Key Reinstallation Attacks: Breaking the WPA2 Protocol

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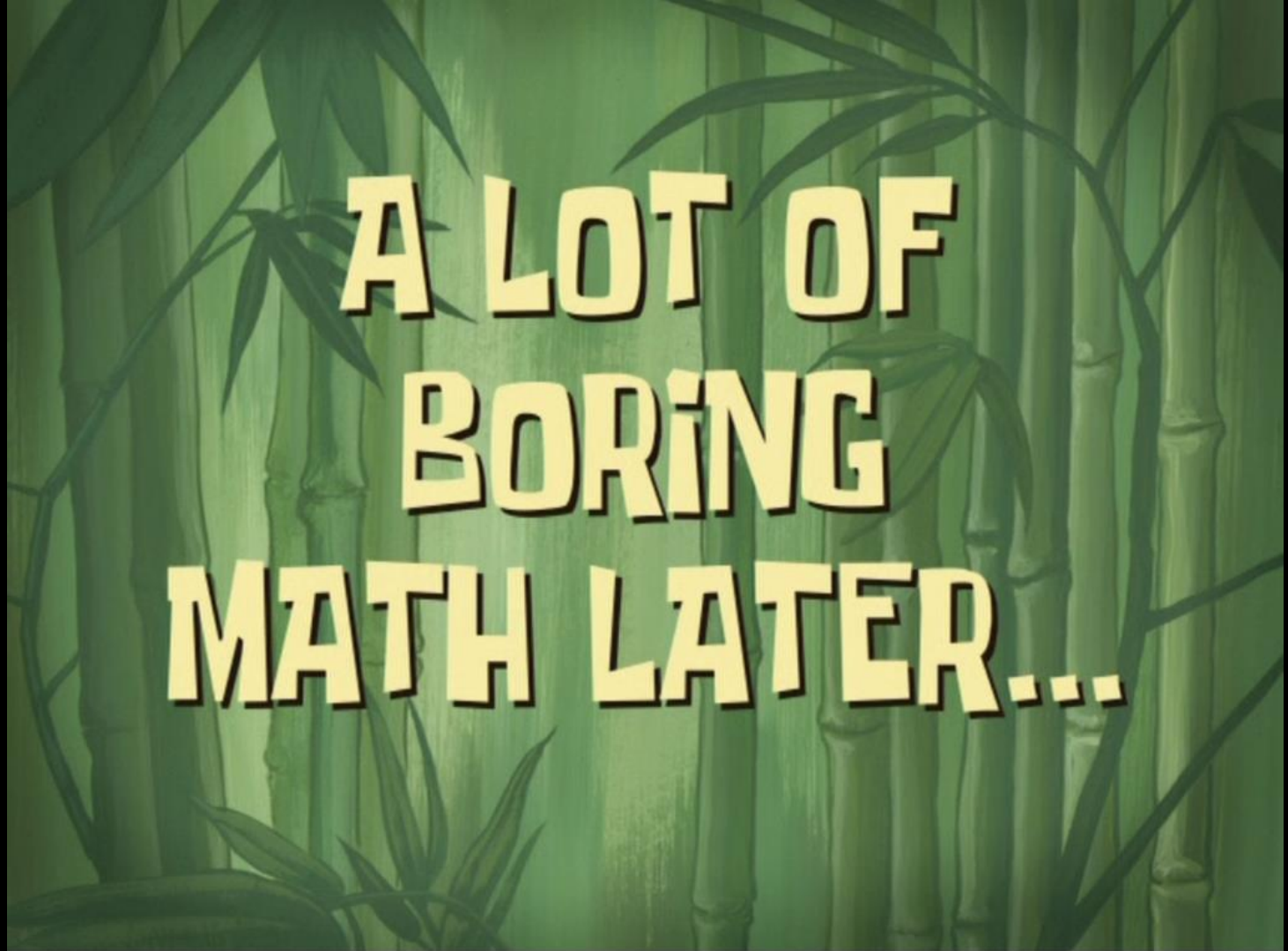
KU LEUVEN DistriNet

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.

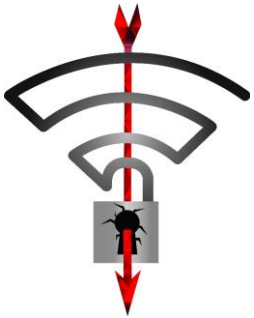

A LOT OF
BORING
MATH LATER...

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



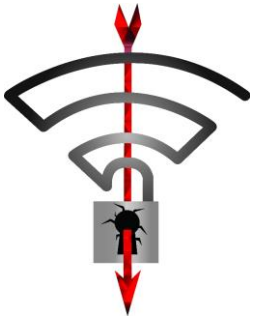
Key reinstalls in
4-way handshake

Misconceptions

Practical impact

Lessons learned

Overview



Key reinstalls in 4-way handshake

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The 4-way handshake

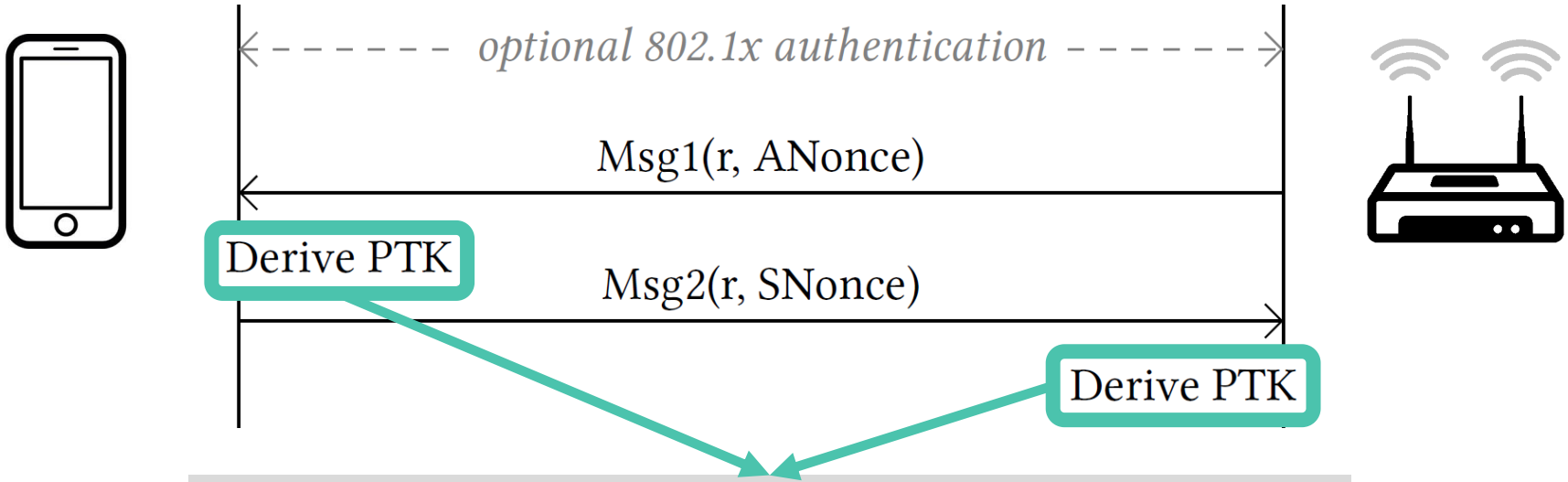
Used to connect to any protected Wi-Fi network

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

Appeared to be secure:

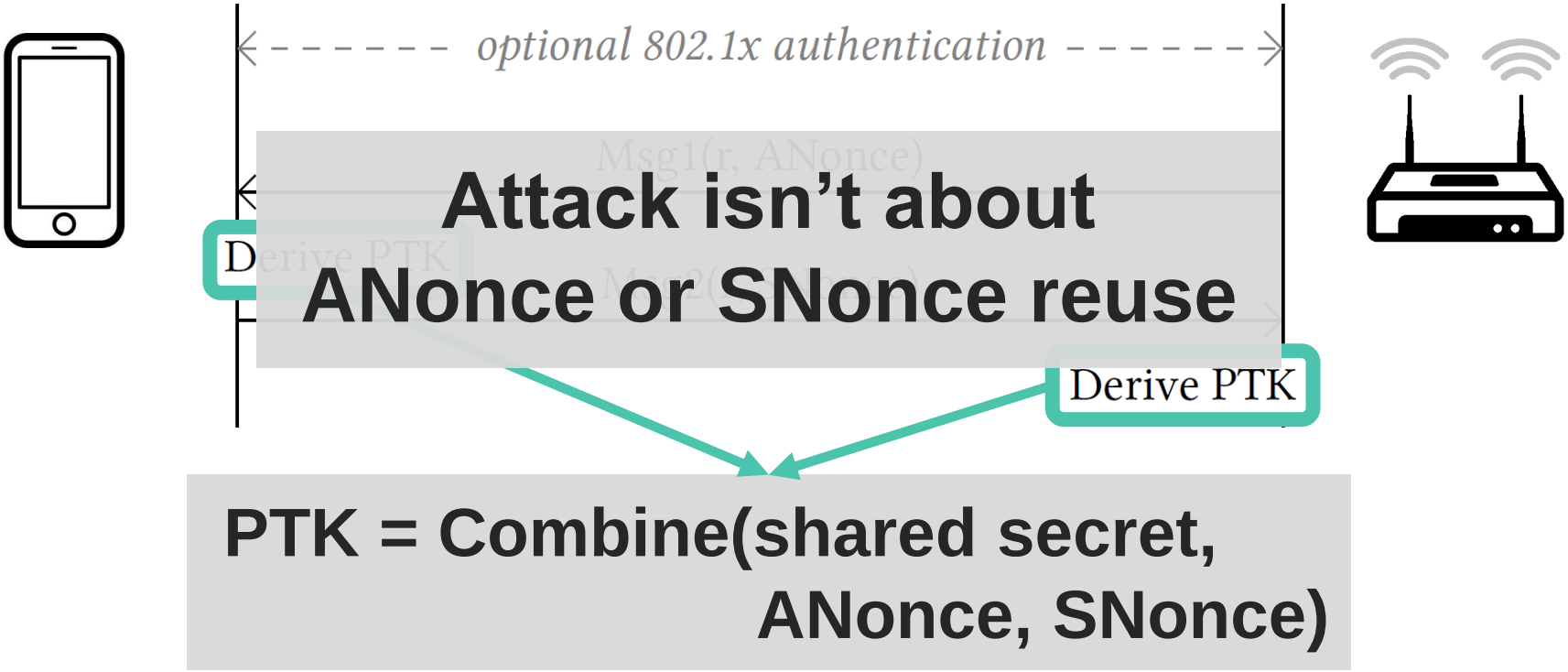
- No attacks in over a decade (apart from password guessing)
- Proven that negotiated key (PTK) is secret[1]
- And encryption protocol proven secure[7]

4-way handshake (simplified)

