KRACKing WPA2 by Forcing Nonce Reuse

Mathy Vanhoef — @vanhoefm

OWASP Chapter Meeting, Brussels, 19 March 2018

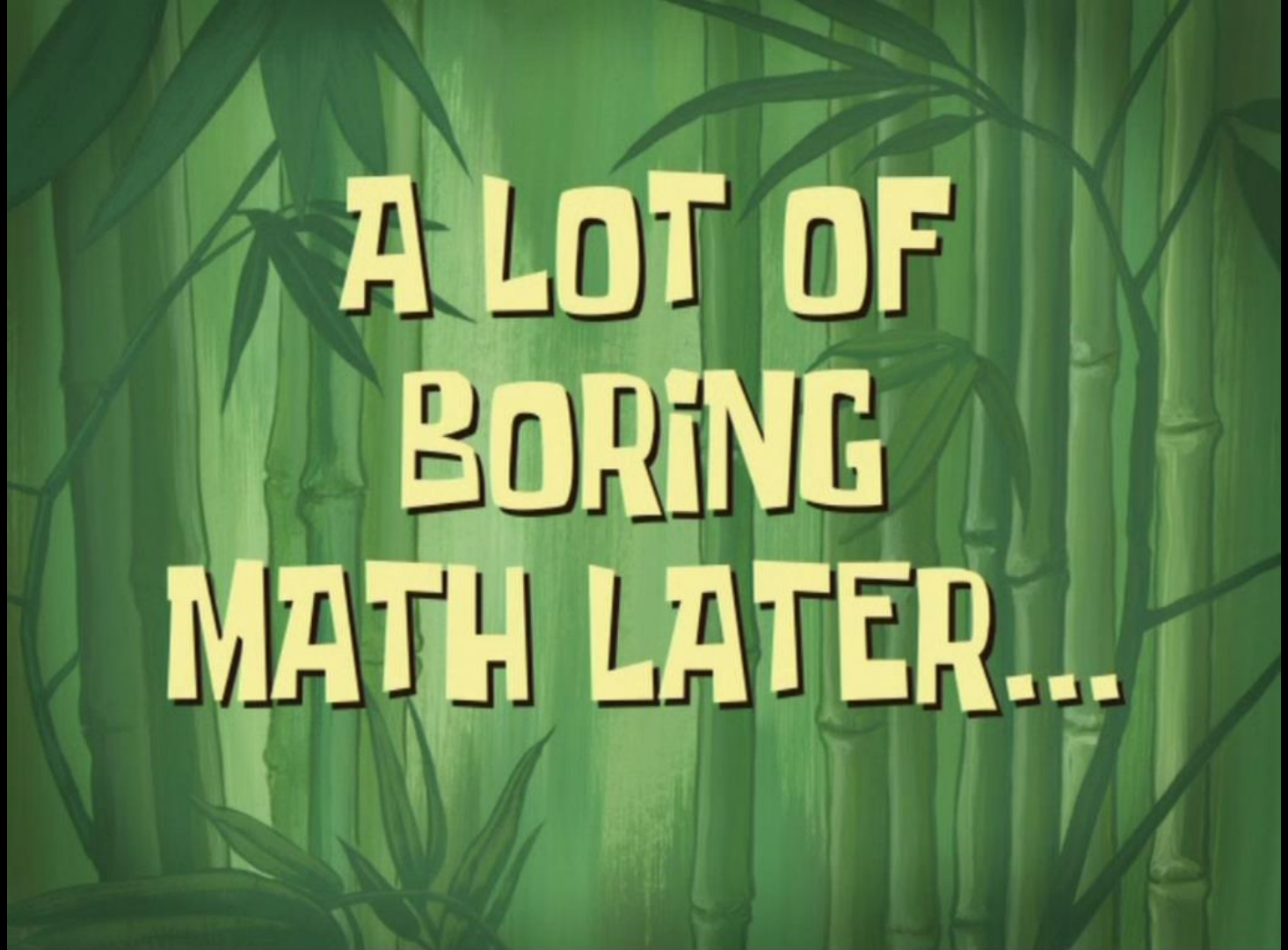
KU LEUVEN DistriNet

Introduction

PhD Defense, July 2016:

“You recommend WPA2 with AES, but are you sure that’s secure?”

Seems so! No attacks in 14 years & proven secure.

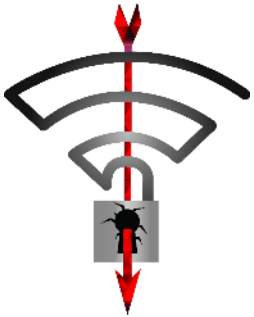

A LOT OF
BORING
MATH LATER...

Introduction

```
/* install the PTK */
if ((*ic->ic_set_key)(ic, ni, k) != 0) {
        reason = IEEE80211_REASON_AUTH_LEAVE;
        goto deauth;
}
ni->ni_flags &= ~IEEE80211_NODE_TXRXPROT;
ni->ni_flags |= IEEE80211_NODE_RXPROT;
```

Key reinstallation when ic_set_key is called again?

Overview



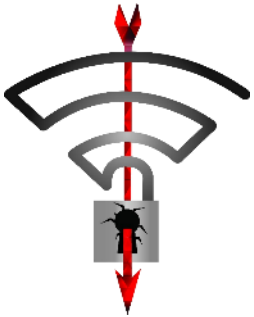
Key reinstalls in
4-way handshake

Misconceptions

Practical impact

Lessons learned

Overview



Key reinstalls in 4-way handshake

Misconceptions

Practical impact

Lessons learned

The 4-way handshake

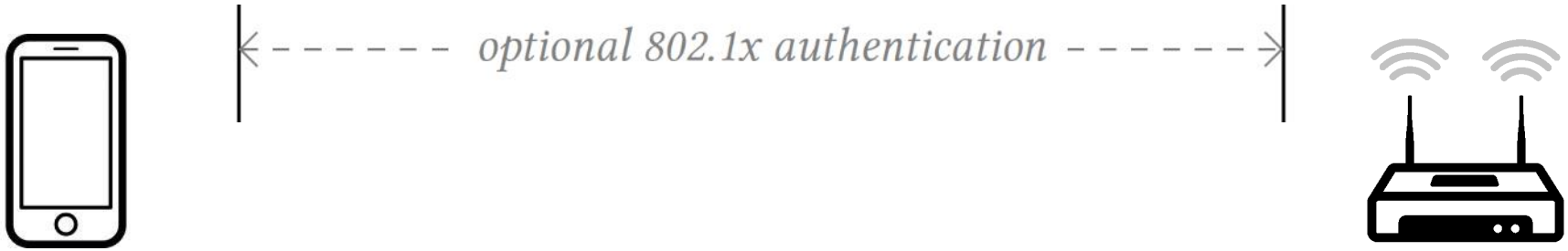
Used to connect to any protected Wi-Fi network

- Provides mutual authentication
- Negotiates fresh PTK: pairwise transient key

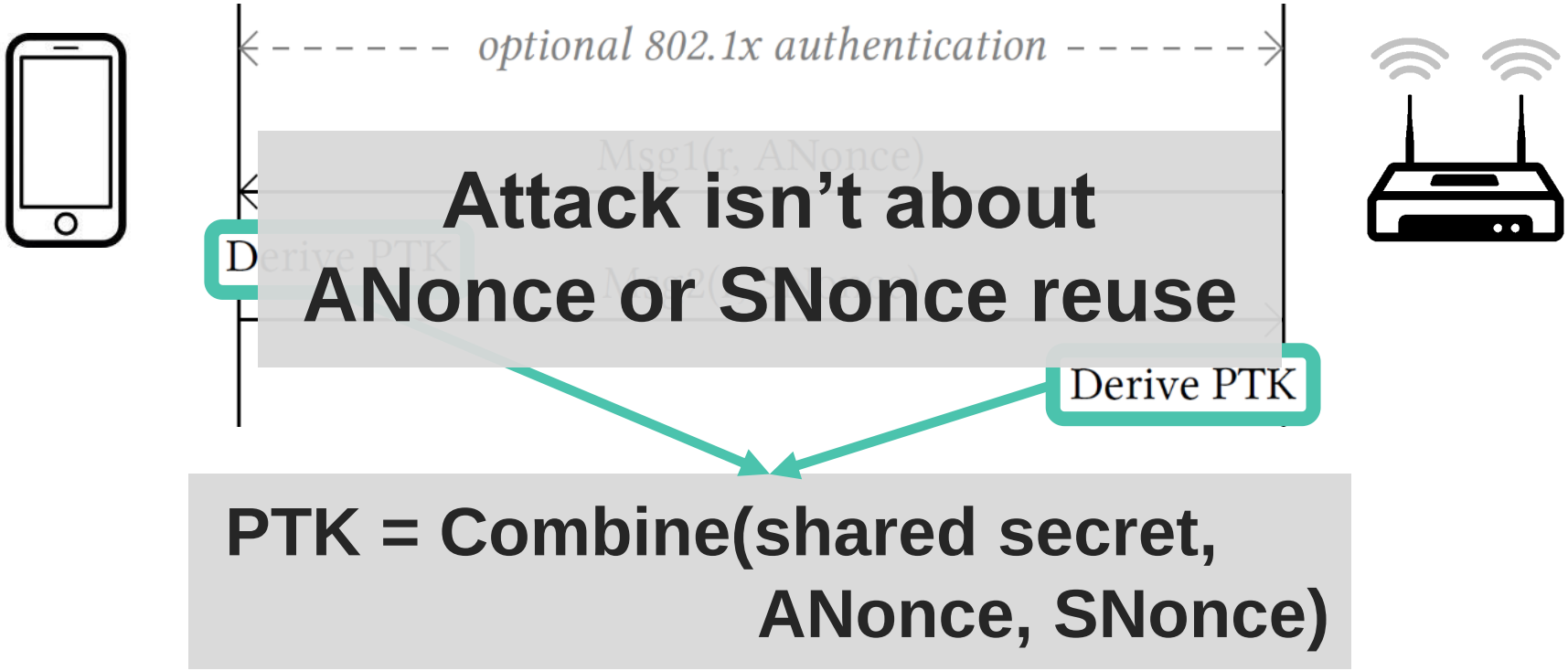
Appeared to be secure:

- No attacks in over a decade (apart from password guessing)
- Proven that negotiated key (PTK) is secret[1]
- And encryption protocol proven secure[7]

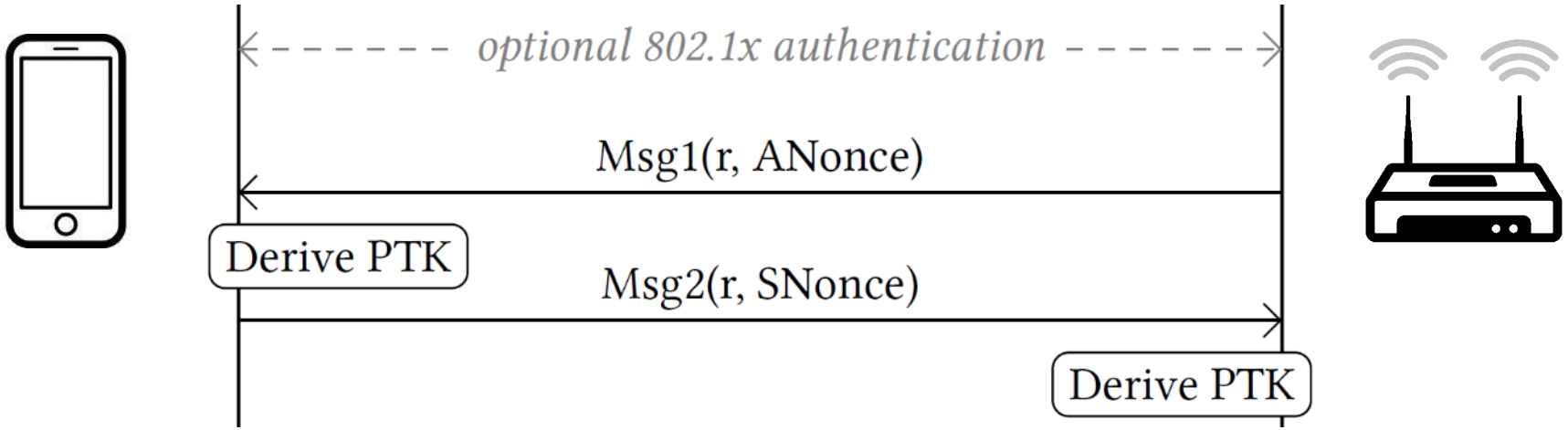
4-way handshake (simplified)



