Rethinking the Security and Privacy of Bluetooth Low Energy

Zhiqiang Lin
Distinguished Professor of Engineering
zlin@cse.ohio-state.edu

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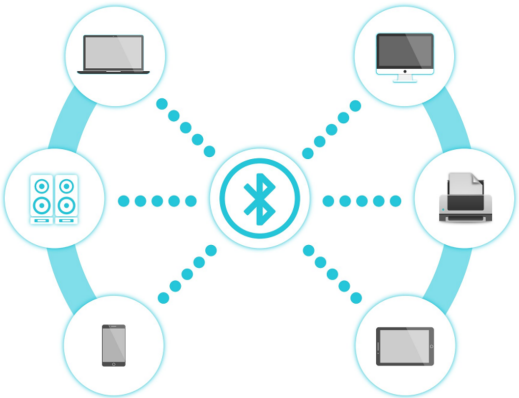
What is Bluetooth

Bluetooth wireless technology

- Low-cost, low-power
- Short-range radio
- For ad-hoc wireless communication
- For voice and data transmission



What is Bluetooth

Google
Contact tracing

Why Named Bluetooth

Harald "Bluetooth" Gormsson

- King of Denmark 940-981.
- He was also known for his bad **tooth**, which had a very dark **blue-grey** shade.
- He united the Tribes of Denmark.

The Bluetooth wireless specification design was named after the king in 1997, based on an analogy **that the technology would unite devices the way Harald Bluetooth united the tribes of Denmark into a single kingdom**.

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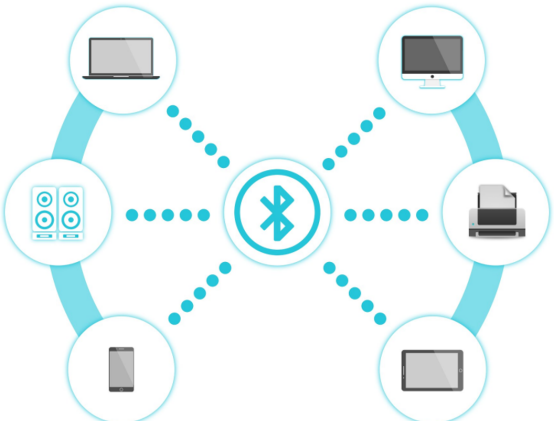
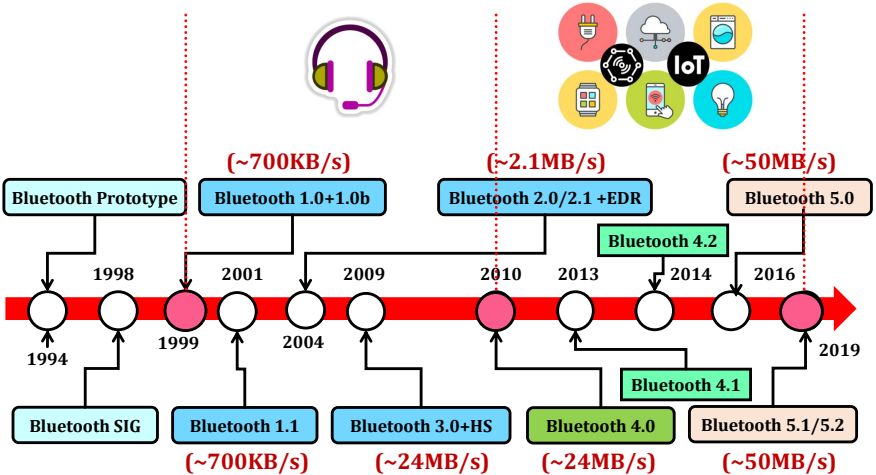
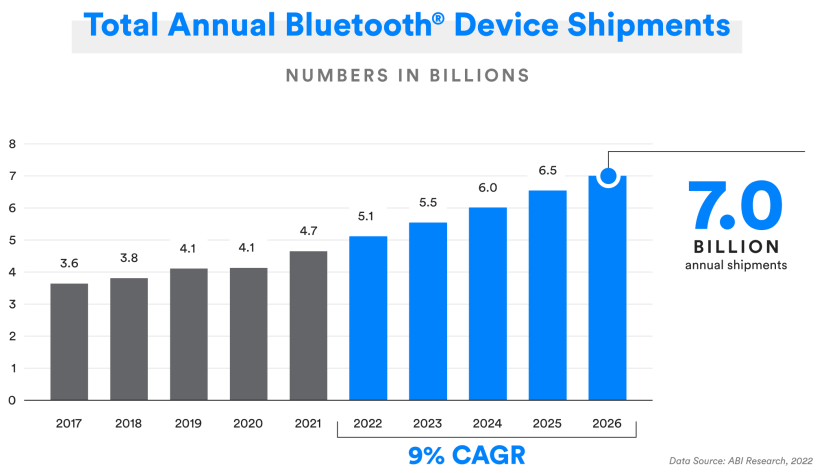


History of Bluetooth



Total Annual Bluetooth Device Shipments



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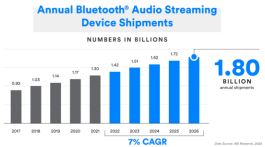

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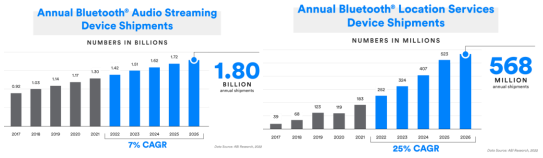
· AirTag ·



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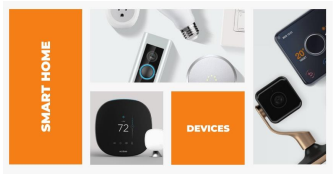
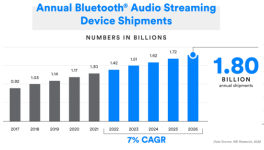
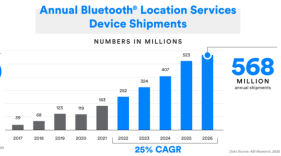
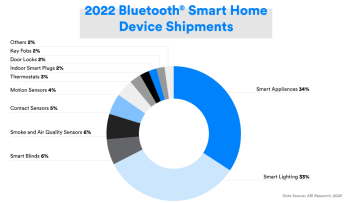
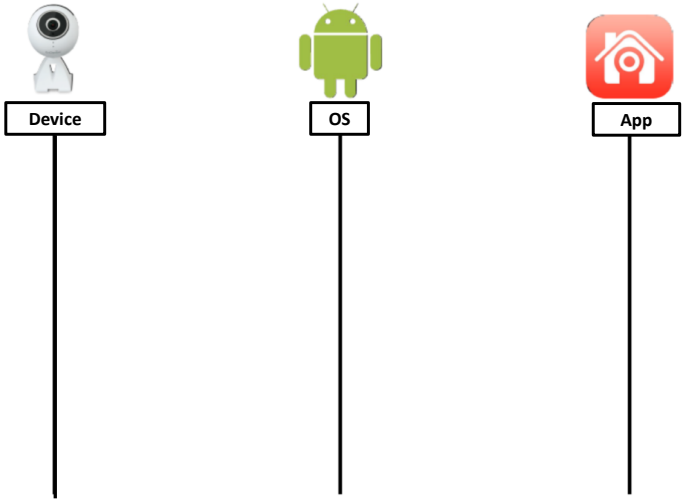








The General Workflow of Device Communication in TCP/IP Setting



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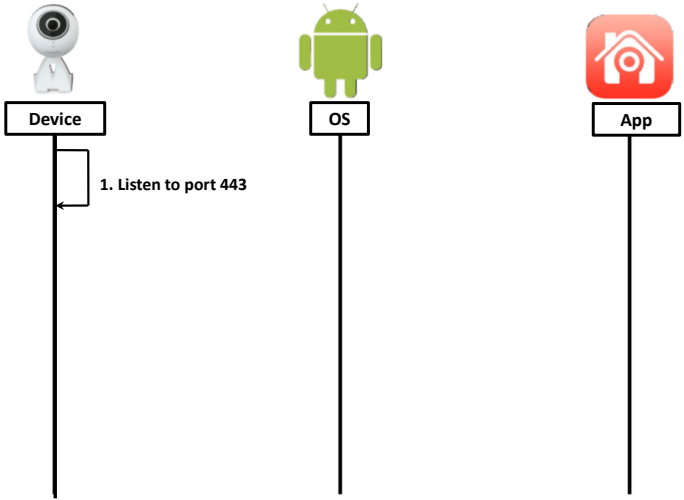

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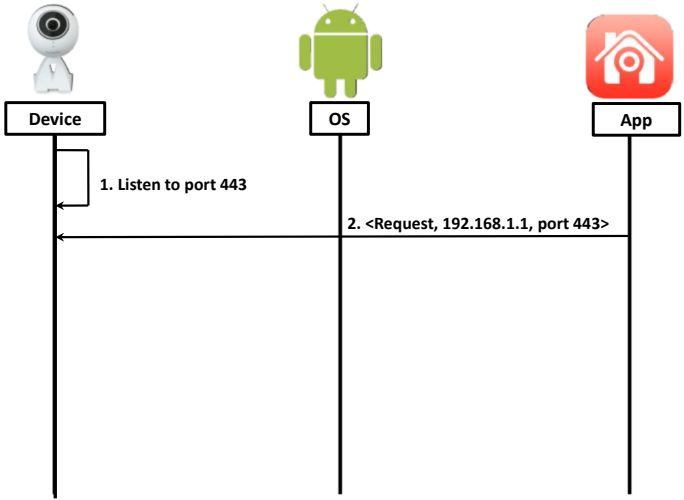

