Abusing Wi-Fi Beacons and Detecting & Preventing Attacks

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With special thanks to various IEEE members.

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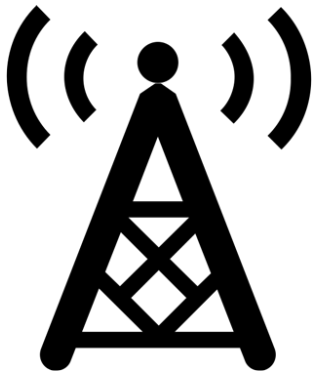
NEW YORK UNIVERSITY NYU | ABU DHABI

Background: beacons

- Wi-Fi networks use beacons to announce their presence
- They are sent every ~100 ms by an Access Point



Contains properties of the network:

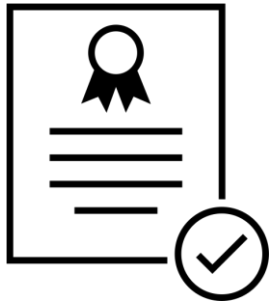
- Name of the network
- Supported bitrates (e.g. 11n or 11ac)
- Regulatory constraints (e.g. transmission power)
- ...

Problem: beacons can be forged by an adversary!

Our contributions

Novel **attacks** abusing beacons

Defense to prevent outsider forgeries



Standardized as part of 802.11

Defense is being **implemented** by Linux and might become **part of WPA3**

Taking a step back: Wi-Fi security

Focus was protecting data, not beacons:

- WEP, WPA1/2: only includes data frame protection
- WPA3: includes management frame protection
- Operating channel validation: verifies channel info

→ In all cases **beacons remain unprotected**

Beacons are not protected

```
› Tag: SSID parameter set: cisco
› Tag: Supported Rates 1(B), 2(B), 5.5(B), 11(B), 6, 9, 12, 18, [Mbit/sec]
› Tag: DS Parameter set: Current Channel: 1
› Tag: Traffic Indication Map (TIM): DTIM 0 of 0 bitmap
› Tag: Country Information: Country Code GB, Environment Unknown (0x04)
› Tag: Power Constraint: 3
› Tag: ERP Information
› Tag: Extended Supported Rates 24, 36, 48, 54, [Mbit/sec]
› Tag: QBSS Load Element 802.11e CCA Version
› Tag: RM Enabled Capabilities (5 octets)
› Tag: HT Capabilities (802.11n D1.10)
› Tag: RSN Information
› Tag: Mobility Domain
› Tag: HT Information (802.11n D1.10)
› Tag: Extended Capabilities (10 octets)
› Ext Tag: HE Capabilities (IEEE Std 802.11ax/D3.0)
› Ext Tag: HE Operation (IEEE Std 802.11ax/D3.0)
› Ext Tag: Spatial Reuse Parameter Set
```

- WPA version & channel: verified when connecting [WiSec'18]
- All other fields can be spoofed by an adversary

Novel Attacks

Power constraint attacks

Beacons contain the maximum allowed transmit power

```
▾Country Info: First Channel Number: 1, Number
  First Channel Number: 1
  Number of Channels: 13
  Maximum Transmit Power Level: 20dBm
▾Tag: Power Constraint: 3
  Tag Number: Power Constraint (32)
  Tag length: 1
  Local Power Constraint: 3
```

→ Adversary can **lower transmission power of victim**

Power constraint attacks

Beacons contain the maximum allowed transmit power

Experiments:

- **iPad, MacBook, and Linux**: lowers transmit power of device
- All other test devices not affected (unknown why)

Power constraint attacks

Beacons contain the maximum allowed transmit power

Vendor-specific power element of Cisco:

- Can also be exploited to lower transmit power of device
- Linux: can be abused to **forcibly disconnect a victim**
  - Normally we cannot set negative transmission limits
  - But with the Cisco power element we can

Power constraint attacks

DEMO!

Lowering a victim’s bandwidth

› Before transmission the medium must be idle:

In use

Lowering a victim’s bandwidth

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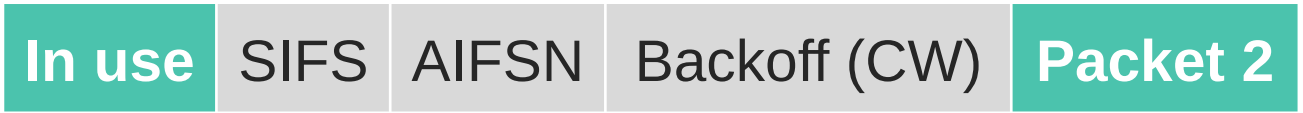

