# KRACKing WPA2 by Forcing Nonce Reuse

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Nullcon, 2 March 2018

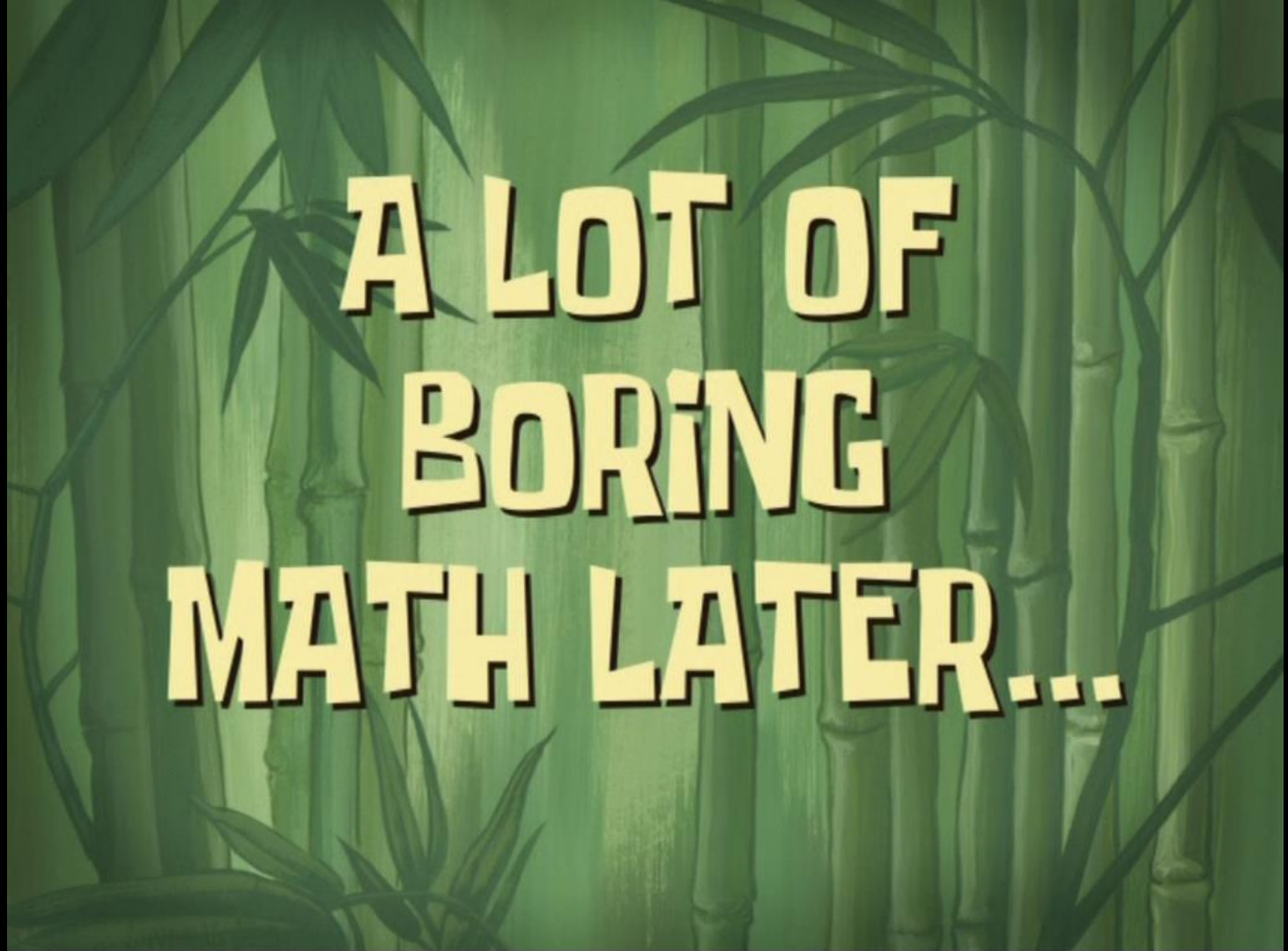
KU LEUVEN DistriNet

# 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.**

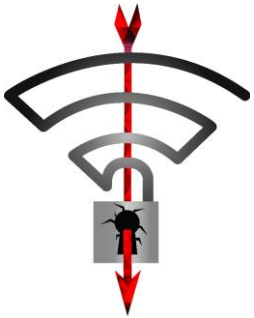

A LOT OF
BORING
MATH LATER...

# 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



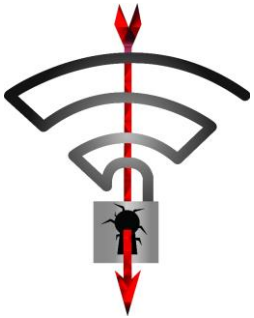
Key reinstalls in
4-way handshake


Misconceptions

Practical impact

Lessons learned

# Overview



**Key reinstalls in 4-way handshake**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# The 4-way handshake

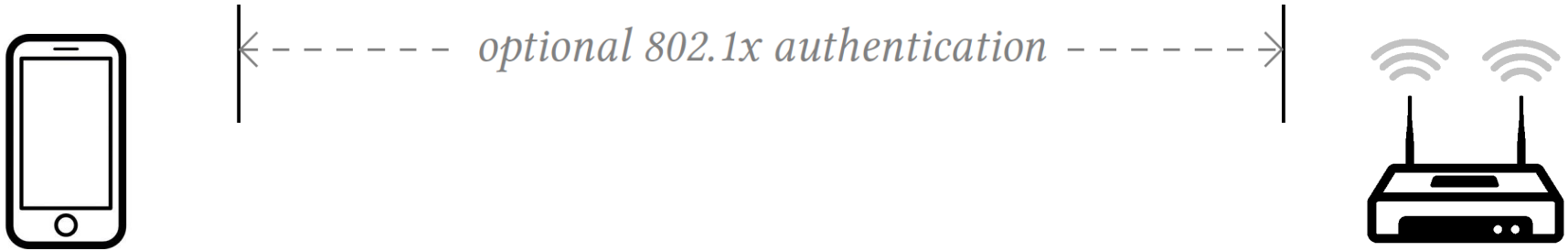
Used to connect to any protected Wi-Fi network

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

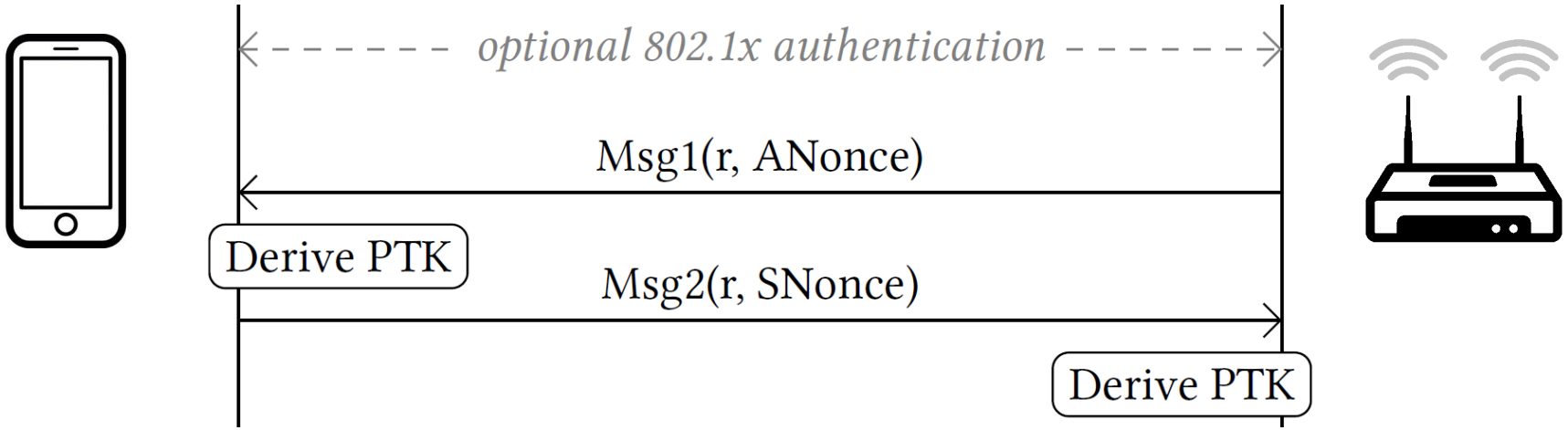
Appeared to be secure:

- 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)



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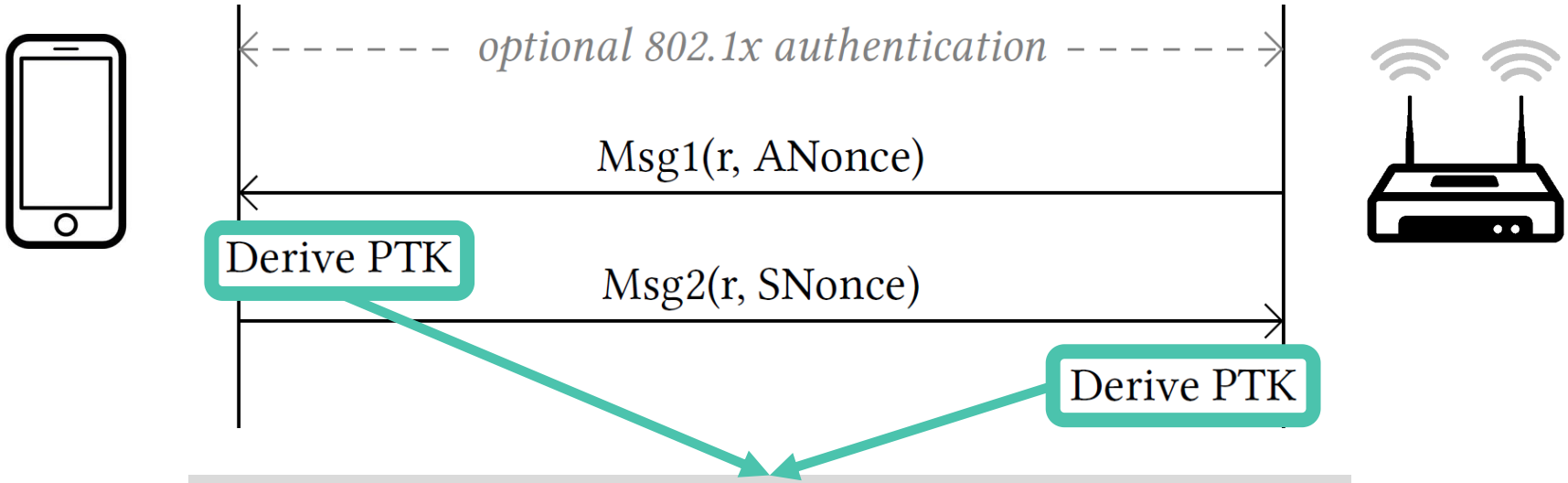


**PTK = Combine(shared secret, ANonce, SNonce)**

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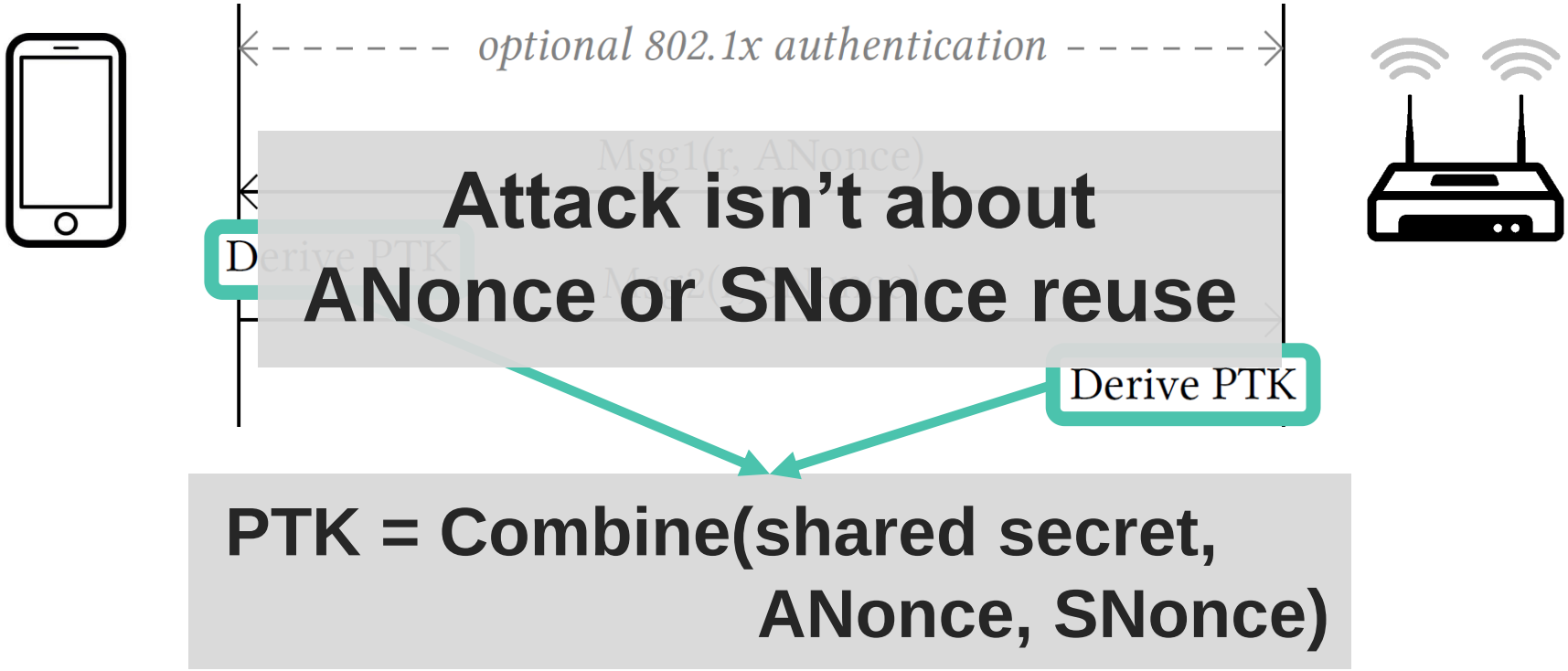

