E-Spoofer: Attacking and Defending Xiaomi Electric Scooter Ecosystem

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THCON
TOULOUSE HACKING CONVENTION

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Research Topics:

- Bluetooth / Bluetooth Low Energy
- Internet-of-Things
- Android

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Talk Outline

- Intro on proprietary e-scooter ecosystems
- Threat model
- Xiaomi BLE protocol vulns and attacks
- Evaluation
- E-Spoofer toolkit and (video) demos
- Countermeasures and responsible disclosure

INTRODUCTION

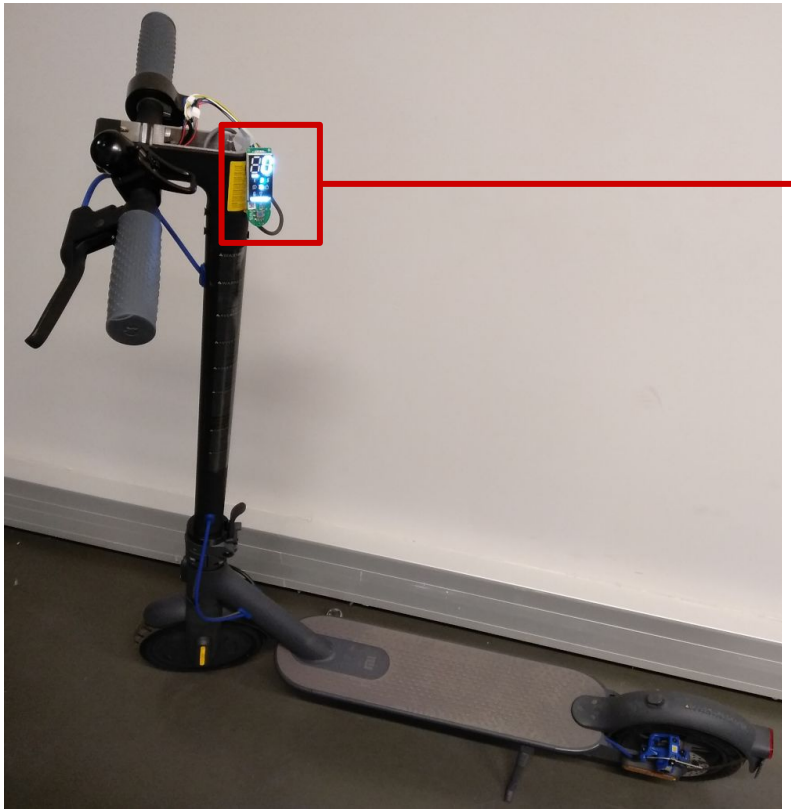
Xiaomi E-Scooter Ecosystem

- Market leader in the private e-scooter segment
  - Also owns Ninebot-Segway
- Released **seven e-scooters** between 2016-2021
  - M365, Pro 1, Pro 2, 1S, Essential, Mi 3, and Mi 4
- Maintains the **Mi Home** smartphone app to manage e-scooters

E-Scooter

- Radio subsystem (**BLE**)
  - BLE communication with Mi Home
  - Gateway to other internal subsystems
- Electric motor subsystem (**DRV**)
  - E.g., max speed and cruise control
- Battery management subsystem (**BMS**)
  - E.g., voltage and charge

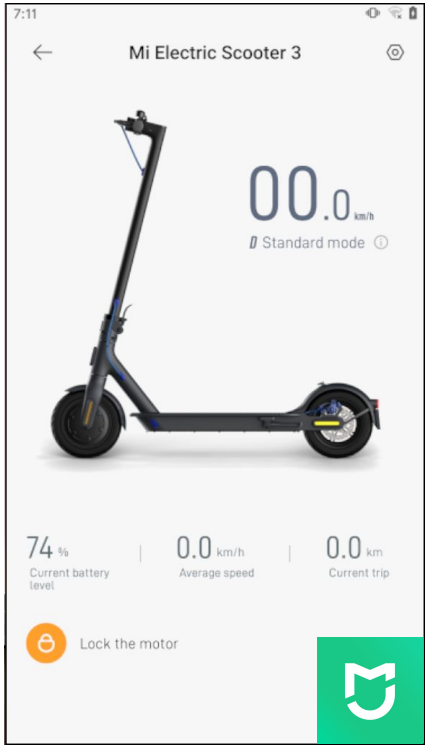
E-Scooter (2)



BLE SoC

Mi Home

- Binds e-scooter to Xiaomi account
  - I.e., pairing
- **Anti-theft software-lock**
  - Locks brakes for 6h
  - Alarm noise
- E-scooter password (optional)
  - 6-digit alphanumeric
  - Required to connect to the e-scooter



THREAT MODEL

System Model

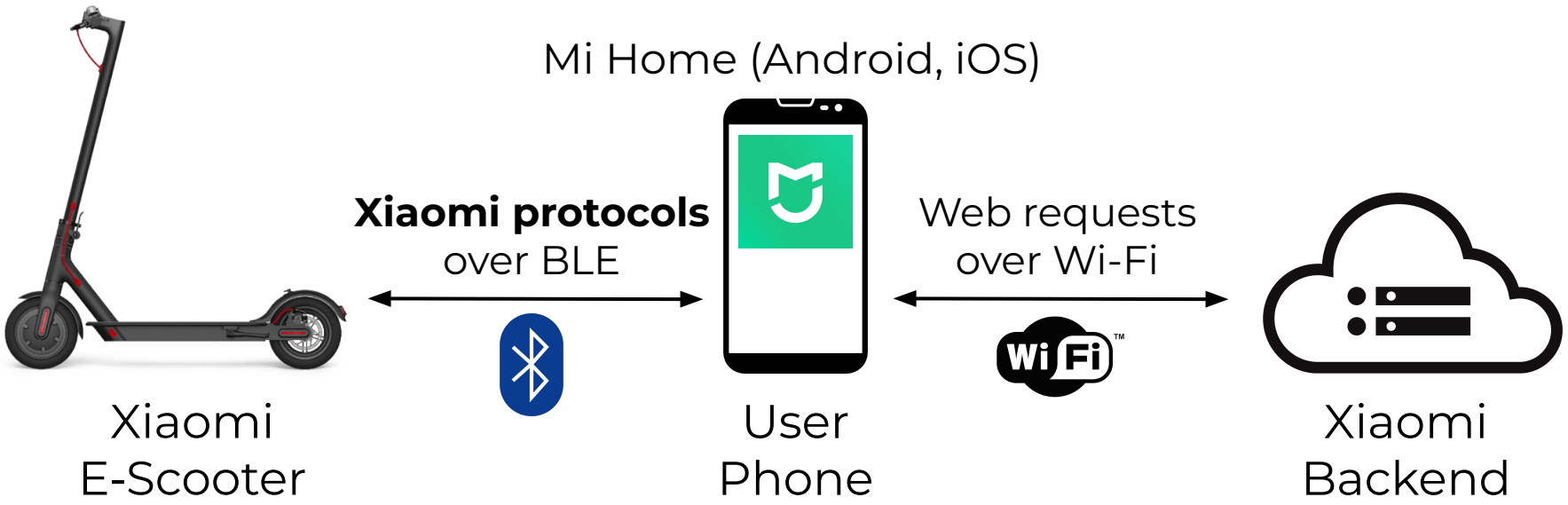
Xiaomi E-Scooter

Mi Home (Android, iOS)