Lowering a victim's bandwidth

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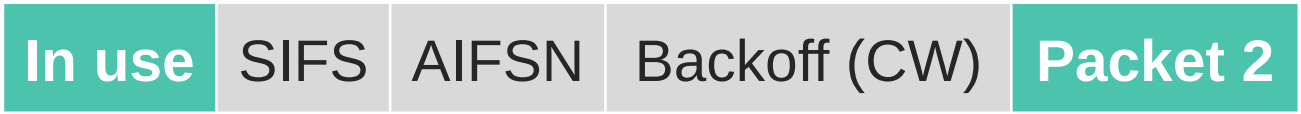
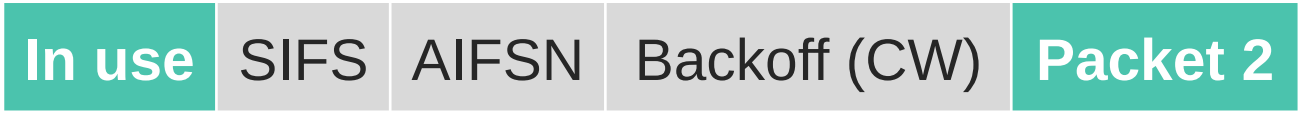


› Beacon contains the duration of these waiting periods:

```
Ac Parameters ACI 0 (Best Effort), ACM no
 ACI / AIFSN Field: 0x03
 ECW: 0xa4
  1010 .... = ECW Max: 10
  .... 0100 = ECW Min: 4
  CW Max: 1023
  CW Min: 15
 TXOP Limit: 0
```

Lowering a victim's bandwidth

› Before transmission the medium must be idle:



› Spoofing this info causes clients to **delay transmissions**:

› If another device transmits in the meantime, the victim restarts the waiting process & **possibly never transmits**

Lowering a victim’s bandwidth: experiments

Linux is affected with any network card we tested

Apple devices are affected (Macbook Pro, iPhone, iPad)

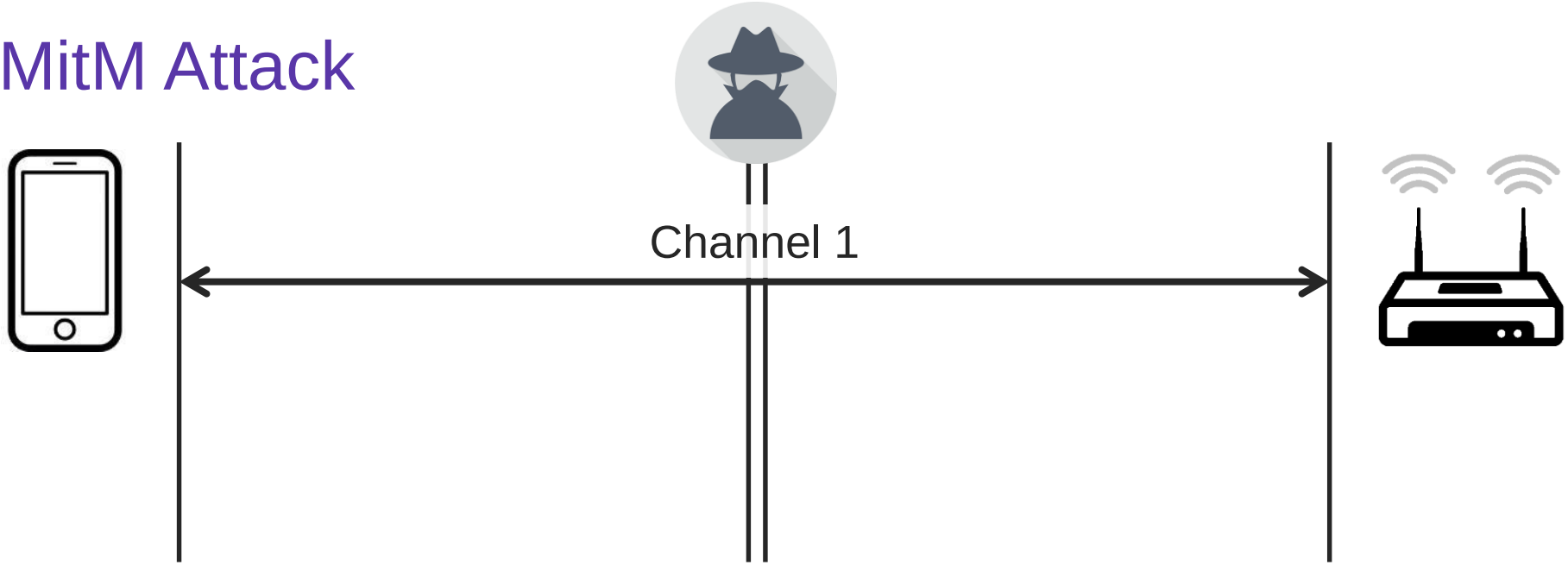
Windows is affected depending on network card (e.g. Alfa and TP-Link cards are affected but not Intel ones)