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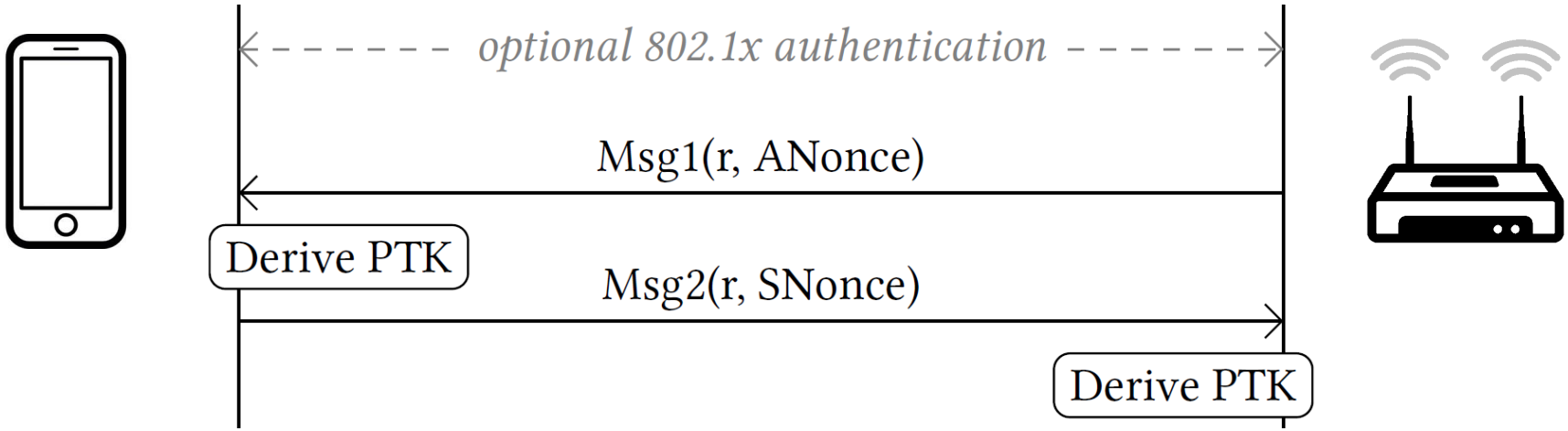

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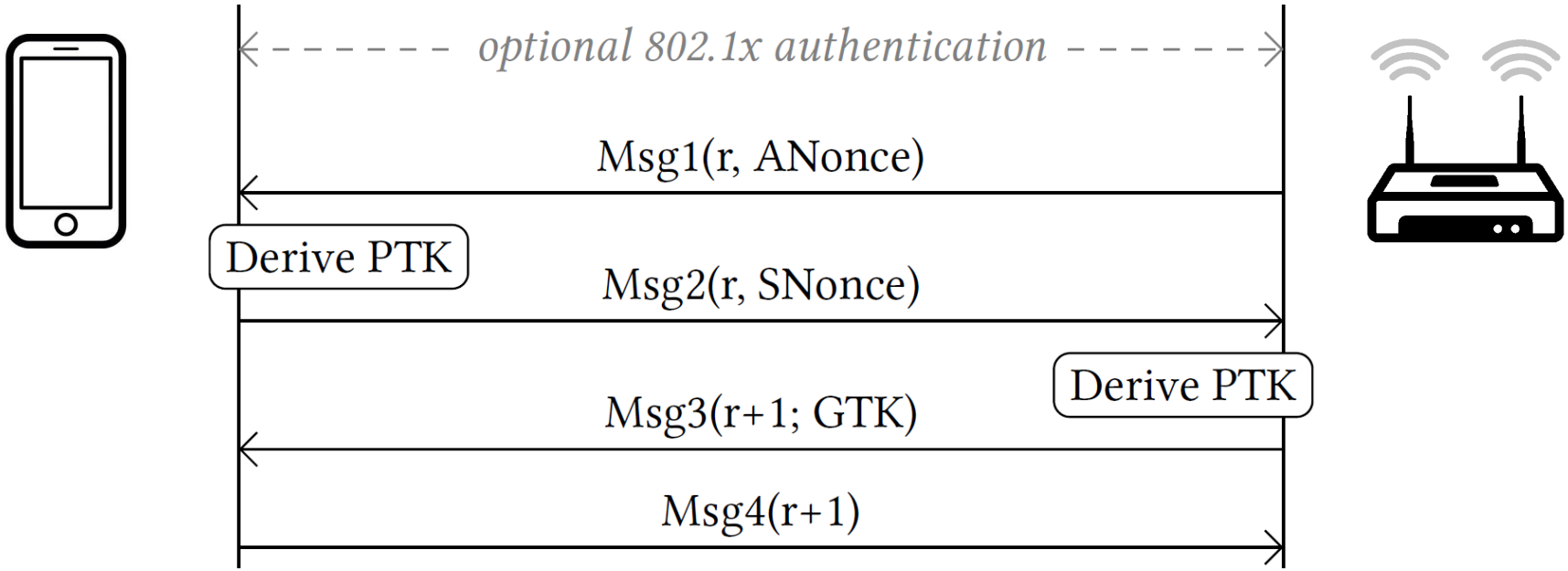

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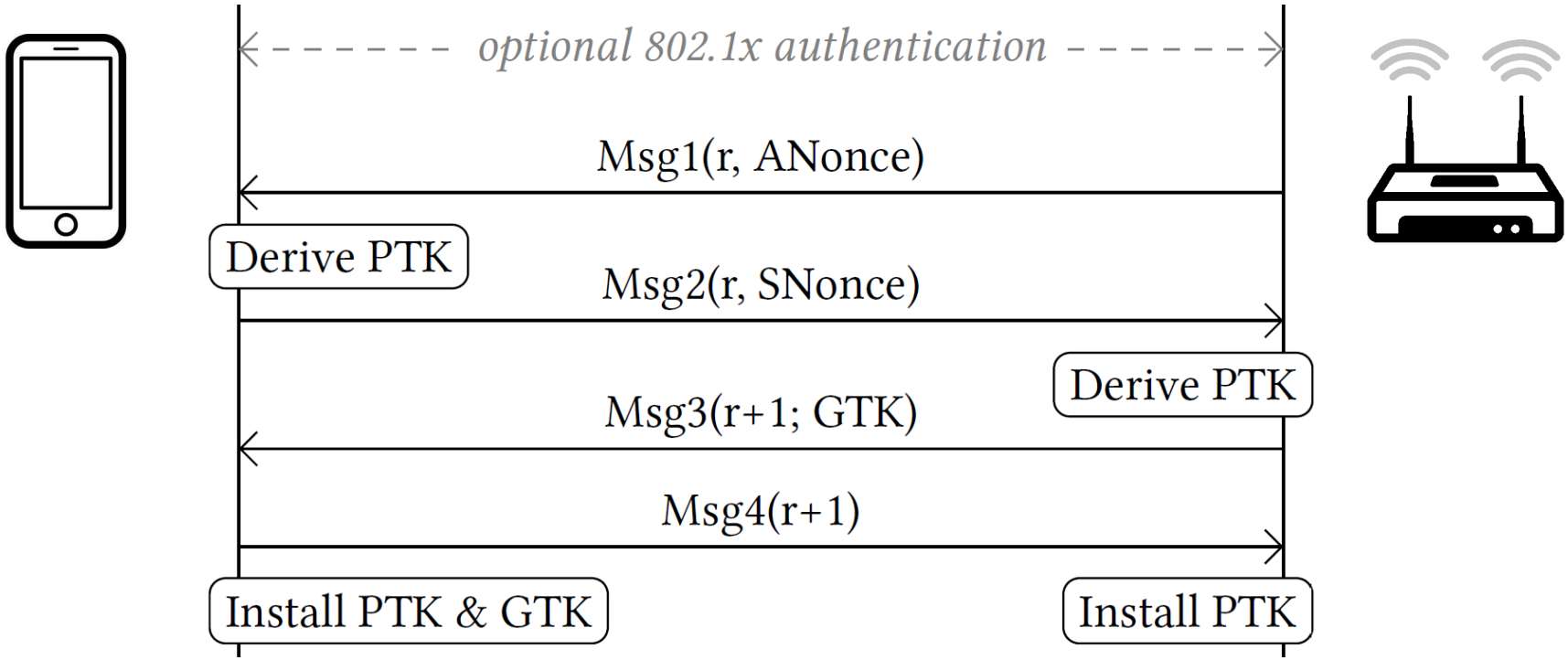

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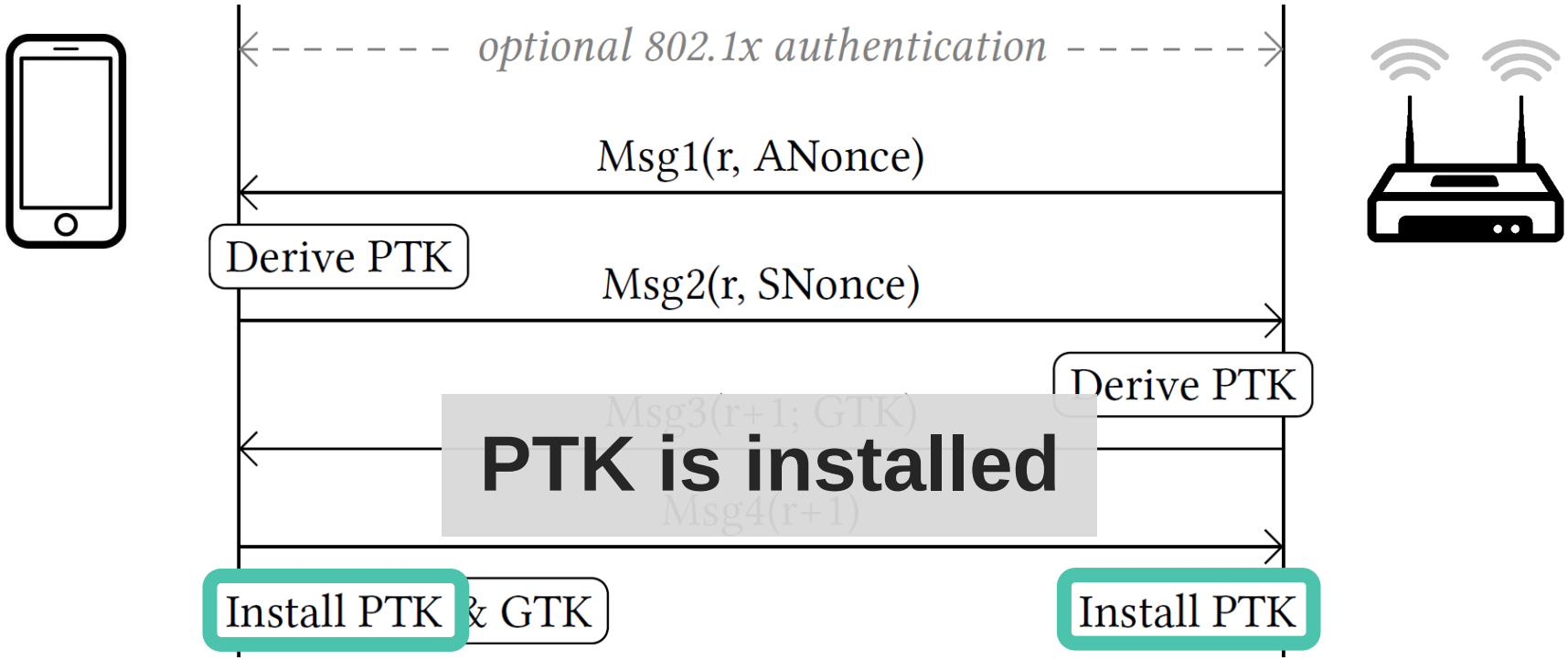