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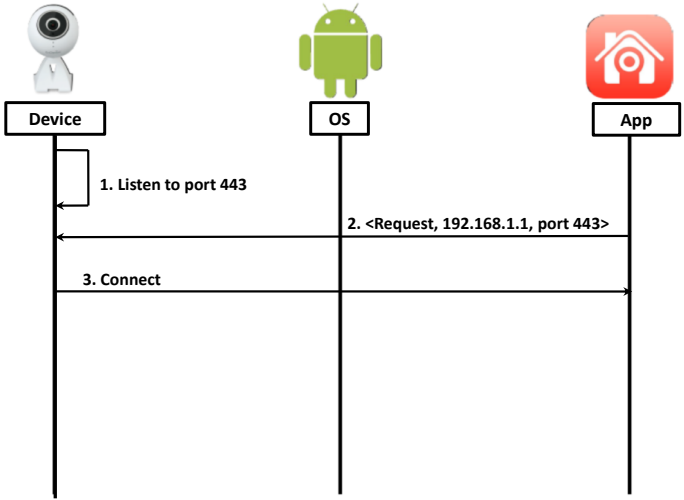

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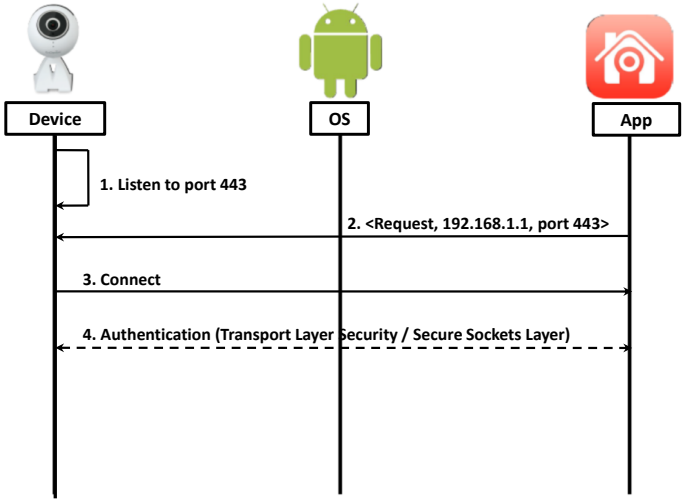

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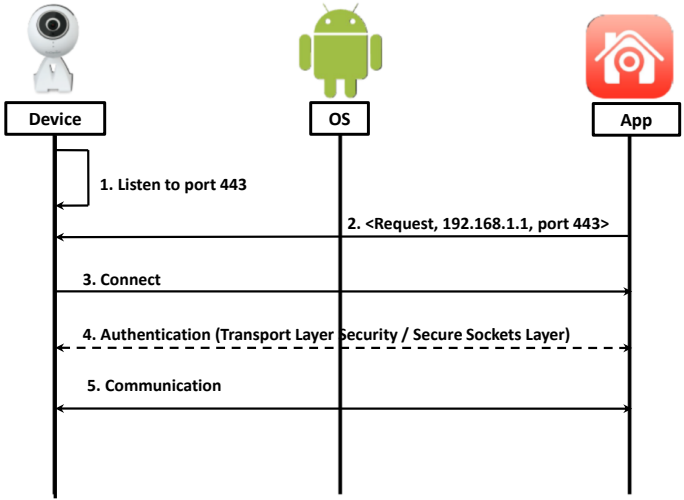

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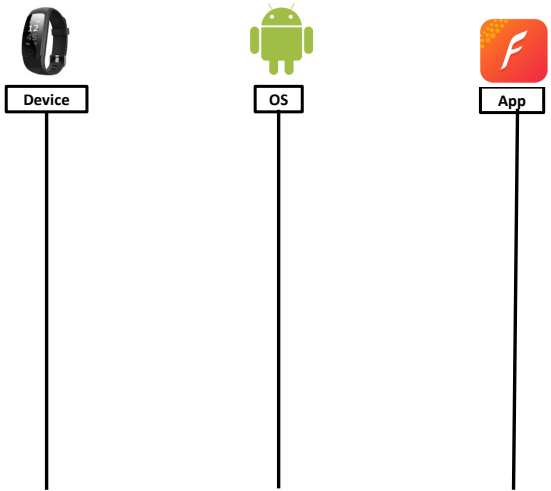
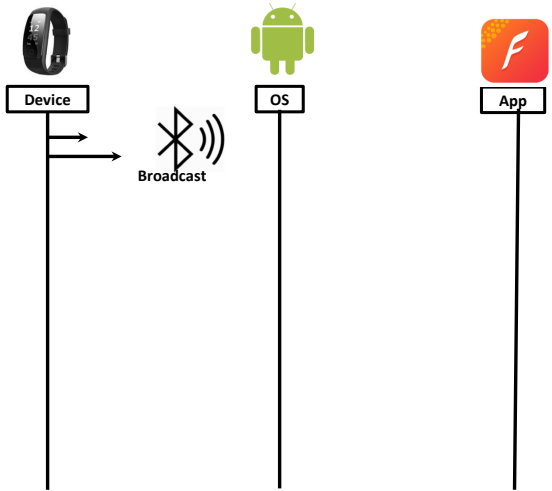


The General Workflow of BLE IoT Devices and Companion Apps



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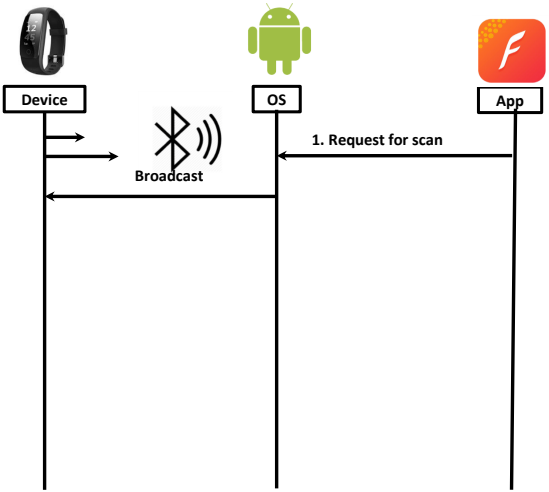

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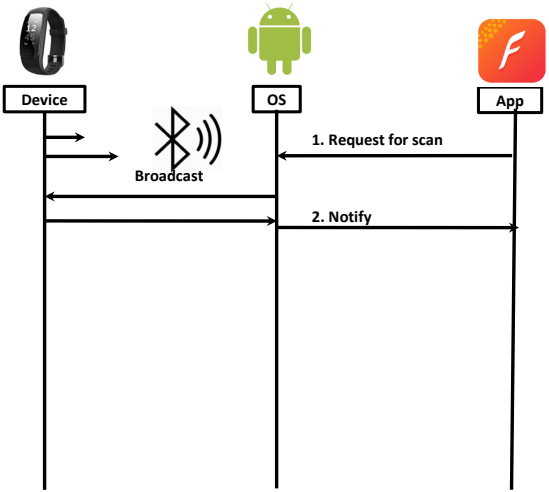

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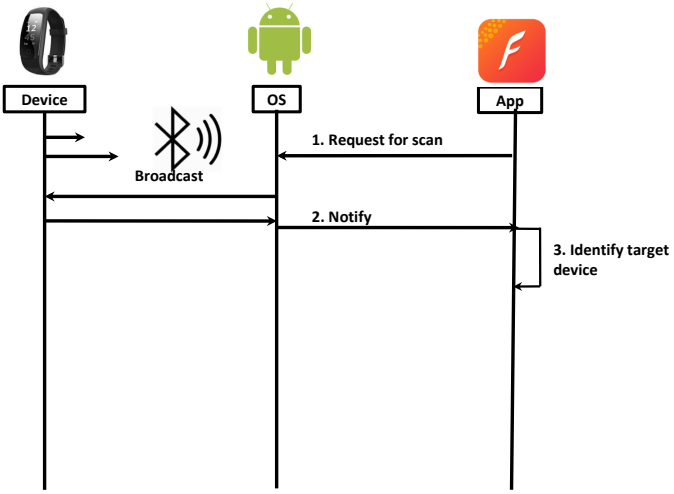

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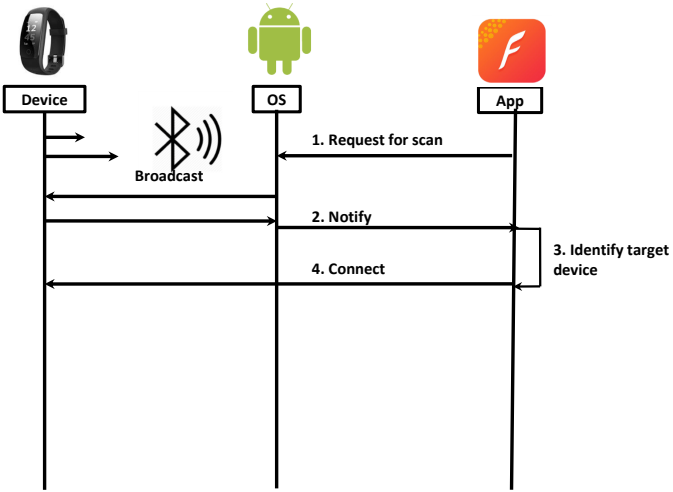

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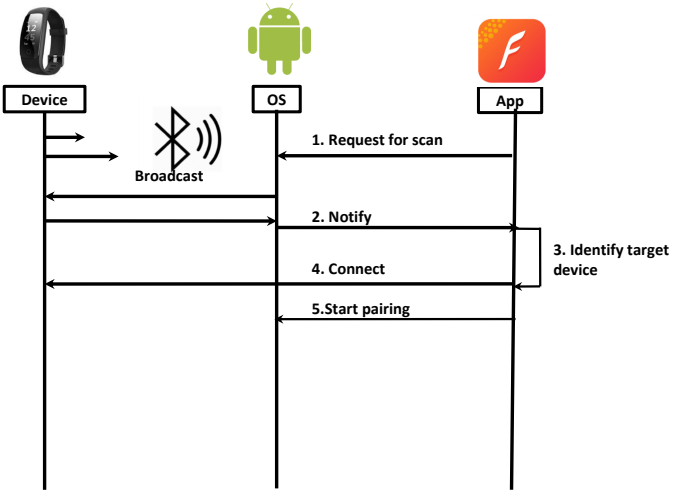