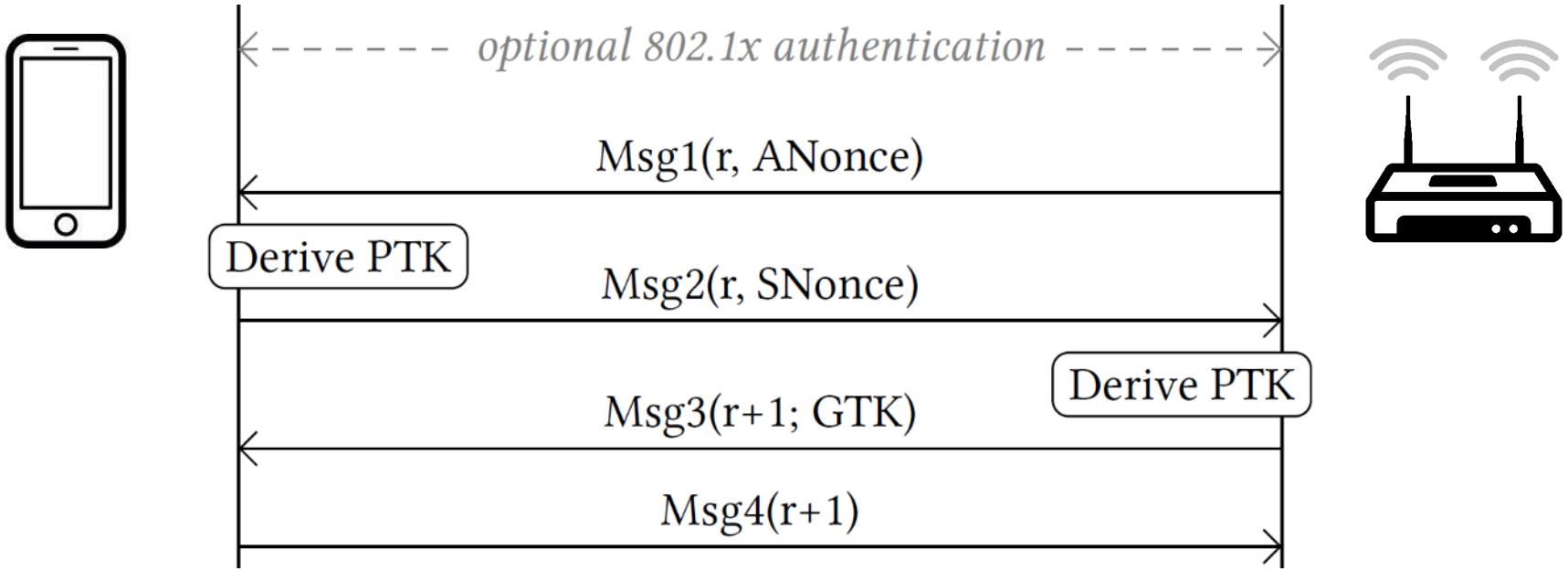
4-way handshake (simplified)



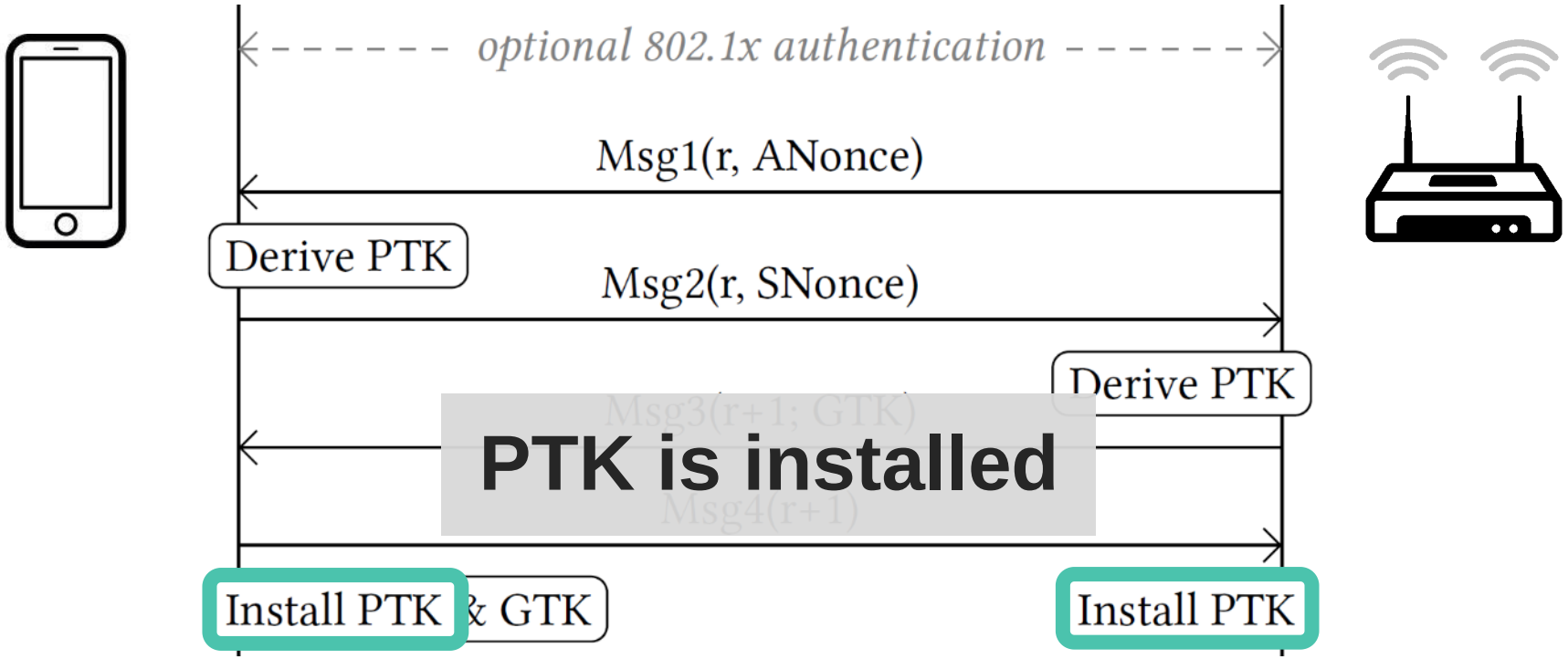
4-way handshake (simplified)



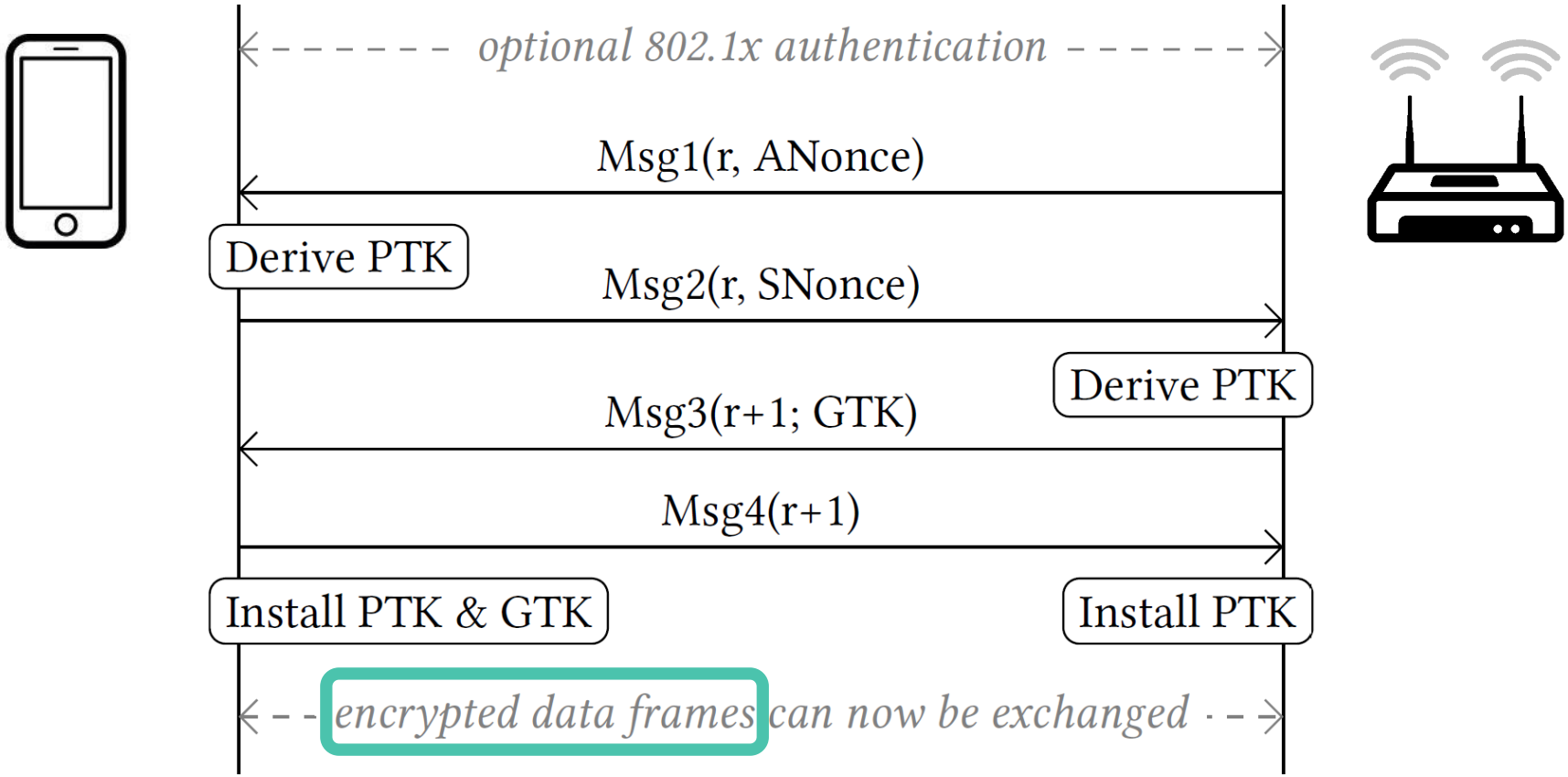
4-way handshake (simplified)



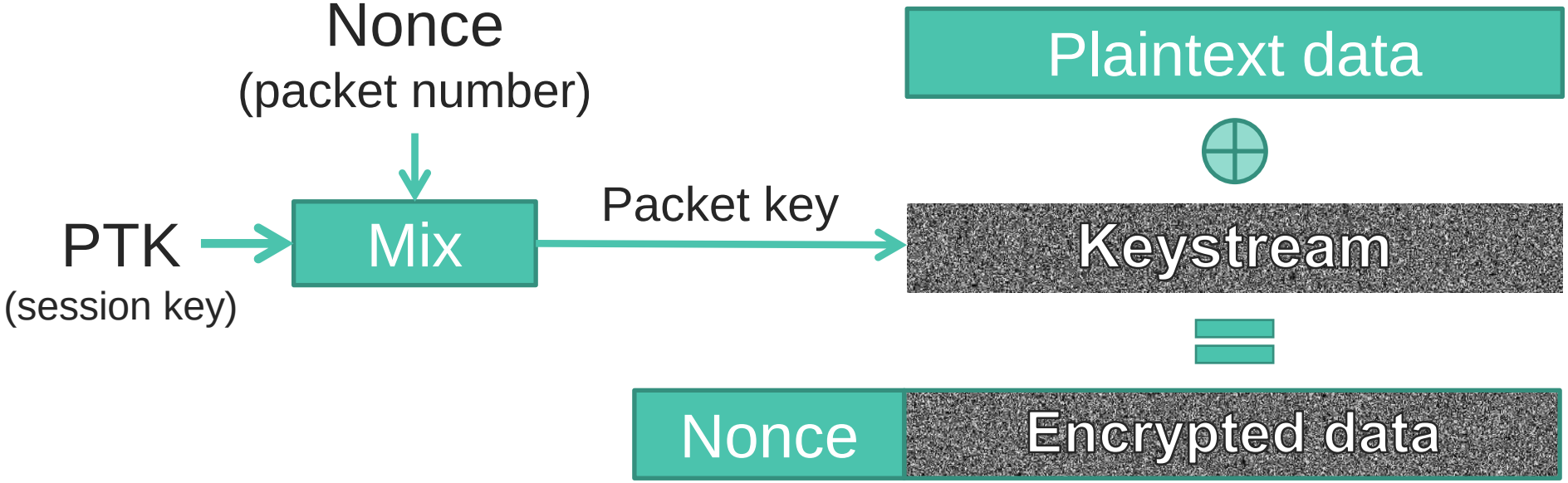
4-way handshake (simplified)