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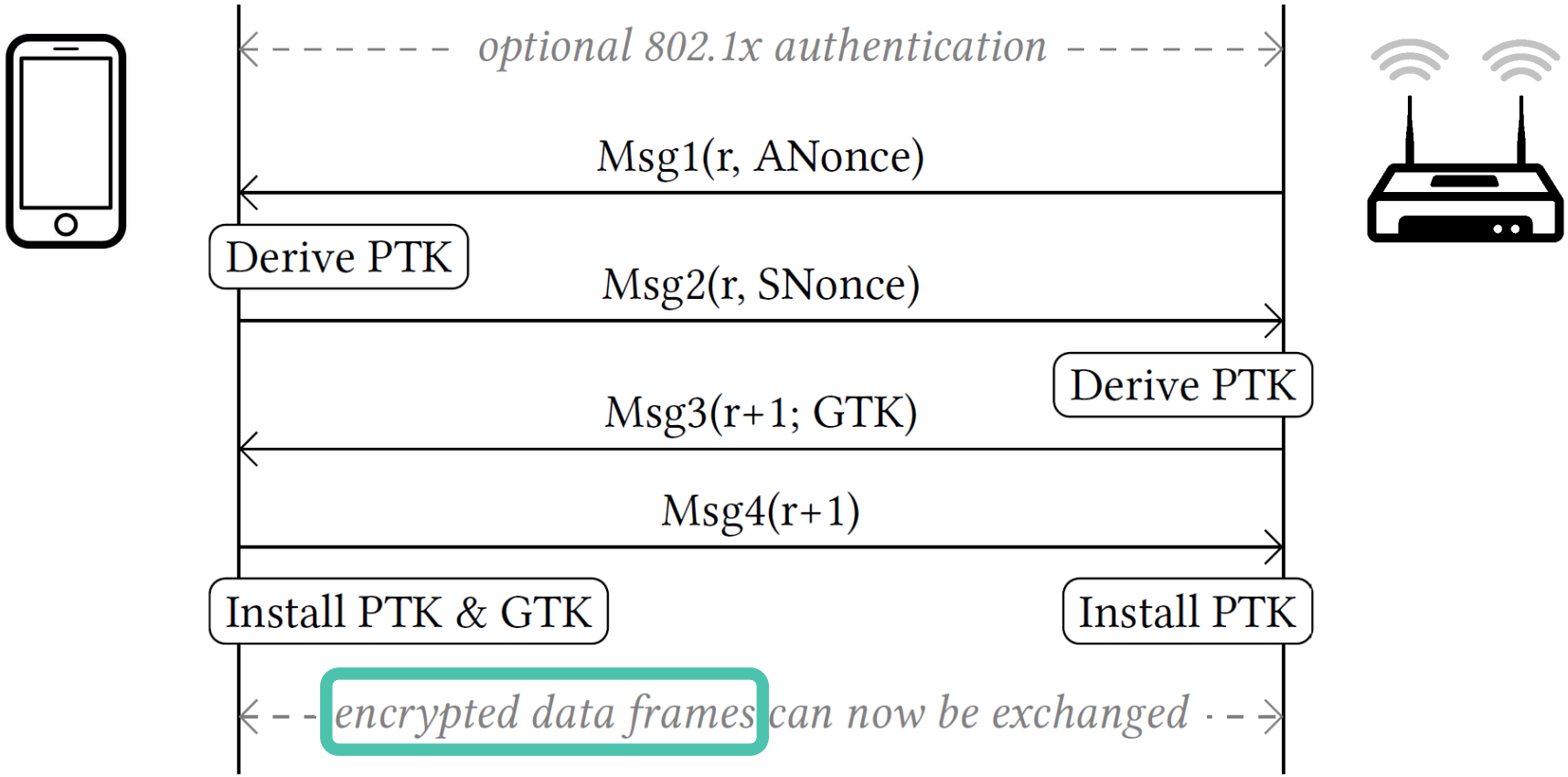
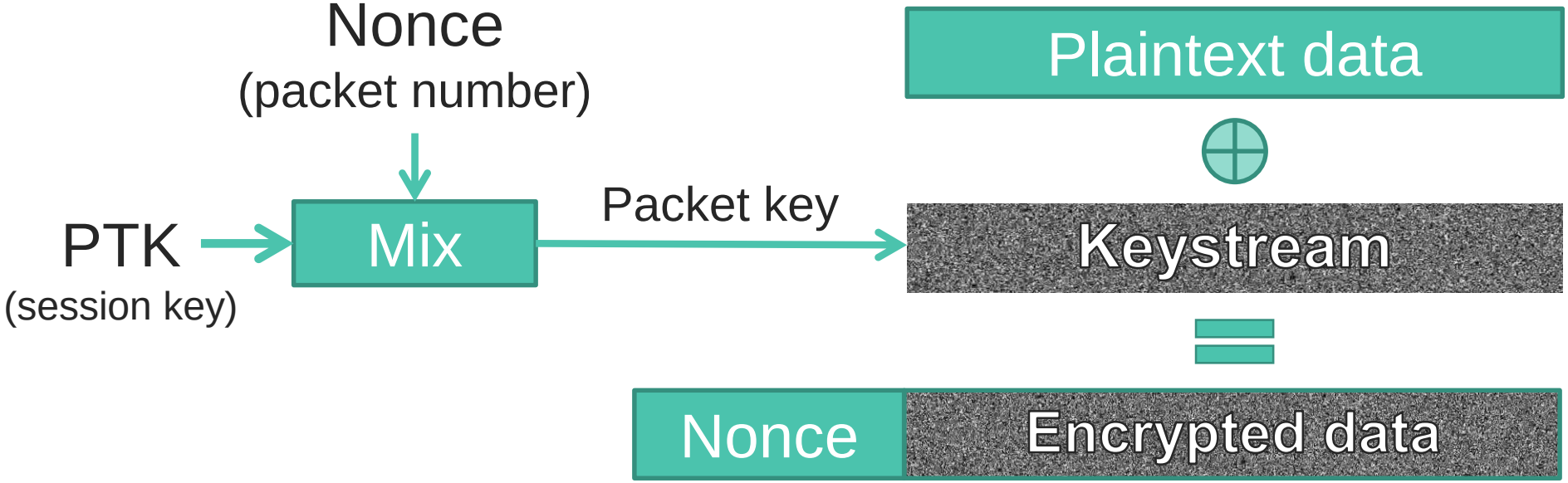
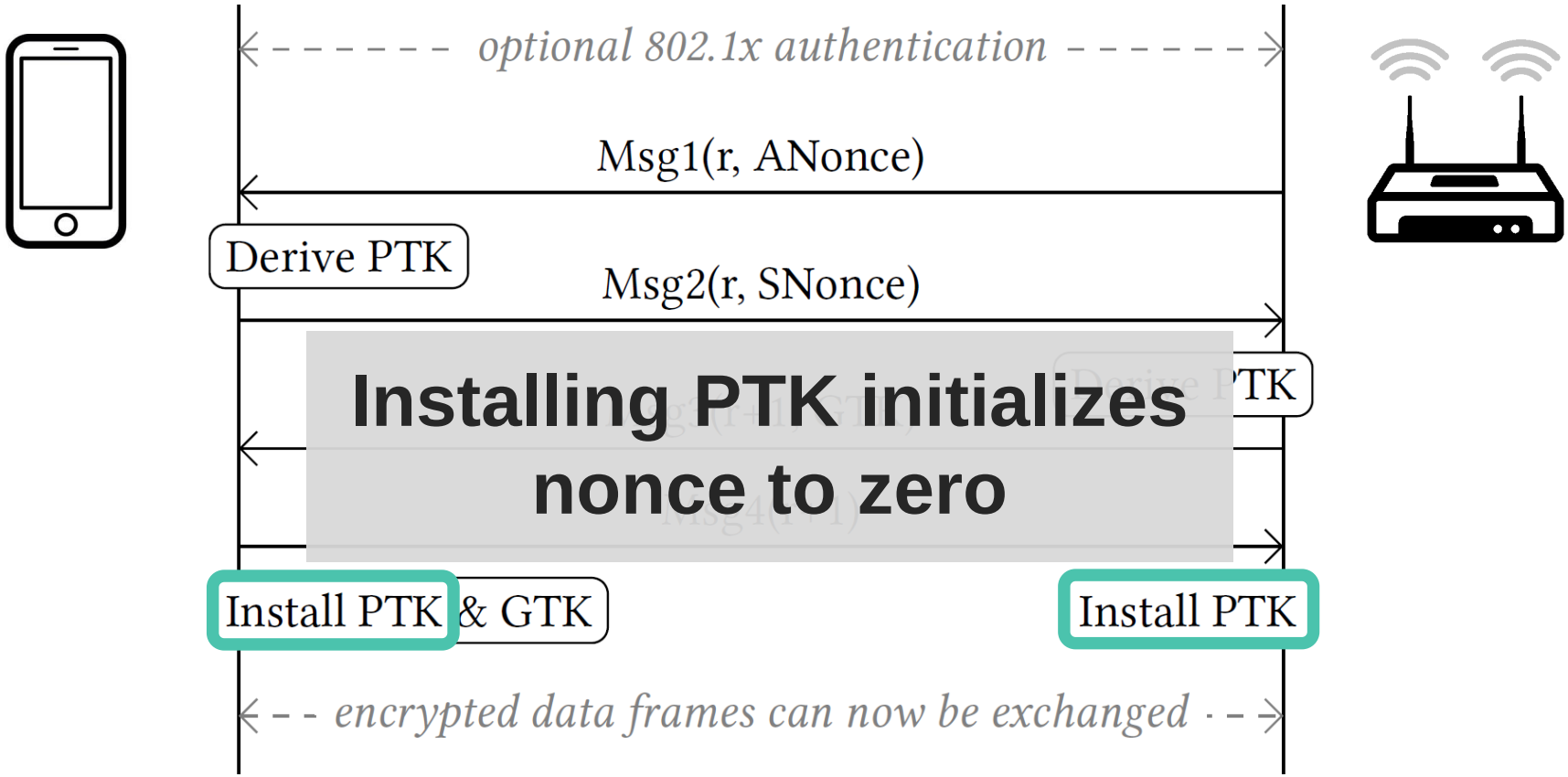


# Frame encryption (simplified)




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

# 4-way handshake (simplified)



# Reinstallation Attack

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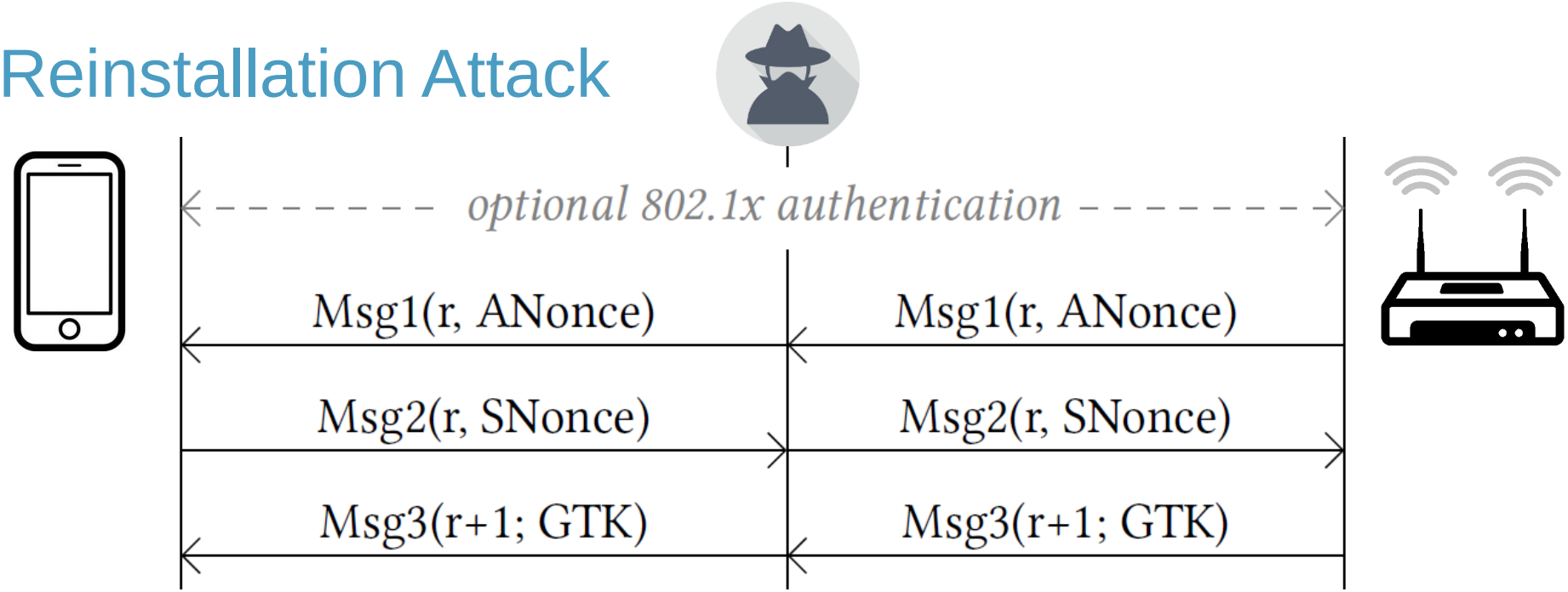

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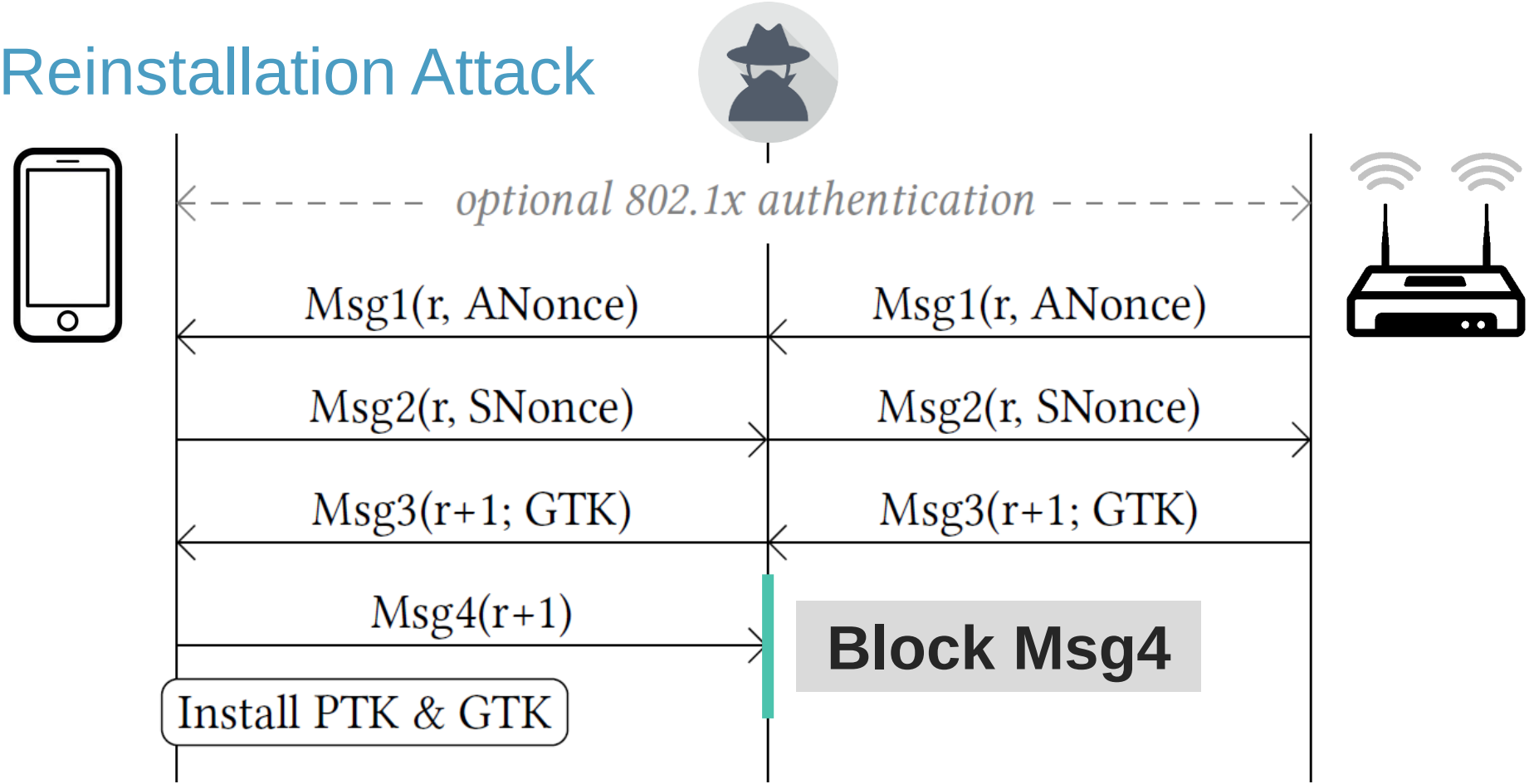