Android is affected depending on the device: Nexus 5X was affected, but not our old Samsung i9305

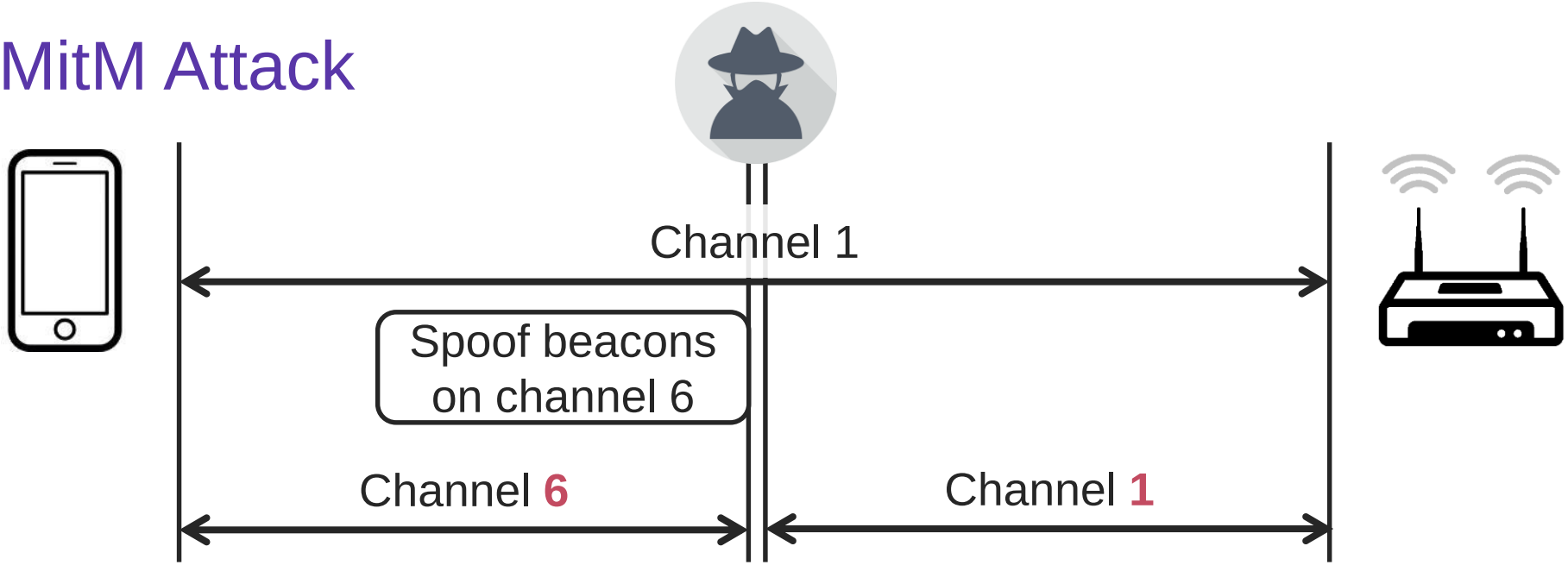
Targeted unfairness

DEMO!