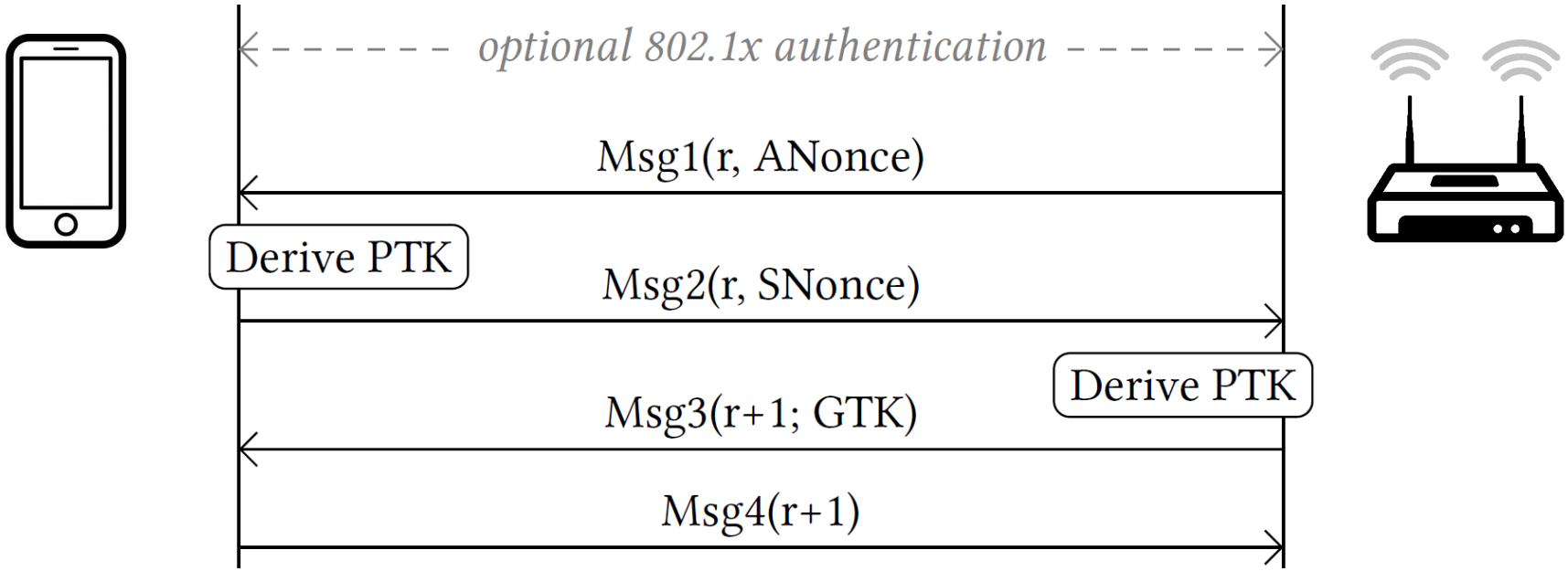


PTK = Combine(shared secret, ANonce, SNonce)

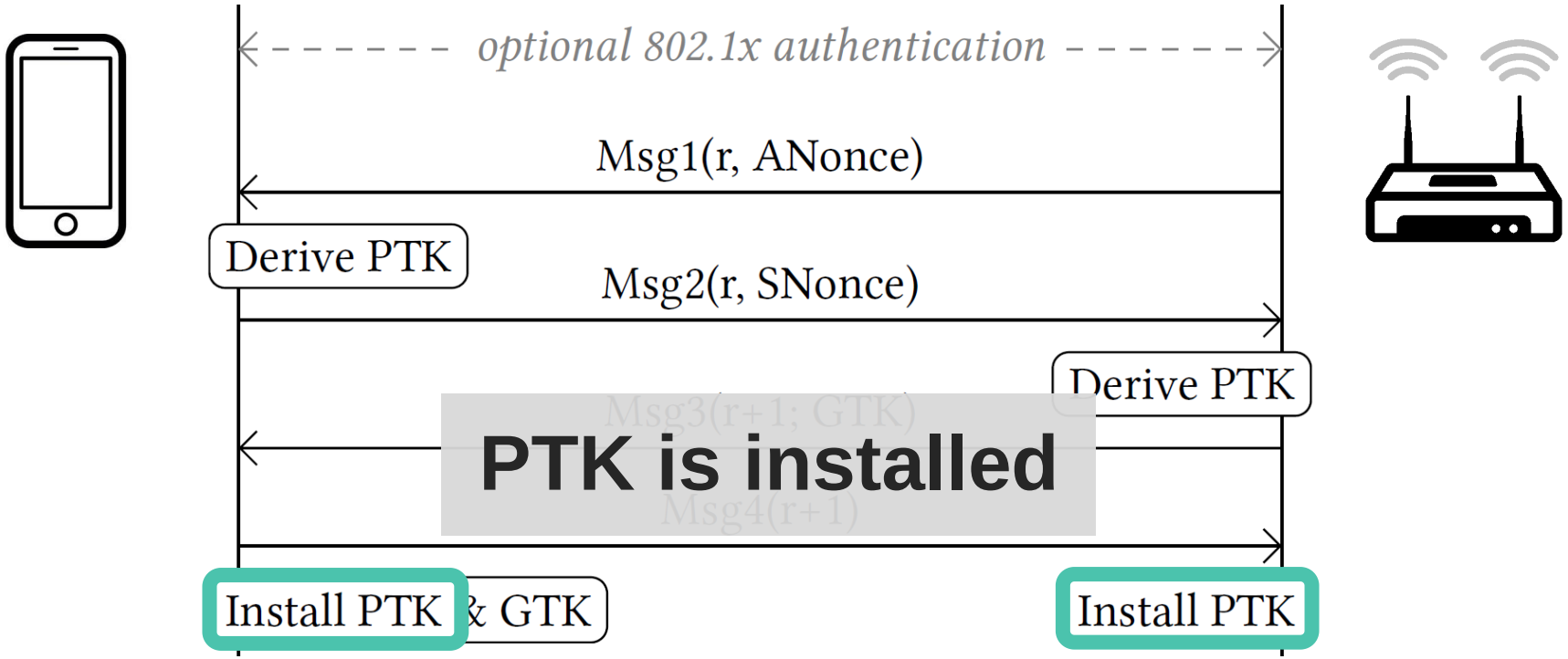
4-way handshake (simplified)



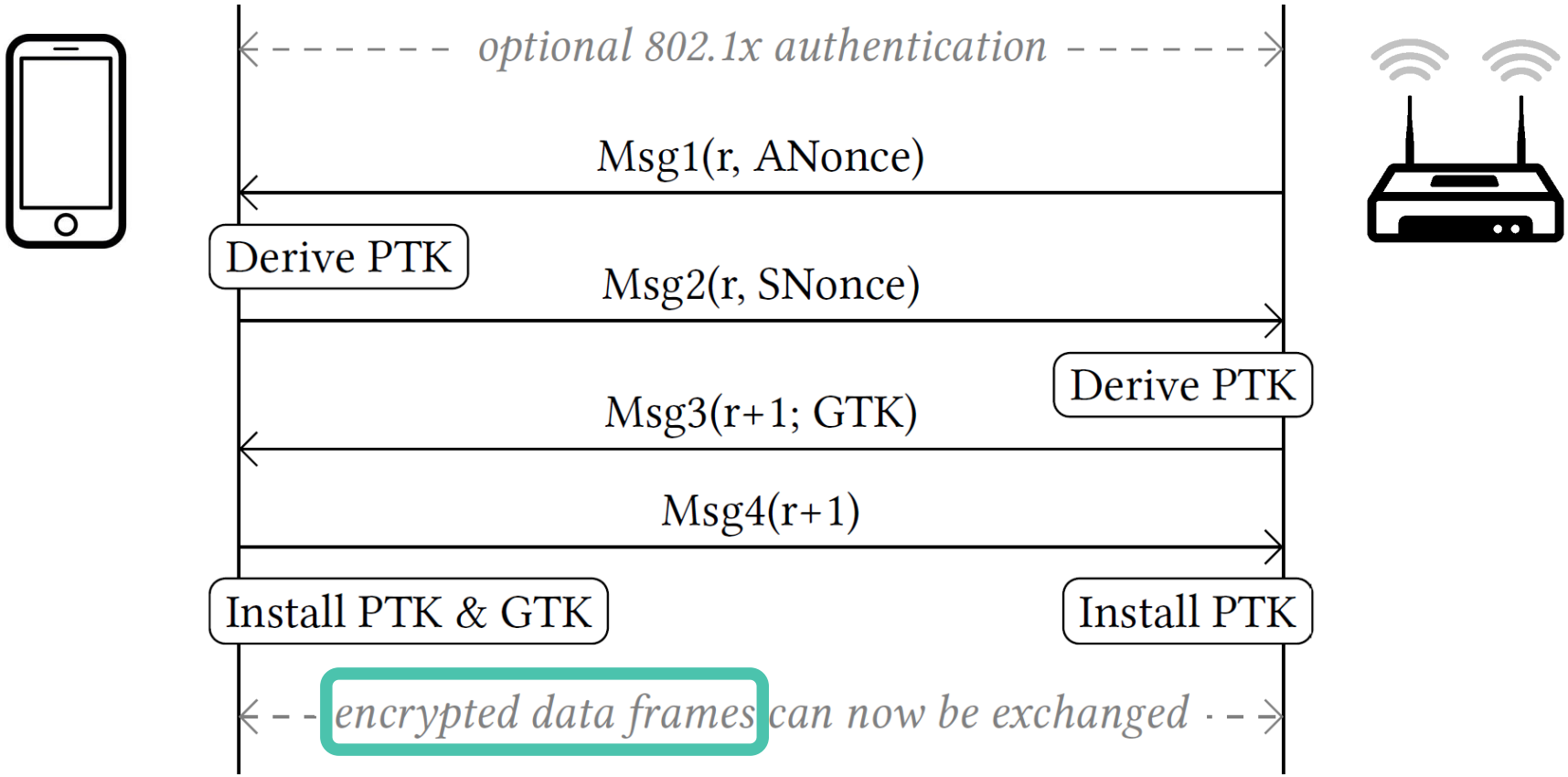
4-way handshake (simplified)



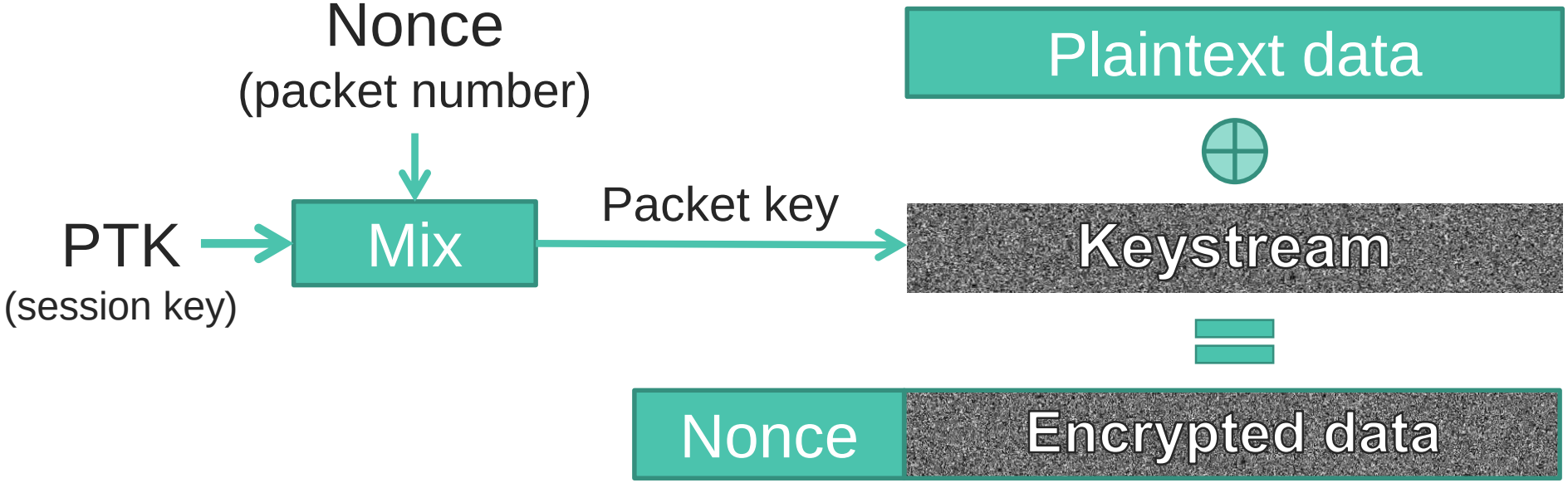
4-way handshake (simplified)



4-way handshake (simplified)