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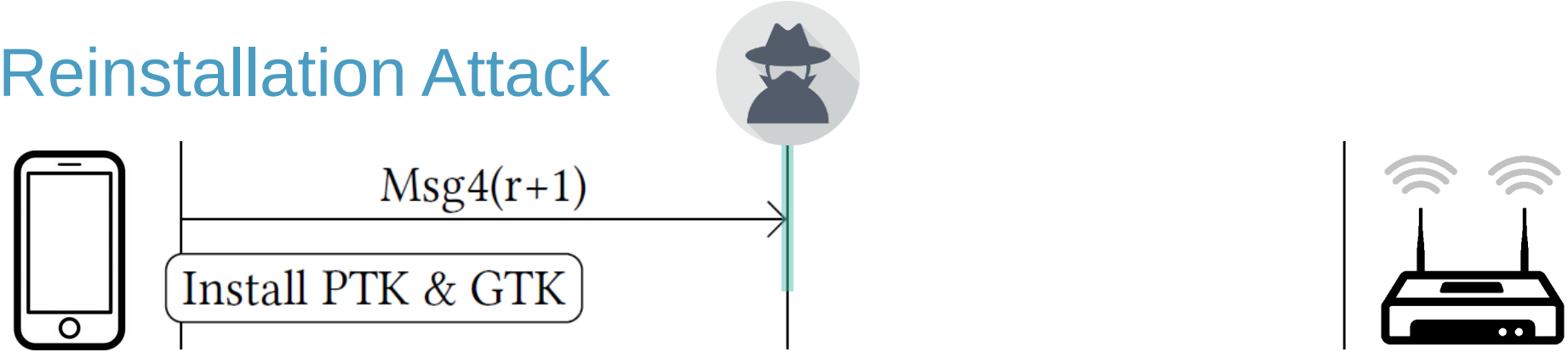

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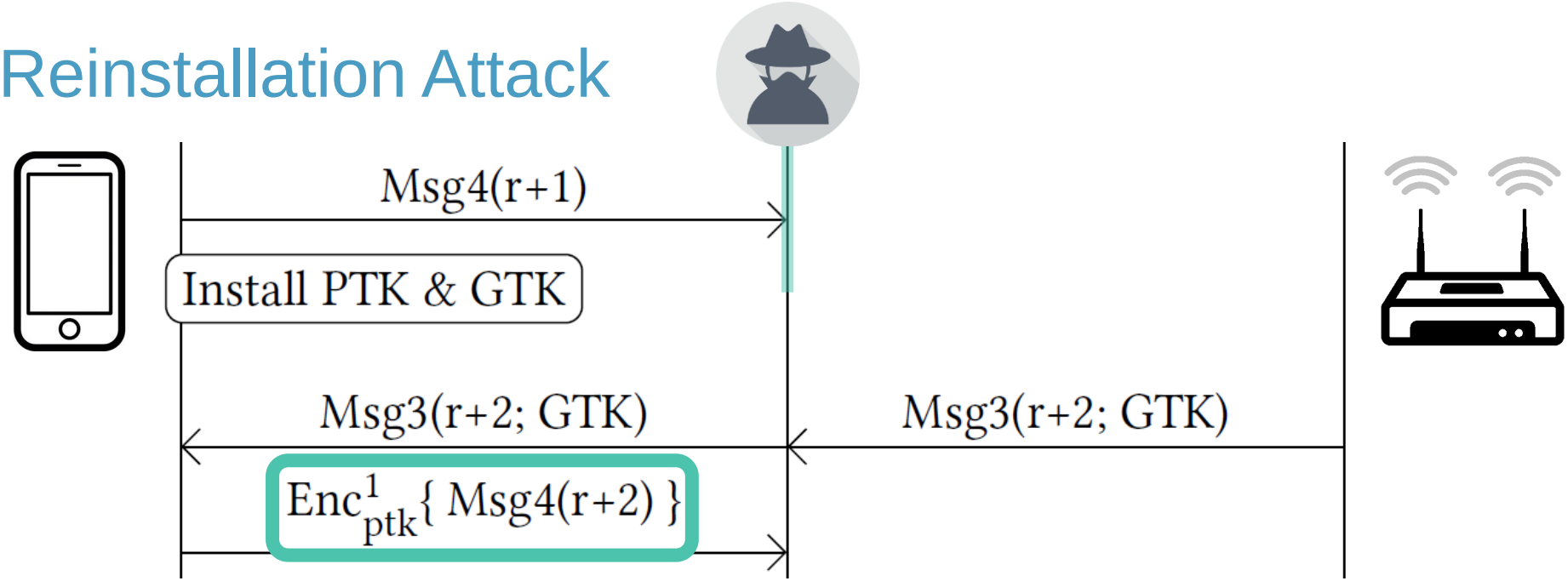

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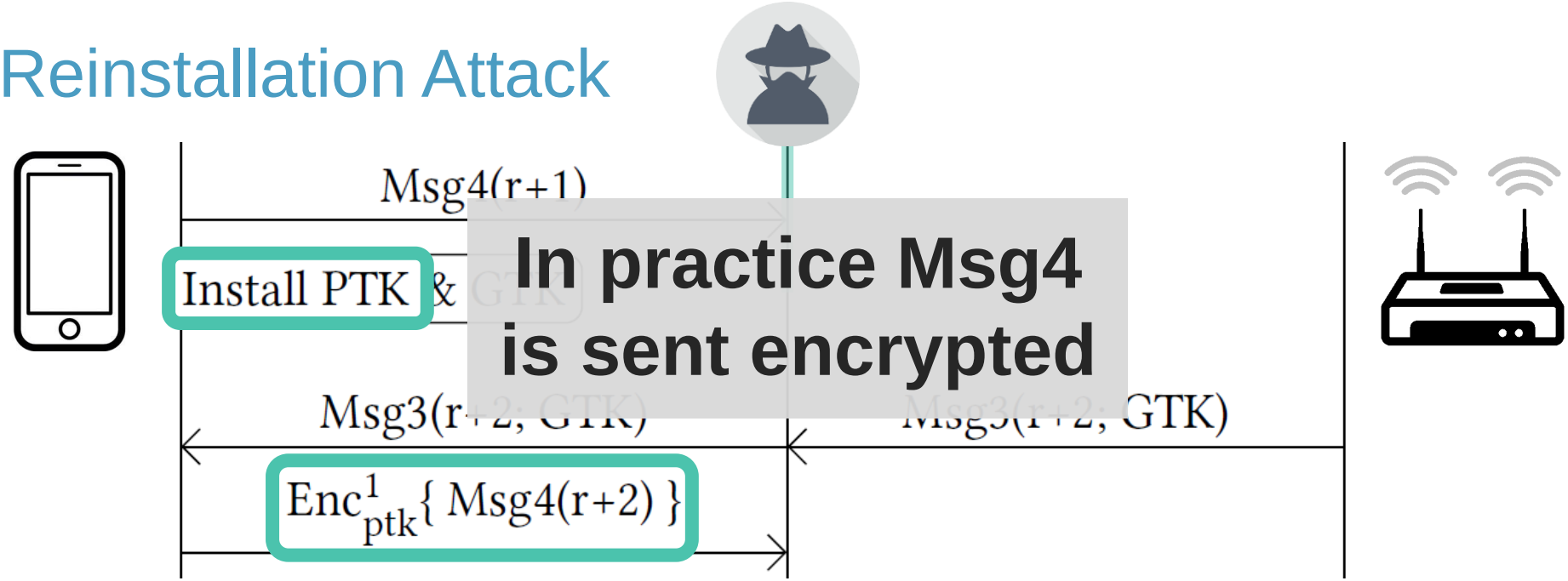
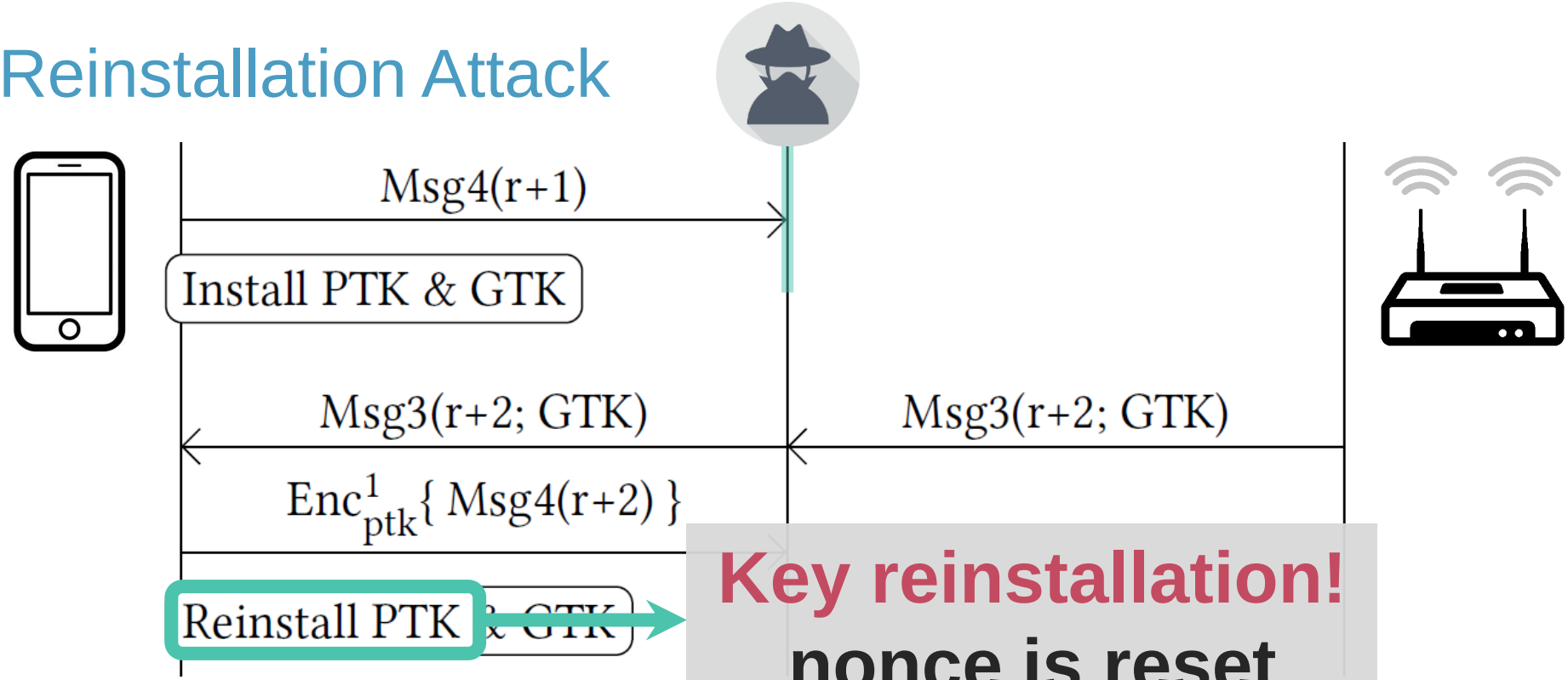



**In practice Msg4 is sent encrypted**

# Reinstallation Attack



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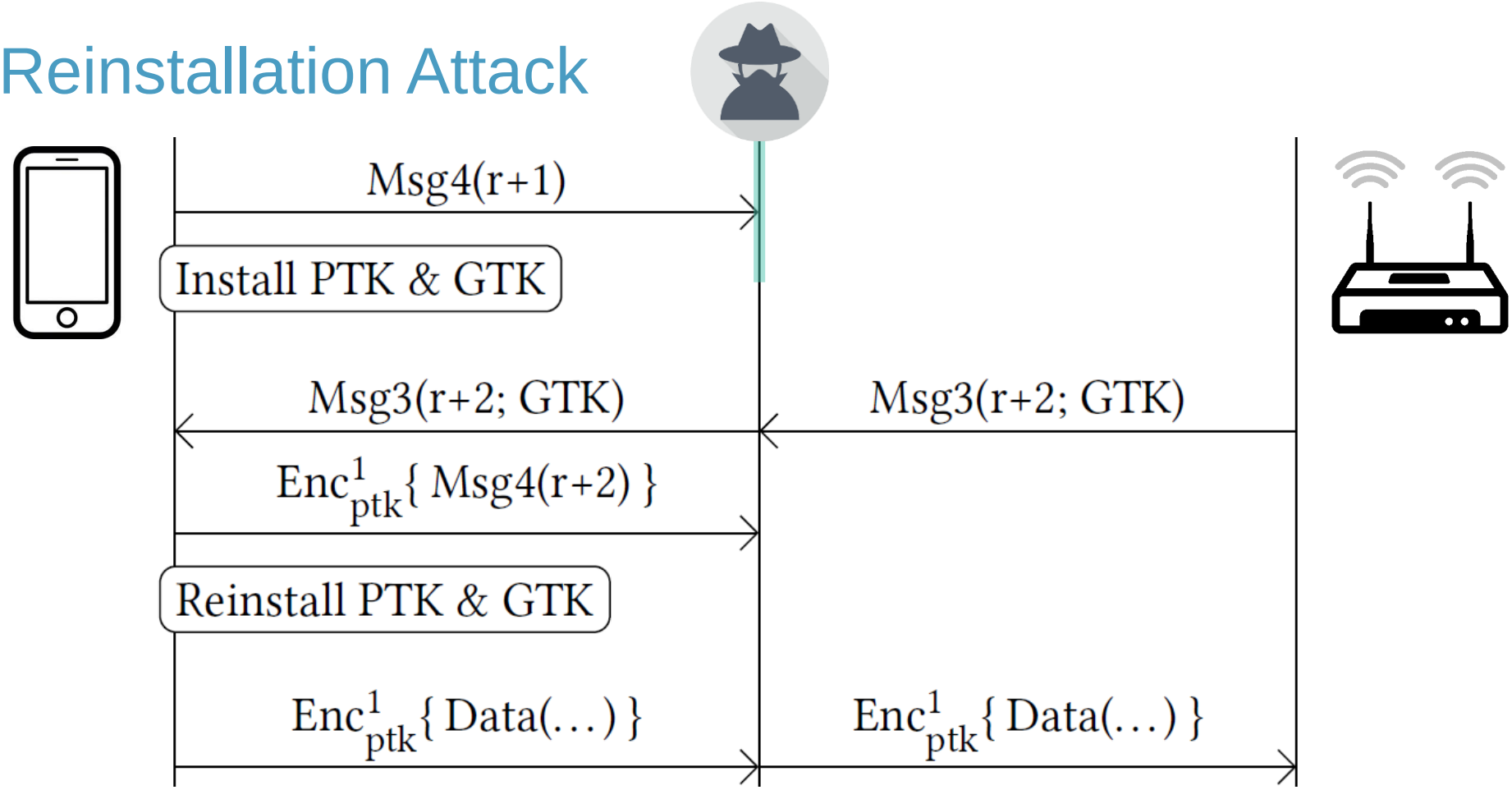