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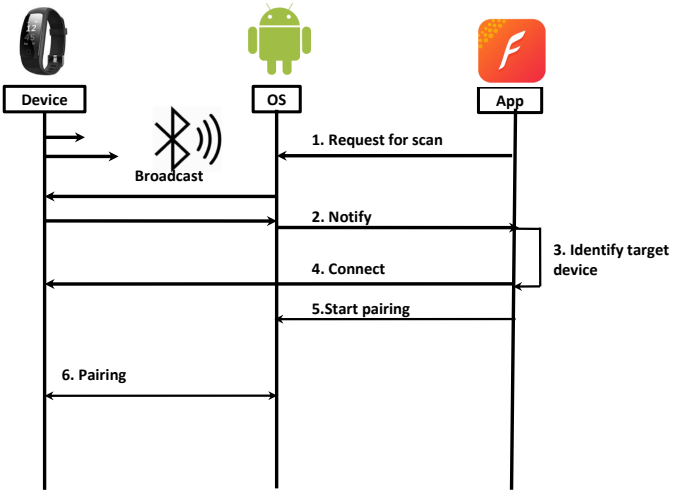

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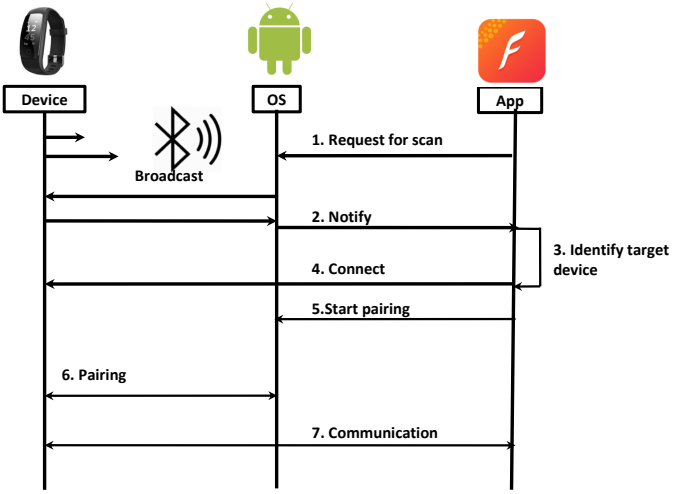
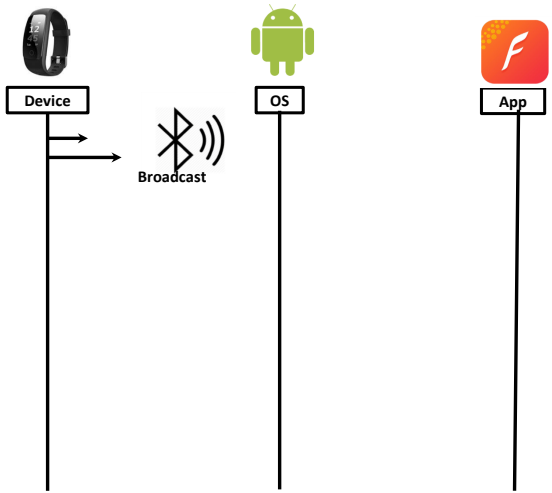


Our Recent Works on Bluetooth Security and Privacy



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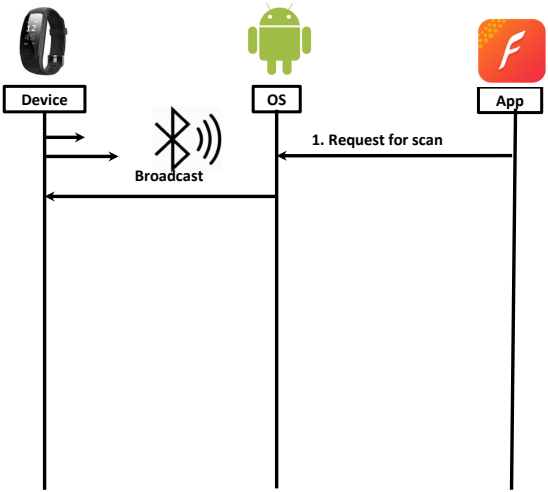

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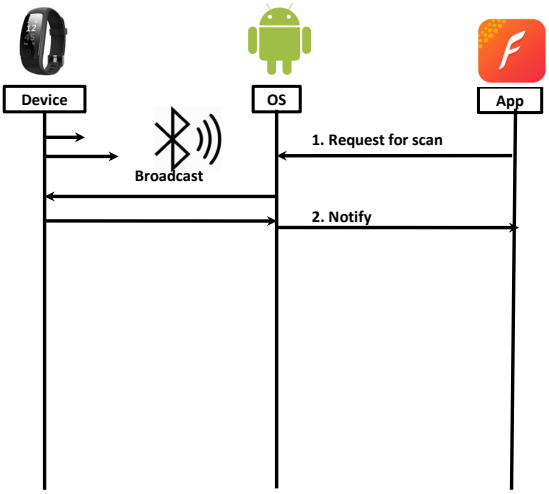

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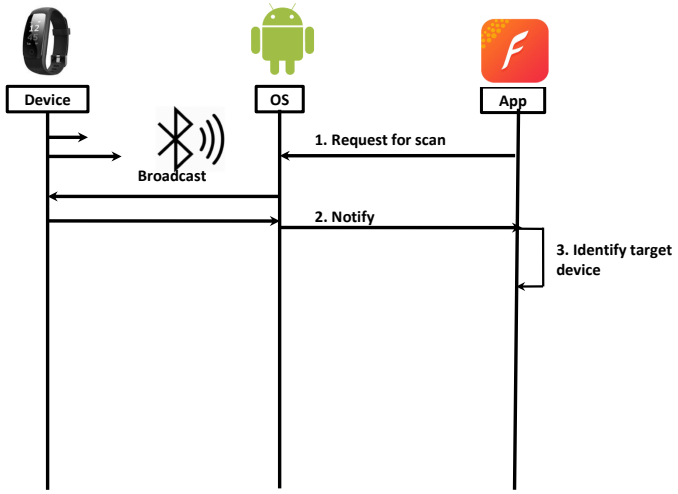

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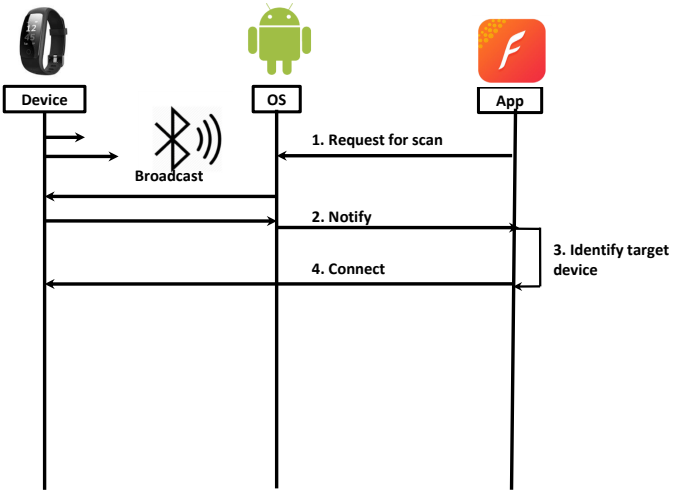

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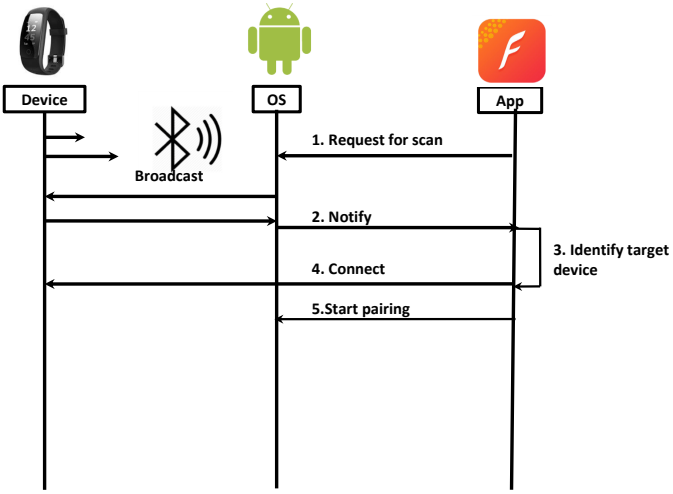

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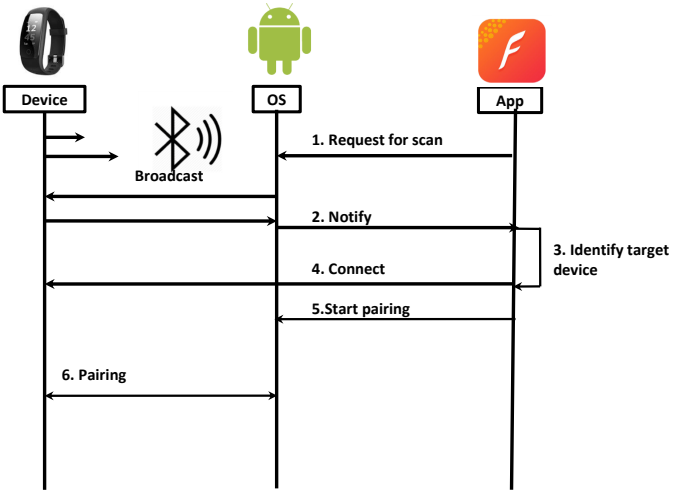

