclude MAC addresses from hash2curve
  - Allows offline computation of password element
- Now uses constant-time hash2curve
- Explicitly prohibit use of weak EC & MODP groups
- Prevent crypto group downgrade attack

Remaining issues

Message **transcript is not included in key derivation**

- Prevents formal proof of protocol
- High risk of implementation issues
  - E.g. prevention of crypto group downgrade attack

Downgrade to WPA2

- **Not addressed in the standard**
- Up to vendor whether to implement trust-on-first-use
  - Done by Android & NetworkManager of Linux

Issue 2: not backwards-compatible

Might lead to WPA3.1?

- Not yet clear how Wi-Fi Alliance will handle this
- **Risk of downgrade attacks** to original WPA3

Should you switch to WPA3?

- WPA2 is trivial to attack... so yes.

Conclusion

- WPA3 vulnerable to side-channels
- Countermeasures are costly
- **Draft 802.11 standard updated**
- Issues could have been avoided!

https://wpa3.mathyvanhoef.com

Thank you! Questions?

- WPA3 vulnerable to side-channels
- Countermeasures are costly
- **Draft 802.11 standard updated**
- Issues could have been avoided!

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