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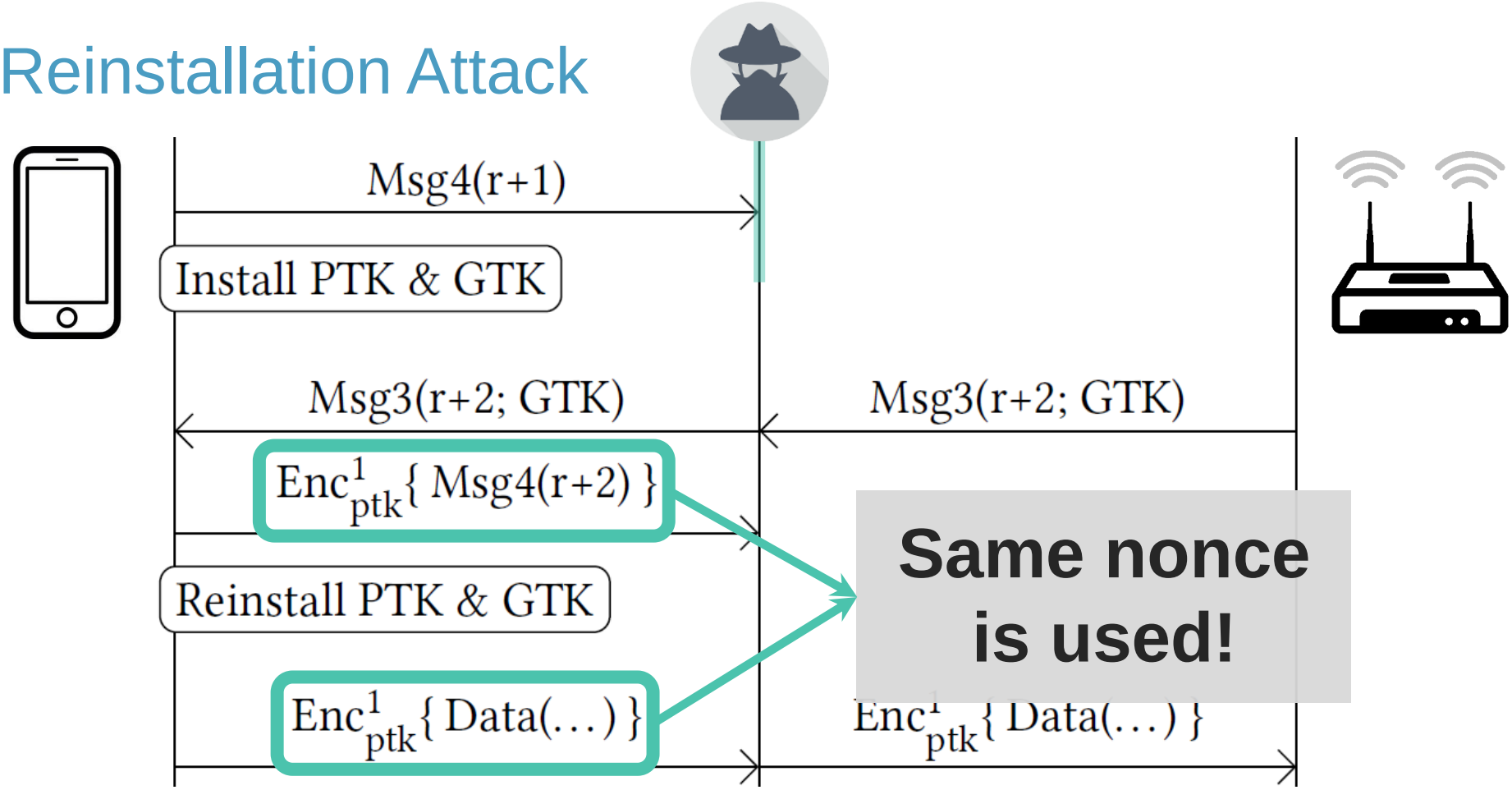

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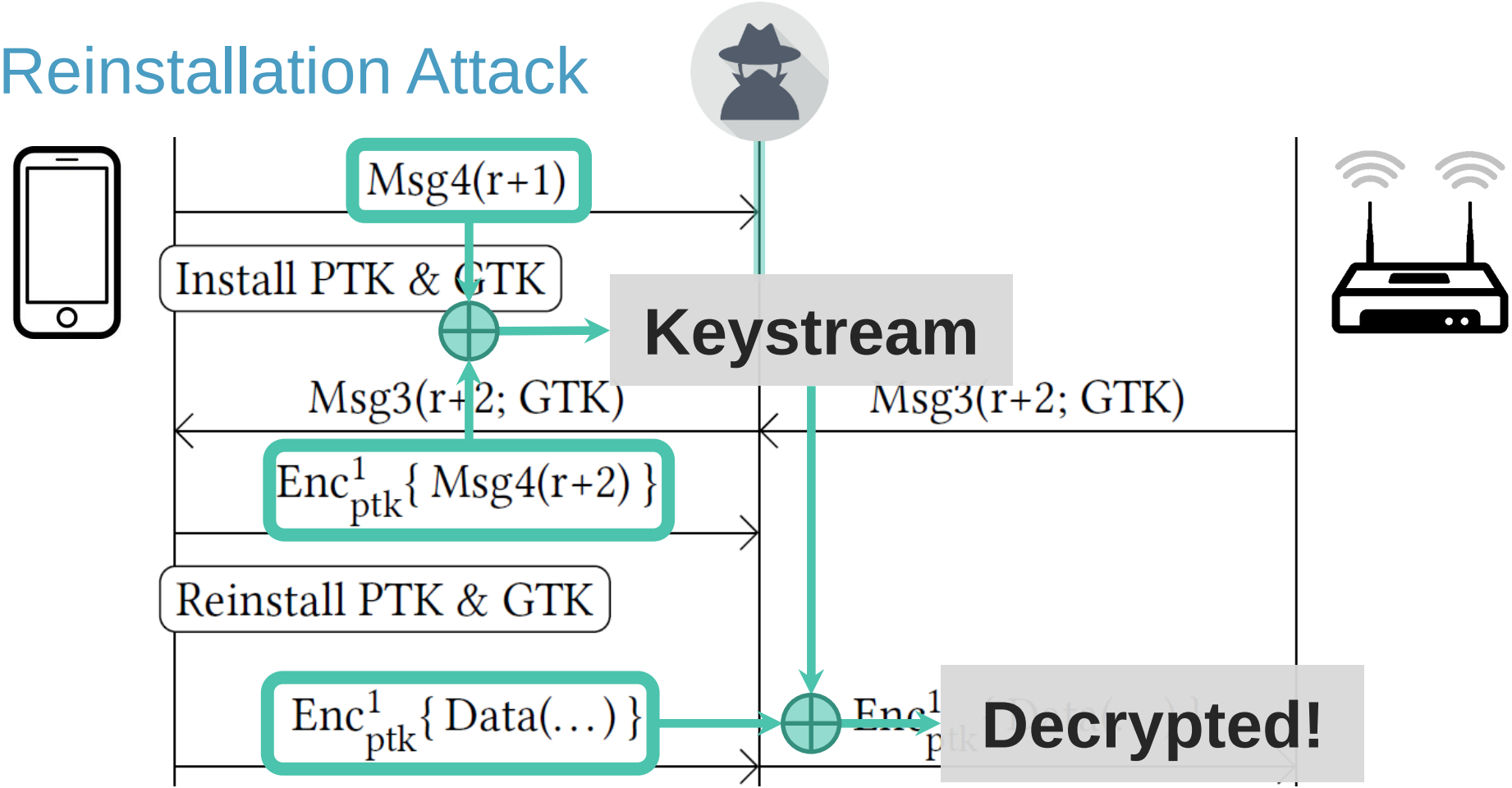


# Key Reinstallation Attack

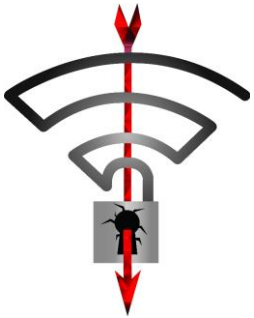
Other Wi-Fi handshakes also vulnerable:

- 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



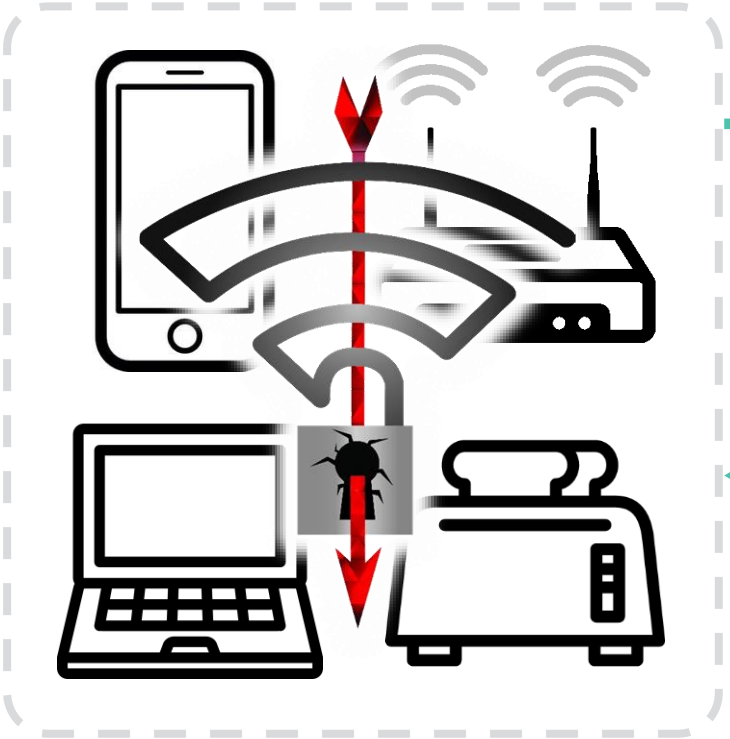
Key reinstalls in
4-way handshake


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

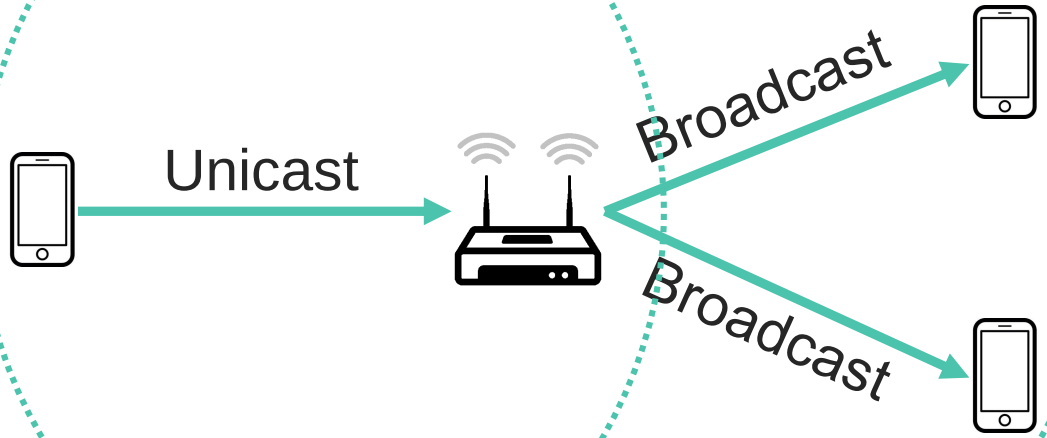
GCMP (WiGig):

- 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:

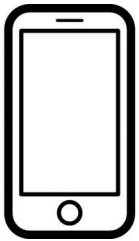
- Client is attacked, but only AP sends real broadcast frames
- Can only replay broadcast frames to client

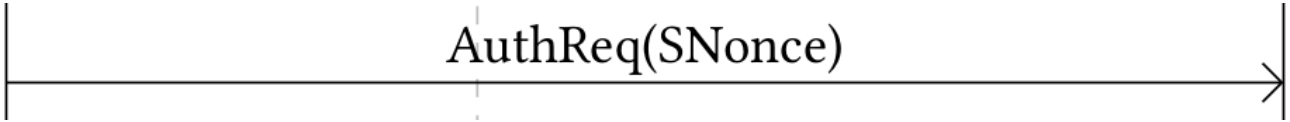
4-way handshake: client is attacked → replay/decrypt/forge