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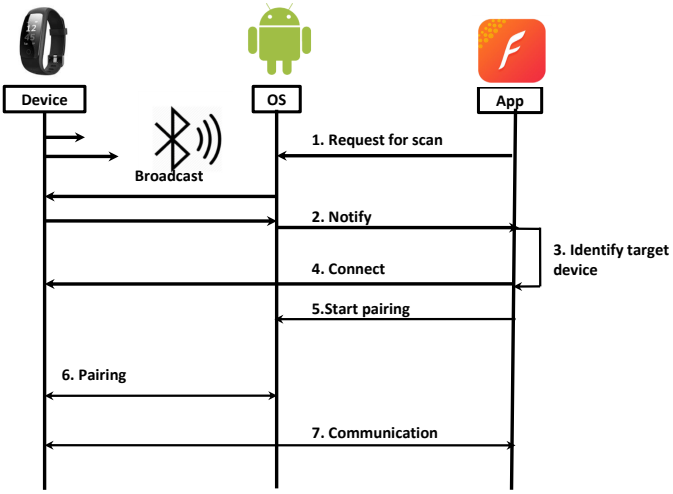

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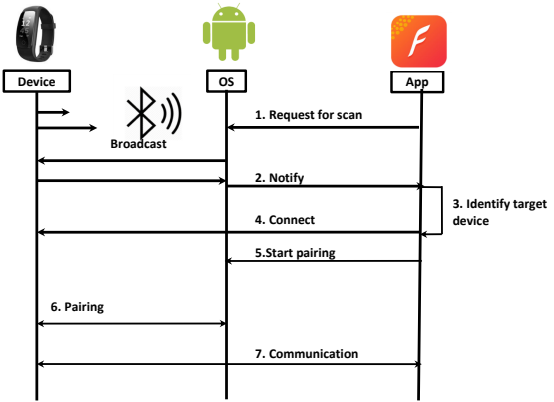

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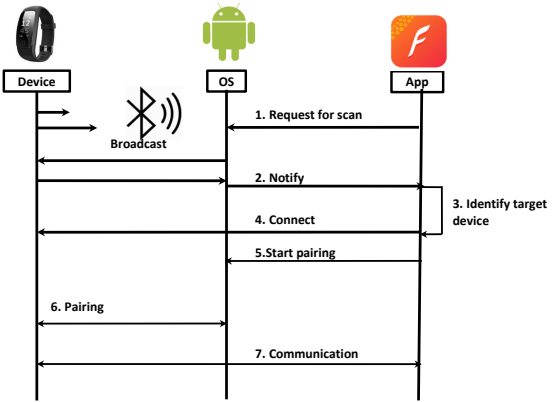

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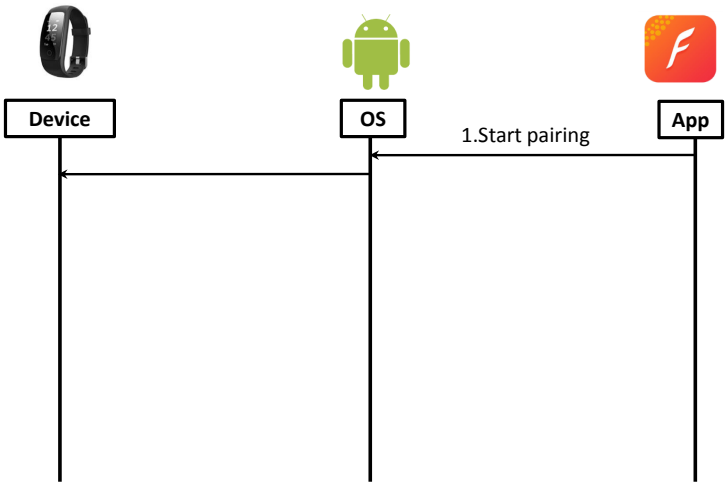
Pairing Workflow

Device

OS

App

Pairing Workflow



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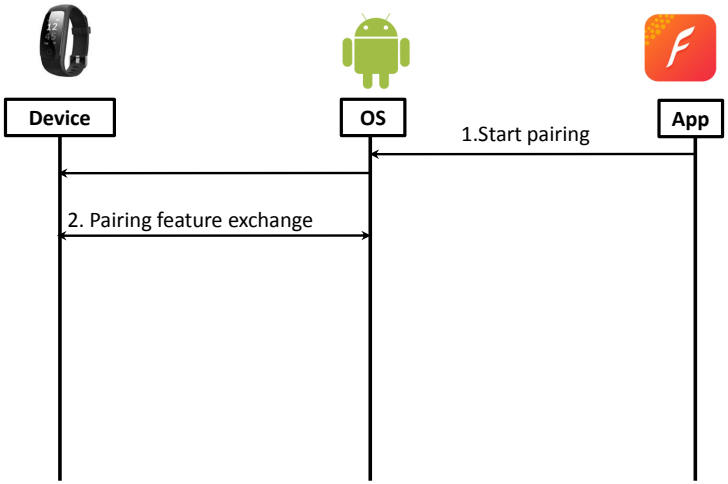
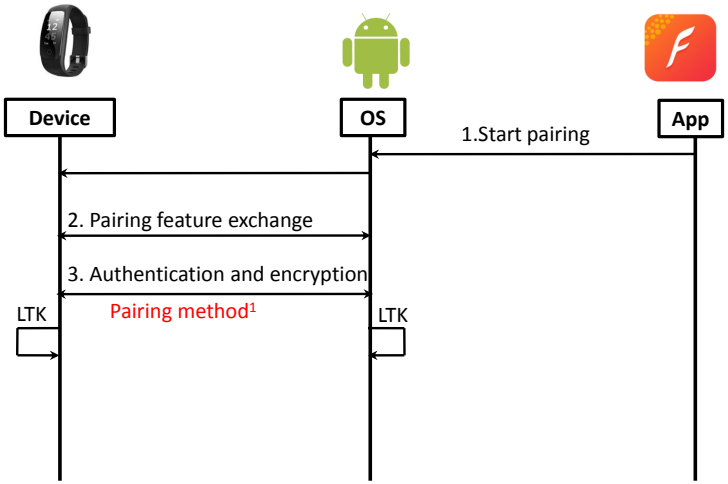


I/O Features

- Keypad
- Screen
- Out of band Channel

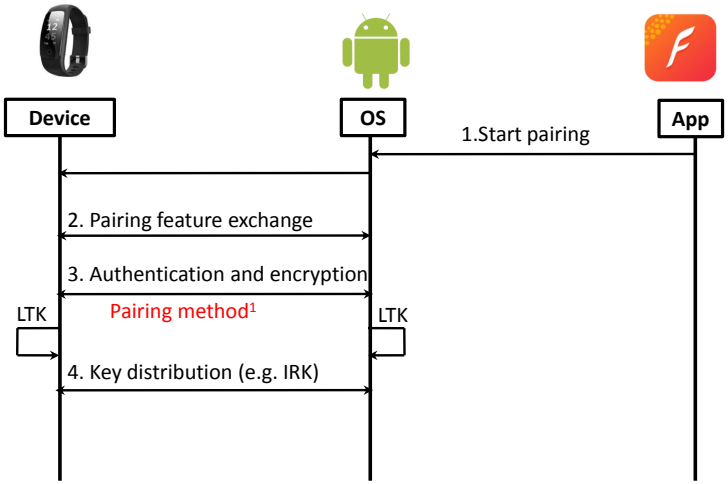
Pairing Workflow



Pairing Methods

- Just Works
- Passkey Entry
- Out of band
- Numeric Comparison

Pairing Workflow



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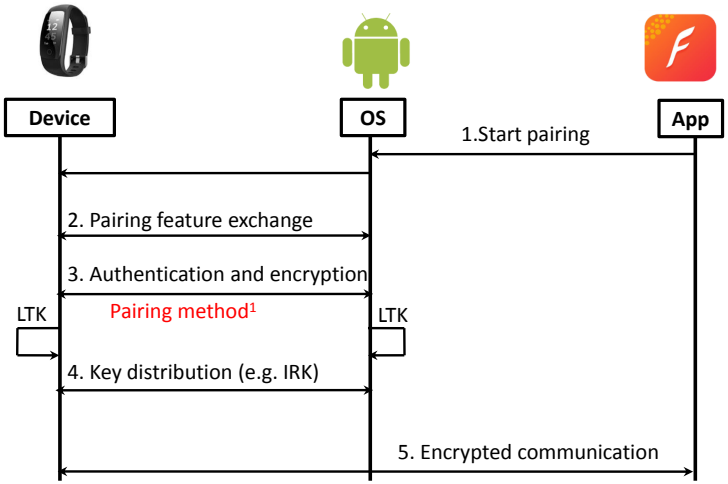

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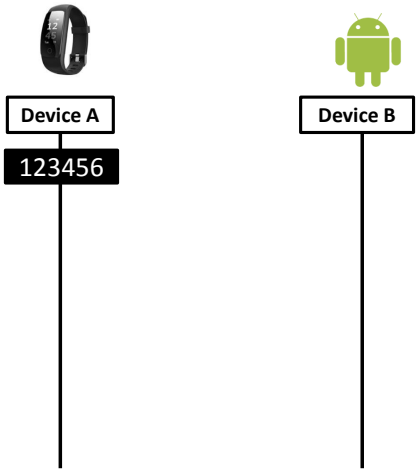
$$Pri_A * (Pri_B * G) = Pri_B * (Pri_A * G)$$

Workflow of Passkey Entry

Device A

Device B

Workflow of Passkey Entry



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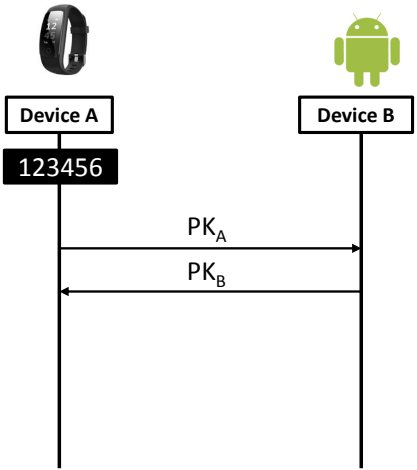