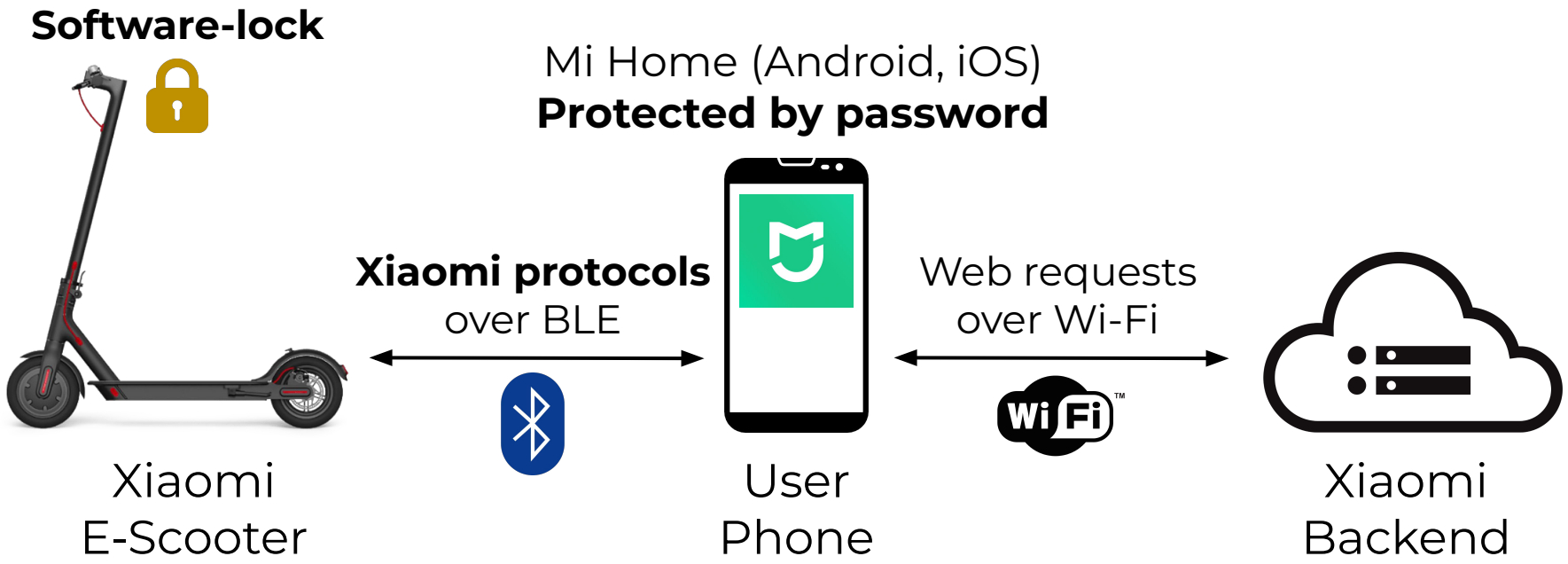
User Phone

Xiaomi Backend

System Model (2)



System Model (3)



Security Assumptions

- E-scooter and Mi Home are **securely paired**
- All firmware (BLE, DRV, BMS) is **up-to-date**
- E-scooter **password** is enabled and strong
- E-scooter is **software-locked** at all times

Proximity Attacker

Xiaomi
E-scooter

Xiaomi proprietary protocol over BLE

Proximity Attacker

Remote Attacker

Xiaomi
E-scooter

Xiaomi proprietary protocol over BLE

Remote Attacker (Android app)

User
Phone

Attacker's Goals

- **Spoof** Mi Home to the e-scooter
- Send **arbitrary and unauthorized** BLE packets
  - Without user consent or warning
  - I.e., memory read and write

SECURITY ANALYSIS OF XIAOMI PROPRIETARY PROTOCOLS

Xiaomi E-Scooter Protocol

Xiaomi
E-Scooter

Xiaomi **application-layer** proprietary protocol built on top of BLE transport

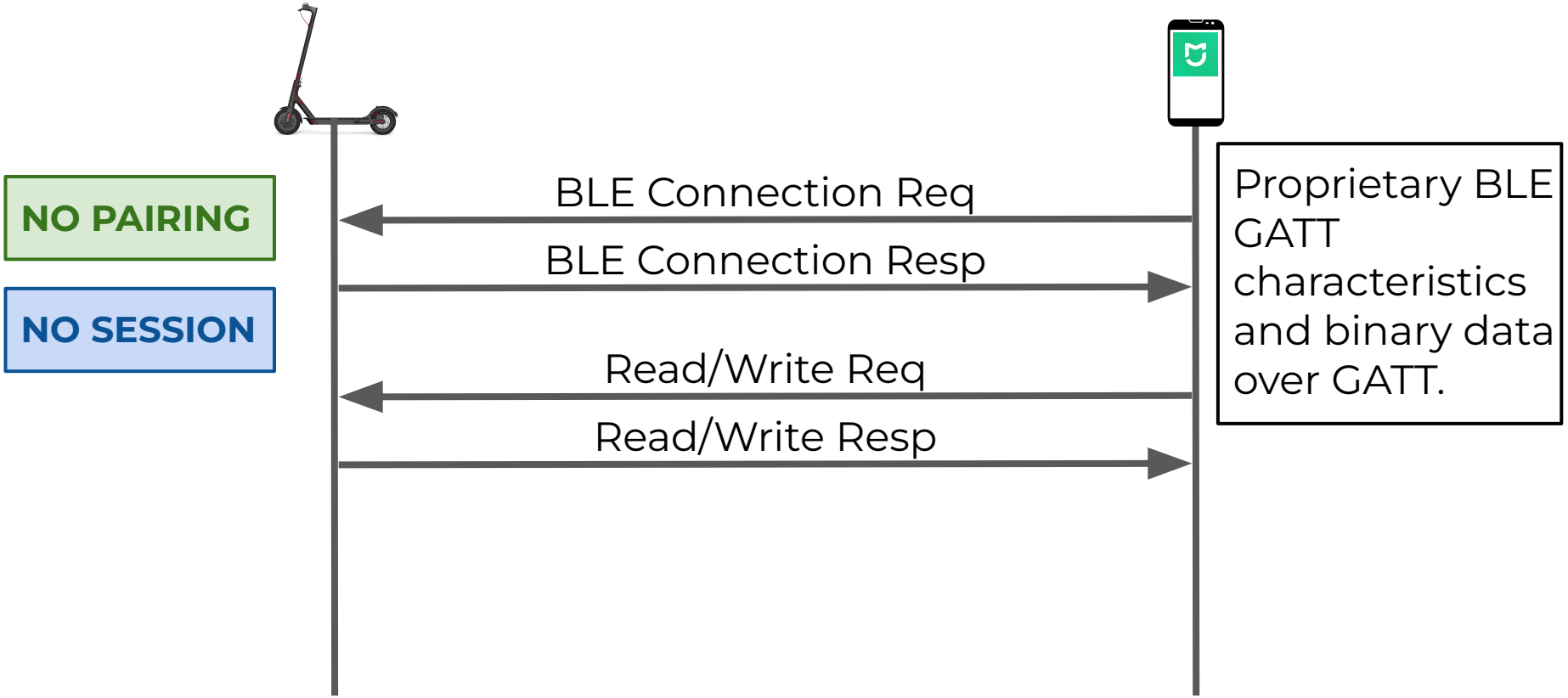
Mi Home (Android, iOS)