4-way handshake (simplified)

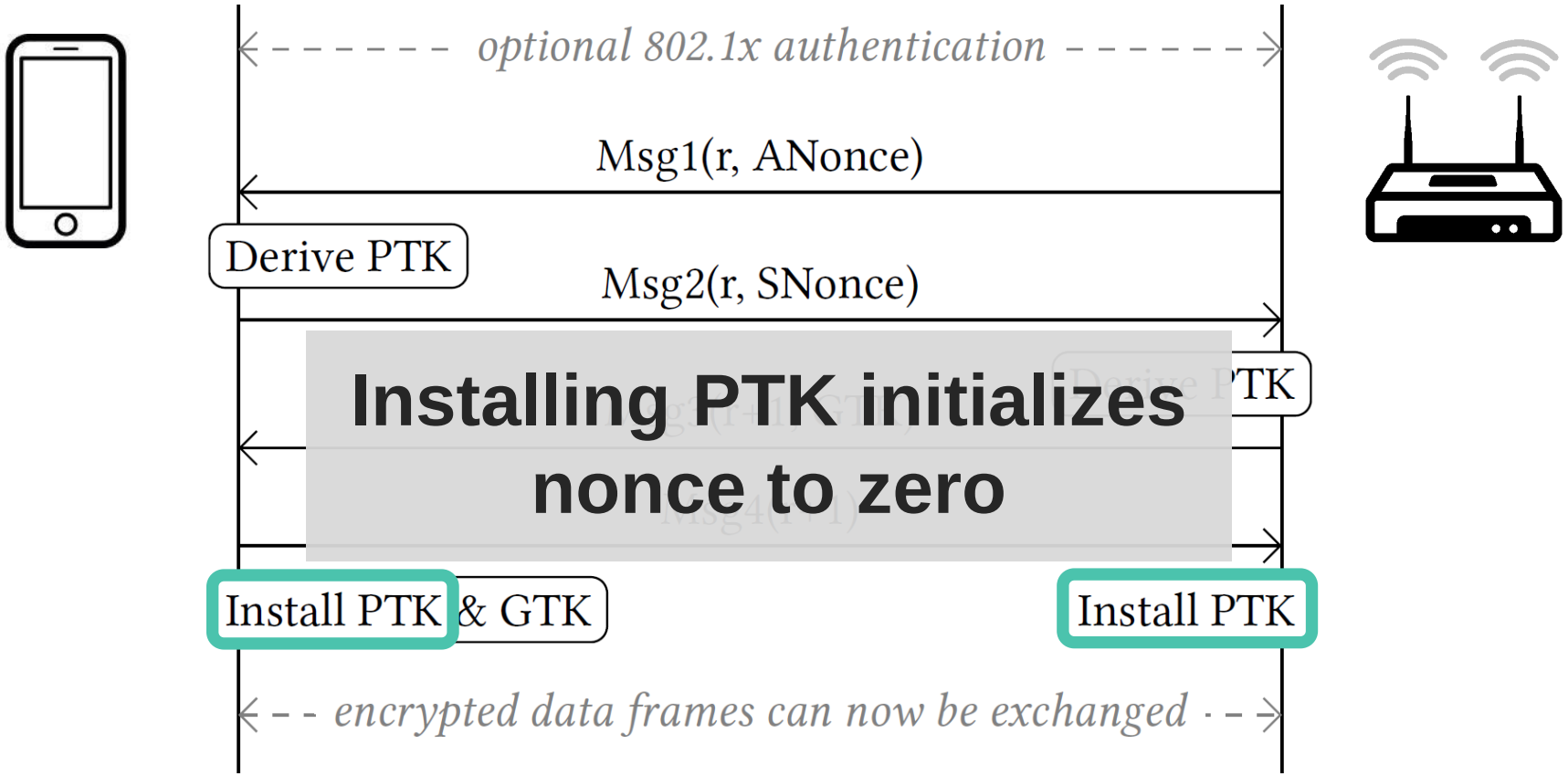


Frame encryption (simplified)

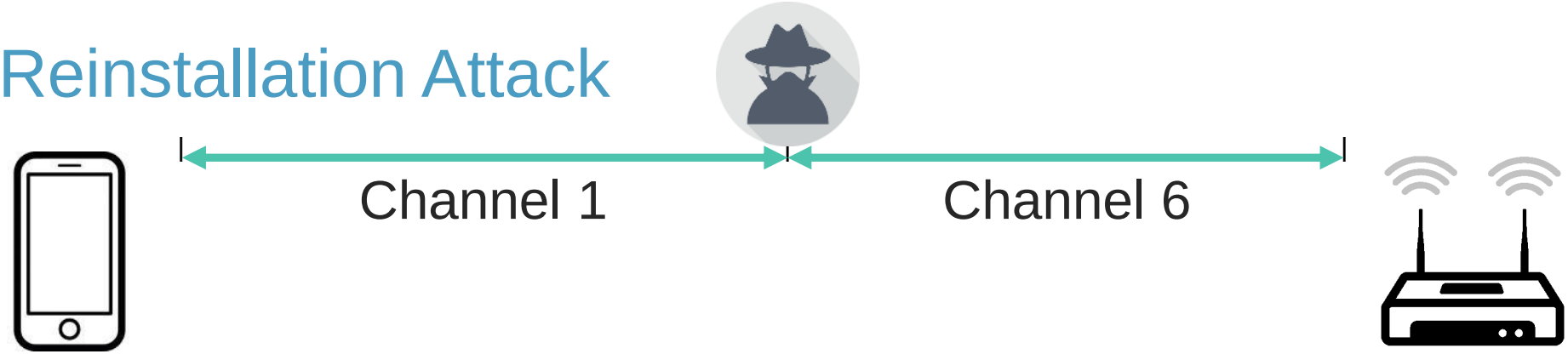


→ Nonce reuse implies keystream reuse (in all WPA2 ciphers)

4-way handshake (simplified)