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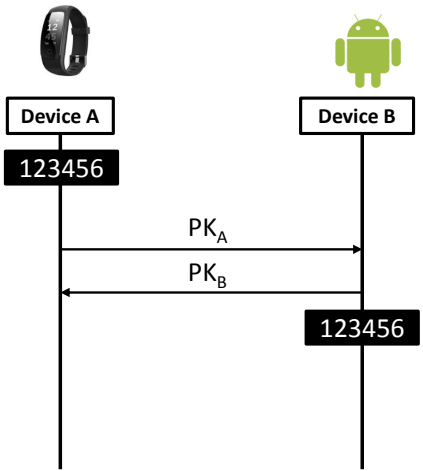

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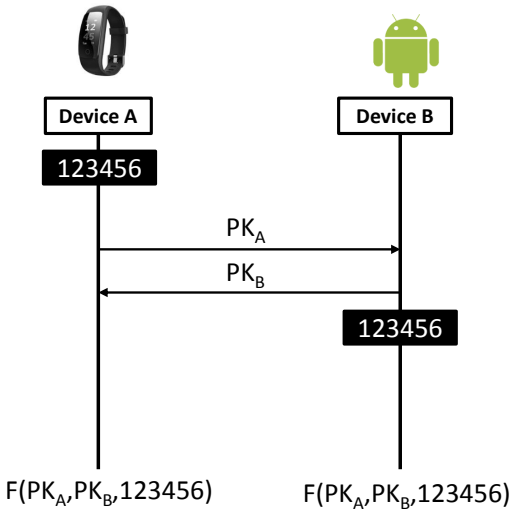

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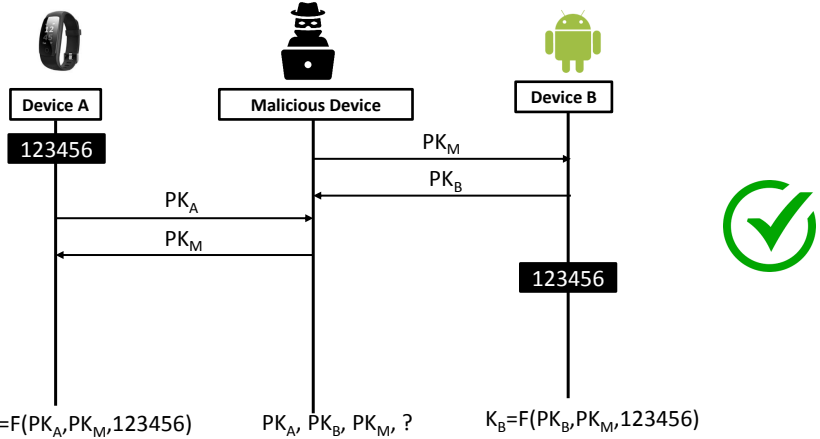
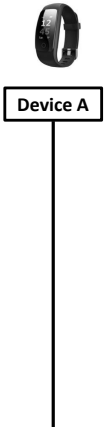
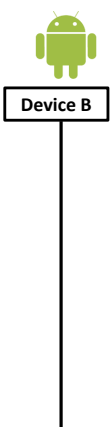
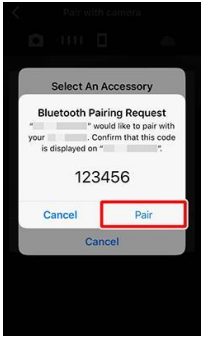
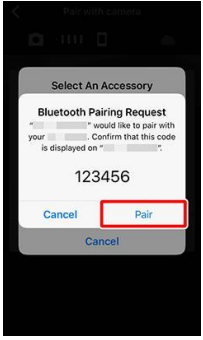