User
Phone

Xiaomi E-Scooter Protocols (2)

- **P1, P2, P3, P4 (since 2016)**
  - Application-layer Pairing and Session phases
  - No BLE link-layer security
- **Pairing** phase
  - Devices agree on a **Pairing Key** (**PK**)
- **Session** phase
  - Devices compute a **Session Key** (**SK**) from PK
  - Devices use SK to establish a secure channel

P1: No Security Mechanisms



P1: Proximity/Remote Attacks

NO PAIRING

NO SESSION

Spoofed BLE Connection Req

BLE Connection Resp

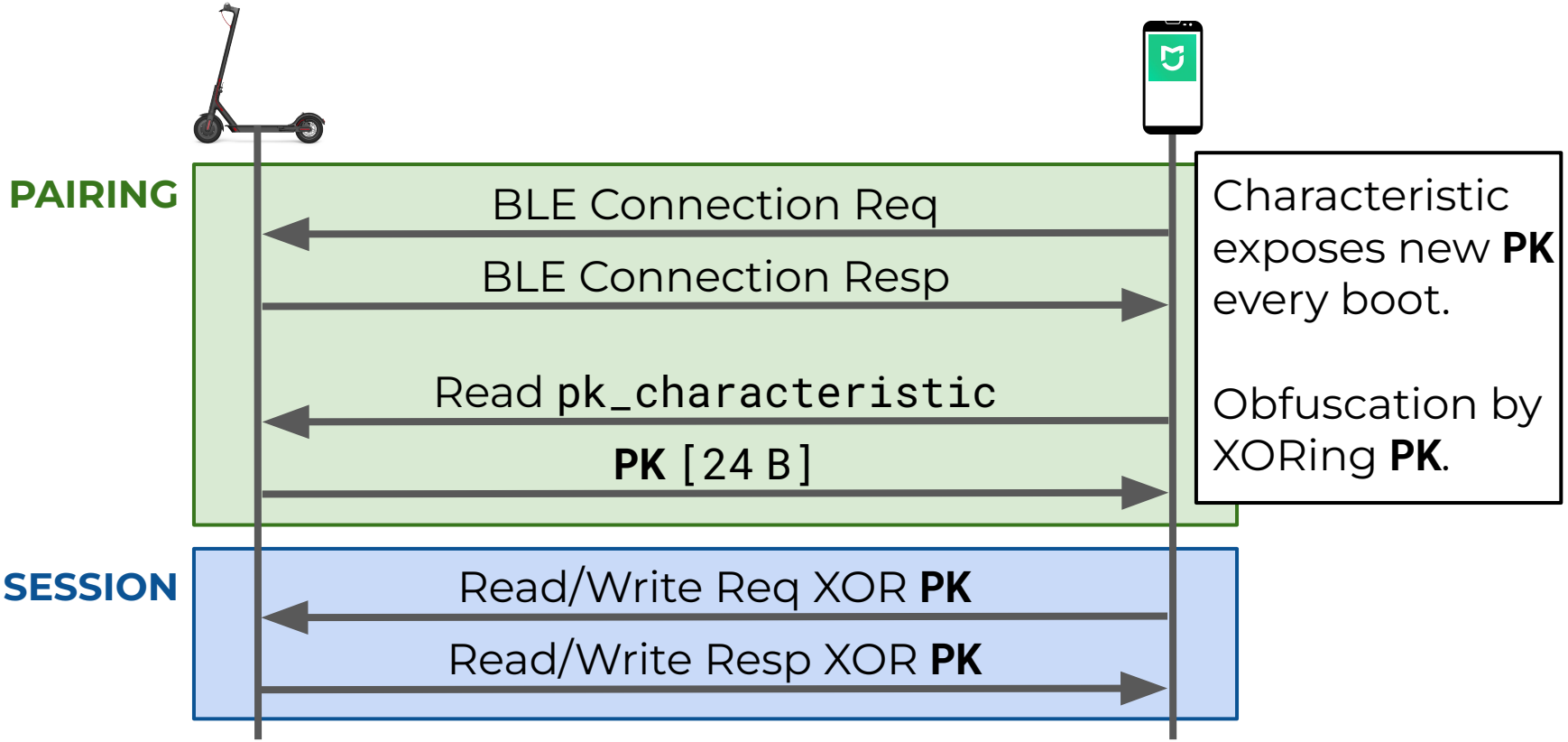
Arbitrary Read/Write Req

Read/Write Resp

Read all data:
password, mileage.

Write all data:
lock/unlock, password, max speed.

P2: Public PK and XOR Obfuscation



P2: Proximity/Remote Attacks

PAIRING

Spoofed BLE Connection Req

BLE Connection Resp

Read `pk_characteristic`

PK [24 B]

SESSION

Arbitrary Read/Write Req XOR **PK**

Read/Write Resp XOR **PK**

PK exposed **publicly**.

PK can be reversed from a BLE capture.

P2: Proximity/Remote Attacks

MALICIOUS PAIRING

Spoofed BLE Connection Req

BLE Connection Resp

Read `pk_characteristic`

PK [24 B]