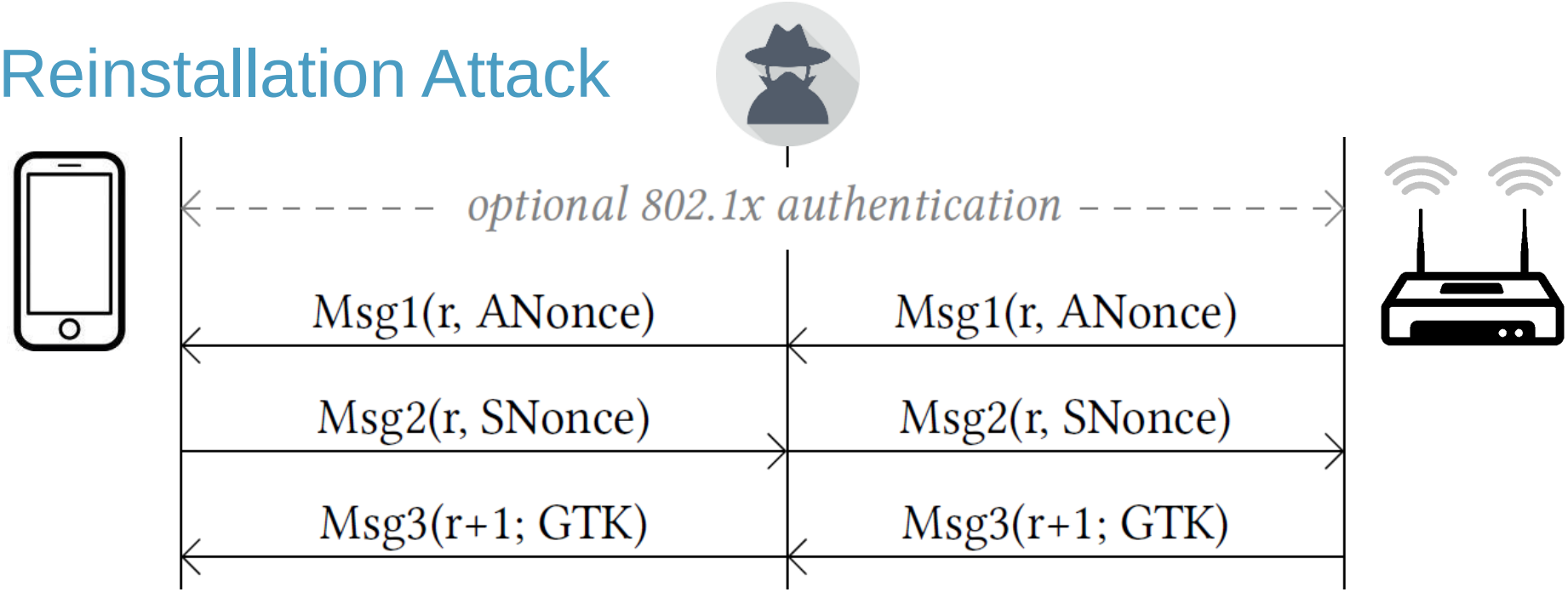


Reinstallation Attack

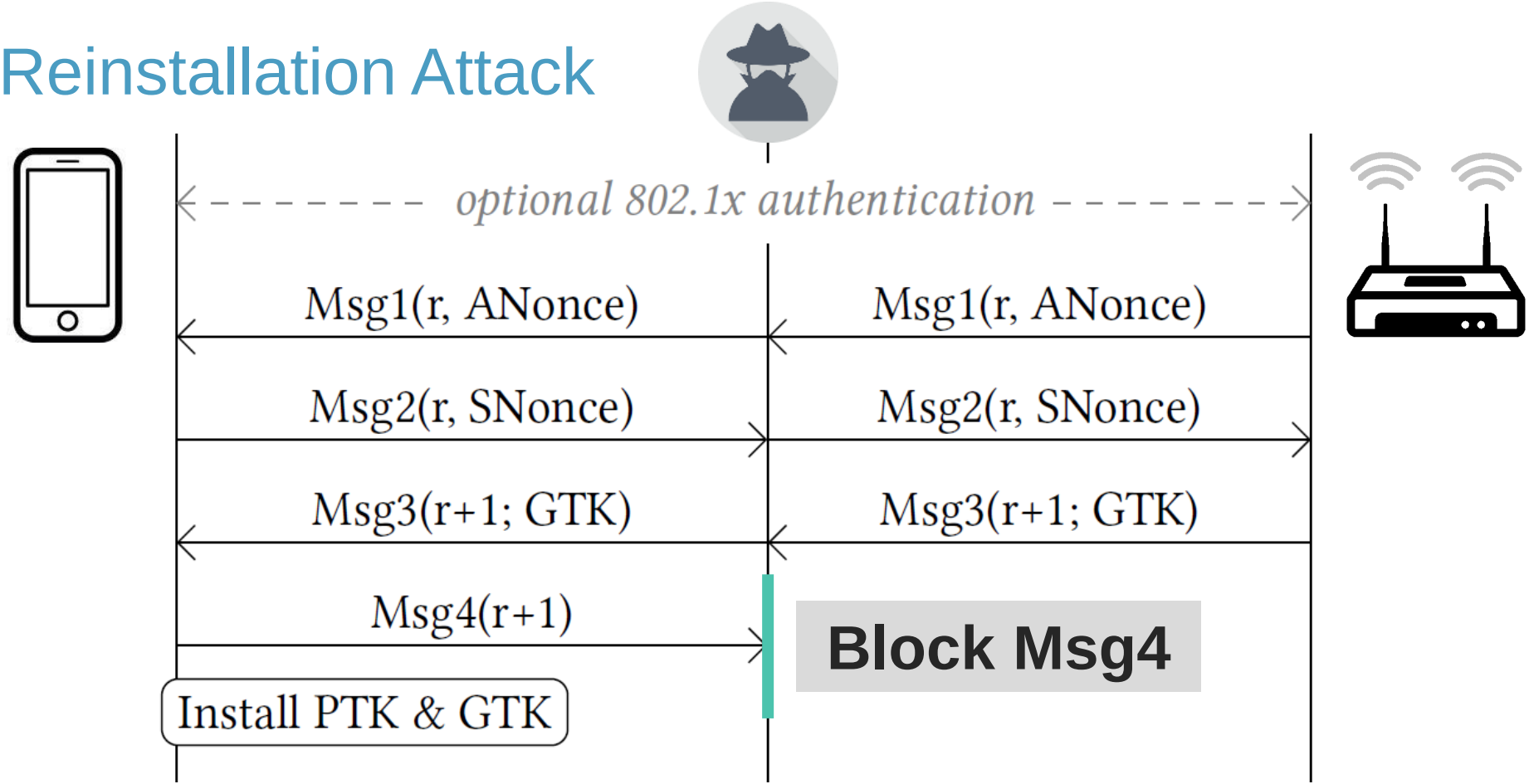


Reinstallation Attack

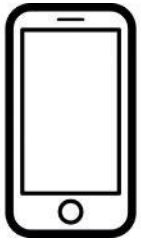
Reinstallation Attack

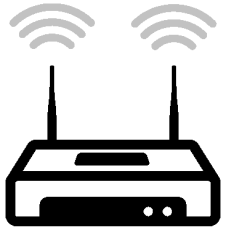


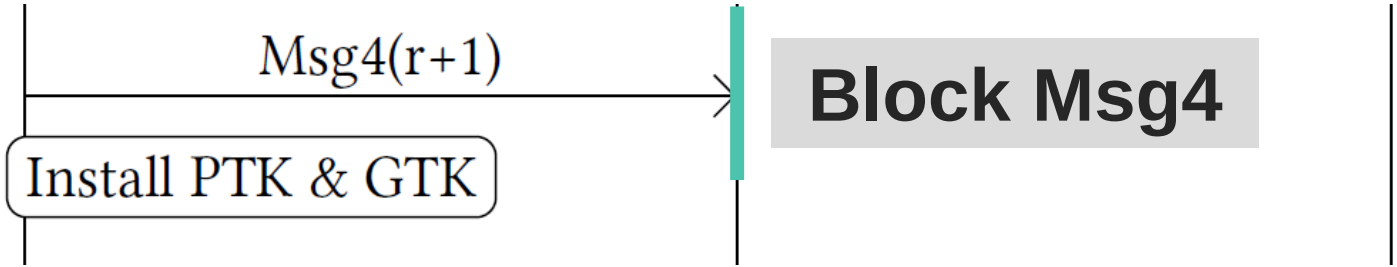
Reinstallation Attack



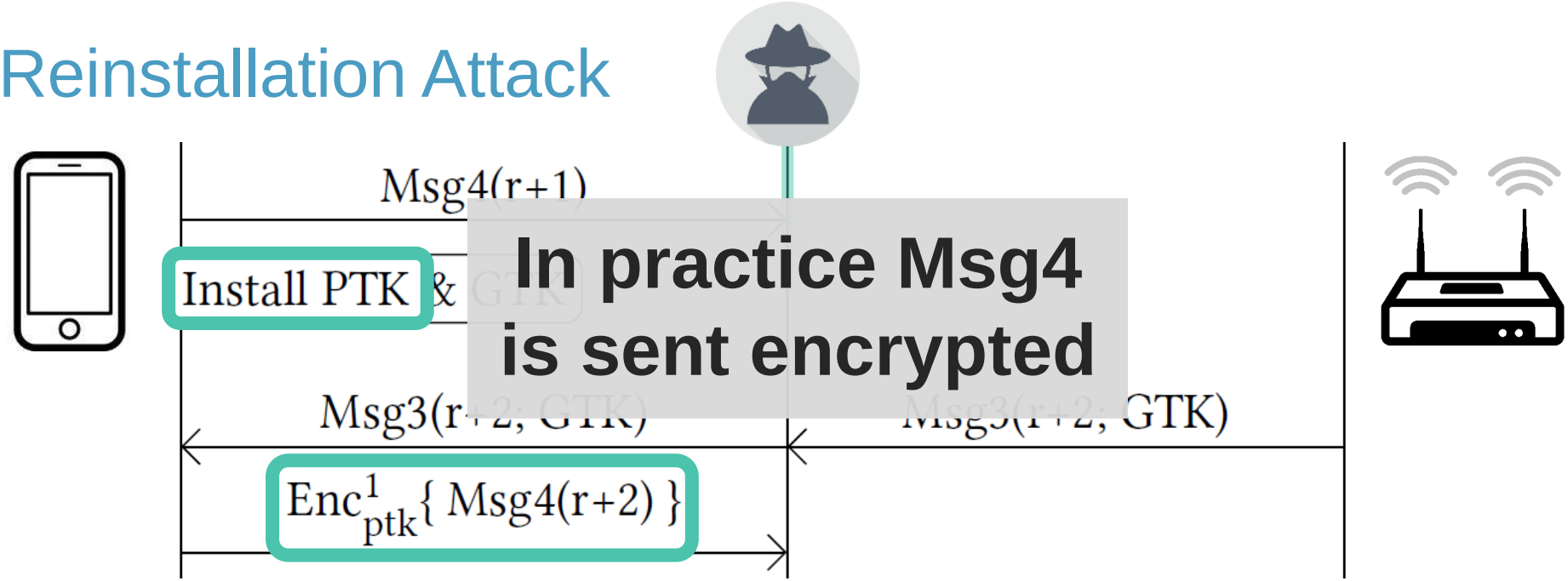
Reinstallation Attack





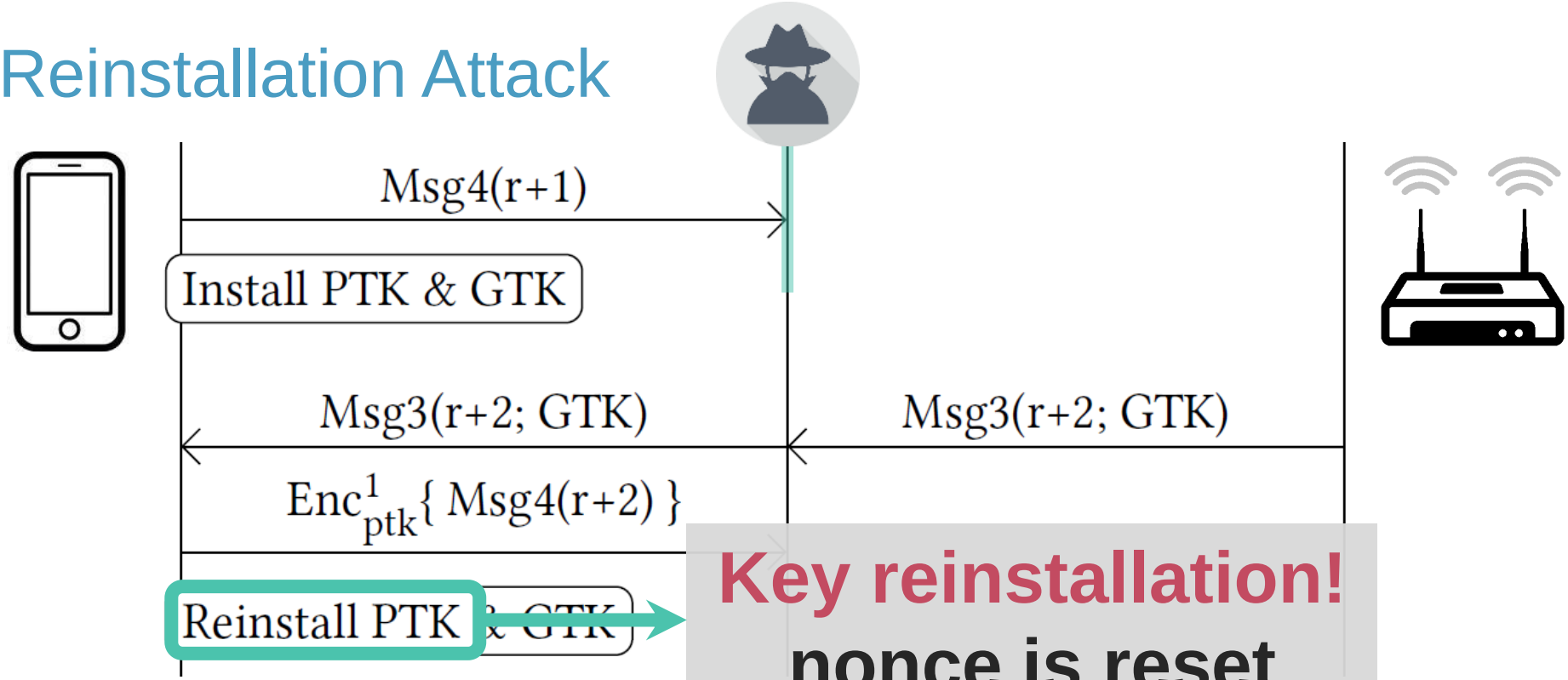


Reinstallation Attack

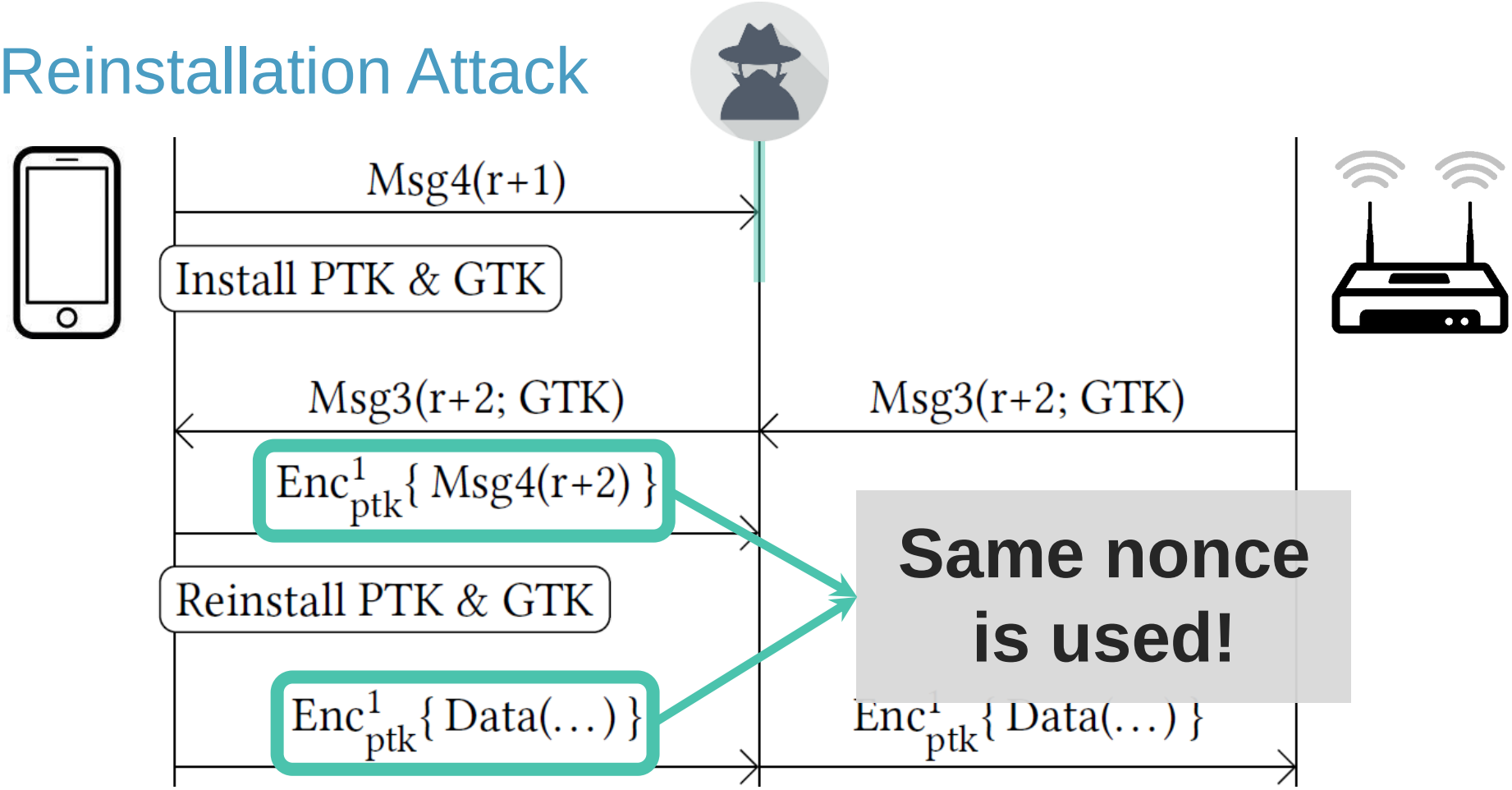


In practice Msg4 is sent encrypted

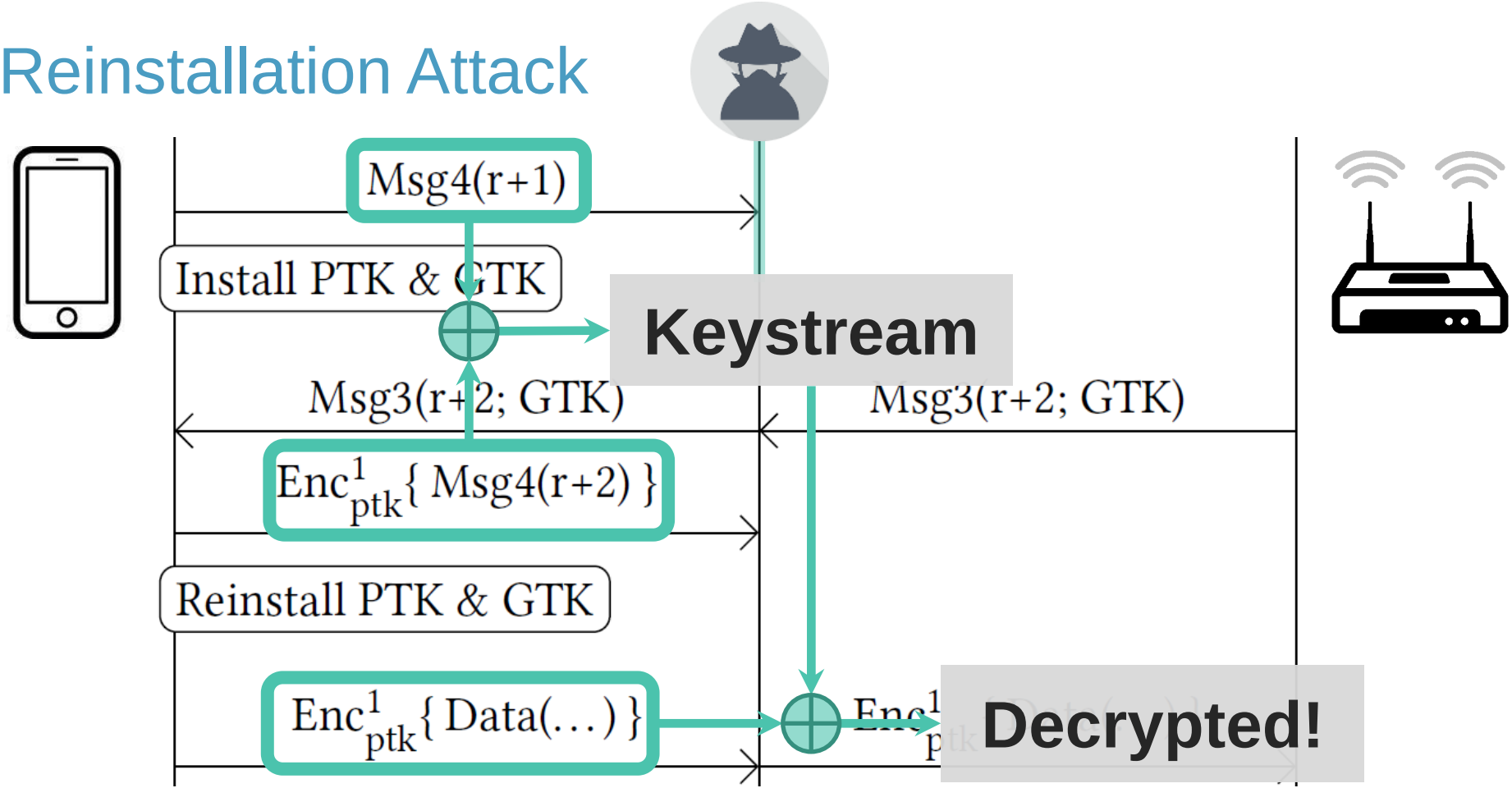
Reinstallation Attack



Reinstallation Attack



Reinstallation Attack



Key Reinstallation Attack

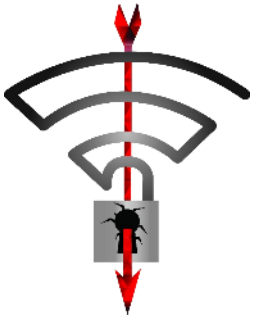
Other Wi-Fi handshakes also vulnerable:

- Group key handshake
- FT handshake
- TDLS PeerKey handshake

For details see our CCS'17 paper[12]:

- "Key Reinstallation Attacks: Forcing Nonce Reuse in WPA2"

Overview



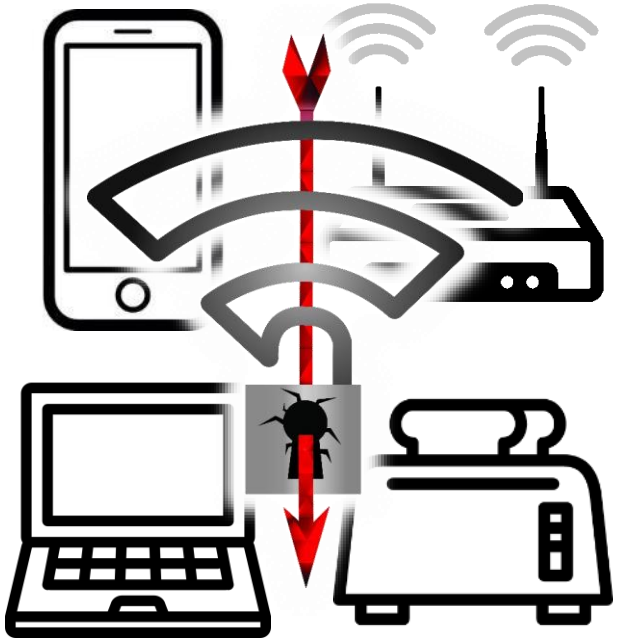
Key reinstalls in
4-way handshake

Misconceptions

Practical impact

Lessons learned