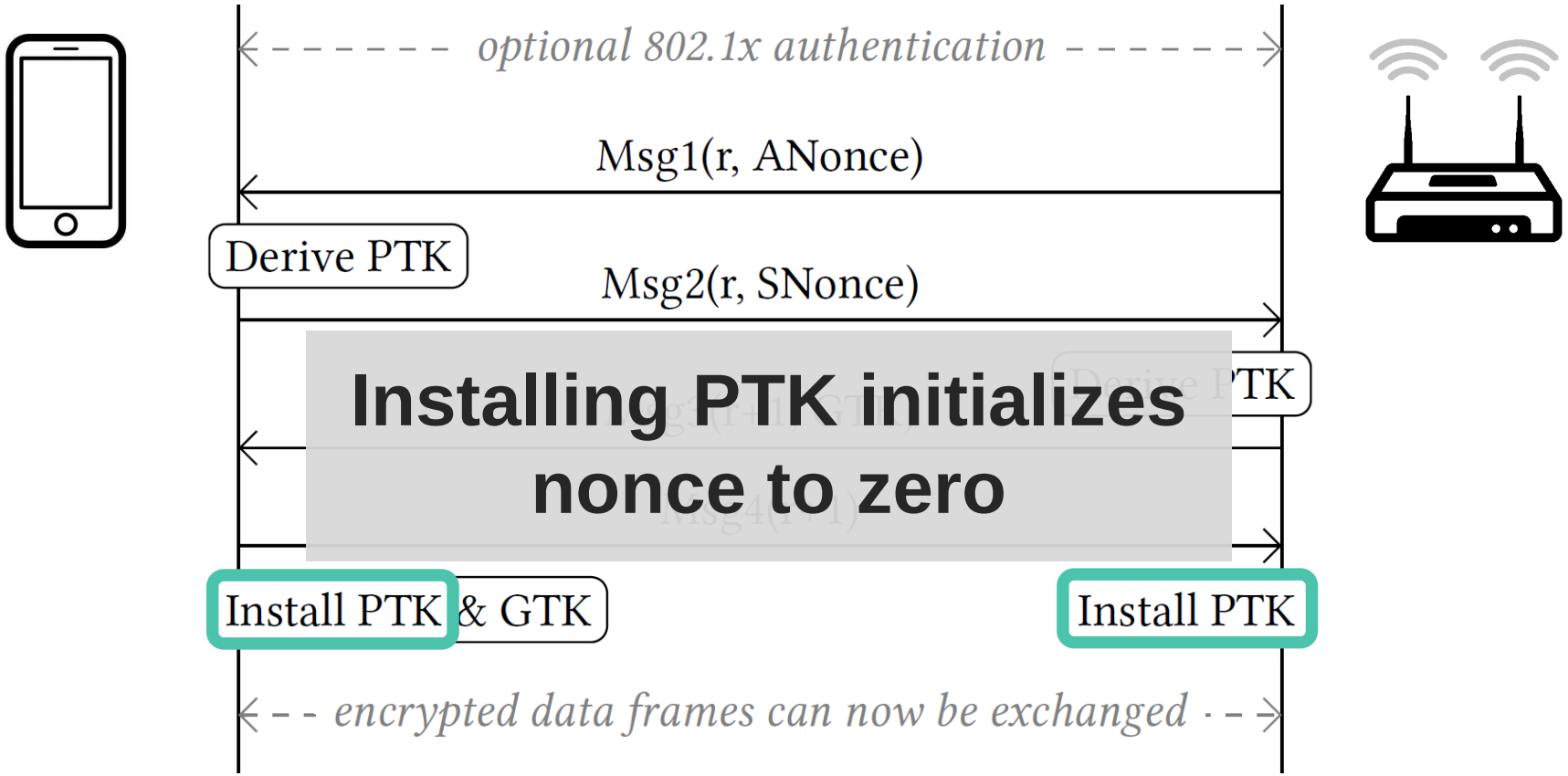


Frame encryption (simplified)

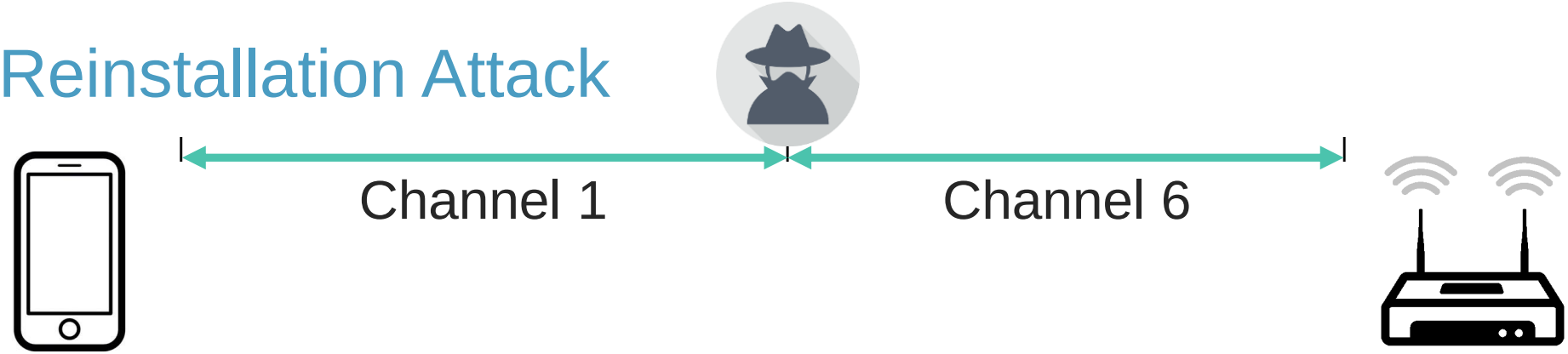


→ Nonce reuse implies keystream reuse (in all WPA2 ciphers)

4-way handshake (simplified)



Reinstallation Attack



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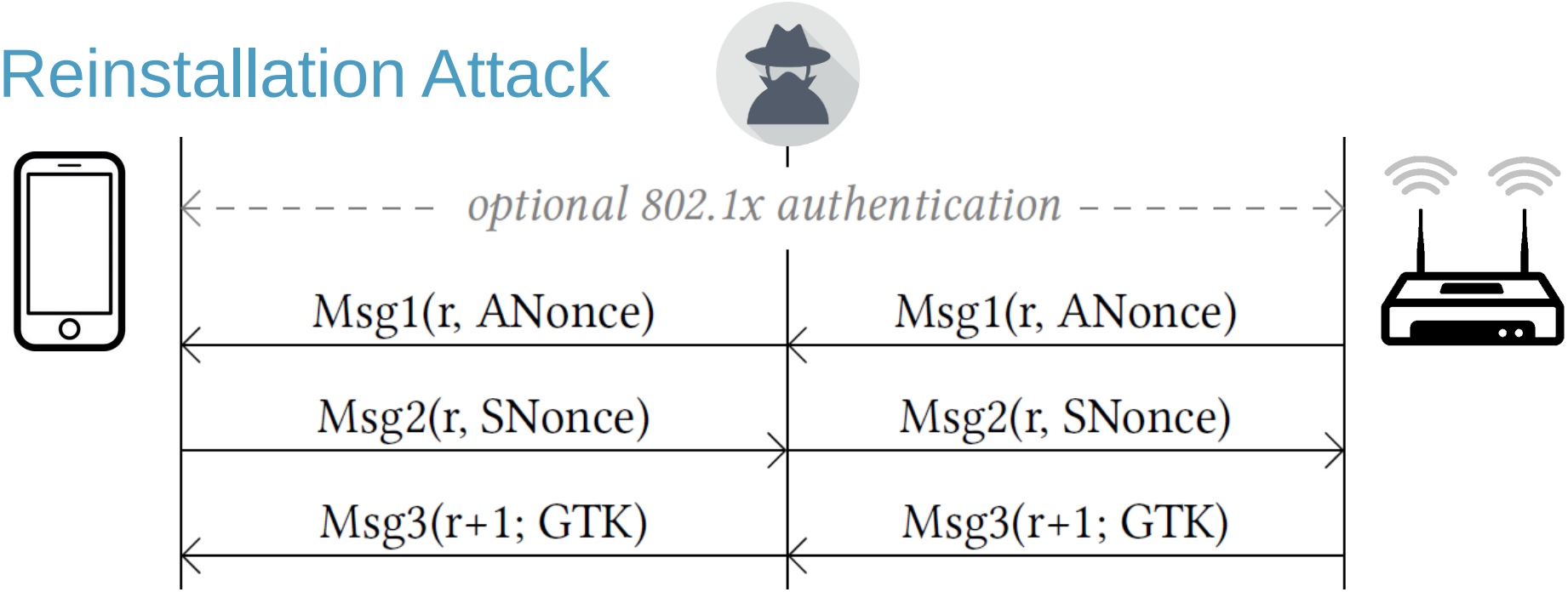
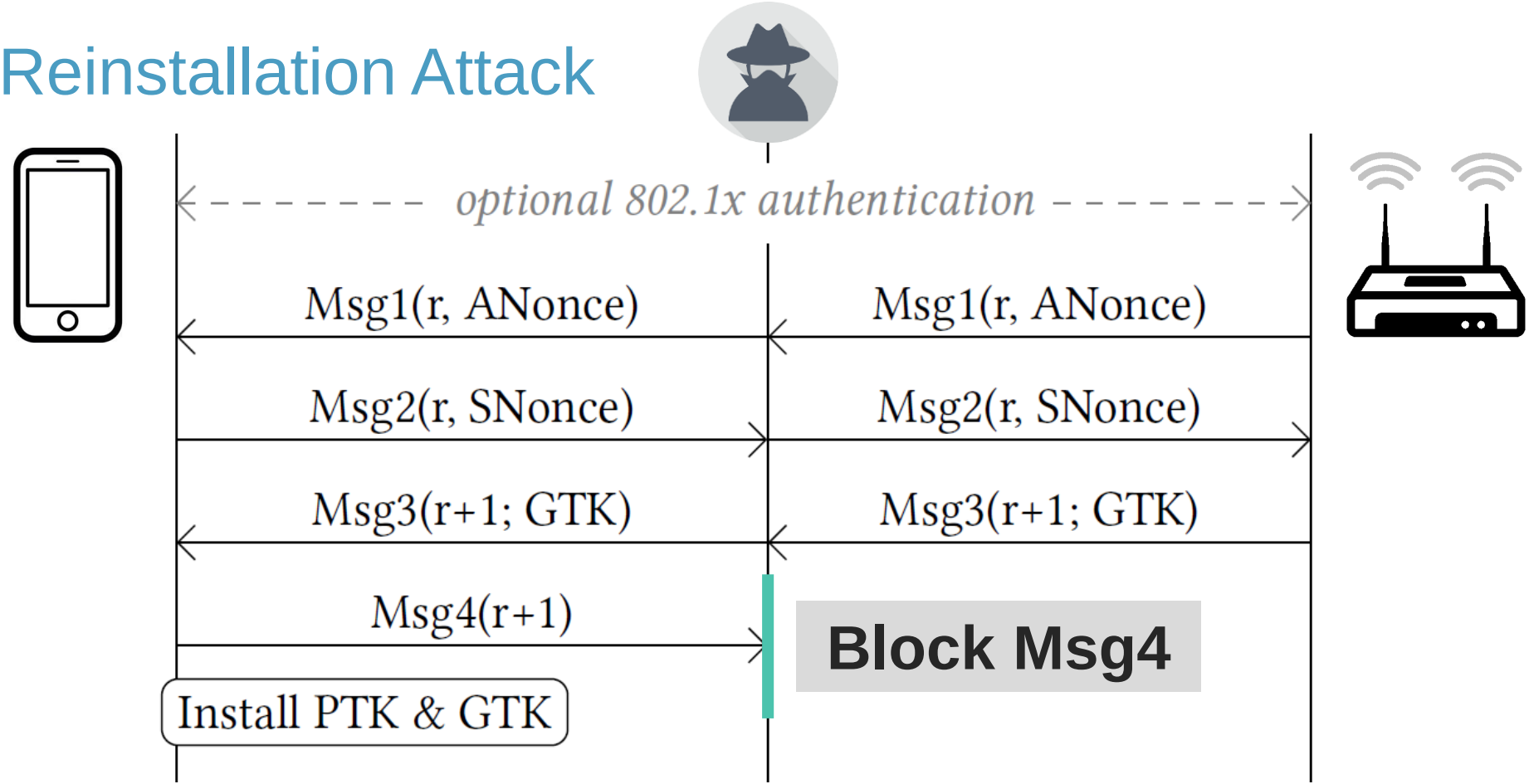