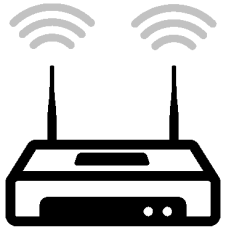
FT handshake (fast roaming = 802.11r):

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

# FT Handshake





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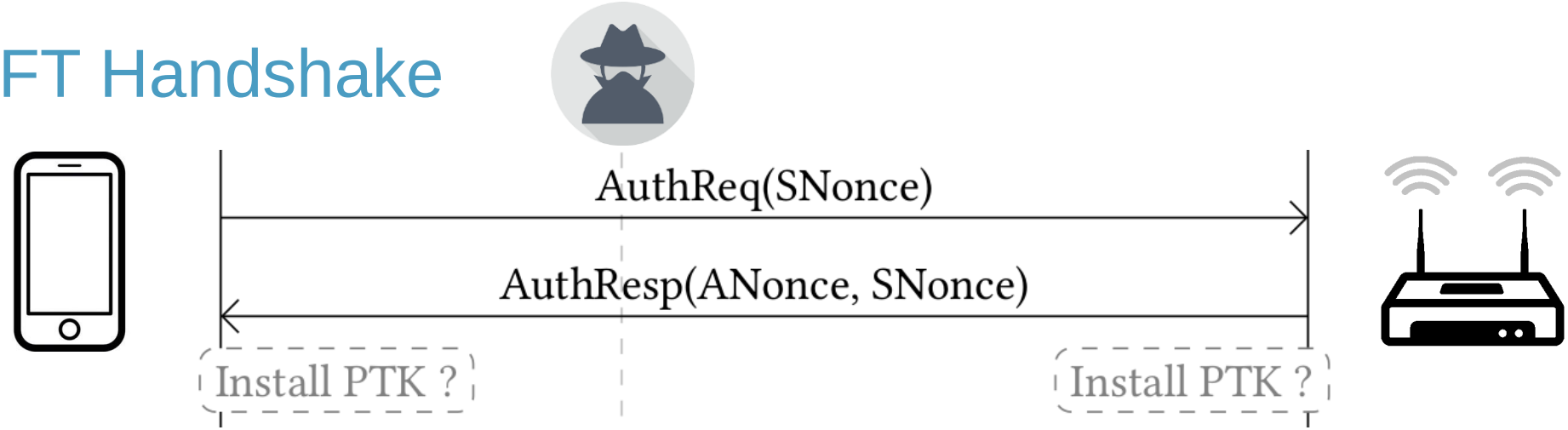

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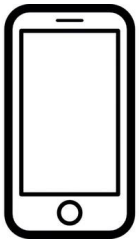

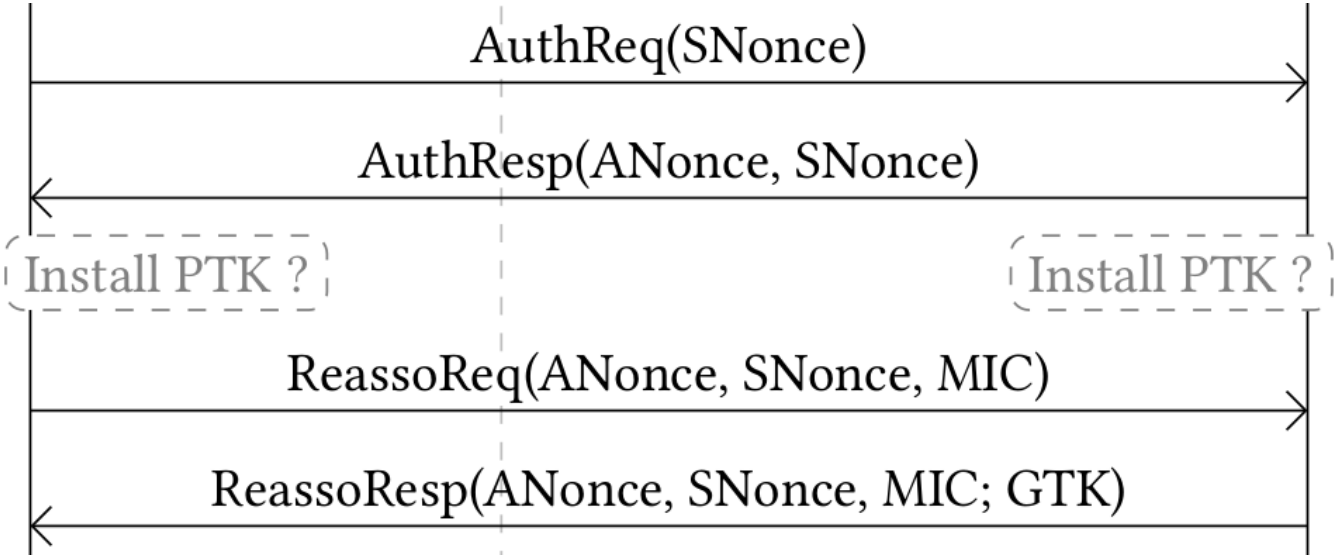


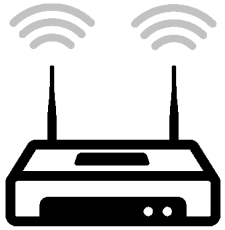

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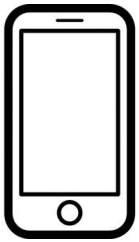

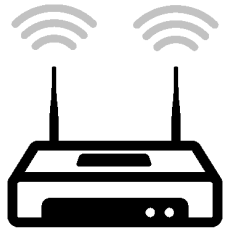

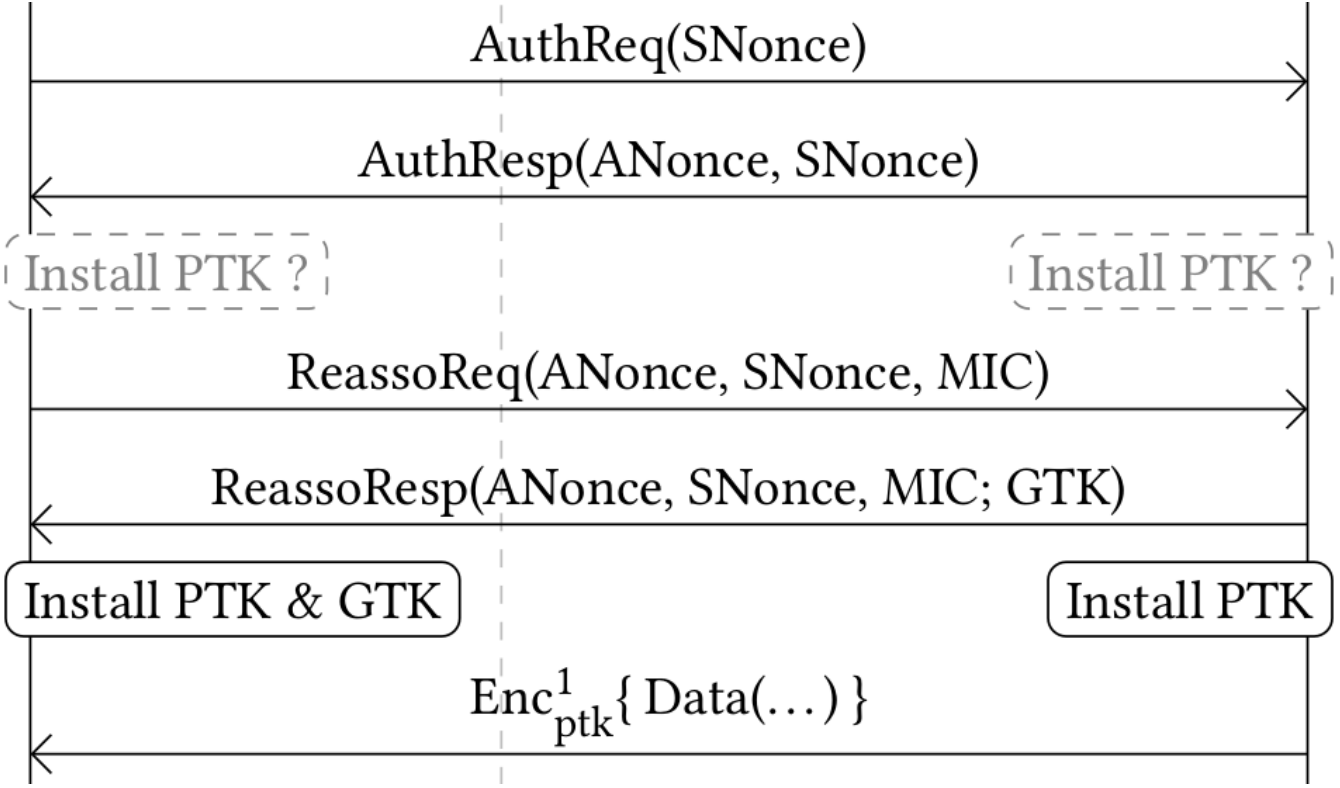

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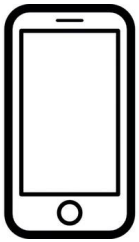

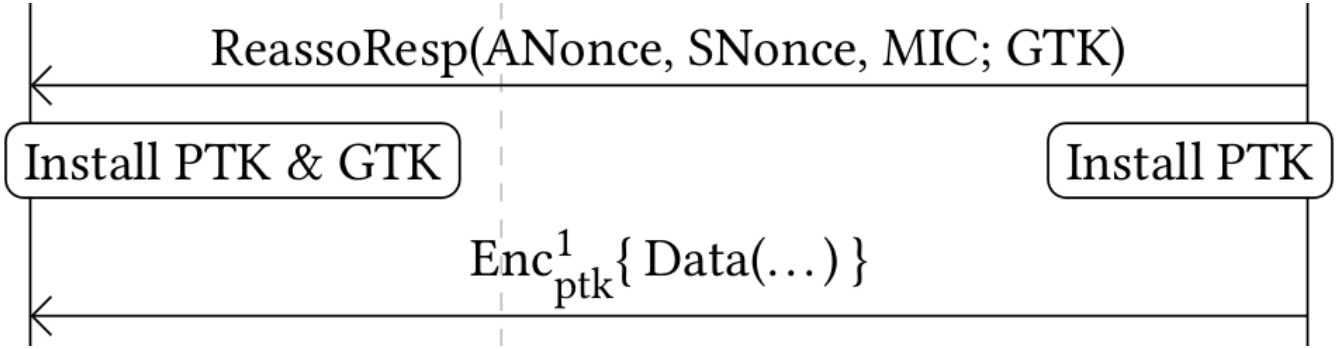


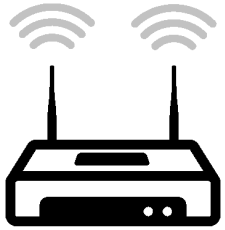

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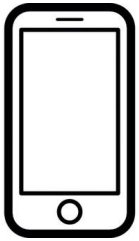

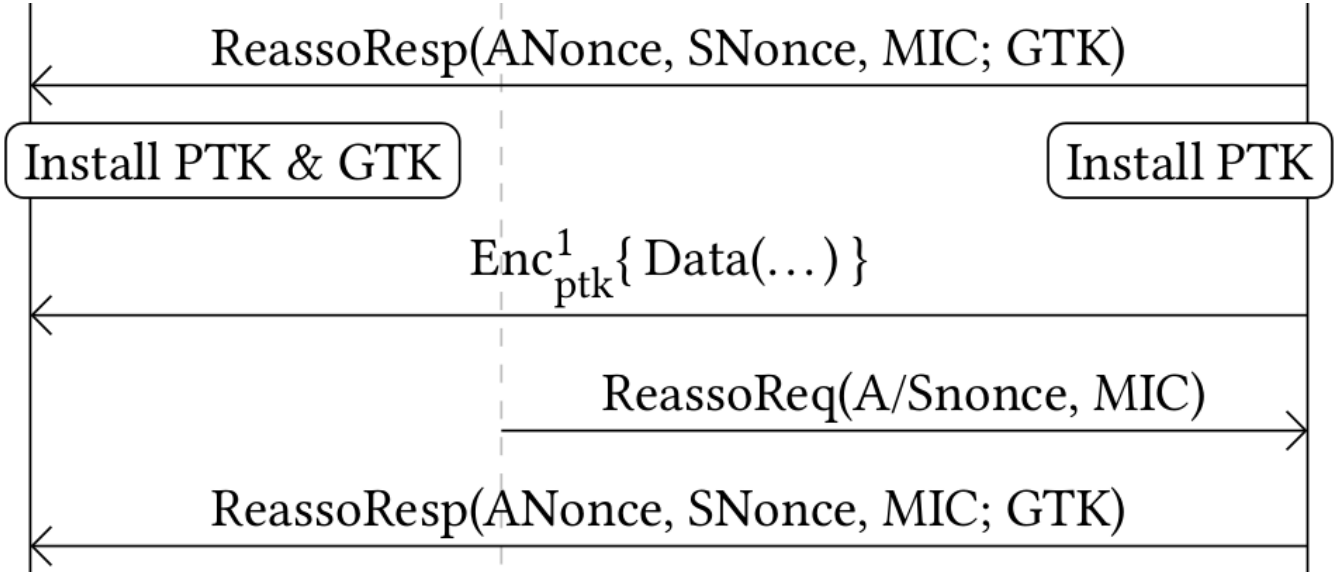


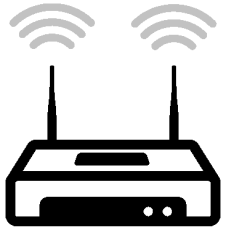

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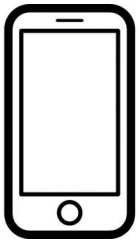