General impact



Transmit nonce reset

Decrypt frames sent by victim

Receive replay counter reset

Replay frames towards victim

Cipher suite specific

AES-CCMP: No practical frame forging attacks

WPA-TKIP:

- Recover Message Integrity Check key from plaintext[4,5]
- **Forge/inject** frames sent by the device under attack

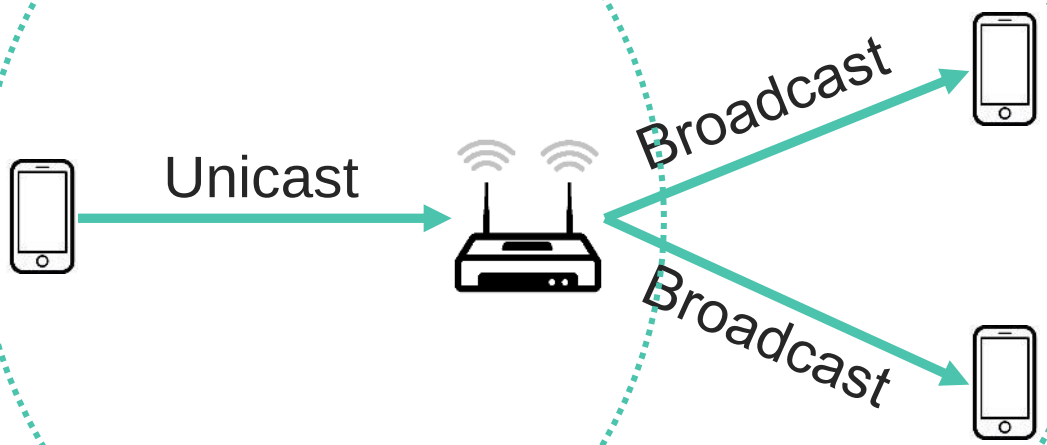
GCMP (WiGig):

- Recover GHASH authentication key from nonce reuse[6]
- **Forge/inject** frames in **both directions**

Handshake specific

Group key handshake:

› Client is attacked, but only AP sends real broadcast frames



Handshake specific

Group key handshake:

- Client is attacked, but only AP sends real broadcast frames
- Can only replay broadcast frames to client

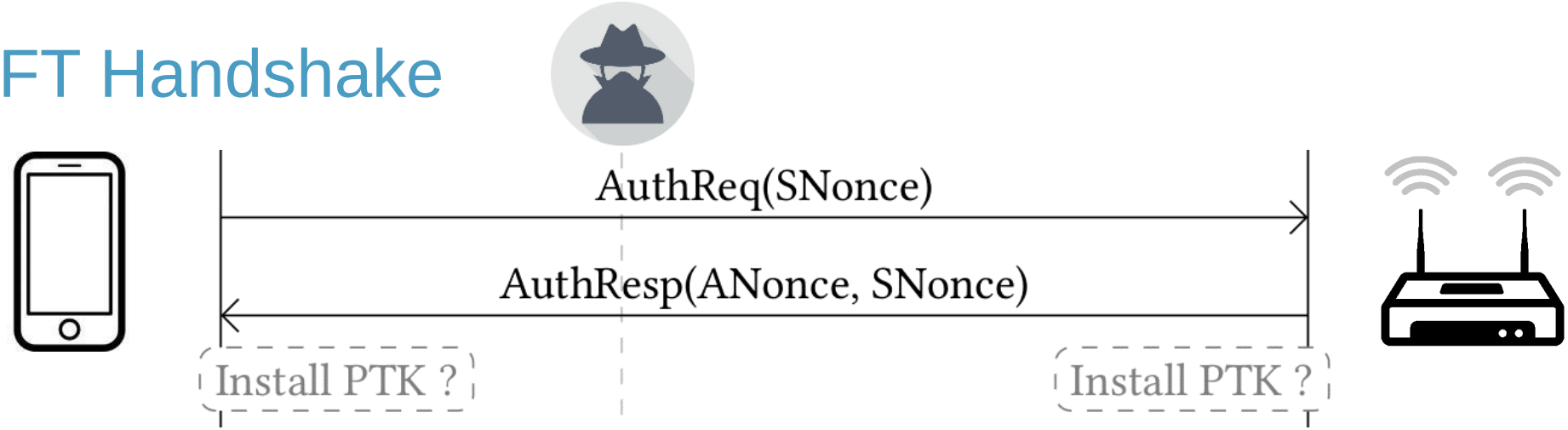
4-way handshake: client is attacked → replay/decrypt/forge

FT handshake (fast roaming = 802.11r):

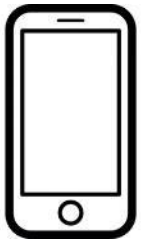
- Access Point is attacked → replay/decrypt/forge
- **No MitM required, can keep causing nonce resets**