MitM Attack

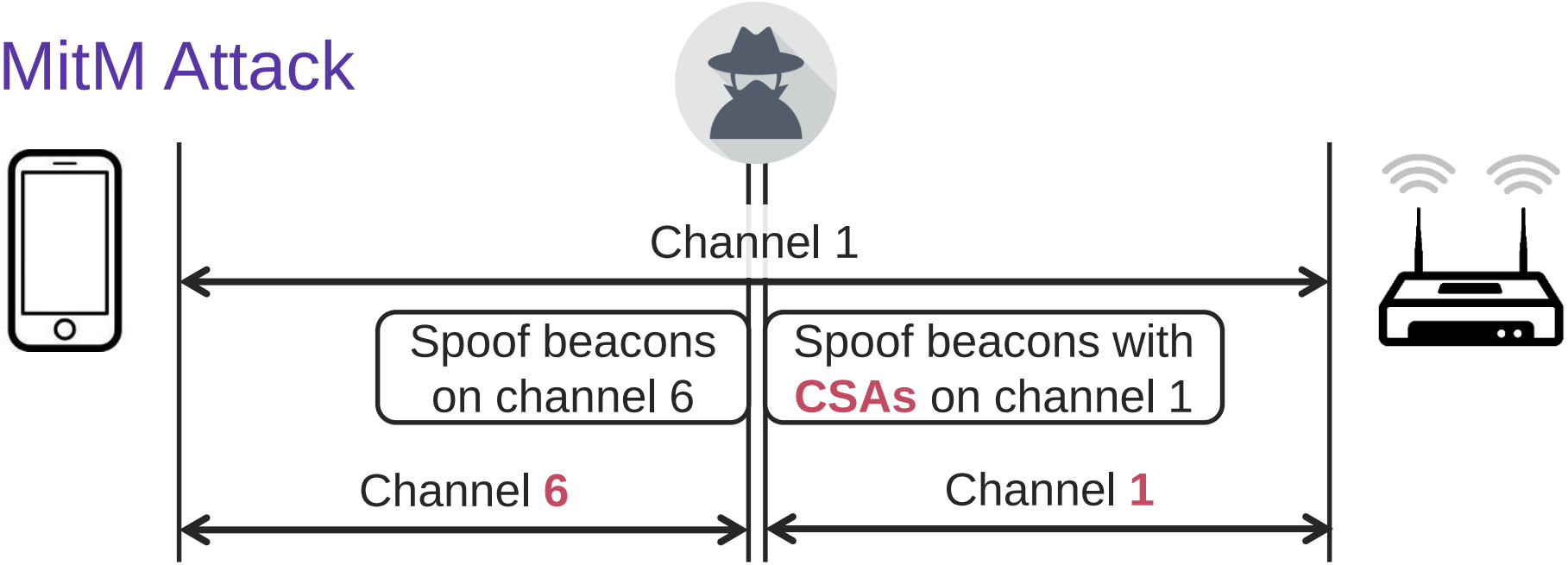


MitM Attack



› Adversary forwards frames between both channels

MitM Attack



- Adversary forwards frames between both channels
- This MitM **makes other attacks easier** (e.g. KRACK)

Other attacks & findings

Partial machine-in-the-middle attack

› Bypasses channel operating validation in Linux

Battery depletion attacks

› Spoof beacons to **make clients stay awake**

Send beacon as unicast frames to target specific clients

› Worked against all tested devices

Practical attack considerations

Beacons are by default broadcasted to all clients

- This means we attack all clients simultaneously

```
Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
Transmitter address: Cisco-Li_82:b2:55 (00:0c:41:82:b2:55)
BSS Id: Cisco-Li_82:b2:55 (00:0c:41:82:b2:55)
```

We can also send them as unicast frames to a specific victim:

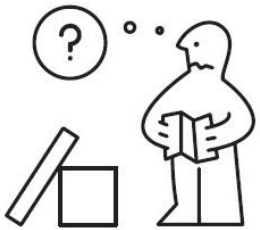
```
Receiver address: Apple_82:36:3a (00:0d:93:82:36:3a)
Transmitter address: Cisco-Li_82:b2:55 (00:0c:41:82:b2:55)
BSS Id: Cisco-Li_82:b2:55 (00:0c:41:82:b2:55)
```

Our Defense

Design goals

Focus on **practicality & simplicity** to encourage adoption

- Cryptographic operations must be efficient
- Bandwidth overhead must be low
  - Beacons are sent at low bitrate and consume significant airtime



Straightforward to implement

- Ideally reuse existing crypto primitives of Wi-Fi

Design approach

To achieve our goals, we rely on **symmetric encryption**

› Reuse crypto primitives of management frame protection

We **defend against outsider attacks**

› Adversary doesn’t possess network credentials

› Similar to protection of broadcast Wi-Fi traffic

Beacon protection: new element

We add a **new type-length-value element** to beacons:

- Clients that do not recognize this element will ignore it
- Nonce: incremental number to **prevent replay attacks**
- Message Integrity Check: **CMAC or GMAC** over the beacon
  - Existing crypto primitive of management frame protection
  - All WPA3-capable devices already support it