Workflow of Numeric Comparison

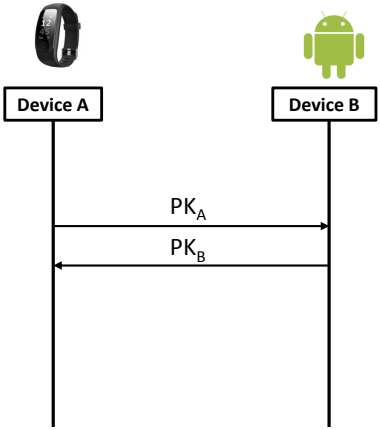




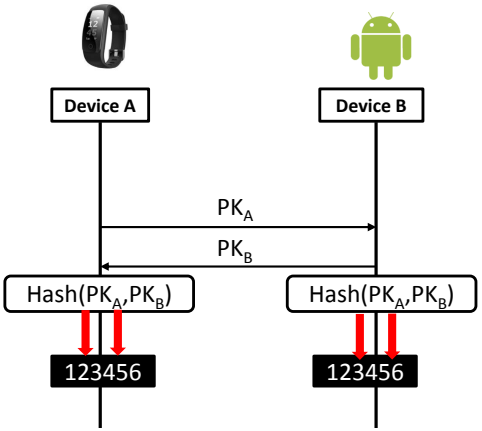




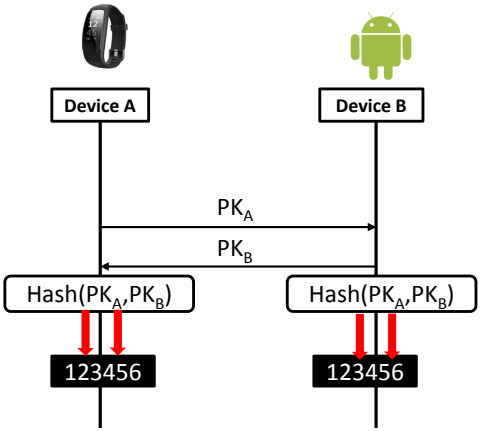
Workflow of Numeric Comparison

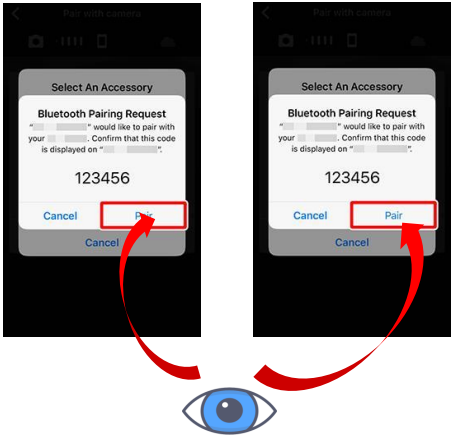


Workflow of Numeric Comparison

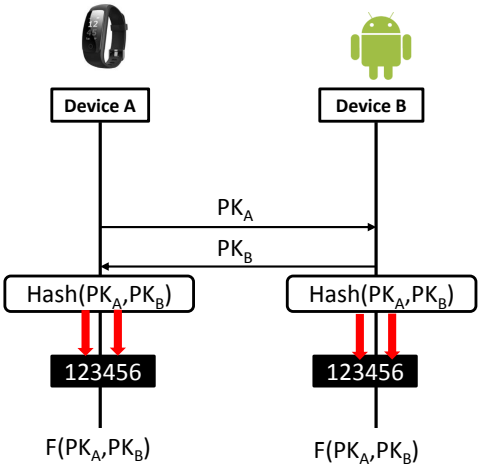


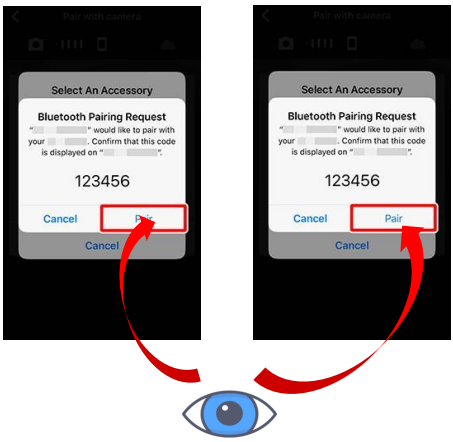
Workflow of Numeric Comparison



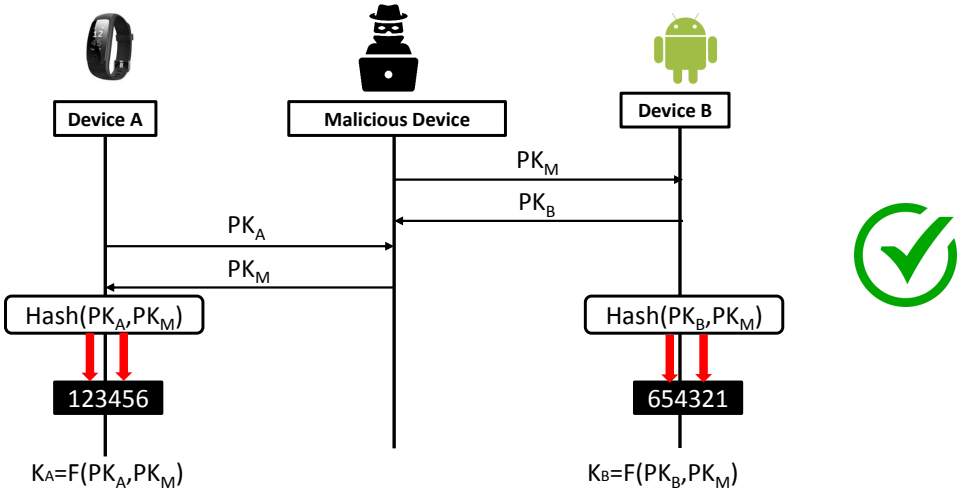


Workflow of Numeric Comparison

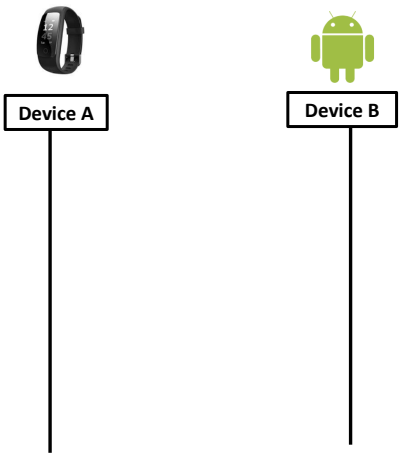




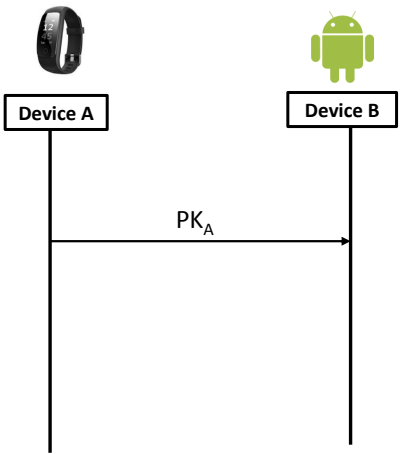
Workflow of Numeric Comparison



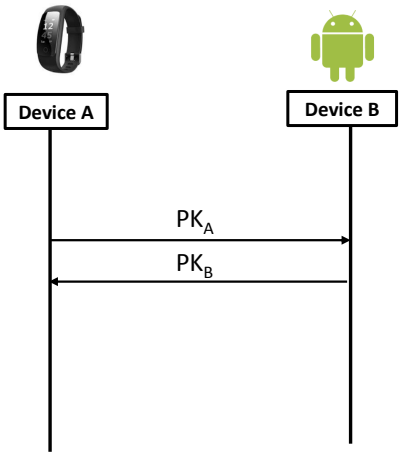
Workflow of Out of Band



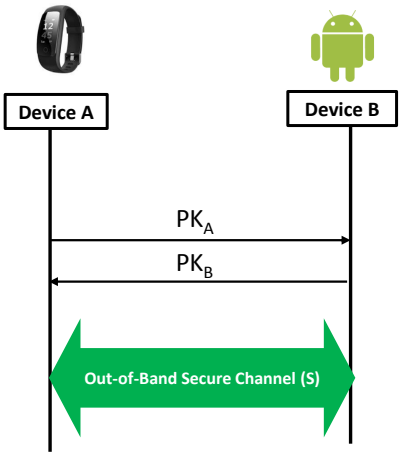
Workflow of Out of Band



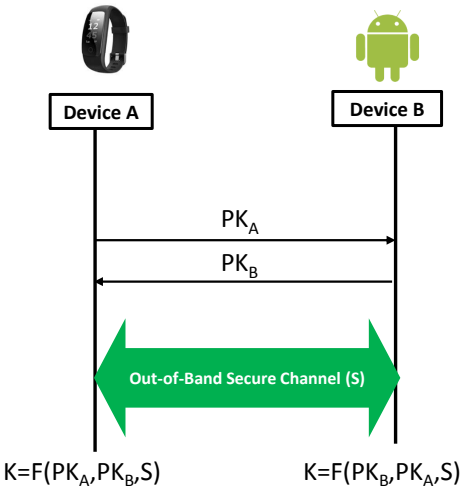
Workflow of Out of Band



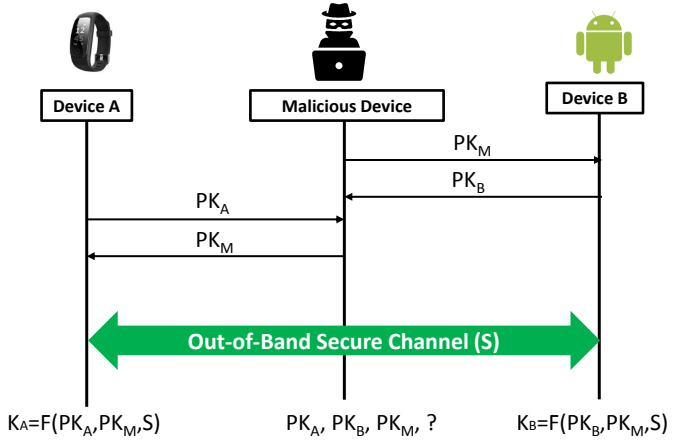
Workflow of Out of Band



Workflow of Out of Band



Workflow of Out of Band

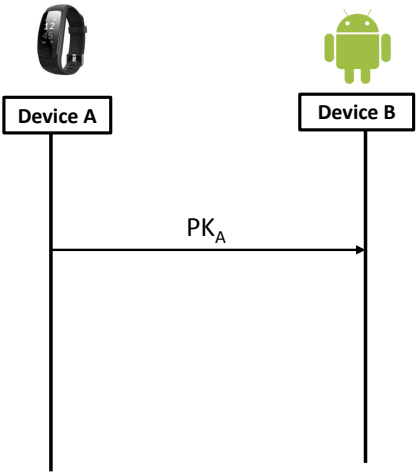


Workflow of Justworks

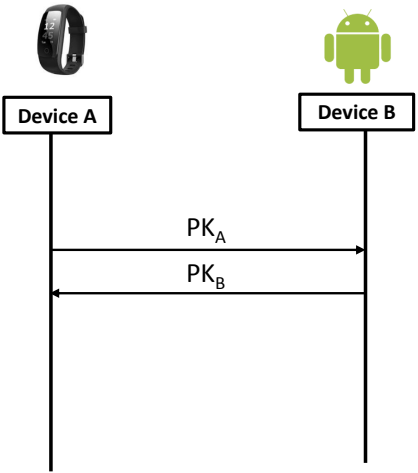
Device A

Device B

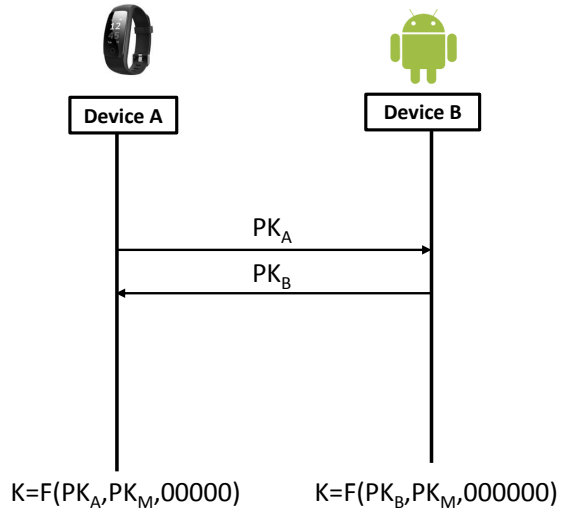
Workflow of Justworks



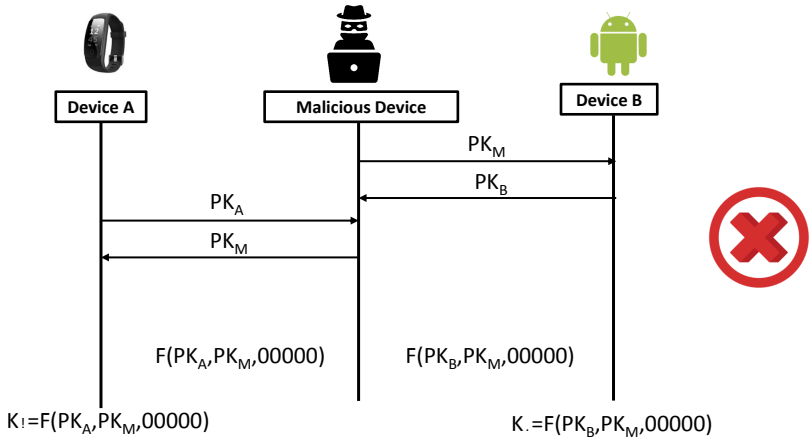
Workflow of Justworks



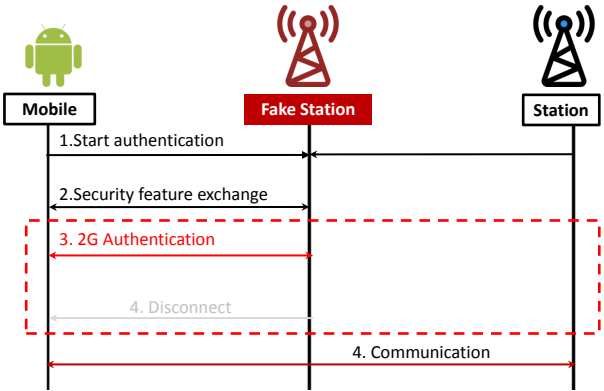
Workflow of Justworks



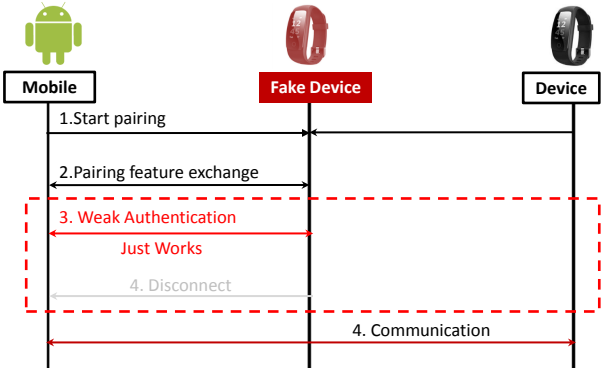
Workflow of Justworks



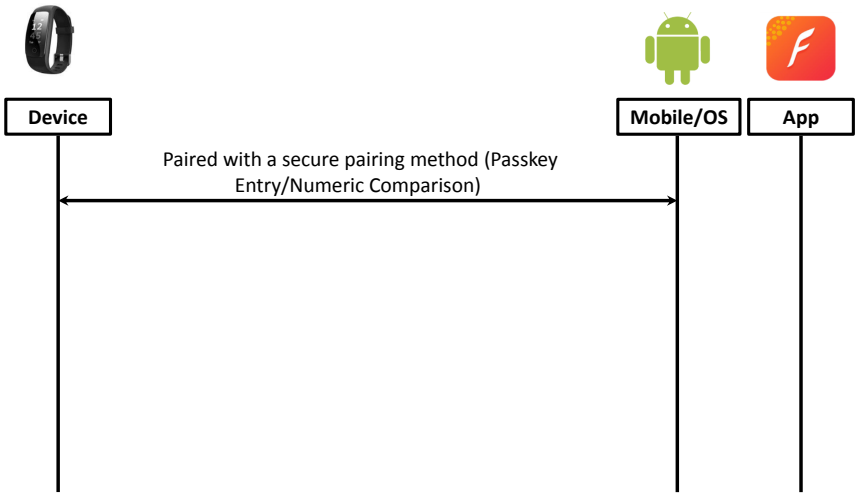
Our Downgrade Attacks against Bluetooth Low Energy