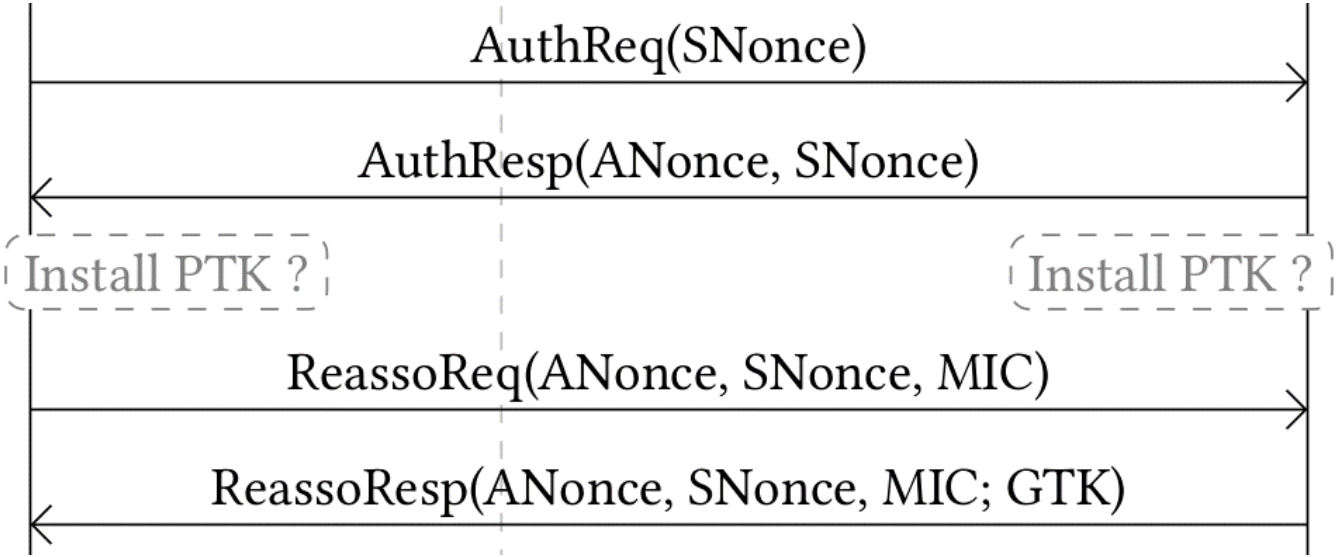
FT Handshake

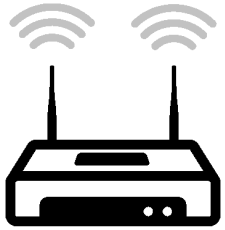
FT Handshake



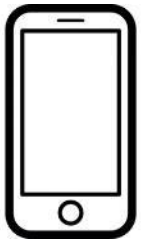
FT Handshake

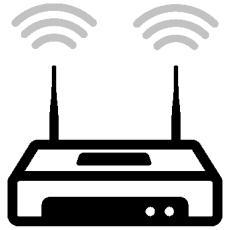


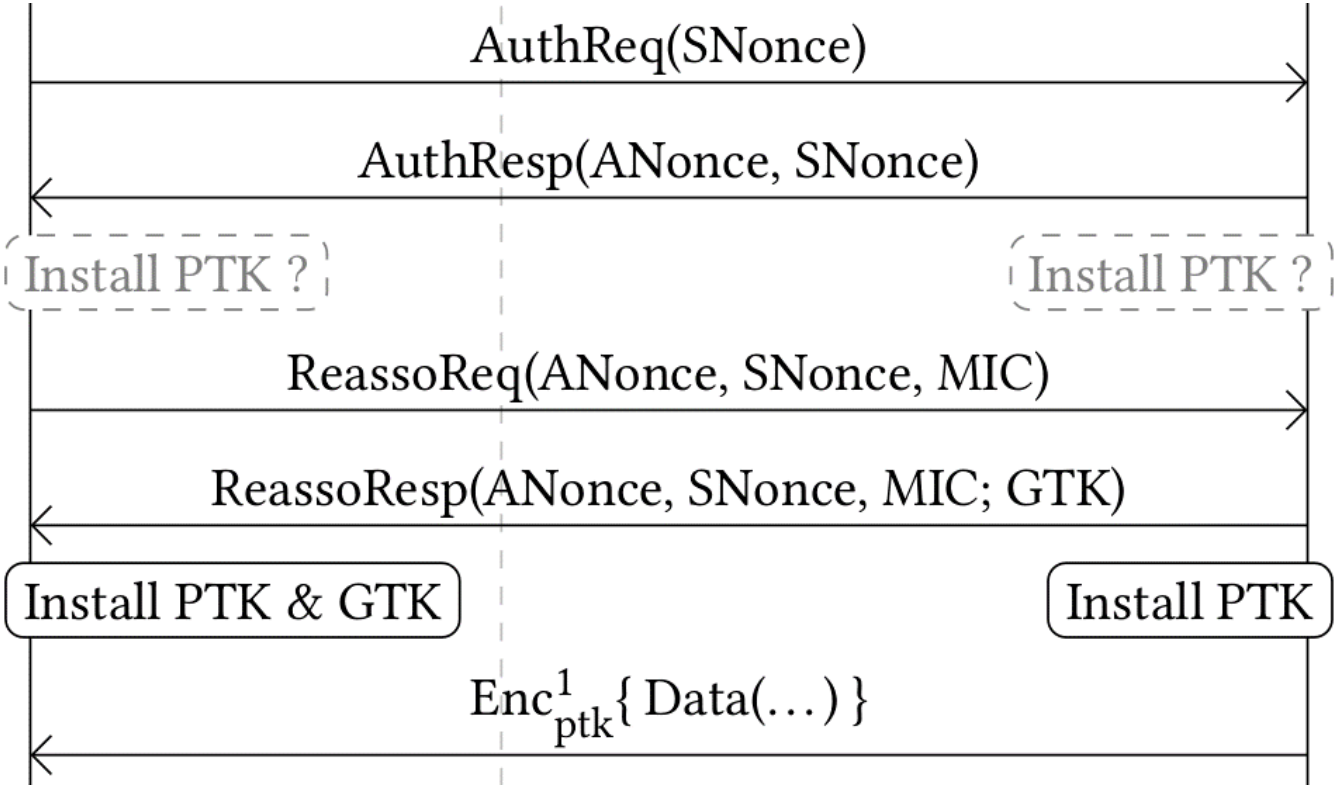




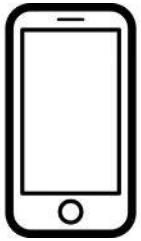
FT Handshake

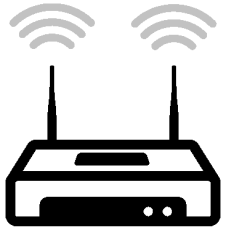


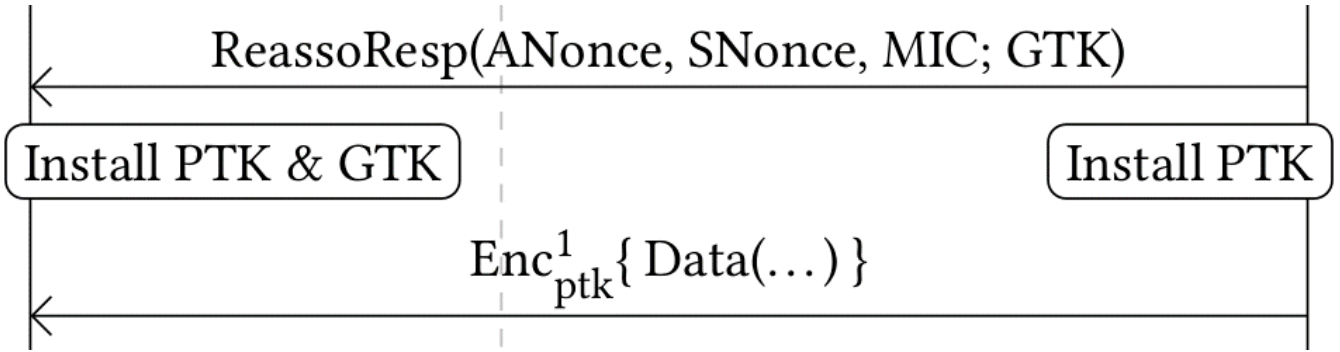




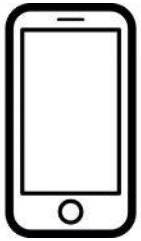
FT Handshake

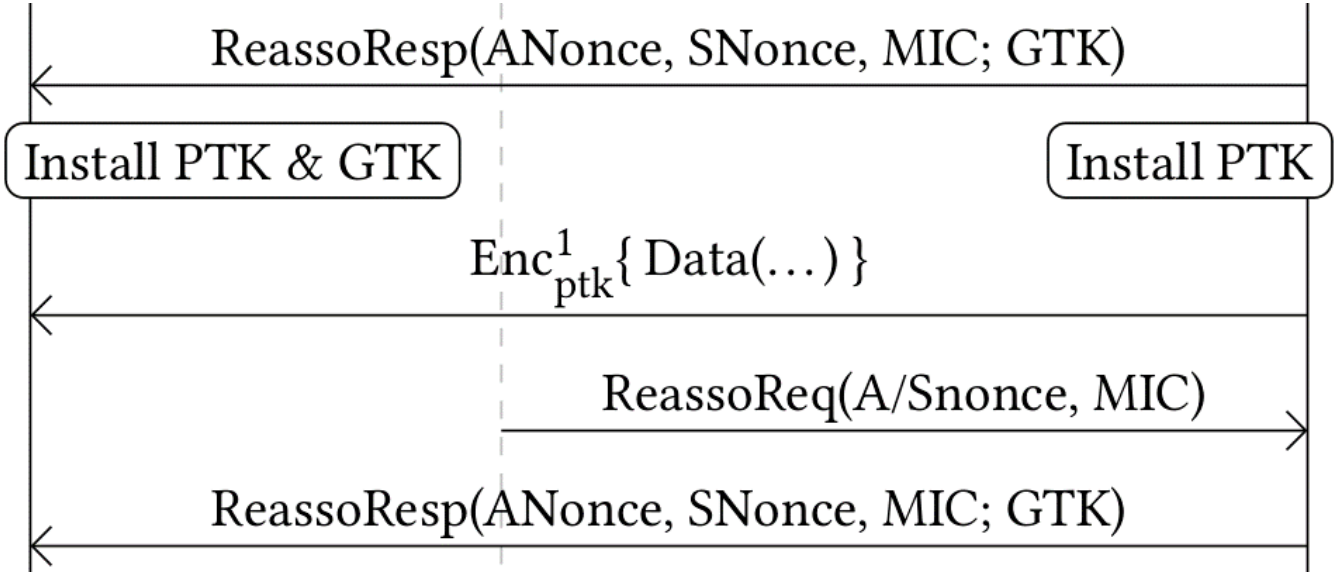


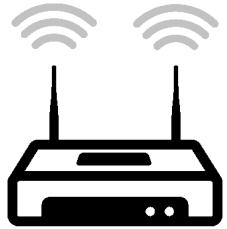




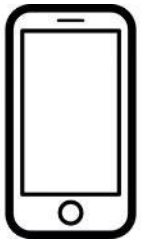
FT Handshake

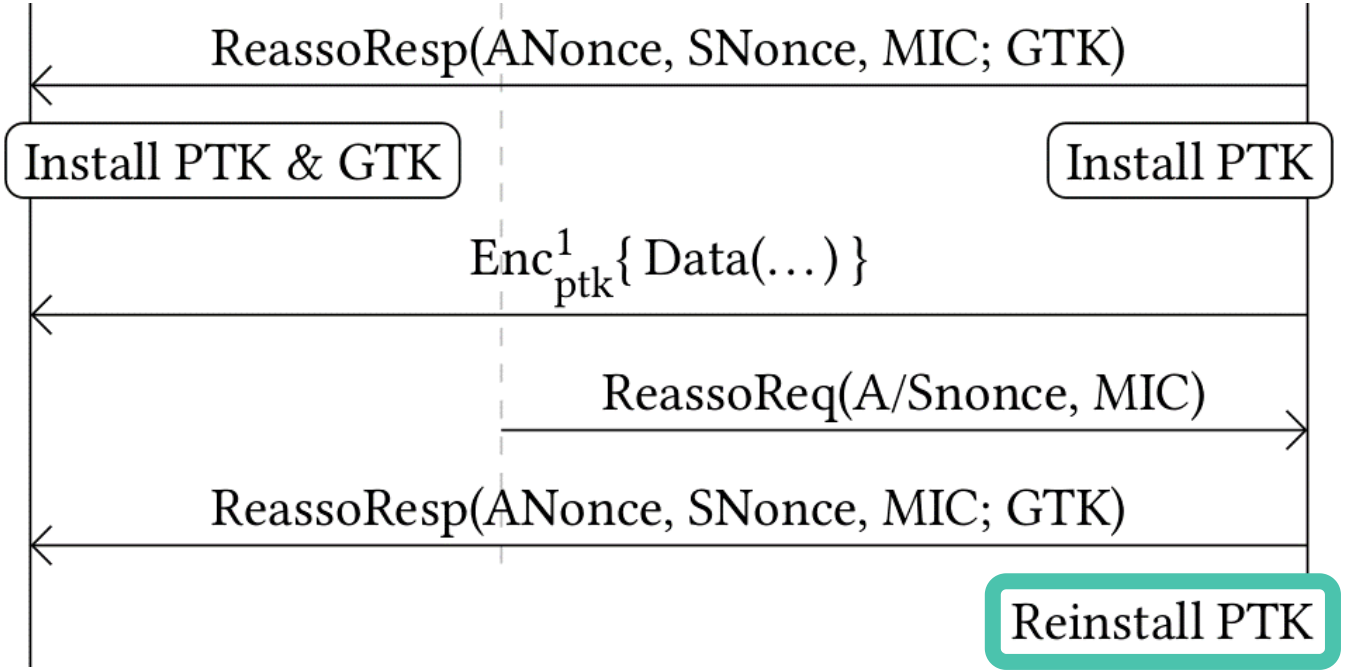


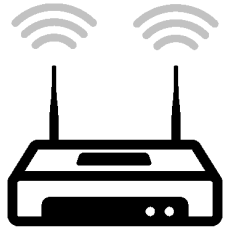




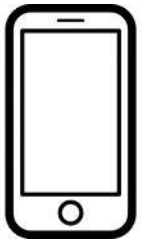
FT Handshake







FT Handshake



ReassoResp(ANonce, SNonce, MIC; GTK)

Install PTK & GTK

Install PTK