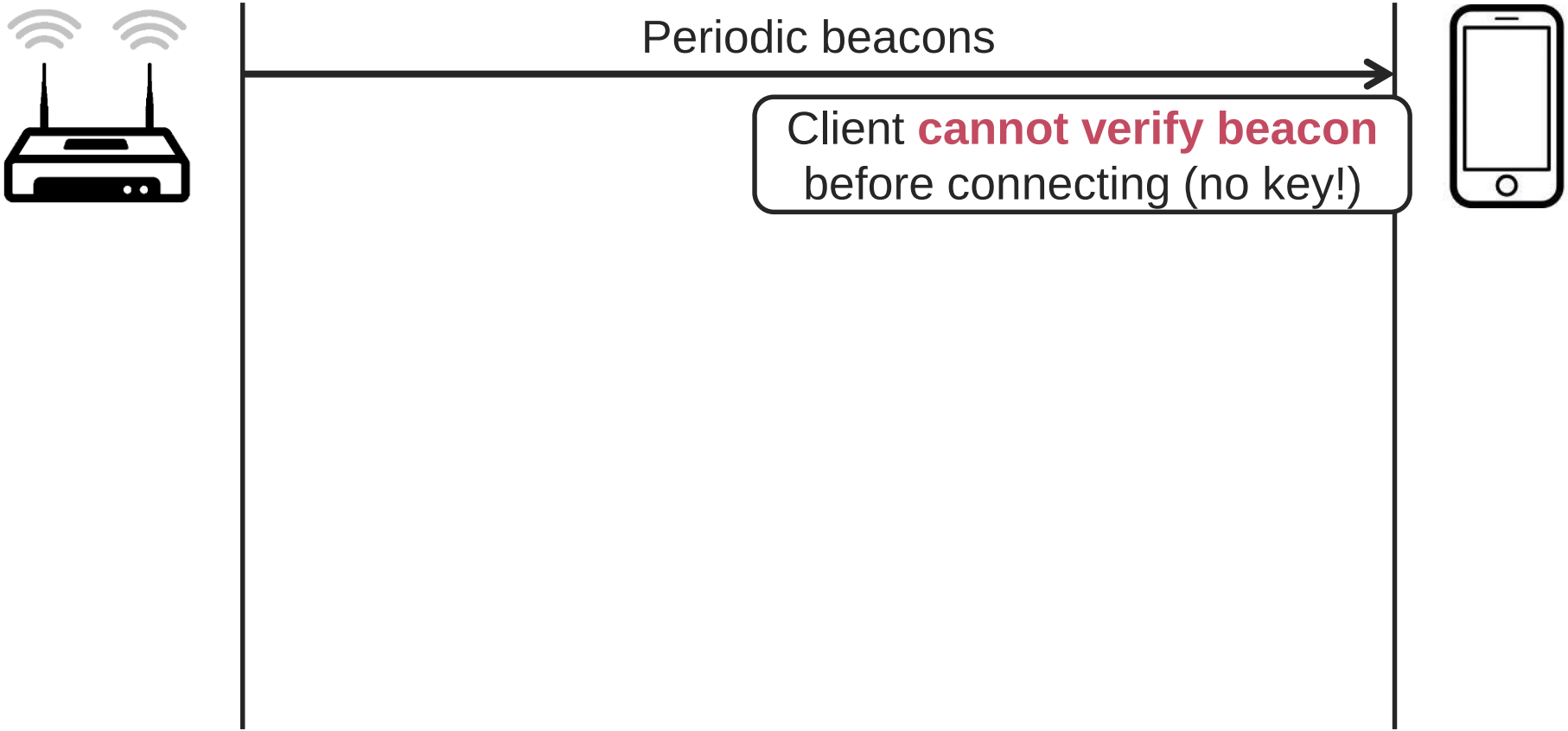
Key management

Key used to generate/verify the authenticity tag?

- AP generates a fresh **beacon protection key** when booting
- **AP always sends the beacon key** when a client connects
  - Older clients will ignore this key
  - New clients will enable beacon protection

→ Adversary can't manipulate handshake that transports the beacon key, **preventing downgrade attacks**.