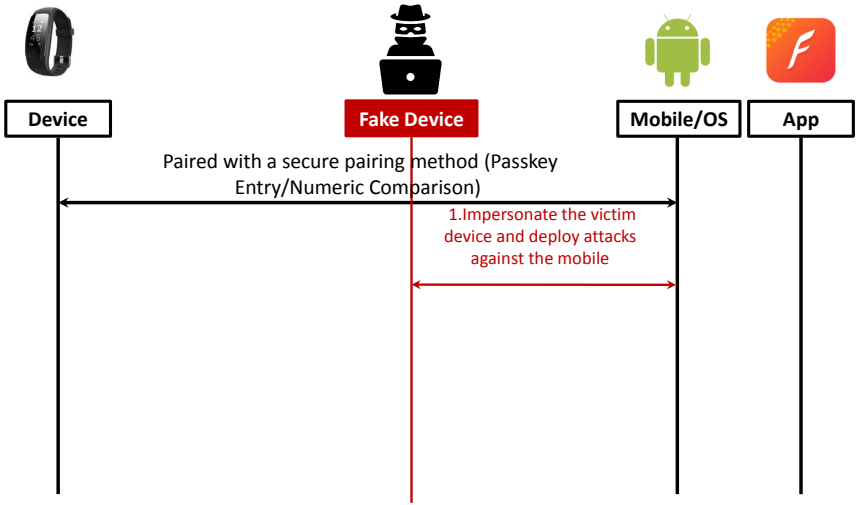
Our Downgrade Attacks against Bluetooth Low Energy



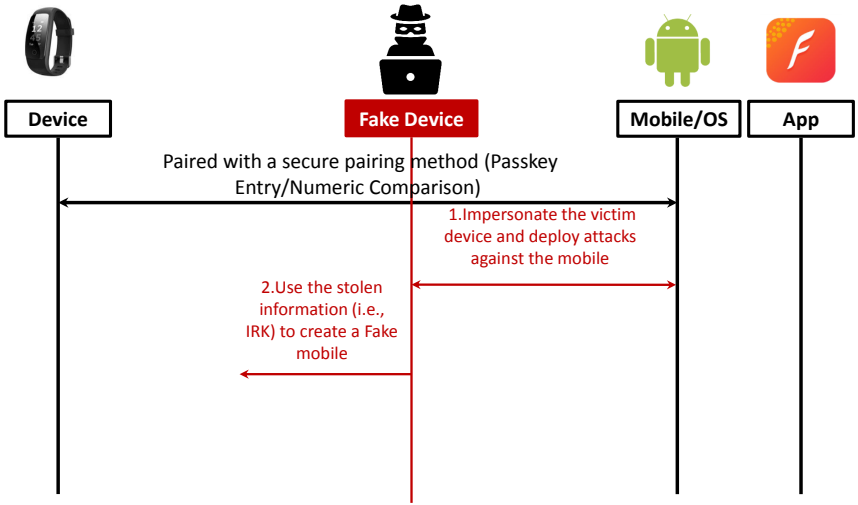
Our Downgrade Attacks against Bluetooth Low Energy



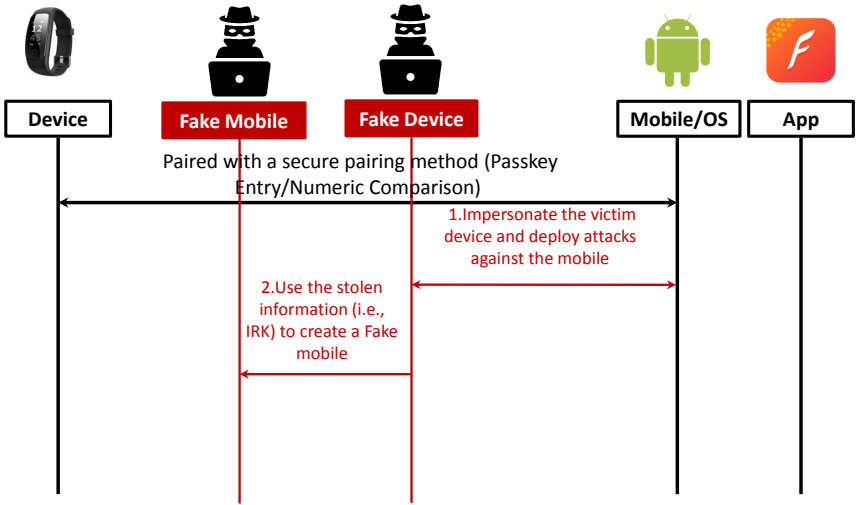
Our Downgrade Attacks against Bluetooth Low Energy



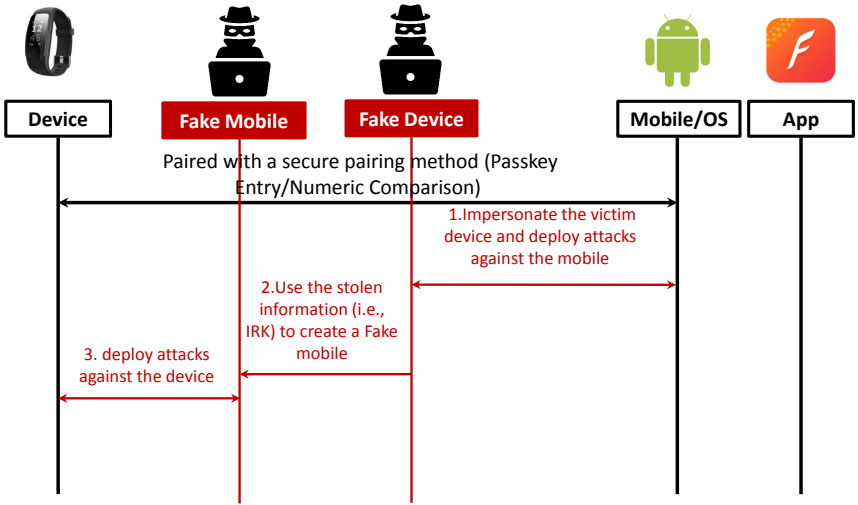
Our Downgrade Attacks against Bluetooth Low Energy



Our Downgrade Attacks against Bluetooth Low Energy

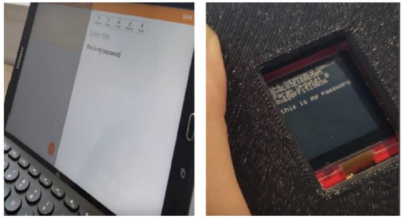


Our Downgrade Attacks against Bluetooth Low Energy



Our Downgrade Attacks against Bluetooth Low Energy

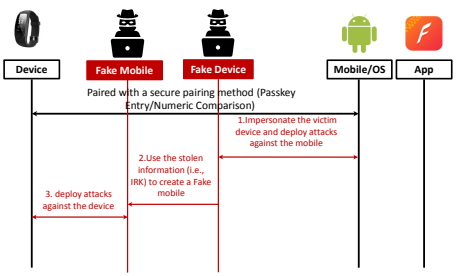
The Tested BLE devices



MITM attack against BLE keyboards

CVE-2020-9770

Our Downgrade Attacks against Bluetooth Low Energy



"Breaking Secure Pairing of Bluetooth Low Energy Using Downgrade Attacks", Yue Zhang, Jian Weng, Rajib Dey, Yier Jin, Zhiqiang Lin, and Xinwen Fu. *In Proceedings of the 29th USENIX Security Symposium*, Boston, MA. August 2020