Reinstallation Attack



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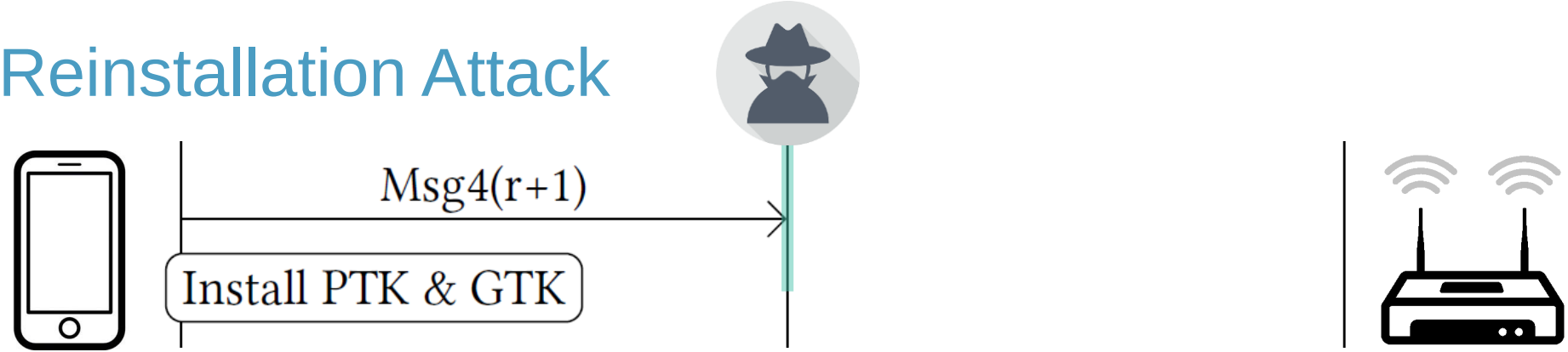

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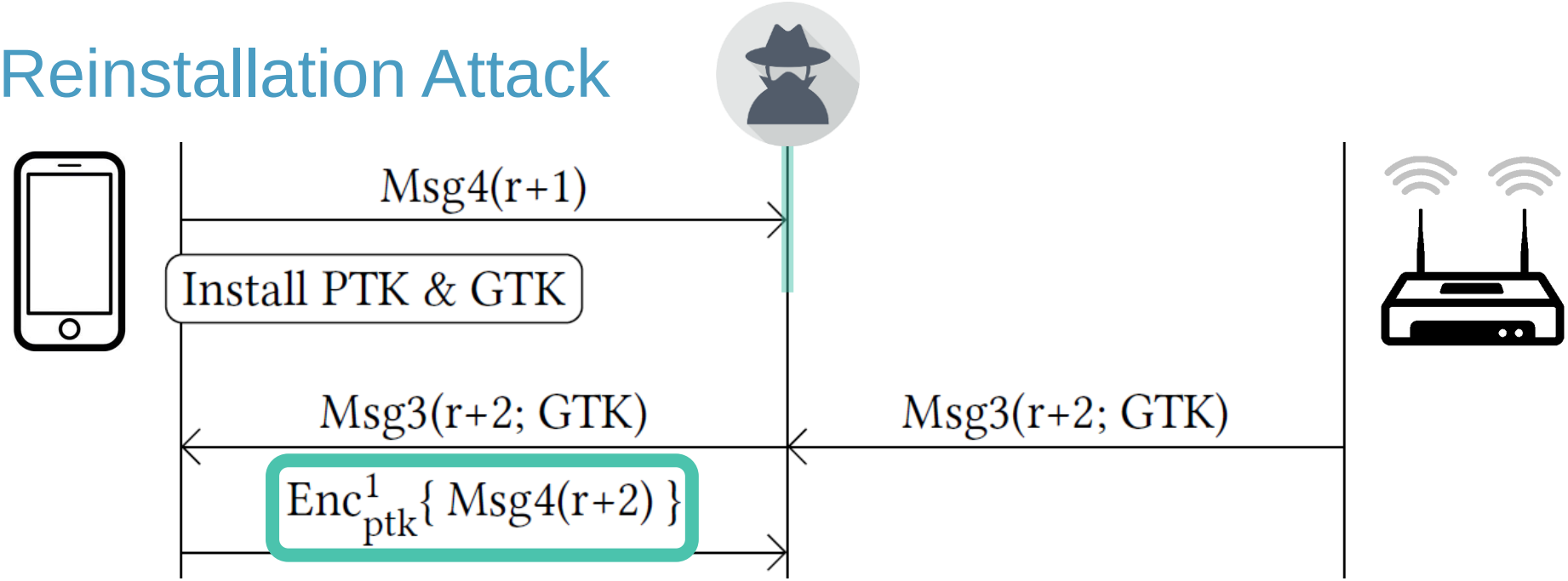

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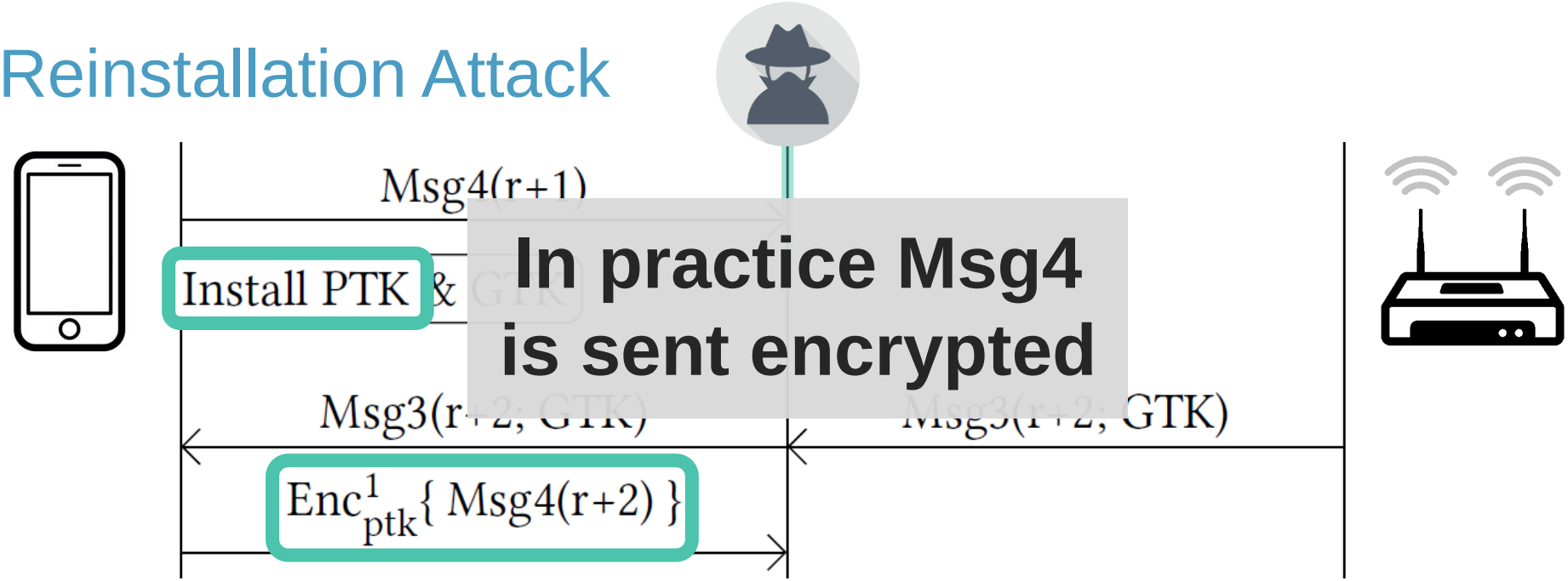
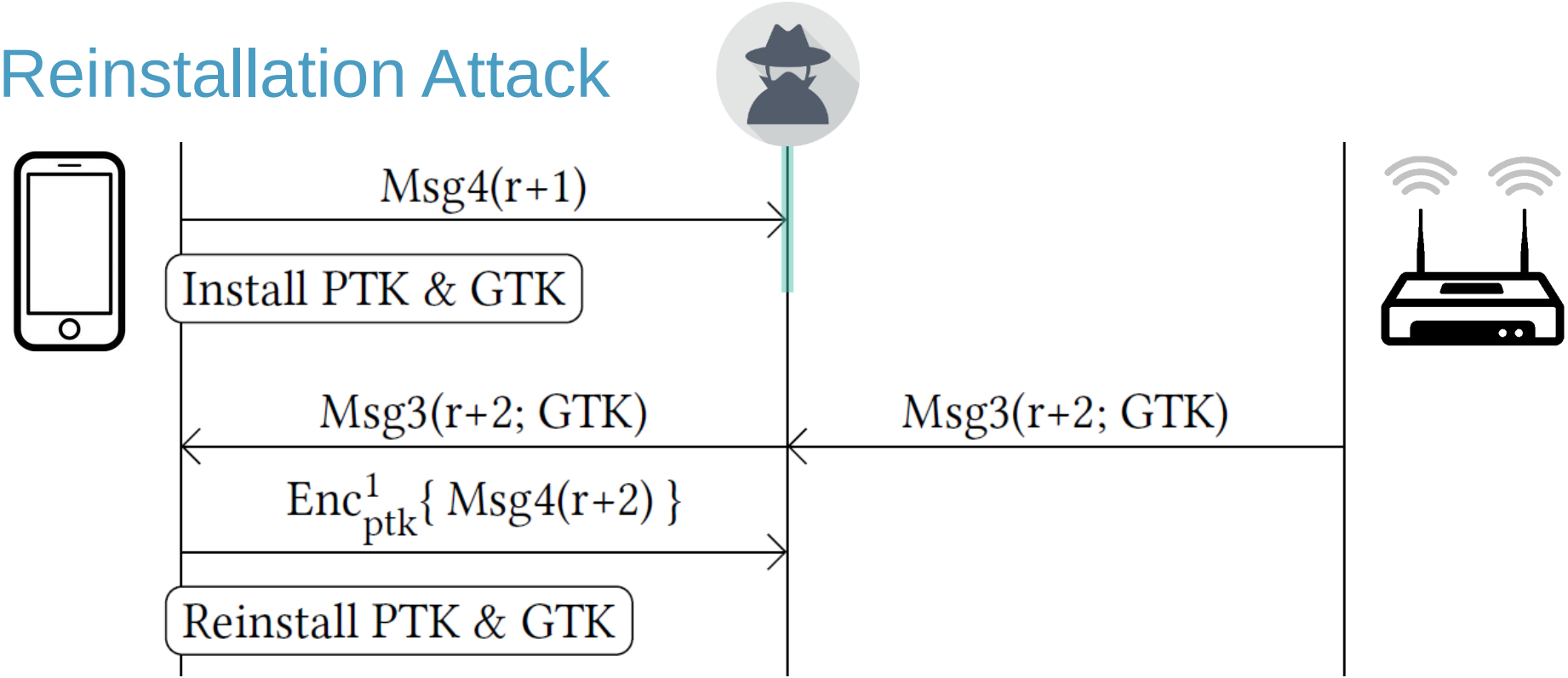
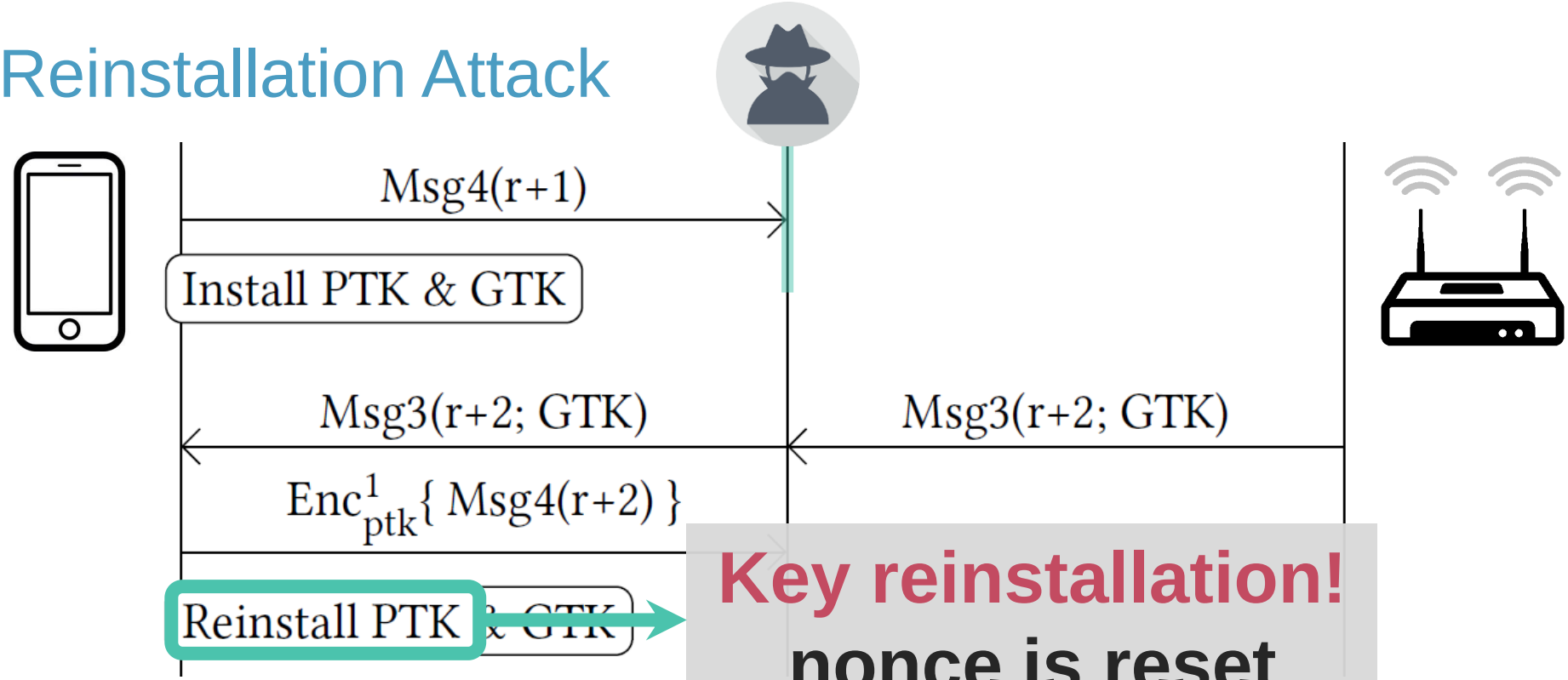