SESSION

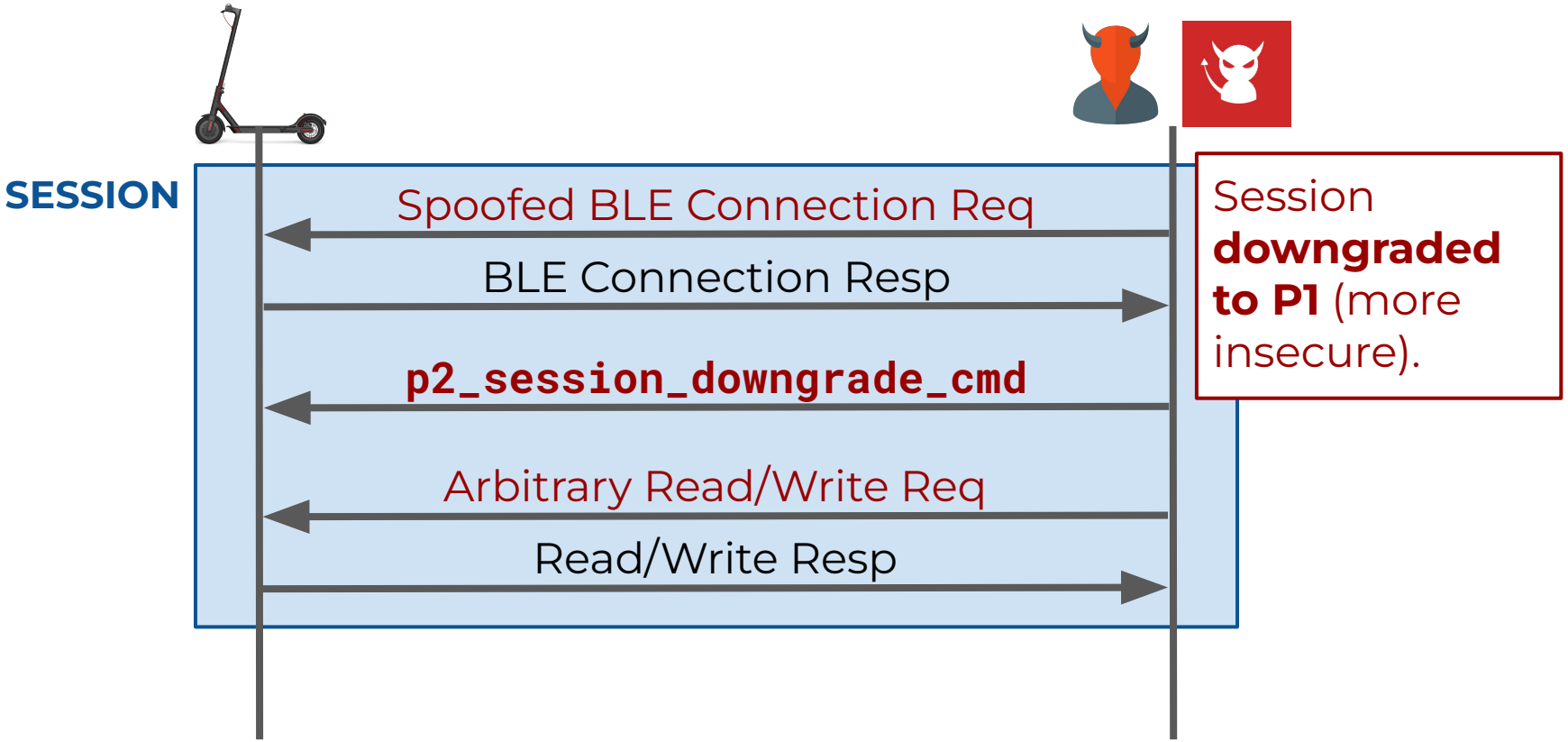
Arbitrary Read/Write Req XOR **PK**

Read/Write Resp XOR **PK**

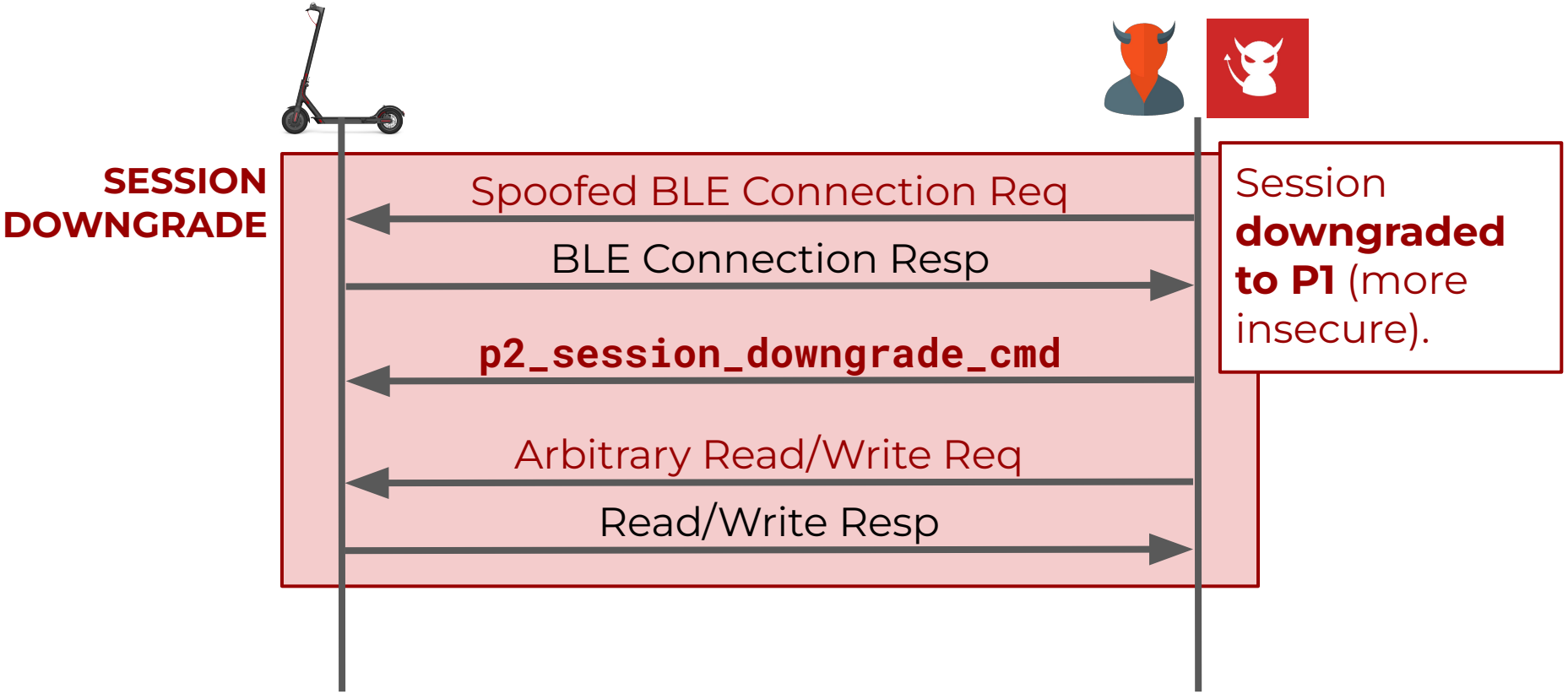
PK exposed **publicly**.

PK can be reversed from a BLE capture.