Pre-authentication behavior



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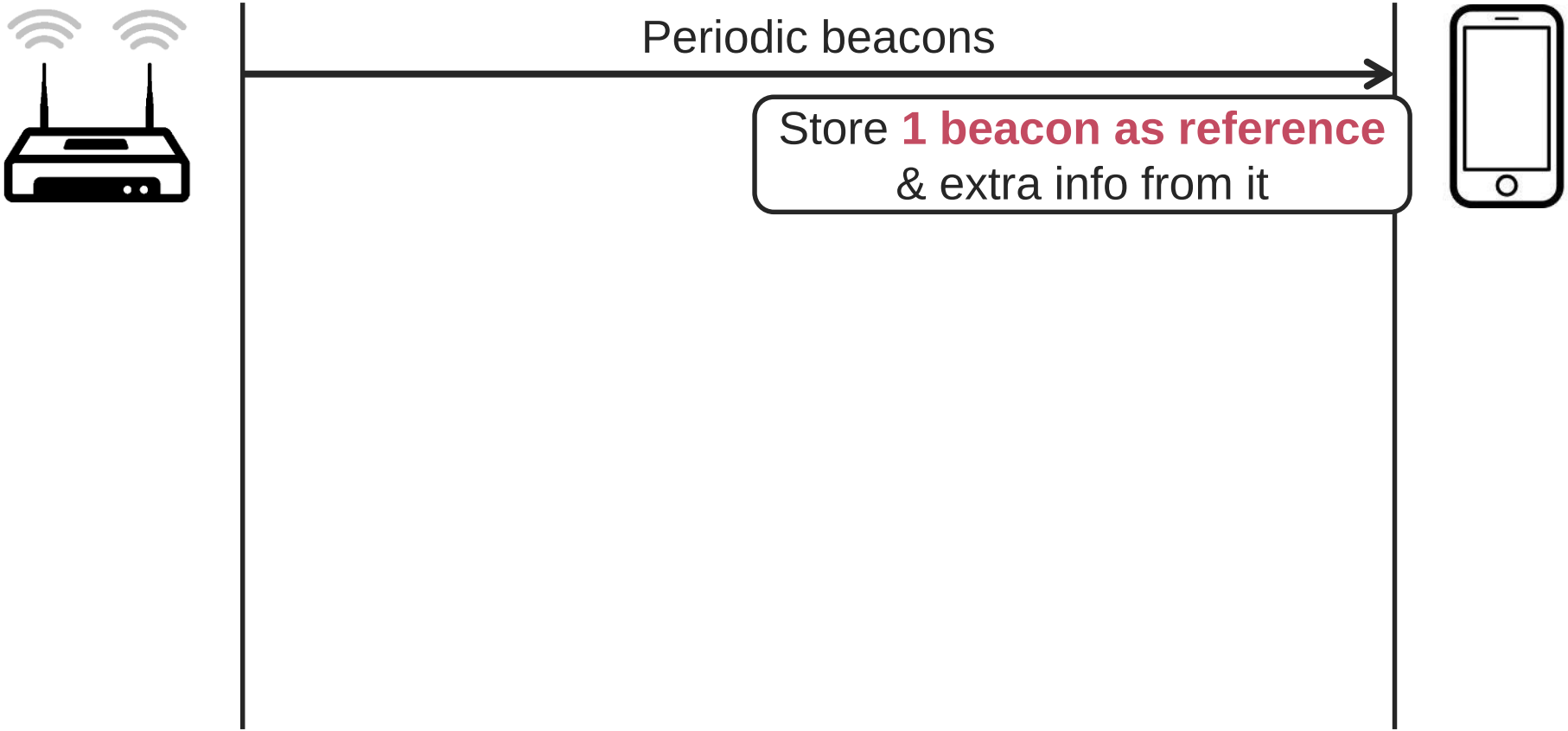

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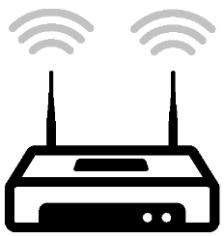
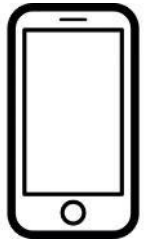


Periodic beacons

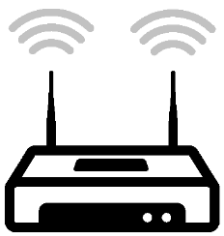
Store **1 beacon as reference** & extra info from it



Connect to network and receive **beacon protection key**

Verify authenticity reference beacon (disconnect if invalid)

Pre-authentication behavior



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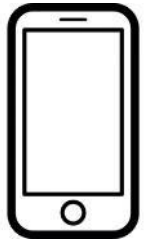