In practice Msg4 is sent encrypted

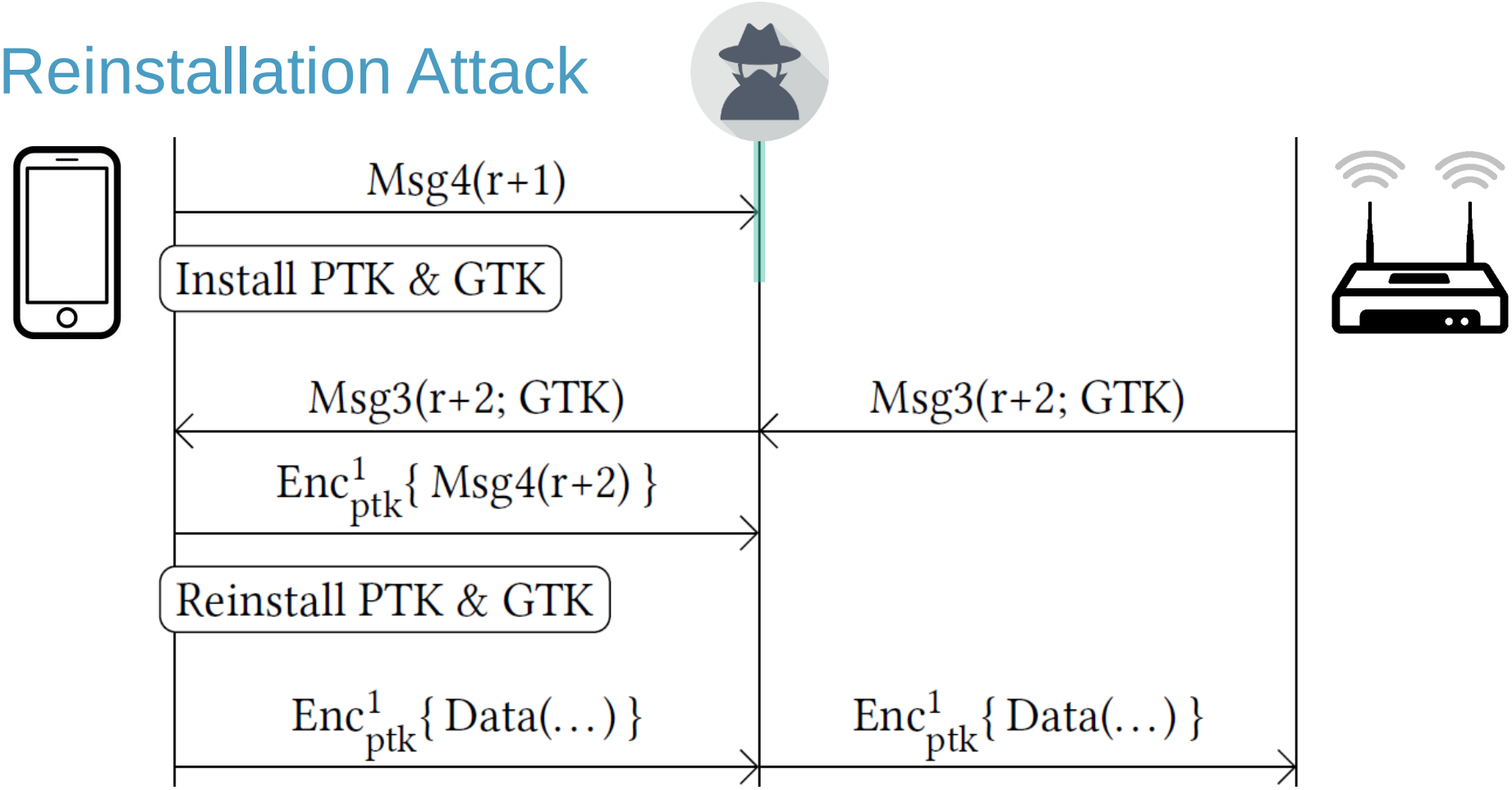
Reinstallation Attack



Reinstallation Attack



Reinstallation Attack



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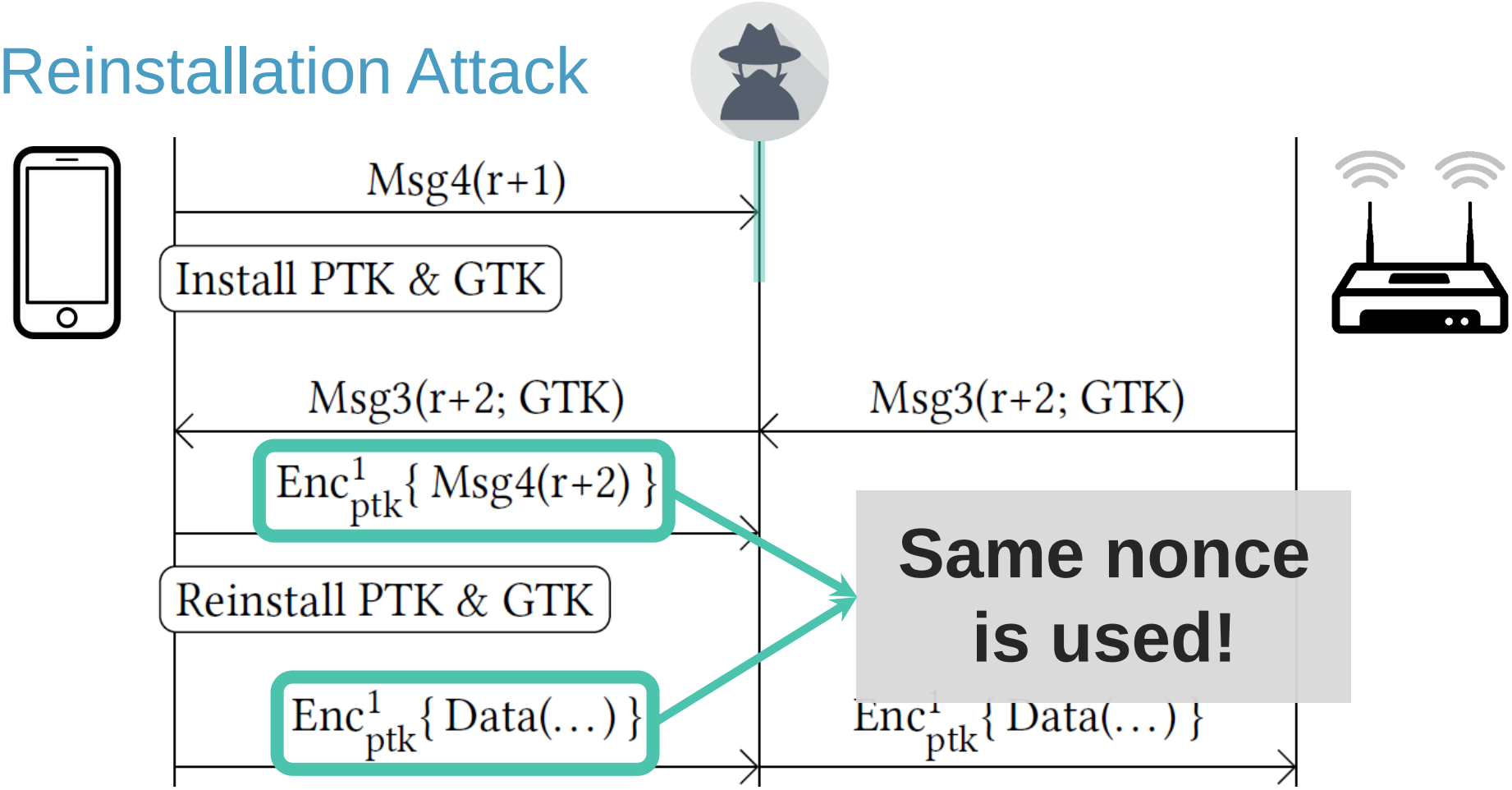