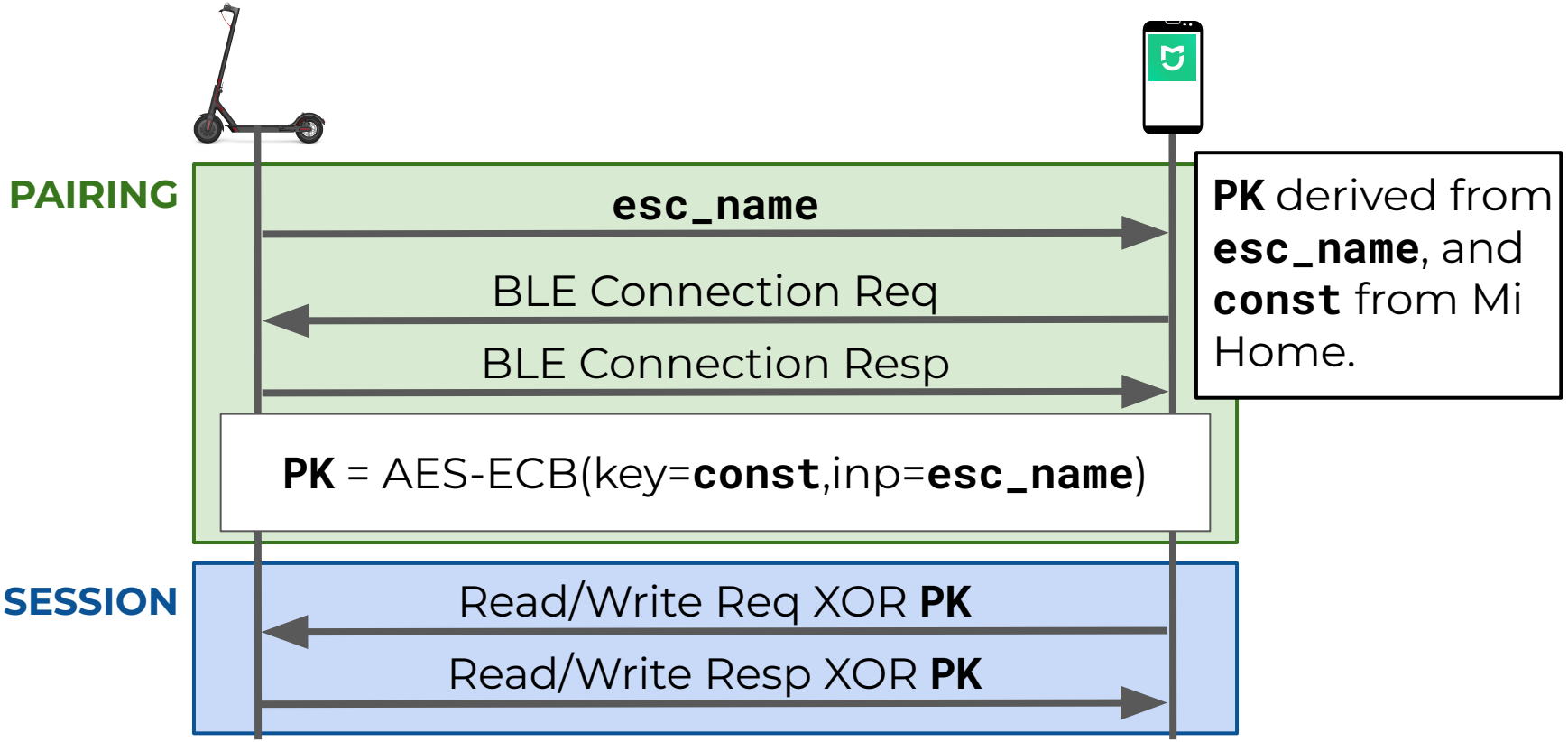
P2: Proximity/Remote Attacks



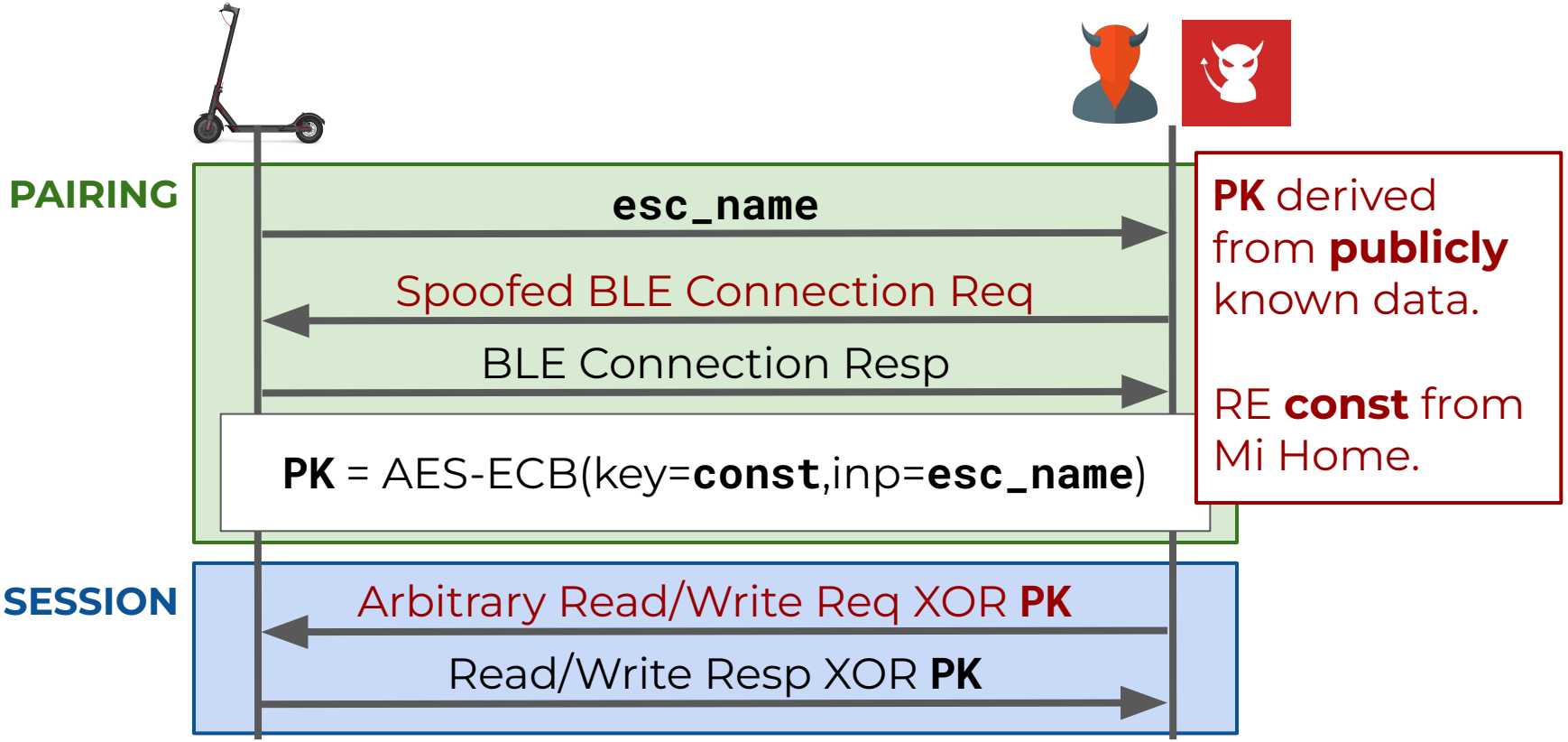
P2: Proximity/Remote Attacks



P3: Const PK and XOR Obfuscation



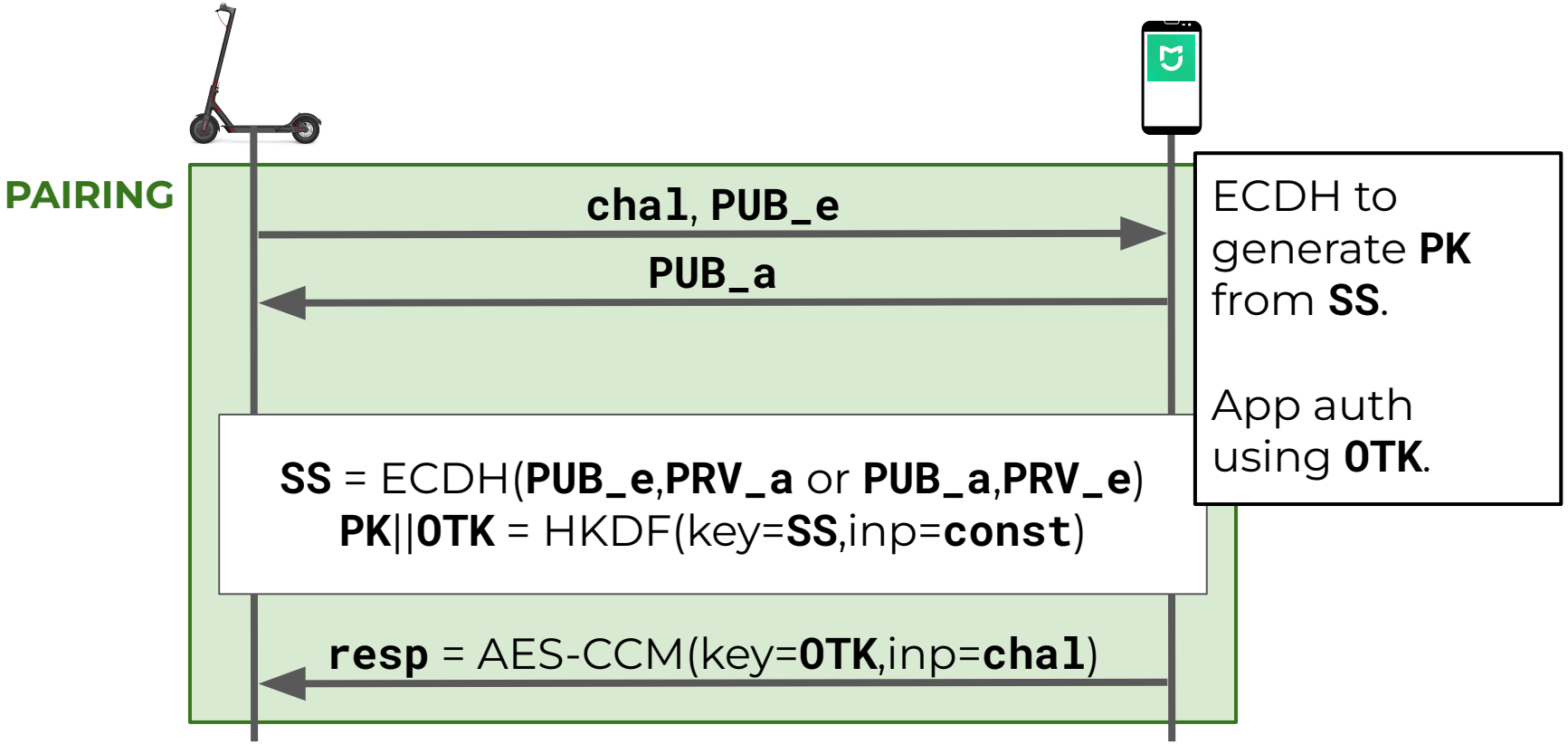
P3: Proximity/Remote Attacks



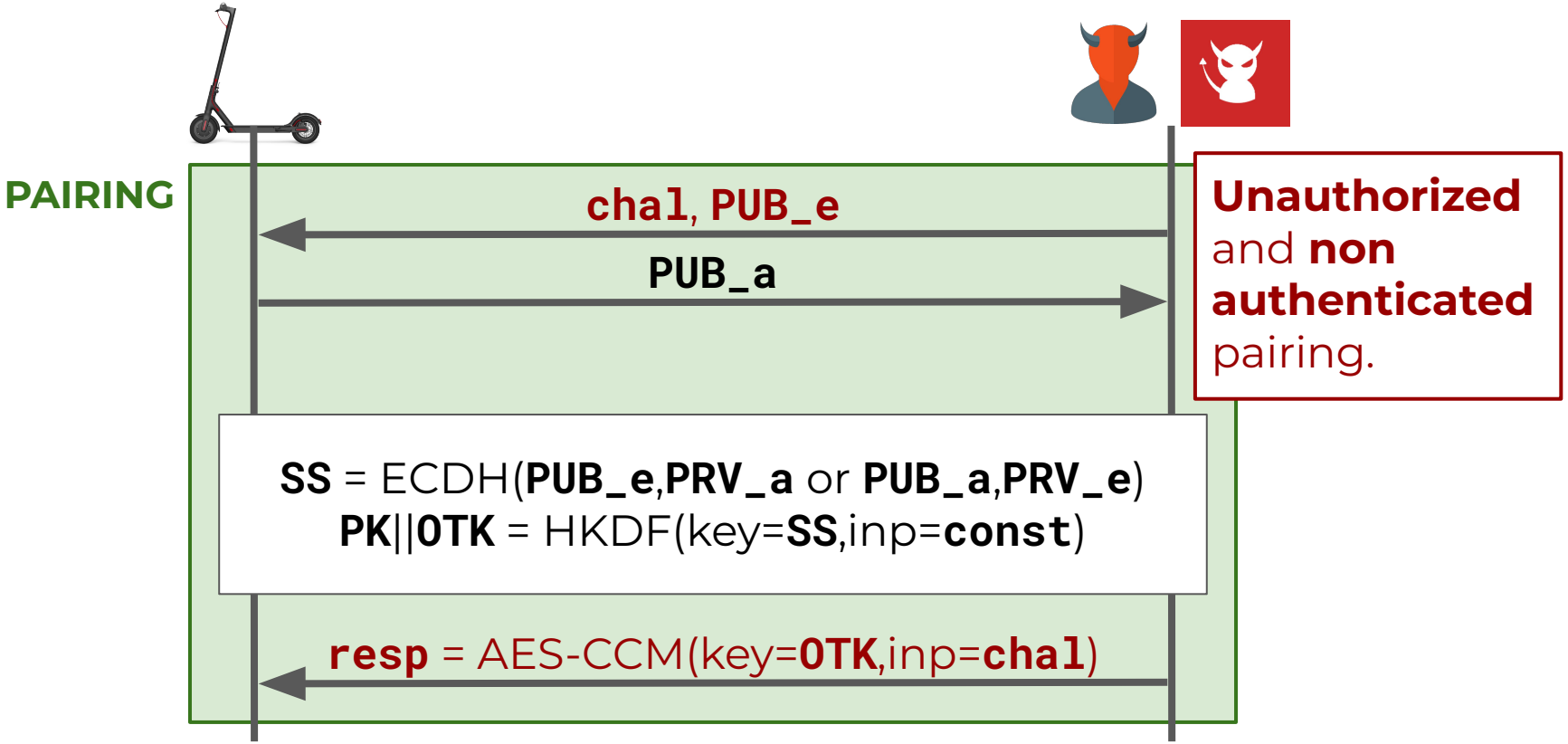
Recap: P1, P2, P3 insecurity

- **P1**, **P2**, and **P3** are **insecure by design**
  - Security through obscurity
  - E.g., XOR, public seeds, and binary data
  - Proximity/remote **impersonation is trivial**
  - Legacy protocols, only exist on non-updated devices
- **P4** to the rescue?
  - **NOT** really

P4: Pairing (ECDH, AES-CCM)