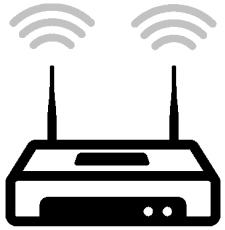
$\text{Enc}^1_{\text{ptk}}\{\text{Data}(\ldots)\}$

Nonce reuse!

Use to decrypt frames

Reinstall PTK

$\text{Enc}^1_{\text{ptk}}\{\text{Data}(\ldots)\}$



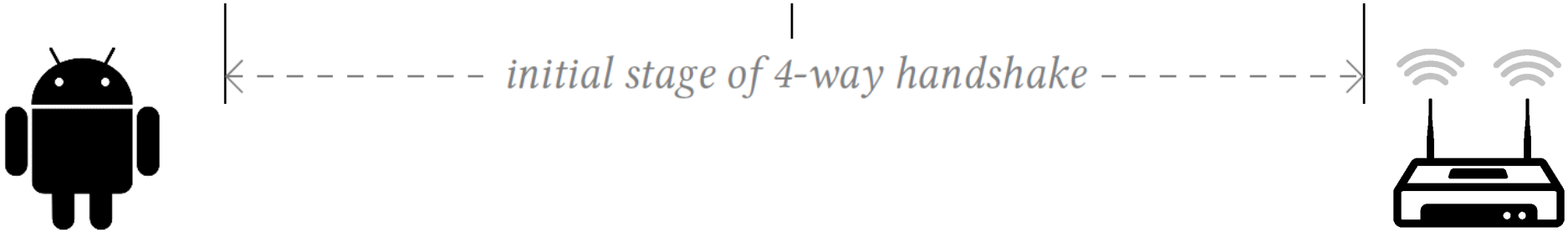
Implementation specific

iOS 10 and Windows: 4-way handshake not affected

- **Cannot decrypt unicast traffic** (nor replay/decrypt)
- But group key handshake is affected (replay broadcast)
- Note: iOS 11 does have vulnerable 4-way handshake[8]

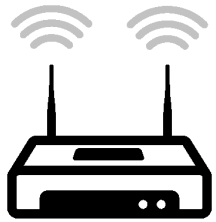
wpa_supplicant 2.4+

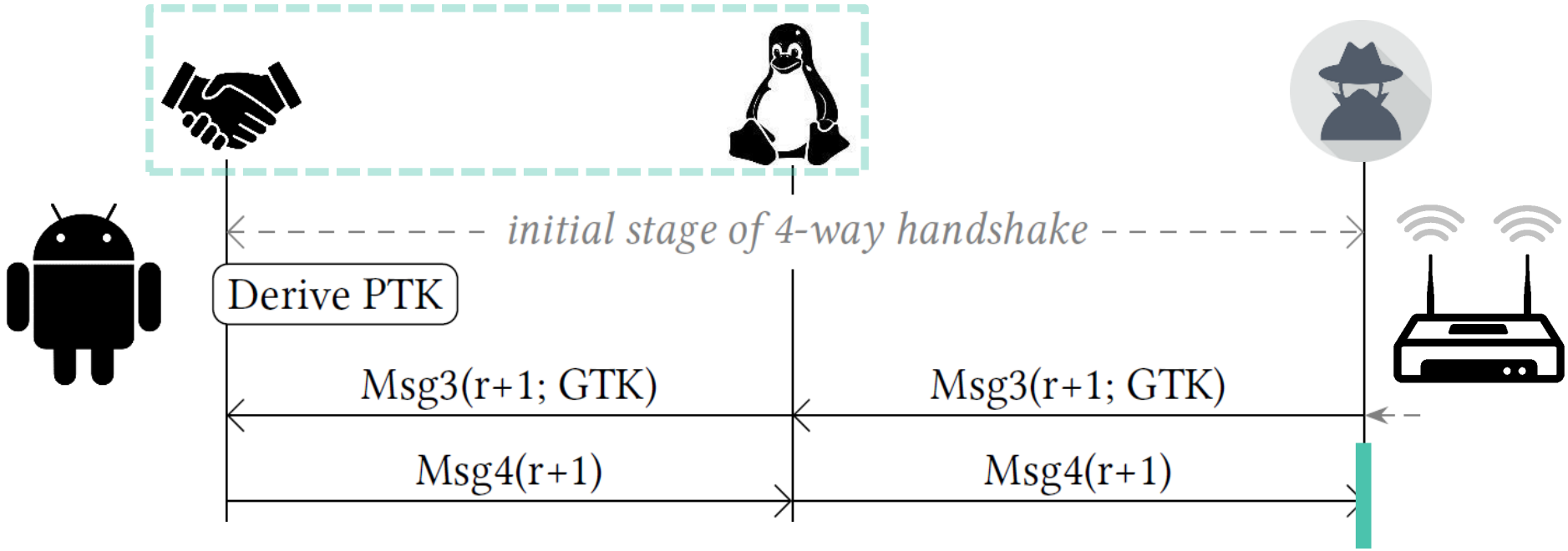
- Client used on Linux and Android 6.0+
- On retransmitted msg3 will **install all-zero key**

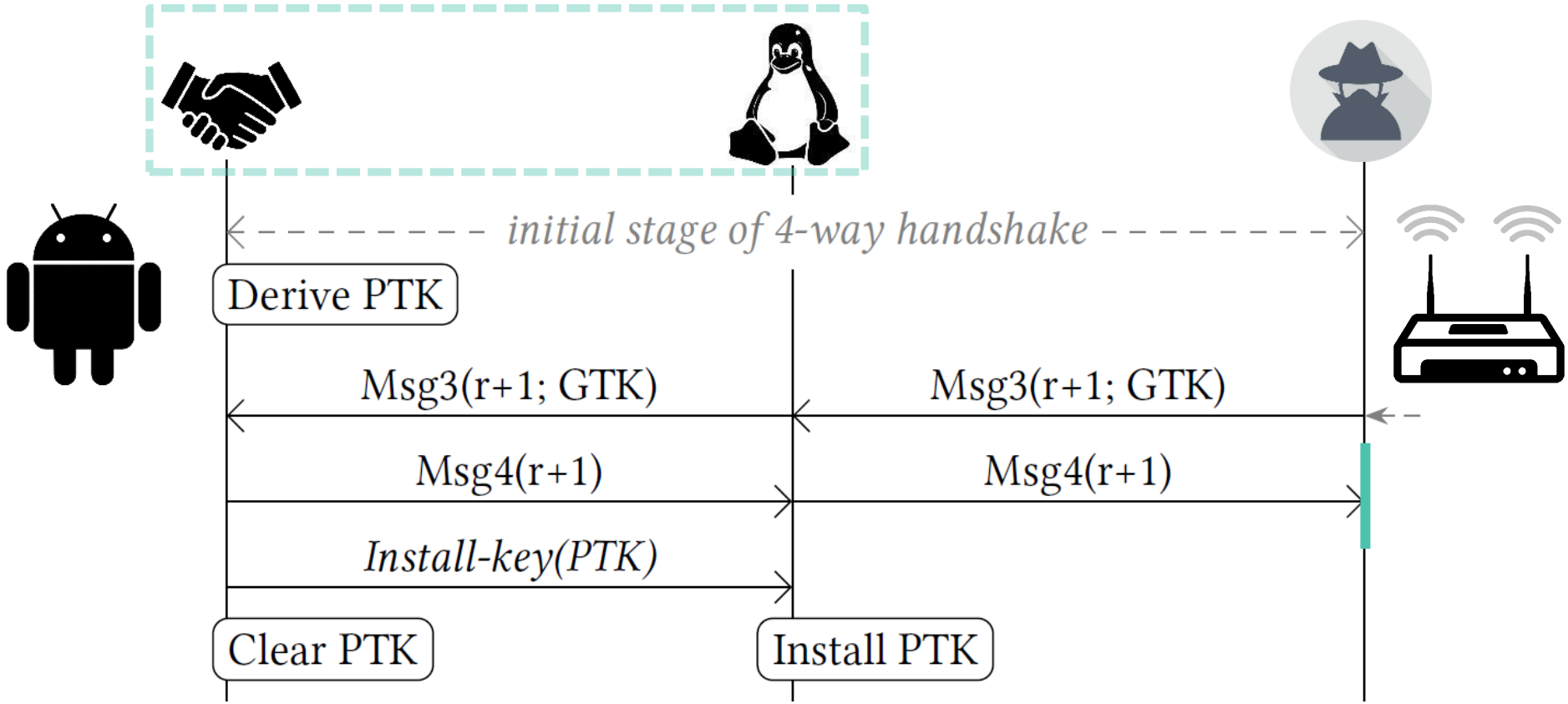

initial stage of 4-way handshake

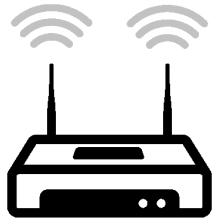
Android (victim)