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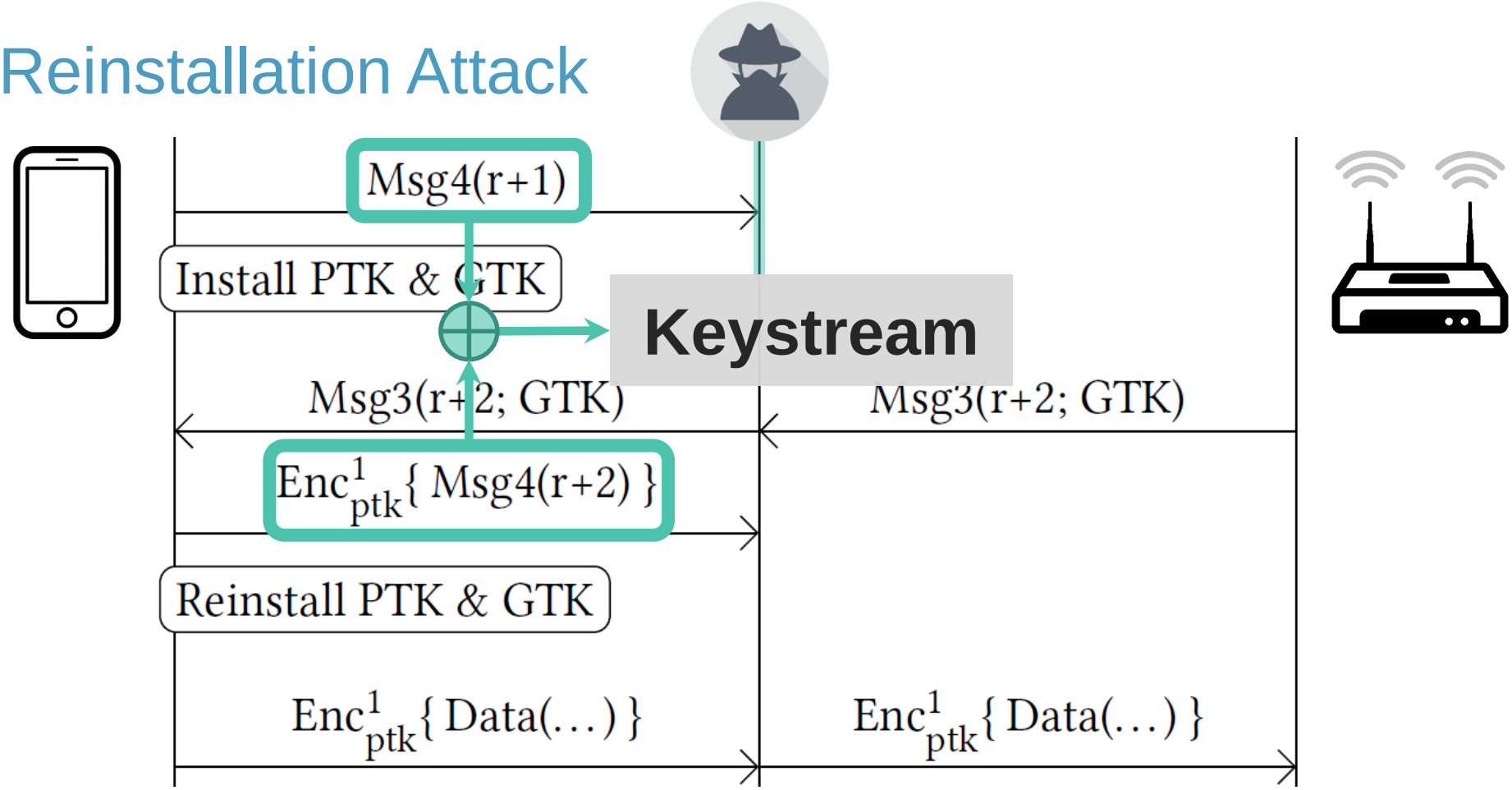

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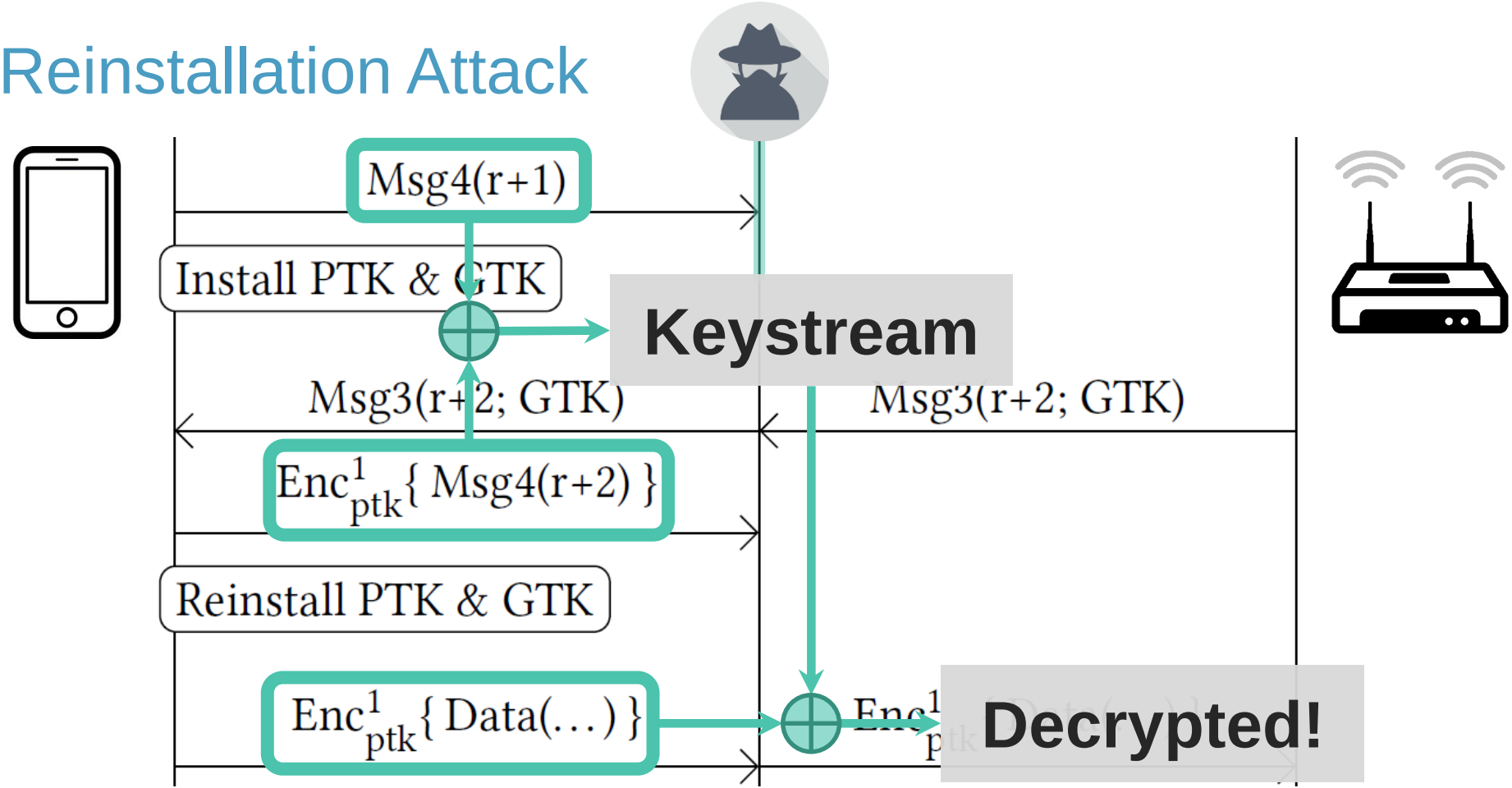


Key Reinstallation Attack

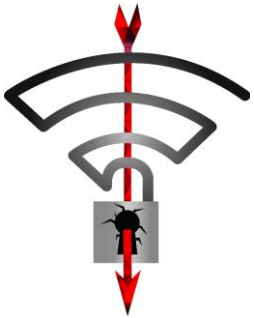
Other Wi-Fi handshakes also vulnerable:

- 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



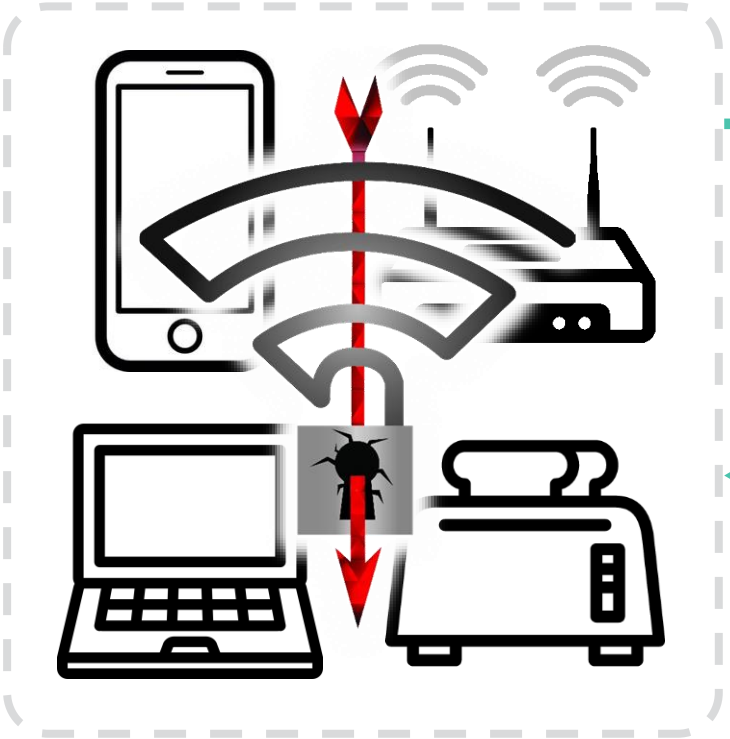
Key reinstalls in
4-way handshake

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

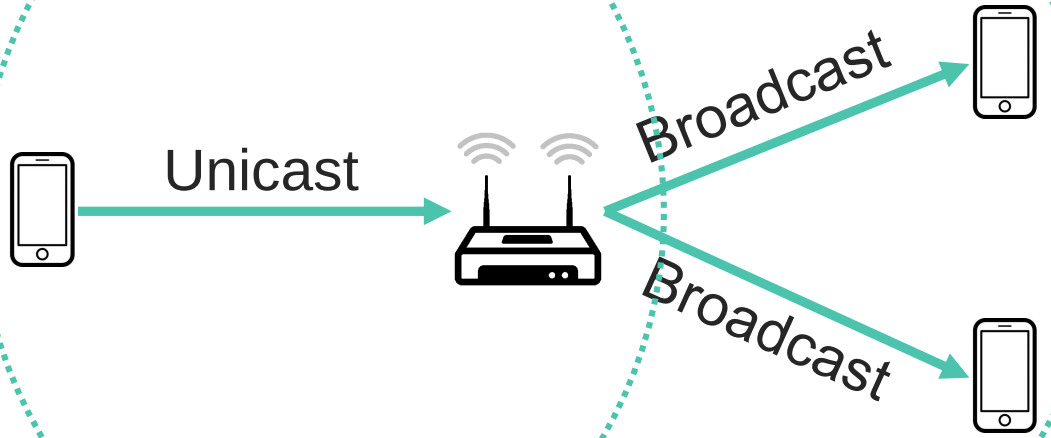
GCMP (WiGig):

- 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**

Implementation specific

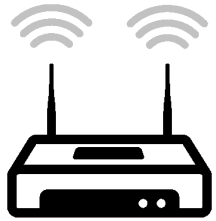
iOS 10 and Windows: 4-way handshake not affected