P4: Proximity/Remote Attacks



P4: Proximity/Remote Attacks

MALICIOUS PAIRING

chal, **PUB_e**

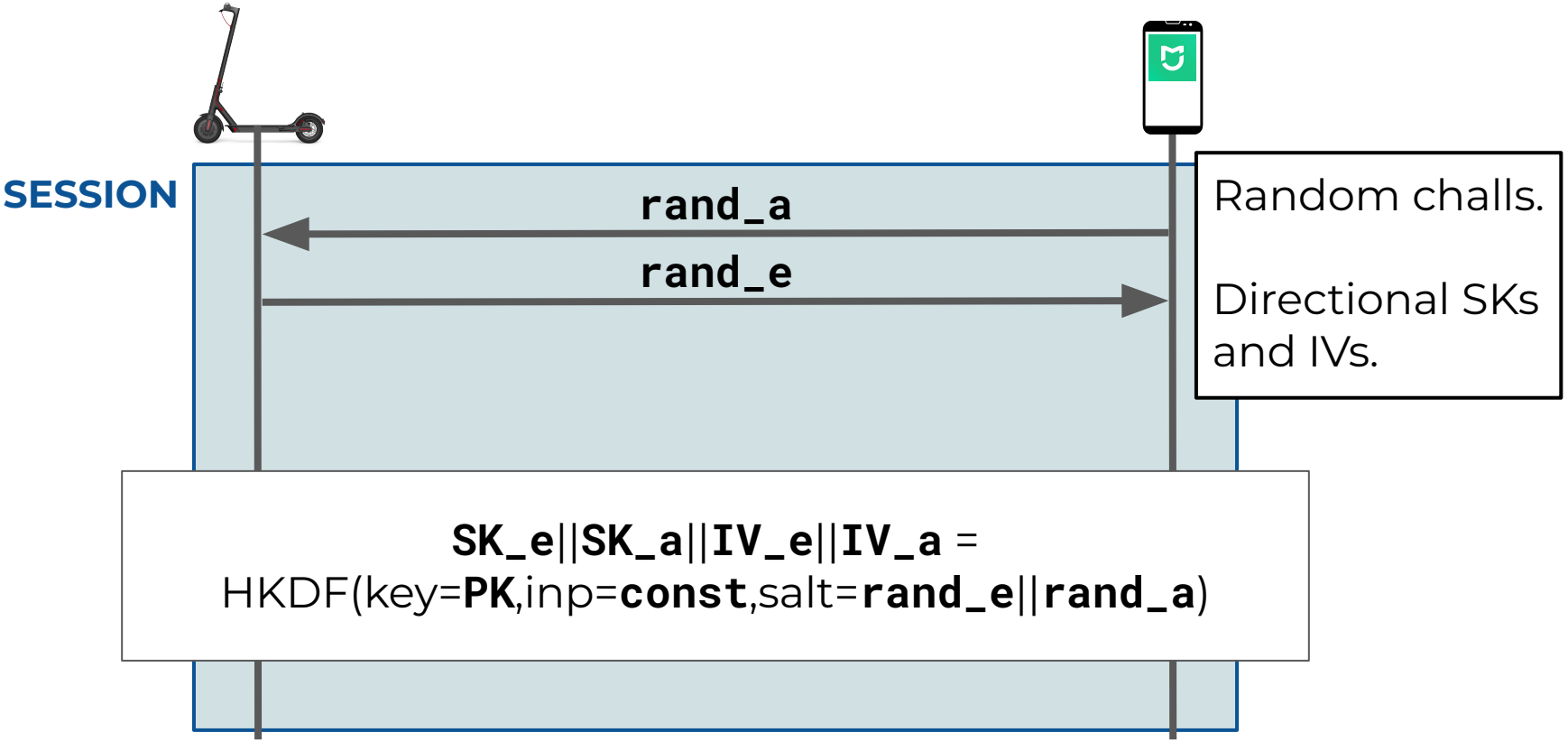
PUB_a

Unauthorized and **non authenticated** pairing.

SS = ECDH(**PUB_e**,**PRV_a** or **PUB_a**,**PRV_e**)
PK||OTK = HKDF(key=**SS**,inp=**const**)

resp = AES-CCM(key=**OTK**,inp=**chal**)

P4: Session (HKDF, AES-CCM) (1)



P4: Session (HKDF, AES-CCM) (2)

SESSION

resp_a = HKDF(key=**SK_a**,inp=**rand_a**||**rand_e**)

resp_e = HKDF(key=**SK_e**,inp=**rand_e**||**rand_a**)

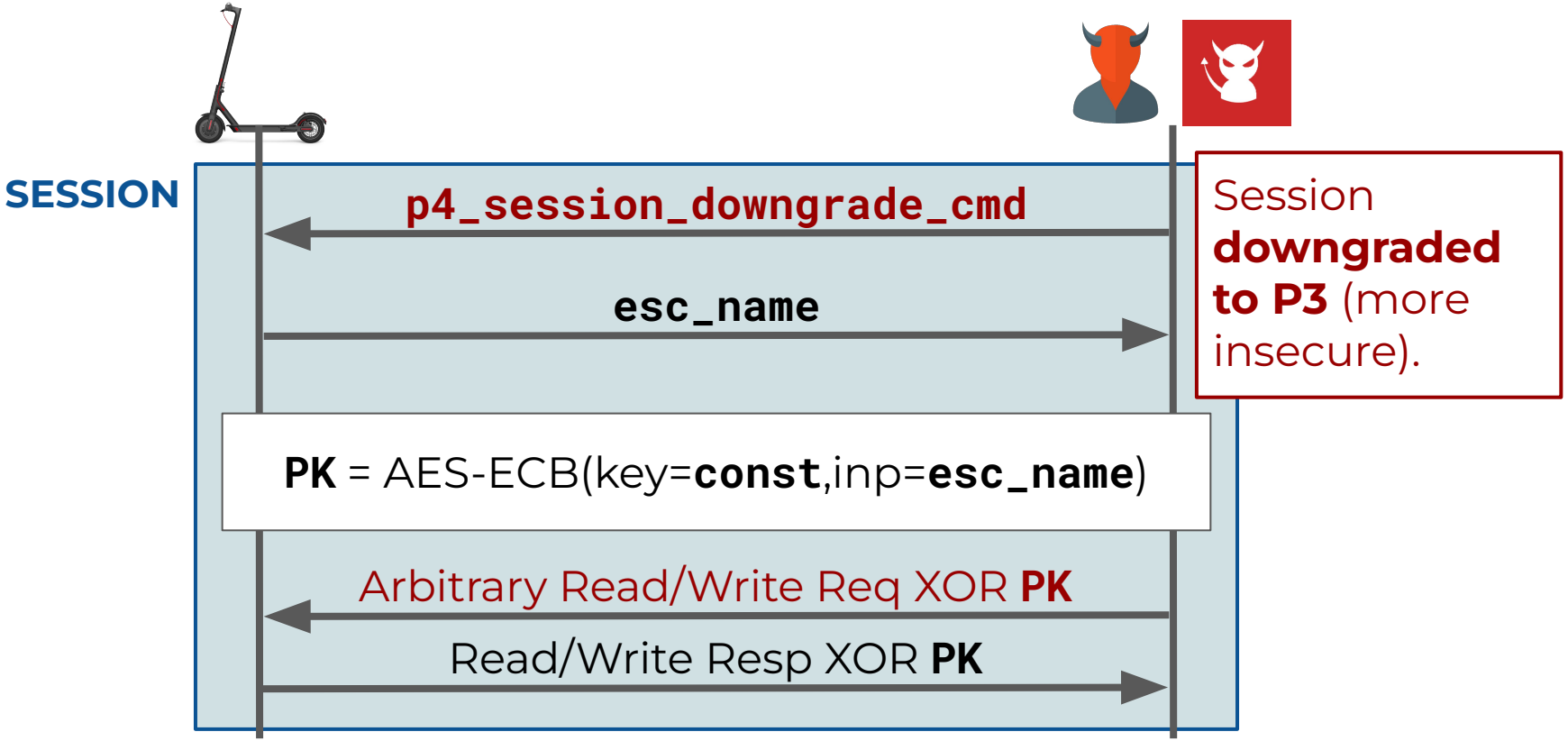
AES-CCM(key=**SK_a**,IV=**IV_a**||**cnt**, inp=**Read/Write Req**)