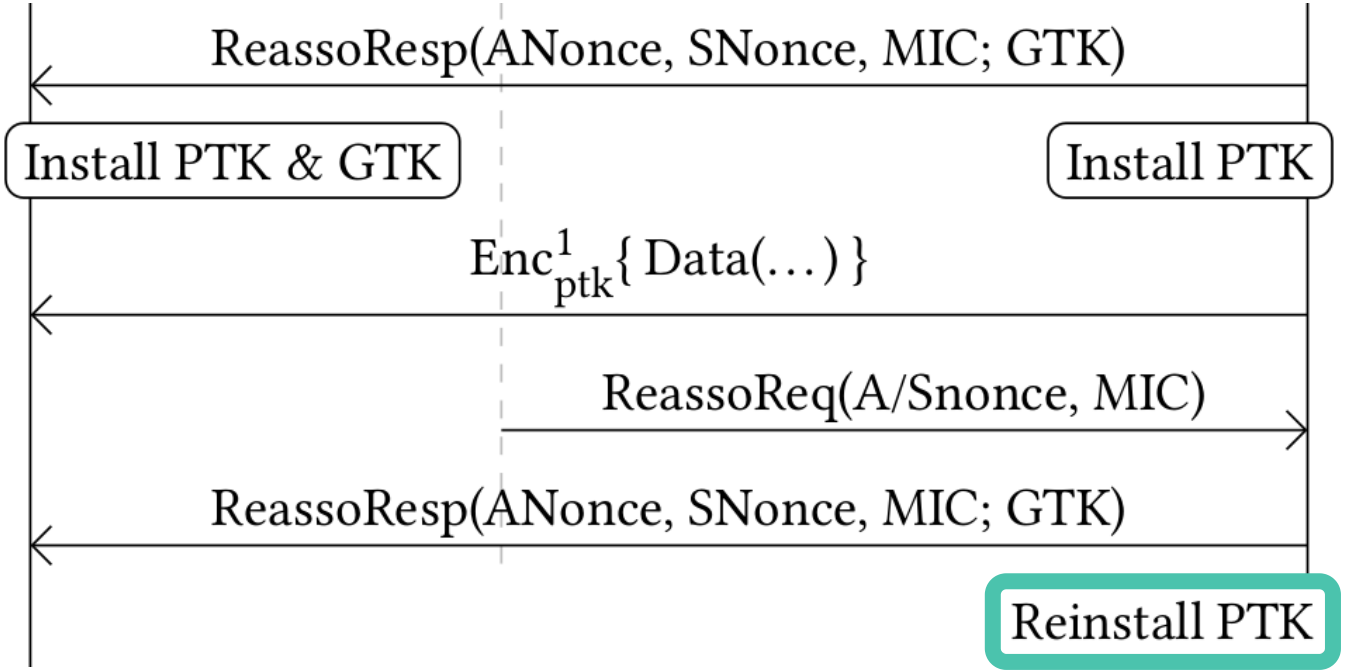


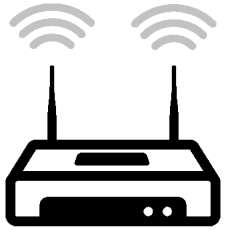

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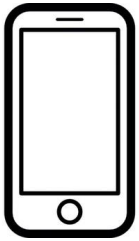
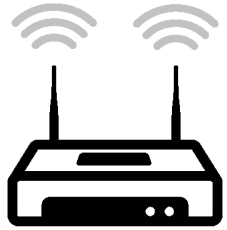




ReassoResp(ANonce, SNonce, MIC; GTK)

Install PTK & GTK

Install PTK

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

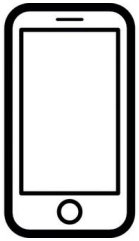
ReassoReq(A/Snonce, MIC)

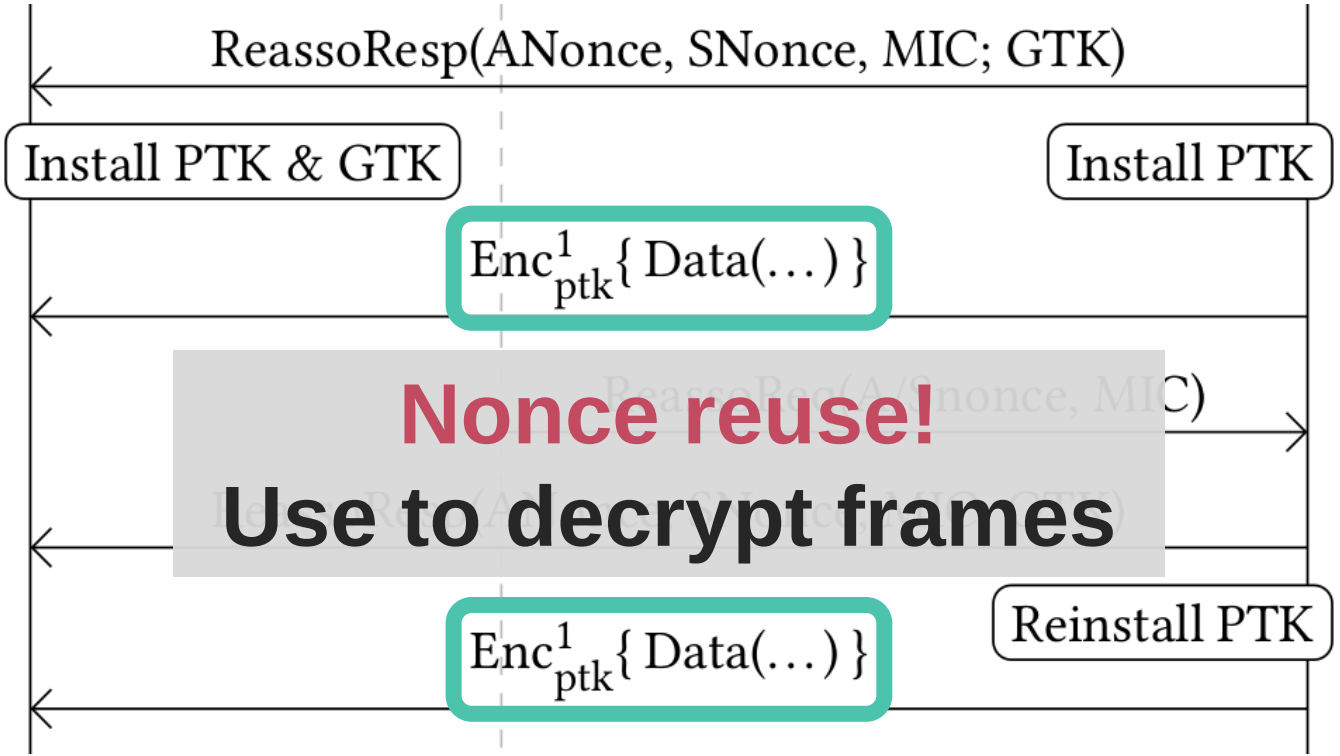
ReassoResp(ANonce, SNonce, MIC; GTK)

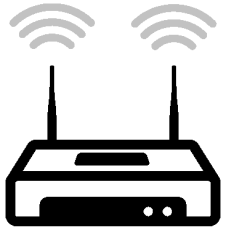
$\text{Enc}^1_{\text{ptk}}\{\text{Data}(\ldots)\}$

Reinstall PTK

# FT Handshake





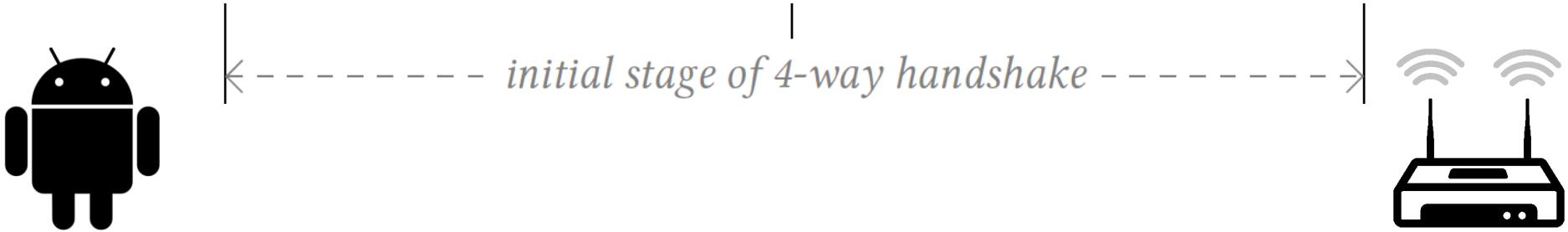
# Implementation specific

iOS 10 and Windows: 4-way handshake not affected

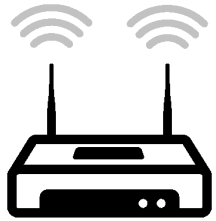
- **Cannot decrypt unicast traffic** (nor replay/decrypt)
- But group key handshake is affected (replay broadcast)
- Note: iOS 11 does have vulnerable 4-way handshake[8]

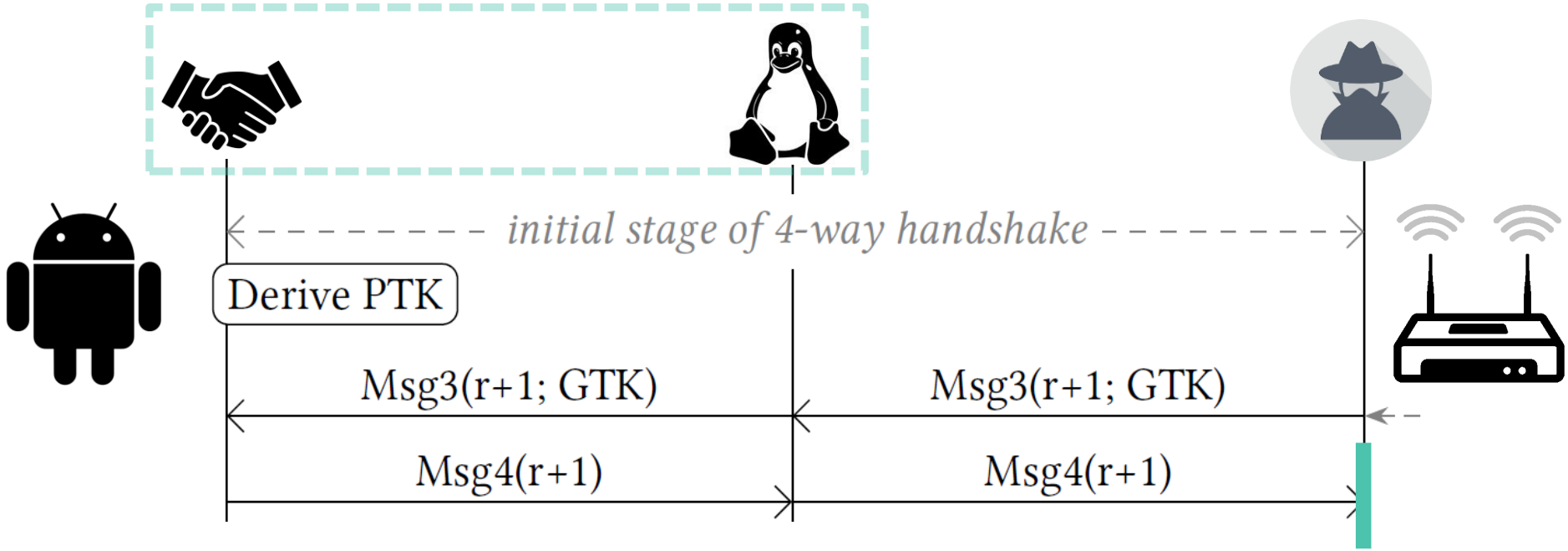
wpa_supplicant 2.4+

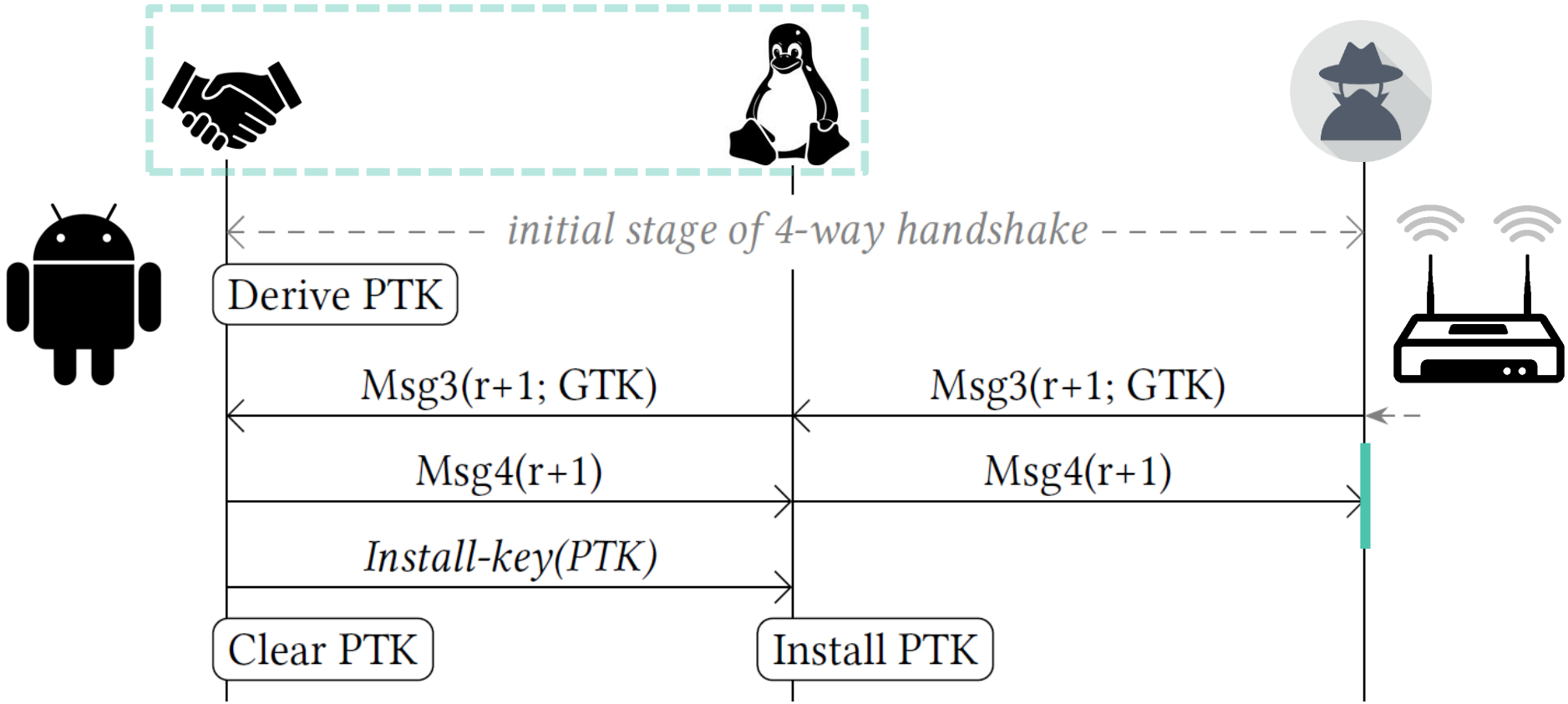
- Client used on Linux and Android 6.0+
- On retransmitted msg3 will **install all-zero key**