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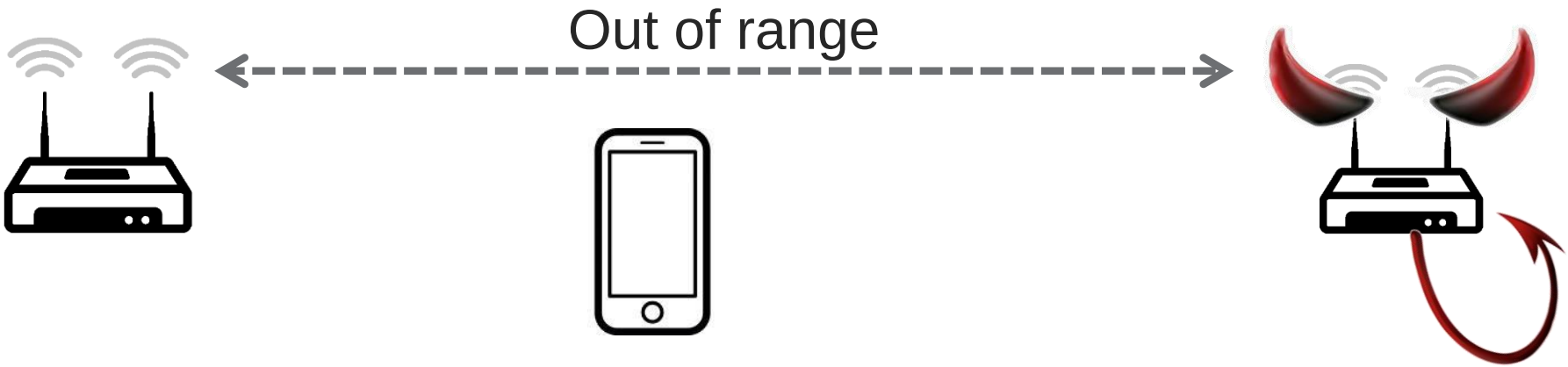
Send data

Reporting forged beacons

- Clients can report forged beacons to the AP
- Can now **detect far away rouge APs**



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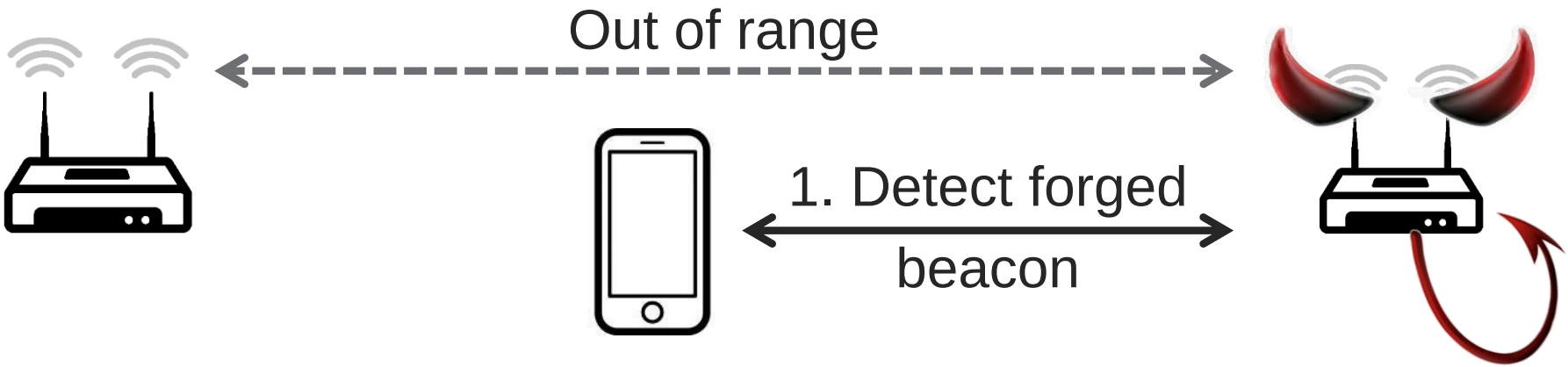