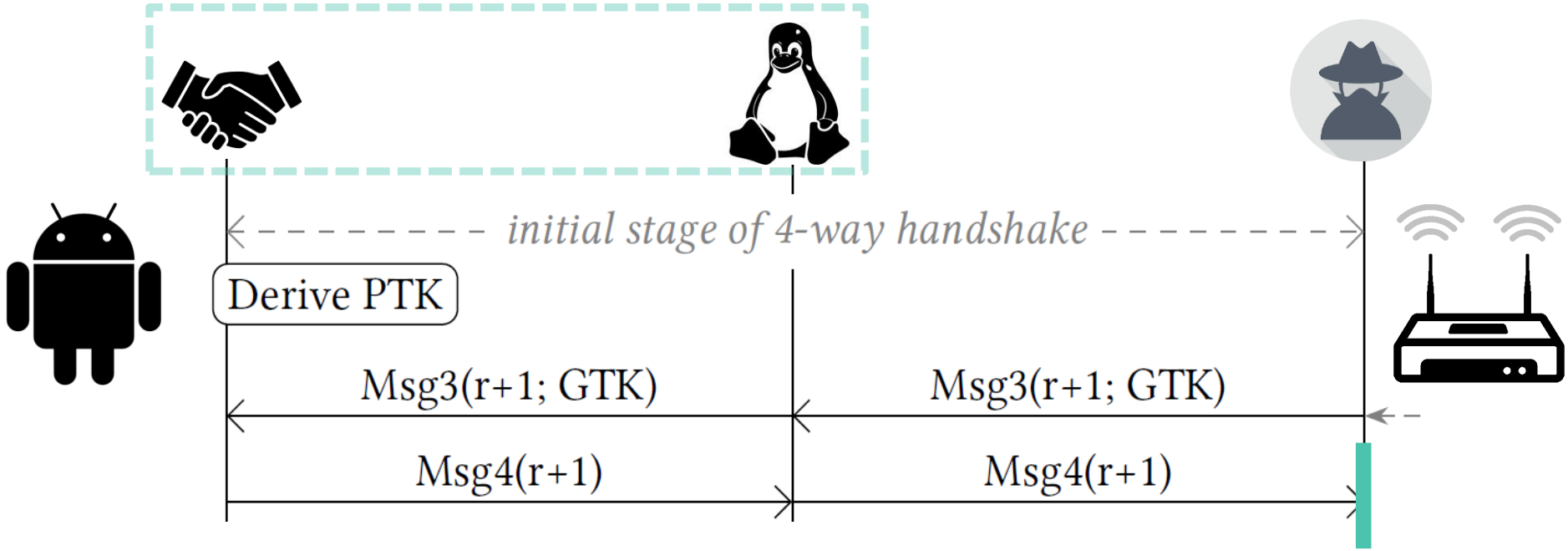
- **Cannot decrypt unicast traffic** (nor replay/decrypt)
- But group key handshake is affected (replay broadcast)
- Note: iOS 11 does have vulnerable 4-way handshake[8]

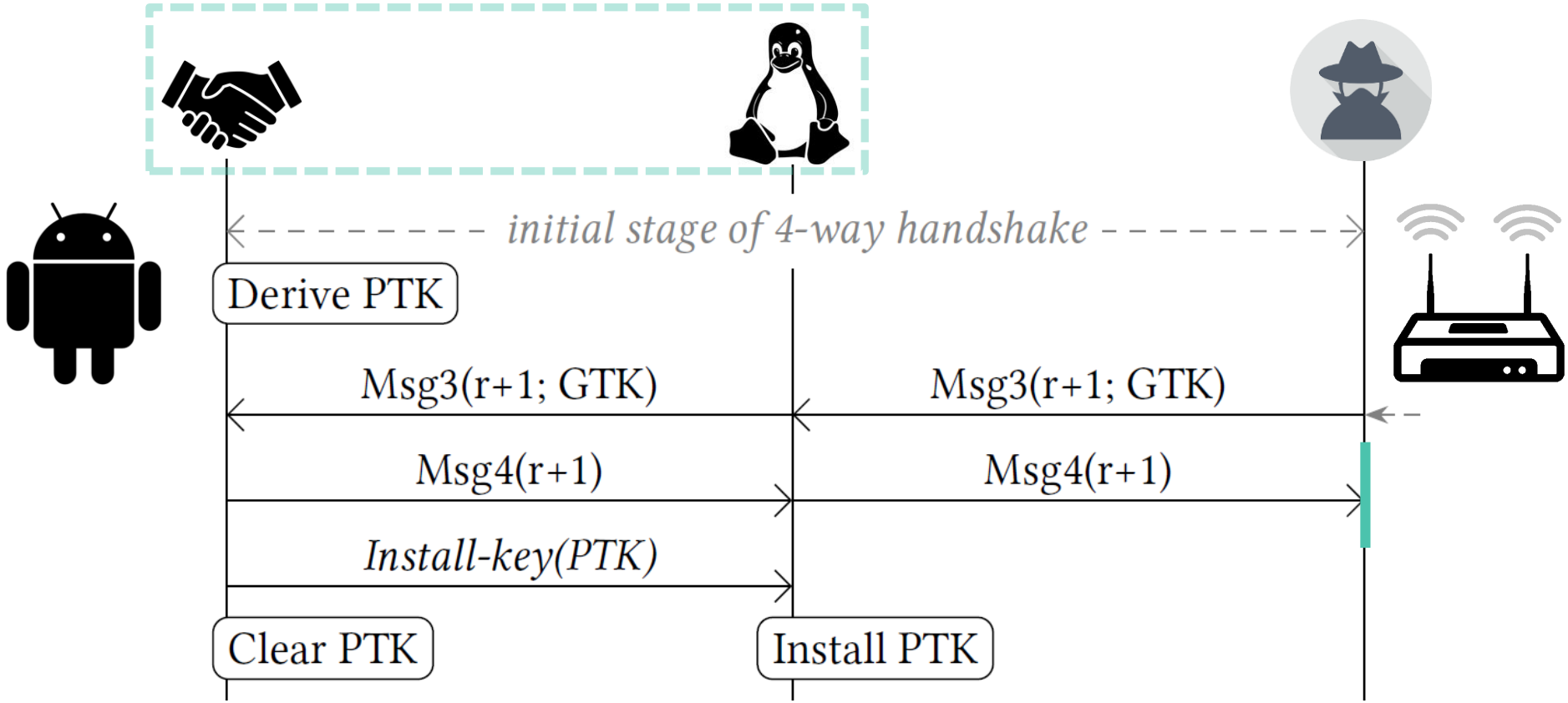
wpa_supplicant 2.4+

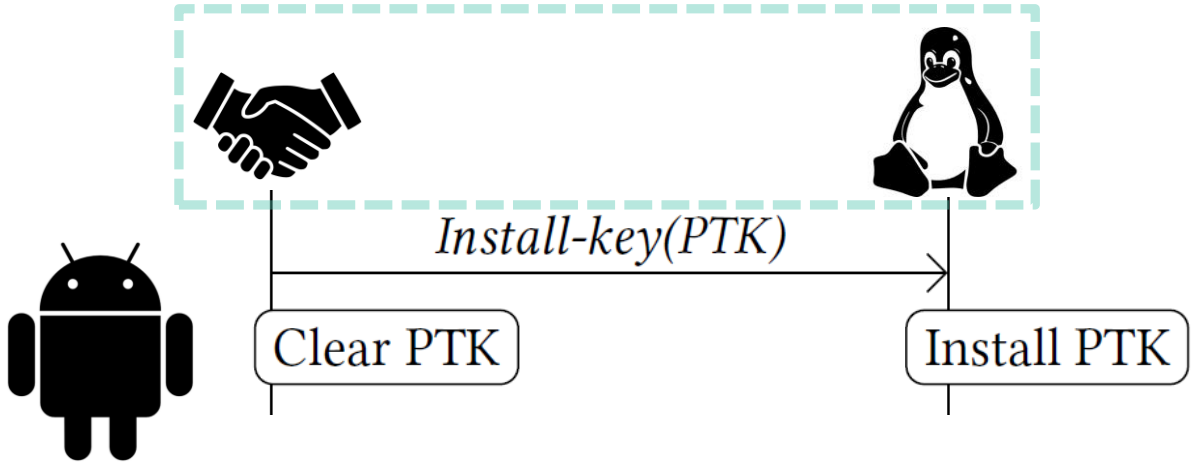
- Client used on Linux and Android 6.0+
- On retransmitted msg3 will **install all-zero key**

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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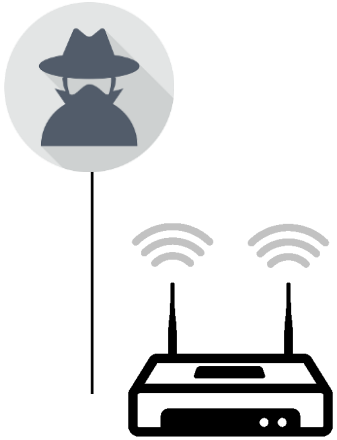