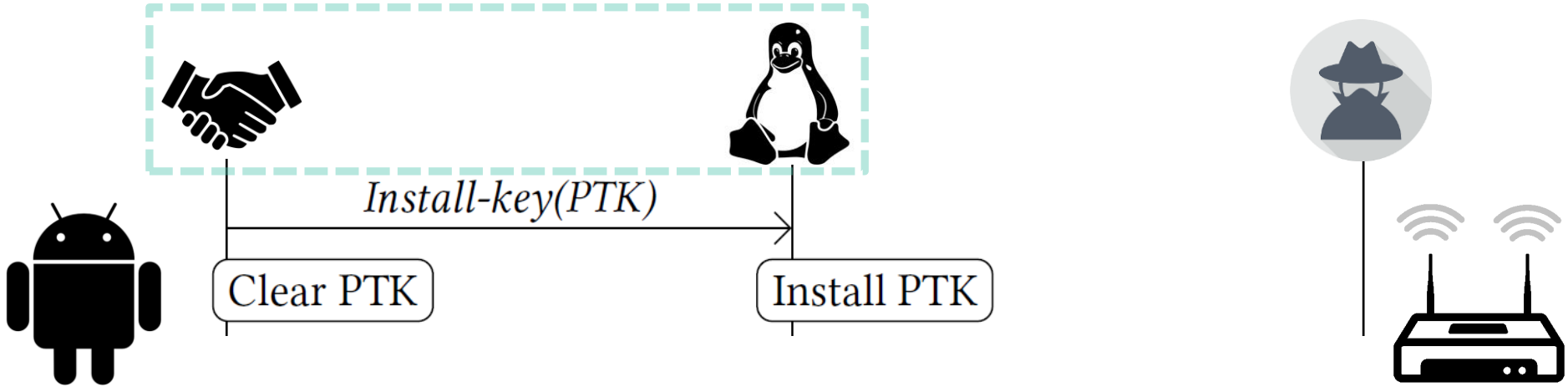

initial stage of 4-way handshake

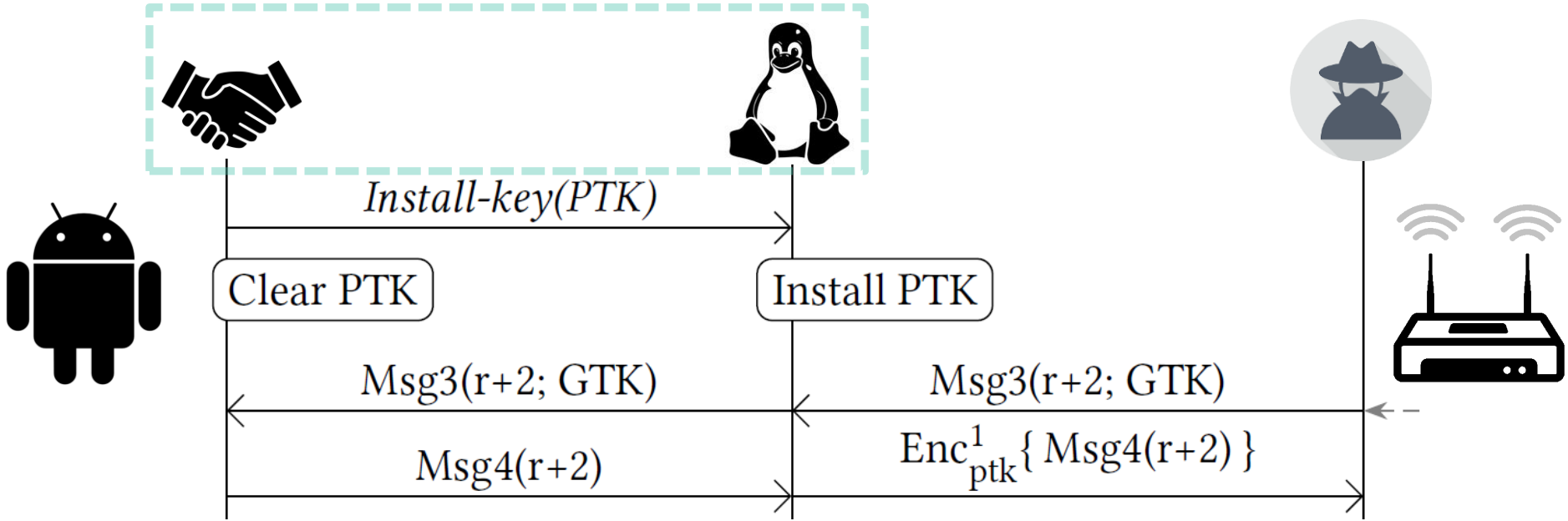
Android (victim)

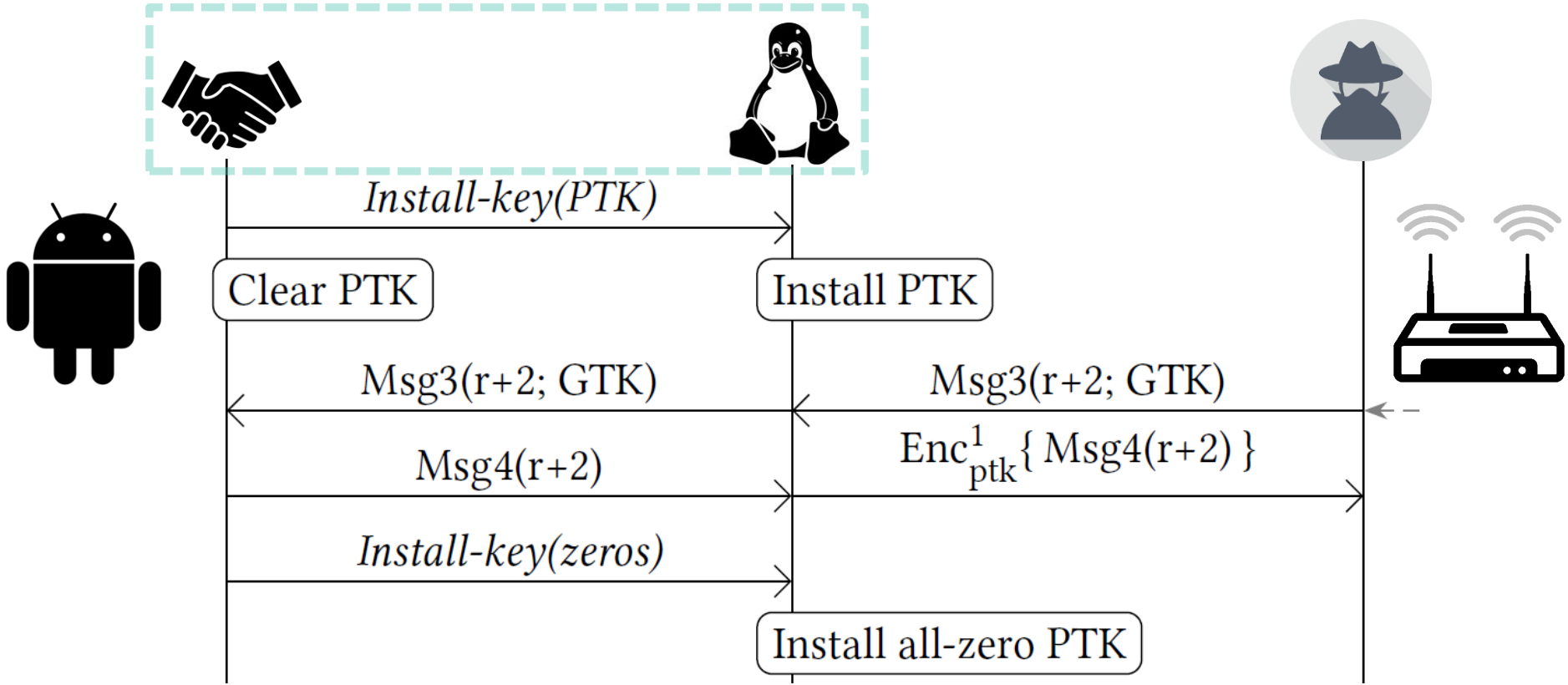


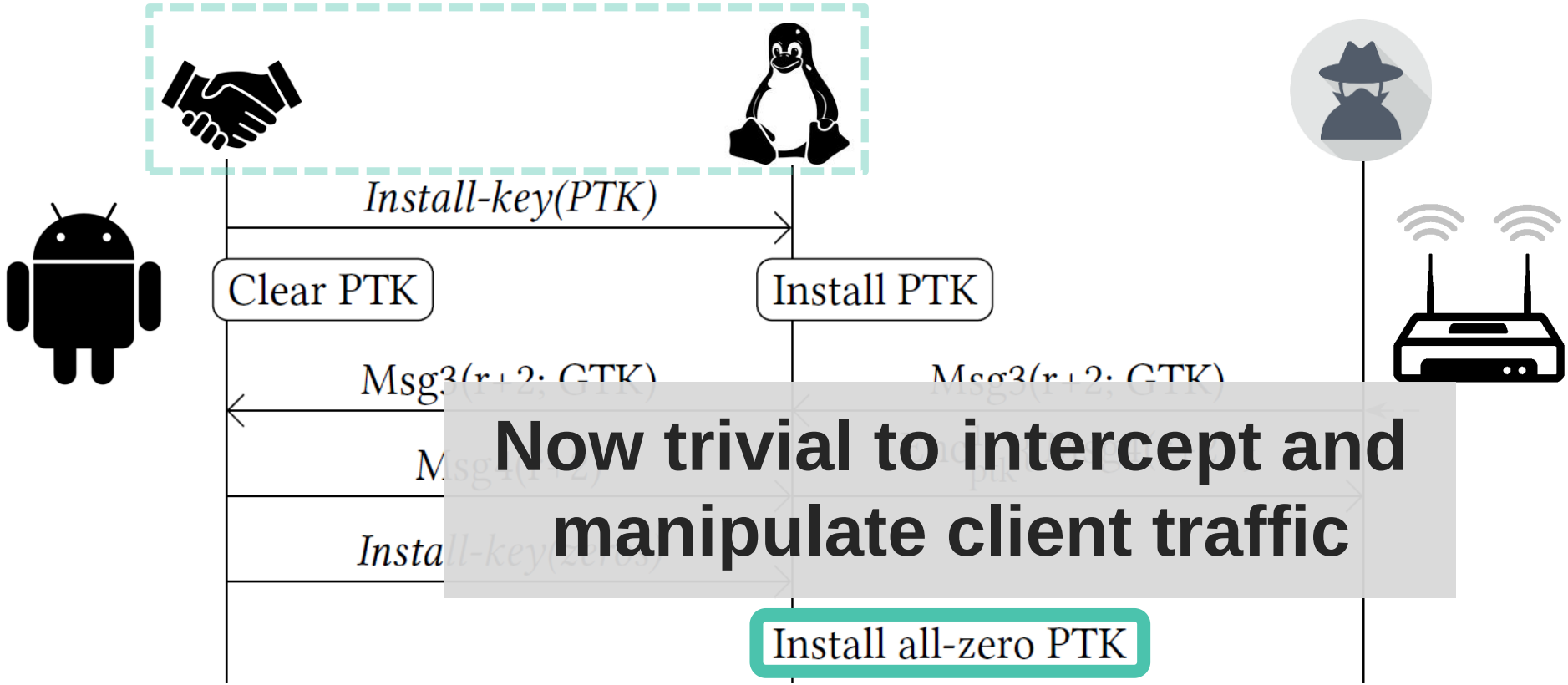

initial stage of 4-way handshake
Derive PTK
Msg3(r+1; GTK)
Msg3(r+1; GTK)
Msg4(r+1)
Msg4(r+1)


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) }


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




**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…

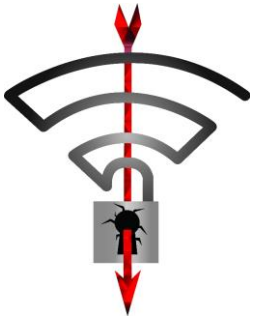
AP can prevent (most) attacks on clients!

- 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

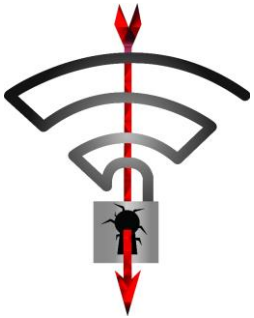
› Also use 4-way handshake & are affected

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

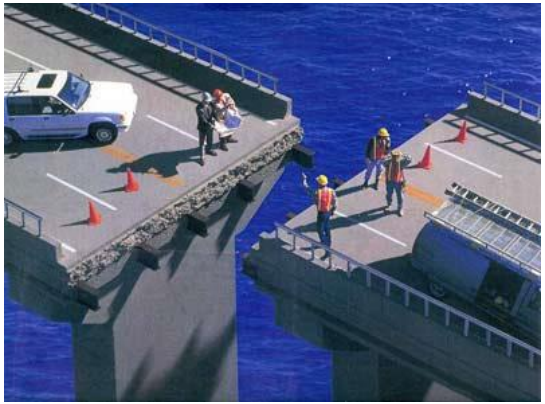

Misconceptions

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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