AES-CCM(key=**SK_e**,IV=**IV_e**||**cnt**, inp=**Read/Write Resp**)

Mutual session auth.

Encrypted and integrity protected comms.

P4: Proximity/Remote Attacks



P4: Proximity/Remote Attacks

SESSION DOWNGRADE

`p4_session_downgrade_cmd`

`esc_name`

Session **downgraded to P3** (more insecure).

PK = AES-ECB(key=**`const`**,inp=**`esc_name`**)

Arbitrary Read/Write Req XOR **PK**

Read/Write Resp XOR **PK**

Xiaomi Custom Protocols

Id	*Name*	*Pairing*	*Session*
P1	No security	None	None
P2	XOR obfuscation	Public XOR mask	XOR mask obfuscation, no auth, no integrity
P3	AES-ECB and XOR obfuscation	Weak AES-ECB key agreement, no auth	XOR obfuscation, implicit auth, no integrity
P4	ECDH and AES-CCM	ECDH, AES-CCM unil. auth	**v1**: HKDF, HMAC, AES-CCM, mutual auth
			v2: v1 with downgrade protection

EVALUATION

Evaluation Setup (E-Scooters)

M365

Essential

Mi 3

- 5 BLE boards (M365, Pro 1, Pro 2, Essential, Mi 3)
- 8 BLE firmware (P1, P2, P3, P4)

Evaluation Setup (Mi Home)

- Mi Home app versions
  - Android v7.11.704 and v7.6.704
  - iOS v7.12.204
- Smartphone models
  - OnePlus 3 (Android 12), Pixel 2 (Android 11), and RealMe GT (Android 9)
  - iPhone 7 (iOS 15.7)

Evaluation Results

E-Scooter	BLE Board	BLE Fw	Protocol	Strategy	Prox/Rem Adv.	
					Spoof Mi Home	*Arb R/W*
M365	M365	072	P1	RE	✓	✓
M365	M365	081	P2	RE, MP, SD	✓	✓
M365	Pro 1	090	P3	RE	✓	✓
M365	M365	122	P4v1	RE, MP, SD	✓	✓
M365	Pro 2	129	P4v1	RE, MP, SD	✓	✓
Essential	Essential	152	P4v1	RE, MP, SD	✓	✓
Mi 3	Mi 3	153	P4v1	RE, MP, SD	✓	✓
Mi 3	Mi 3	157	P4v2	RE, MP	✓	✓

E-SPOOFER TOOLKIT

E-Spoofer Toolkit

- **E-Spoofer** is open-source
  - Automated Proximity MP
  - Automated Remote SD
- **Reversed BLE firmware** (Ghidra)
- Xiaomi **protocol dissectors** (pyshark, scapy)
- **Code hooks** for dynamic testing (Frida)

E-Spoofer: Proximity MP Demo

E-Spoofer: Remote SD Demo

COUNTERMEASURES AND DISCLOSURE

Countermeasures

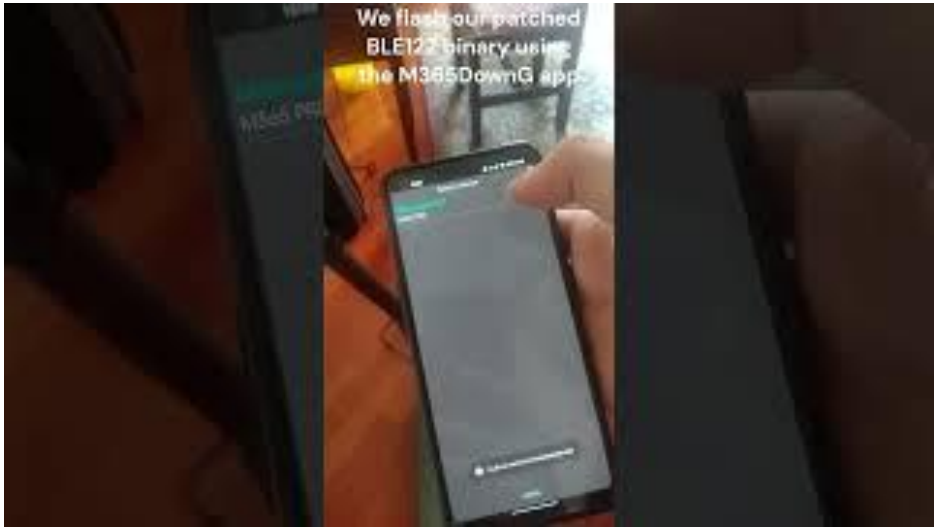
- (C1) Update firmware via Mi Home
  - From P1, P2, P3 to P4v1 or P4v2
- (C2) **Authorized and authenticated pairing**
  - Addresses MP on P4v1 and P4v2
- (C3) **Anti-downgrade BLE fw patching script**
  - Addresses SD on P4v1
  - Evaluated on a real M365

Authorized and Authenticated Pairing

- Upgrade to Xiaomi pairing
  - Secure and backward-compatible
- **Authorized pairing mode**
  - Mandatory gesture to enable pairing mode
- **Password-protected authenticated pairing**
  - Mandatory e-scooter password to start pairing

Anti-Downgrade BLE Fw Patching Script

- Automated tool that modifies BLE122 binary
  - Deletes P4v1 session downgrade command
  - Blocks any P3 packet received



Disclosure

- Xiaomi Bug Bounty on Hackerone
  - Sent paper, toolkit, and demos (21/11/22)
  - Made a few requests for an update
  - Xiaomi: "**Cannot reproduce the attacks**" (06/02/23)
- Also disclosed a Mi Home app bug
  - UI delay allows e-scooter software-unlock even without a password (14/08/22)
  - Xiaomi awarded a 200$ **bounty** (23/12/22)

Conclusion and Q&A

- RE all **Xiaomi e-scooter protocols** since 2016
  - Pairing and Session phases
- Uncover critical **protocol-level vulnerabilities**
  - E.g., unwanted pairing and weak authentication
- **Proximity** and **remote** wireless attacks
  - I.e., malicious pairing and session downgrade
- **E-Spoofer** open-source toolkit
- **Countermeasures** and **disclosure** to Xiaomi