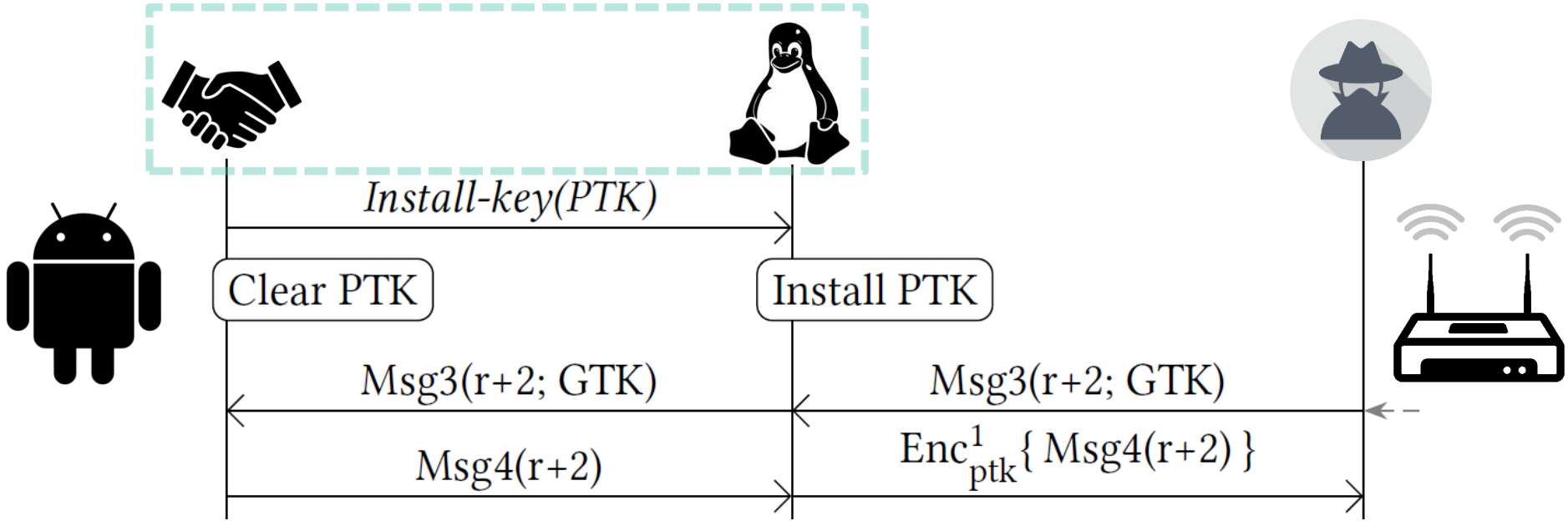
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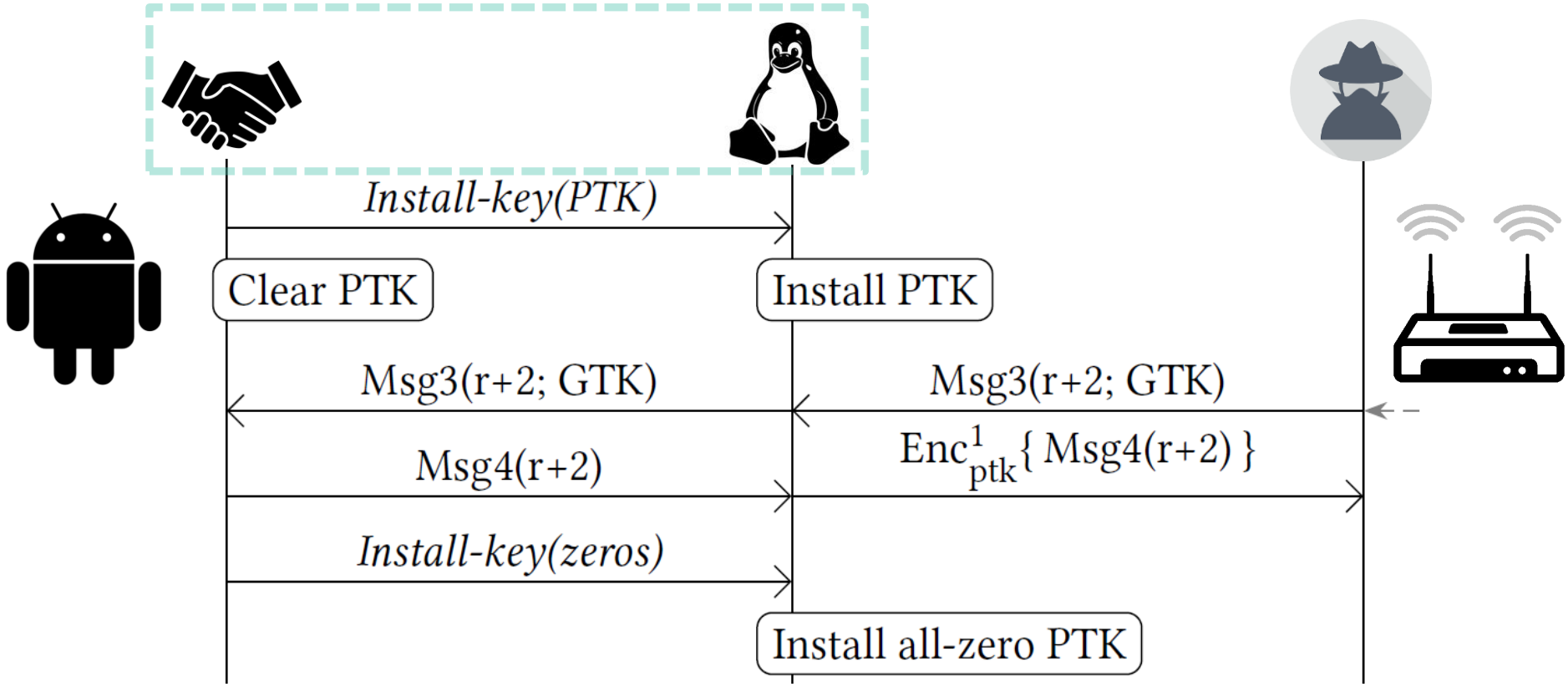
Msg3(r+2; GTK)
Msg3(r+2; GTK)
Msg4(r+2)
Enc$^{1}_{ptk}$ { Msg4(r+2) }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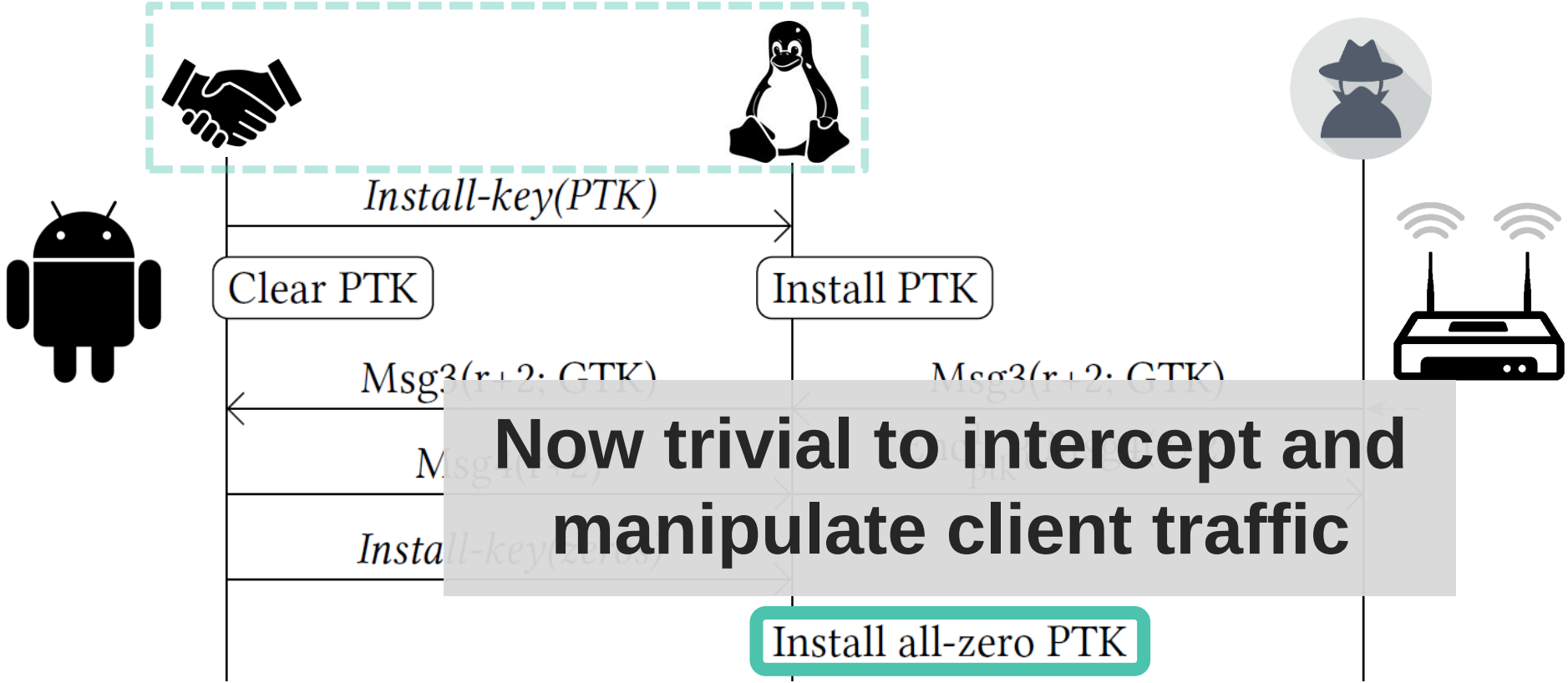
Install PTK
Msg3(r+2; GTK)
Msg3(r+2; GTK)
Msg4(r+2)
Enc$^{1}_{ptk}$ { Msg4(r+2) }
Install-key(zeros)
Install all-zero PTK



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

Problem: many clients won’t get updates

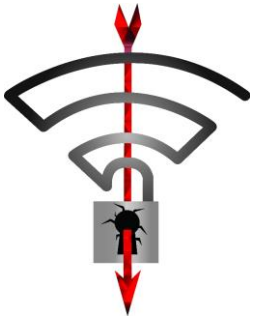
Solution: AP can prevent (most) attacks on clients!

- 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

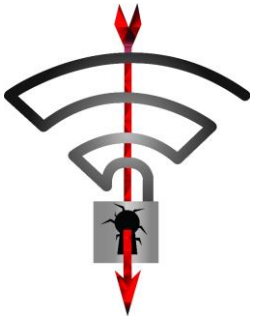
› Also use 4-way handshake & are affected

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
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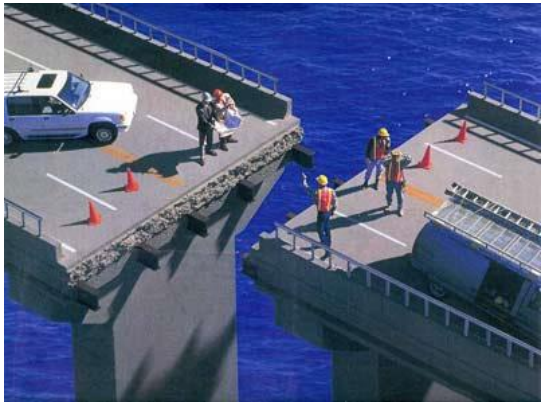
Limitations of formal proofs I

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

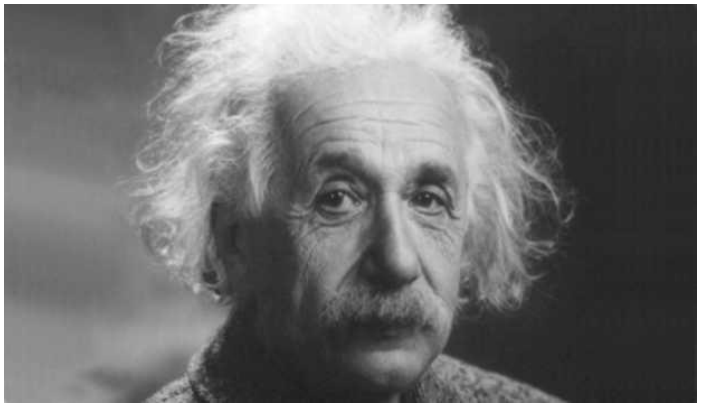


The combination was not proven secure!

Limitations of formal proofs II

Were the proofs too abstract?

- They did not model retransmissions
- **Abstract model ≠ real code**



“In theory, theory and practice are the same. In practice, they are not.”

Keep protocols simple I

The wpa_supplicant 2.6 case:

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

Discovered other vulnerabilities:

- Hostapd reuses ANonce during rekey
- $POPULAR_CLIENT reuses SNonce during rekey
- When combined, **rekeying reinstalls the existing PTK**

Keep protocols simple II

Network Operations Division Cryptographic Requirements[9]:

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

→ Keep the protocol and code simple!

Need rigorous specifications

Original WPA2 standard (802.11i amendment)

- State machine described in pseudo code
- Doesn't define when messages are accepted

```
StaProcessEAPOL-Key (S, M, A, I, K, RSC, ANonce, RSC, MIC, RSNE, GTK[N], IGTK[M], IPN)
    . . .
    if M = 1 then
        if Check MIC(PTK, EAPOL-Key frame) fails then
            State ← FAILED
        else
            State ← MICOK
        endif
    endif
    if K = P then
        if State ≠ FAILED then
```

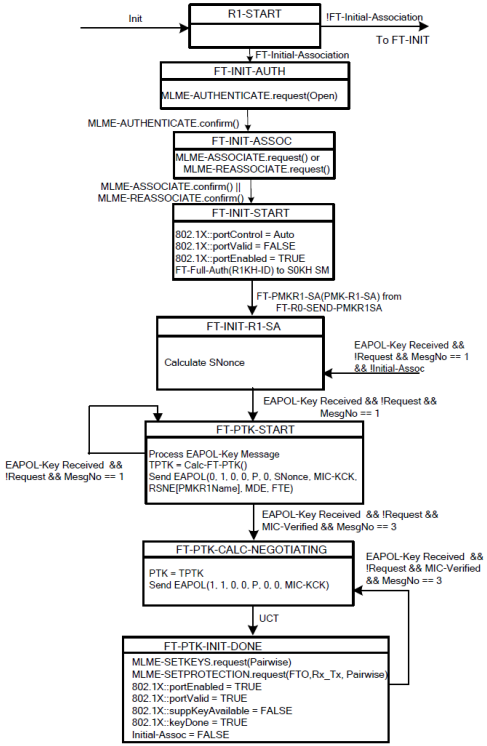
Need rigorous specifications

Original WPA2 standard (802.11i amendment)

- State machine described in pseudo code
- Doesn't define when messages are accepted

802.11r amendment (FT handshake)

- Better defines how/when to handle messages
- But **some terms and cases still unclear**



S1KH state machine

On a related note…

Workshop on:

Security Protocol Implementations: Development and Analysis (SPIDA)

Co-located with EuroS&P 2018

“focuses on improving development & analysis of security protocol implementations”

Thank you!

Questions?

krackattacks.com

References

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