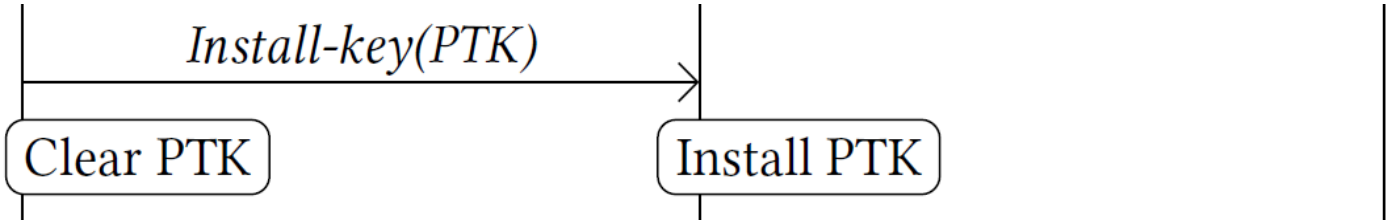
-way handshake

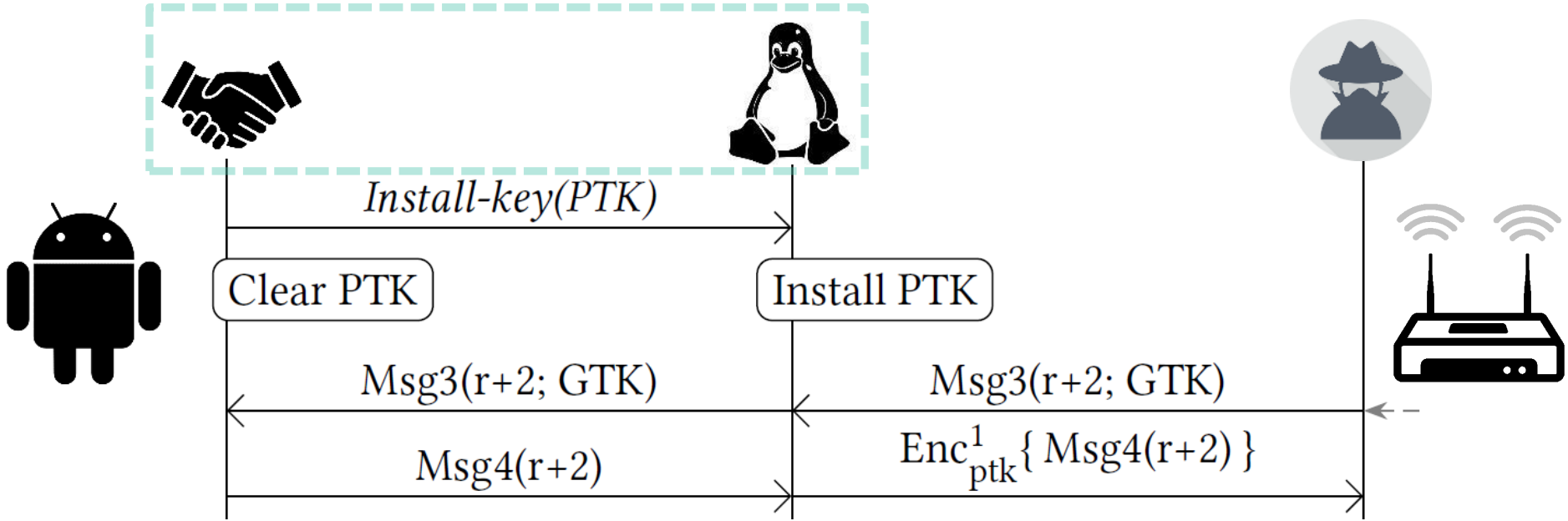


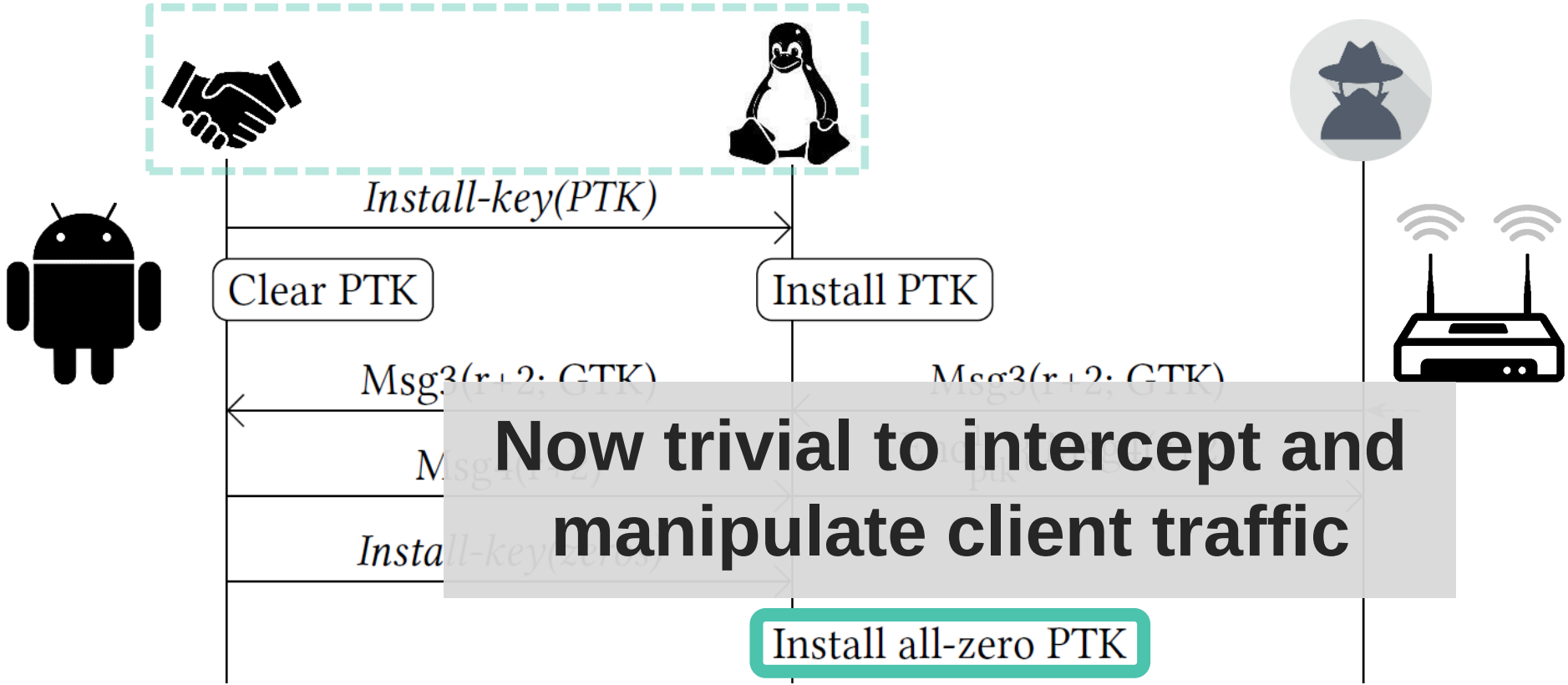

initial stage of 4-way handshake
Derive PTK
Msg3(r+1; GTK)
Msg3(r+1; GTK)
Msg4(r+1)
Msg4(r+1)


initial stage of 4-way handshake
Derive PTK
Msg3(r+1; GTK)
Msg3(r+1; GTK)
Msg4(r+1)
Msg4(r+1)
Install-key(PTK)
Clear PTK
Install PTK




Install-key(PTK)
Clear PTK
Install PTK


Install-key(PTK)
Clear PTK
Install PTK
Msg3(r+2; GTK)
Msg3(r+2; GTK)
Msg4(r+2)
Enc$^{1}_{ptk}$ { Msg4(r+2) }



Now trivial to intercept and manipulate client traffic

Is your devices affected?

github.com/vanhoefm/krackattacks-scripts

- Tests clients and APs
- Works on Kali Linux

Remember to:

- Disable hardware encryption
- Use a supported Wi-Fi dongle!

Countermeasures

Many clients won’t get updates…

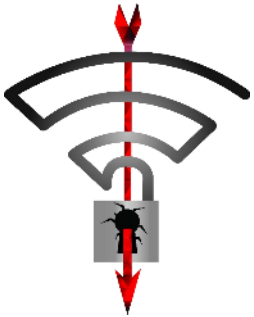
AP can prevent (most) attacks on clients!

- Don’t retransmit message 3/4
- Don’t retransmit group message 1/2

However:

- Impact on reliability unclear
- Clients still vulnerable when connected to unmodified APs

Overview



Key reinstalls in
4-way handshake

Misconceptions

Practical impact

Lessons learned

Misconceptions I

Updating only the client or AP is sufficient

› Both vulnerable clients & vulnerable APs must apply patches

Need to be close to network and victim

› Can use special antenna from afar

Must be connected to network as attacker (i.e. have password)

› Only need to be nearby victim and network

Misconceptions II

No useful data is transmitted after handshake

- Trigger new handshakes during TCP connection

Obtaining channel-based MitM is hard

- Nope, can use channel switch announcements

Attack complexity is hard

- Script only needs to be written once …
- … and some are (privately) doing this!

Misconceptions III

Using (AES-)CCMP mitigates the attack

› Still allows decryption & replay of frames

Enterprise networks (802.1x) aren't affected

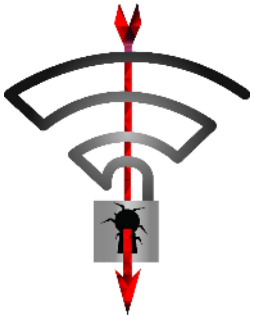
› Also use 4-way handshake & are affected

It's the end of the world!

› Let's not get carried away ☺

Image from "KRACK: Your Wi-Fi is no longer secure" by Kaspersky

Overview



Key reinstalls in
4-way handshake

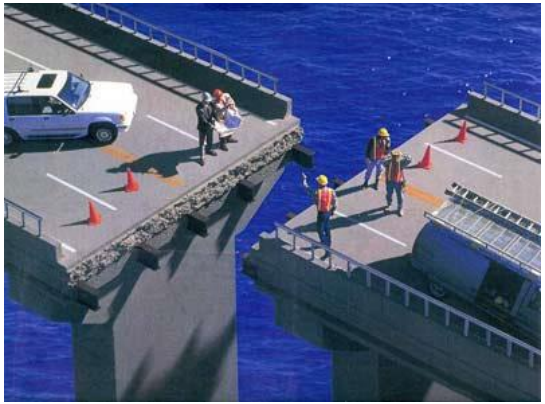
Misconceptions

Practical impact

Lessons learned

Limitations of formal proofs

- 4-way handshake proven secure
- Encryption protocol proven secure



The combination was not proven secure!

Keep protocols simple

The wpa_supplicant 2.6 case:

- Complex state machine & turned out to still be vulnerable
- Need **formal verification of implementations**

“Re-keying introduces **unnecessary complexity (and therefore opportunities for bugs** or other unexpected behavior) without delivering value in return.” [9]

Disclosure coordination: preparation

Flawed standard! How to disclose?

Is it truly a widespread issue?

- Contacted vendors we didn't test ourselves
- They're vulnerable + feedback on report

Determining who to inform?

- Notifying more vendors → higher chance of leaks
- We relied on CERT/CC to contact vendors

Disclosure coordination: planning

Duration of embargo:

- Long: risk of details leaking
- Short: not enough time to patch
- Avoid uncertainty: set clear deadline

Open source patches?

- Developed and tested in private
- Shared 1 week in advance over private mailing lists

Multi-party vulnerability coordination

For more advice see:

Guidelines and Practices for Multi-Party Vulnerability Coordination (Draft)[11]

Remember:

- Goal is to protect users
- There are various opinions

Conclusion

- Flaw is in WPA2 standard
- Proven correct but is insecure!
- Attack has practical impact
- Update all clients & check APs

Thank you!

Questions?

krackattacks.com

References

1. C. He, M. Sundararajan, A. Datta, A. Derek, and J. Mitchell. A Modular Correctness Proof of IEEE 802.11i and TLS. In CCS, 2005.
2. S. Antakis, M. van Cuijk, and J. Stemmer. Wardriving - Building A Yagi Pringles Antenna. 2008.
3. M. Parkinson. Designer Cantenna. 2012. Retrieved 23 October 2017 from https://www.mattparkinson.eu/designer-cantenna/
4. E. and M. Beck. Practical attacks against WEP and WPA. In WiSec, 2009.
5. M. Vanhoef and F. Piessens. Practical verification of WPA-TKIP vulnerabilities. In ASIA CCS, 2013.
6. A. Joux. Authentication failures in NIST version of GCM. 2016.
7. J. Jonsson. On the security of CTR+ CBC-MAC. In SAC, 2002.
8. Apple. About the security content of iOS 11.1. November 3, 2017. Retrieved 26 November from https://support.apple.com/en-us/HT208222
9. US Central Intelligence Agency. Network Operations Division Cryptographic Requirements. Retrieved 5 December 2017 from https://wikileaks.org/ciav7p1/cms/files/NOD%20Cryptographic%20Requirements%20v1.1%20TOP%20SECRET.pdf
10. J. Salowey and E. Rescorla. TLS Renegotiation Vulnerability. Retrieved 5 December 2017 from https://www.ietf.org/proceedings/76/slides/tls-7.pdf
11. Bhargavan et al. Triple Handshakes and Cookie Cutters: Breaking and Fixing Authentication over TLS. In IEEE S&P, 2014.
12. M. Vanhoef and F. Piessens. Key Reinstallation Attacks: Forcing Nonce Reuse in WPA2. In CCS, 2017.