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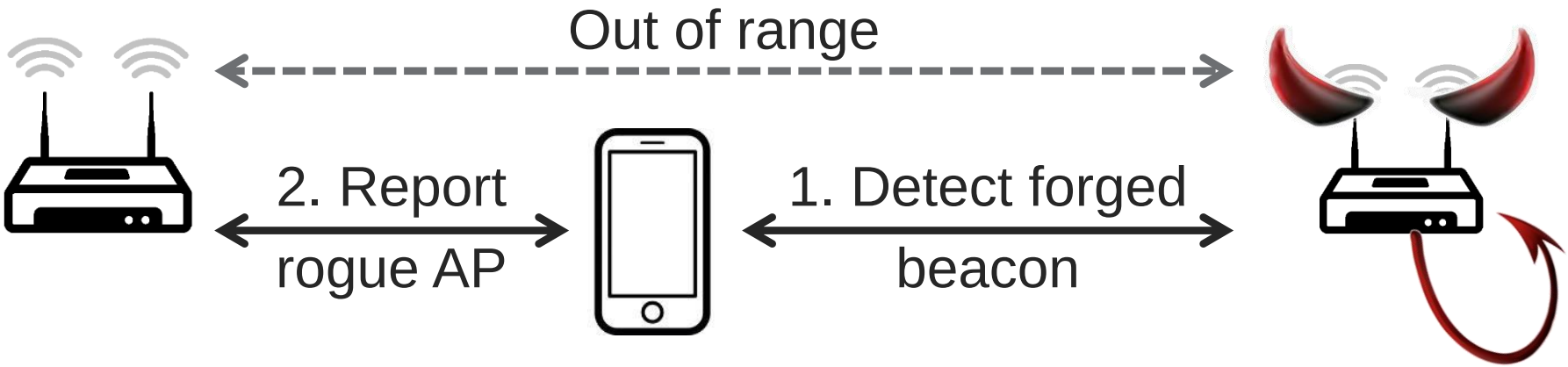
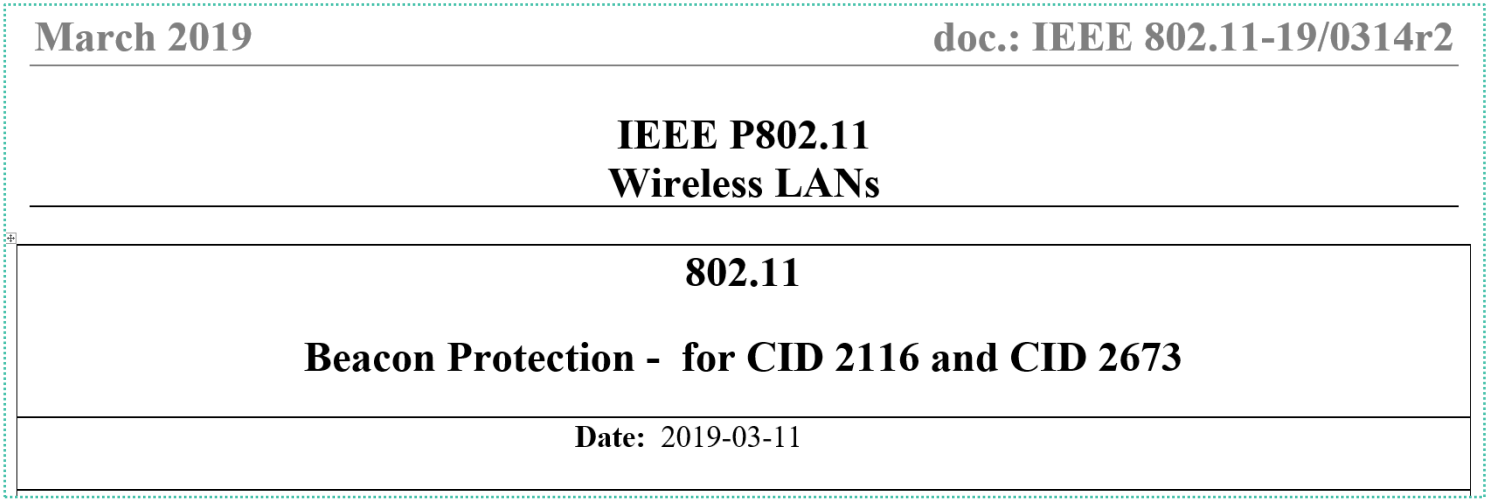


Practical Results

Specification

- Collaborated with industry to standardize our defense (Intel, Broadcom, Qualcomm and Huawei)
- Since March 2019 **part of the (draft) IEEE 802.11 standard**:



March 2019 doc.: IEEE 802.11-19/0314r2

IEEE P802.11
Wireless LANs

802.11

Beacon Protection - for CID 2116 and CID 2673

Date: 2019-03-11

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Might become **part of WPA3 specification?** ☺

In addition, Wi-Fi Alliance has identified the following potential security protocol updates and will review all comments received:

15. Hash-to-element password generation, Client Privacy Mechanisms, Operation Channel Validation, and Beacon protection in IEEE Draft

Source: https://www.wi-fi.org/security-development (July 2020)

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Special thanks to:

- Nehru Bhandaru and Thomas Derham (**Broadcom**)
- Emily Qi and Ido Ouzueli (**Intel**)
- Jouni Malinen and Menzo Wentink (Qualcomm)
- Yunsong Yang (Huawei)

Implementation

Now being implemented by Linux:

- Kernel: generate and verify authentication tags
- Hostap: manages keys and enables beacon protection

DEMO!

Conclusion

- Prevent outsiders from forging beacons
- Our focus on practicality paid off:
  - **Defense is now part of the 802.11 standard**
  - Being implemented by **Linux**
  - Might become part of WPA3?