Bluetooth Sniffers

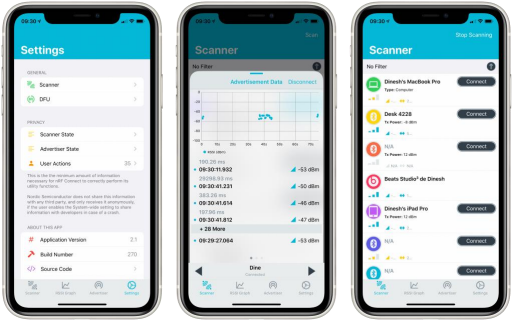
Ubertooth One Sniffer

125 USD

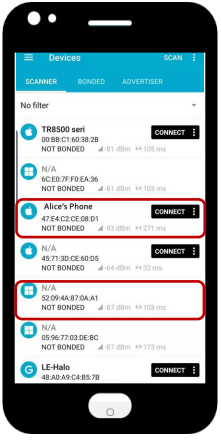
Adafruit LE sniffer

25 USD

nRF Connect
The #1 Bluetooth LE utility
Nordic Semiconductor ASA



Bluetooth Sniffers

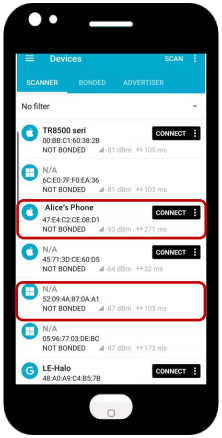


Alice's phone

Bob's phone

T1: 52:09:4A:87:0A:A1

Bluetooth Sniffers



Alice's phone

Bob's phone

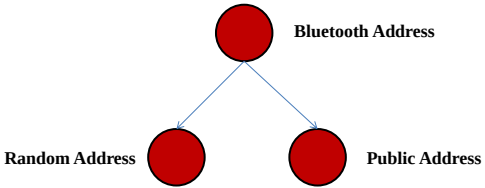
T1: 52:09:4A:87:0A:A1

T2: 52:09:4A:87:0A:A1

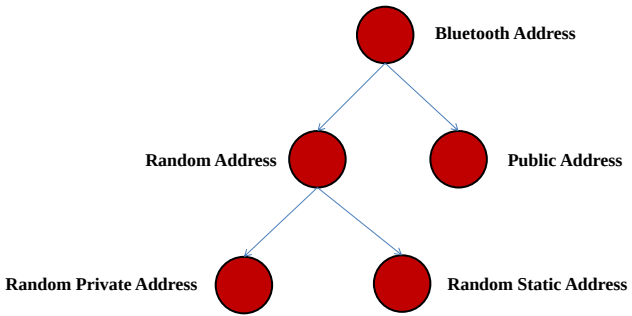
Bluetooth Address Types

Bluetooth Address

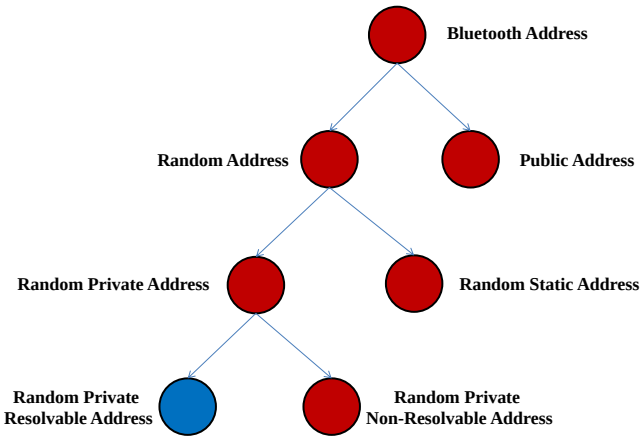
Bluetooth Address Types



Bluetooth Address Types



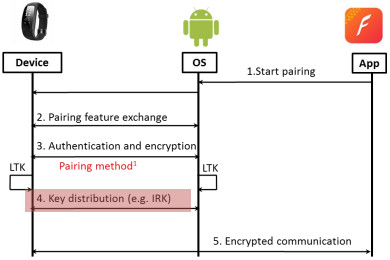
Bluetooth Address Types



How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)



How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || irk_p)$$

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} | H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} \,|\, H_{24}(Prand_{24}||irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} \| H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

(I) RPA Generation

$$rpa_p = prand_{24} \; H_{24}(Prand_{24}||irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

Identity Resolving Key (irk_c)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} \,||\, H_{24}(Prand_{24}||irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} \,||\, H_{24}(Prand_{24}||irk_c)$$

How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} \,||\, H_{24}(Prand_{24}||irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} \,||\, H_{24}(Prand_{24}||irk_c)$$

$irk_p = irk_c \Rightarrow rpa_p = rpa_c$

Our Discovery I — Allowlist-based Side Channel

58:D7:8E:C7:8e:31

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND

Our Discovery I — Allowlist-based Side Channel

58:D7:8E:C7:8e:31

7e:D7:8E:C7:8e:51

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
2	00:00:08	7e:D7:8E:C7:8e:51	58:D7:8E:C7:8e:31	SCAN_REQ
3	00:00:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP

Our Discovery I — Allowlist-based Side Channel

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
2	00:00:08	7e:D7:8E:C7:8e:51	58:D7:8E:C7:8e:31	SCAN_REQ
3	00:00:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP
4	00:00:16	4f:b7:8E:C7:8e:38	58:D7:8E:C7:8e:31	SCAN_REQ
5	00:00:24	58:D7:8E:C7:8e:31	Broadcast	ADV_IND

Our Discovery I — Allowlist-based Side Channel

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
2	00:00:08	7e:D7:8E:C7:8e:51	58:D7:8E:C7:8e:31	SCAN_REQ
3	00:00:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP
4	00:00:16	4f:b7:8E:C7:8e:38	58:D7:8E:C7:8e:31	SCAN_REQ
5	00:00:24	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
.....				
200	00:15:08	73:D7:8E:C7:8e:45	58:D7:8E:C7:8e:31	SCAN_REQ
201	00:15:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP

Our Discovery I — Allowlist-based Side Channel

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
2	00:00:08	7e:D7:8E:C7:8e:51	58:D7:8E:C7:8e:31	SCAN_REQ
3	00:00:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP
4	00:00:16	4f:b7:8E:C7:8e:38	58:D7:8E:C7:8e:31	SCAN_REQ
5	00:00:24	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
.....				
200	00:15:08	73:D7:8E:C7:8e:45	58:D7:8E:C7:8e:31	SCAN_REQ
201	00:15:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP

1. Cache
2. Timing
3. Power
4. Votage
5. Electromagnetic
6. Acoustic
7. Allow-list
8. ...

Passive Bluetooth Address Tracking (BAT) Attacks

Attack I: Monitoring a Victim's Status

Passive Bluetooth Address Tracking (BAT) Attacks

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Passive Bluetooth Address Tracking (BAT) Attacks

Attack I: Monitoring a Victim's Status

Passive Bluetooth Address Tracking (BAT) Attacks

Attack I: Monitoring a Victim's Status

Passive Bluetooth Address Tracking (BAT) Attacks

Attack I: Monitoring a Victim's Status

Our Discovery II — MAC Address Replay

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

Our Discovery II — MAC Address Replay

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

Our Discovery II — MAC Address Replay

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} || H_{24}(Prand_{24} || irk_c)$$

$irk_p = irk_c$ ➔ $rpa_p = rpa_c$

rpa_p

Our Discovery II — MAC Address Replay

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

No Identity Resolving Key

RPA Replay (rpa'_p)

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} || H_{24}(Prand_{24} || irk_c)$$

$irk_p = irk_c$ ➔ $rpa_p = rpa_c$

rpa_p

Our Discovery II — MAC Address Replay

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

No Identity Resolving Key

RPA Replay (rpa'_p)

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

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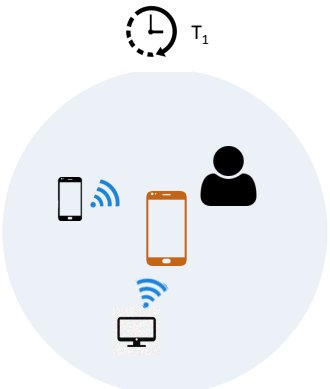
$$rpa_c = prand_{24} || H_{24}(Prand_{24} || irk_c)$$

$irk_p = irk_c$ ➔ $rpa_p = rpa_c$

rpa_p

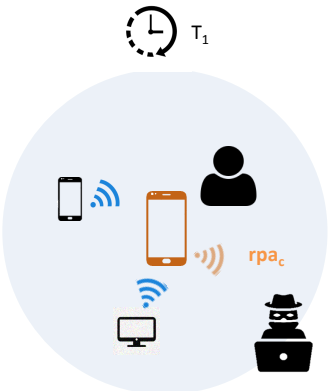
rpa'_p

Active BAT Attacks: Tracking a Victim's Past Trajetory



Attack II: Tracking a Victim's Past Trajectory

Active BAT Attacks: Tracking a Victim's Past Trajetory



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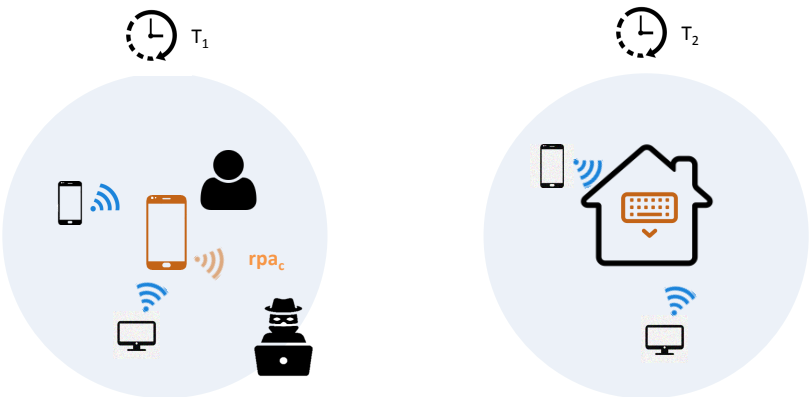

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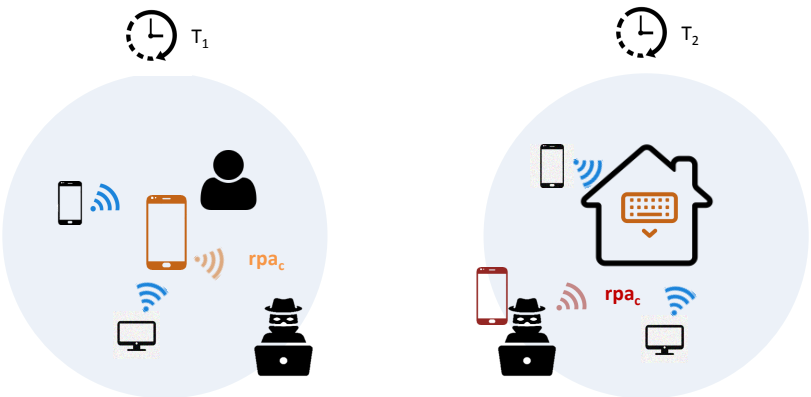
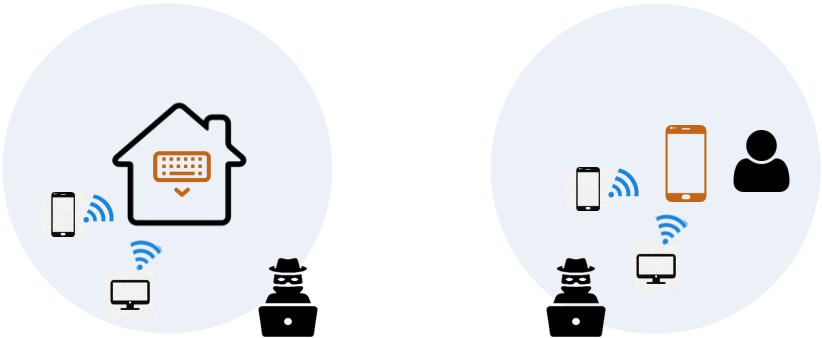


Attack II: Tracking a Victim's Past Trajectory

Active BAT Attacks: Tracking a Victim's Real-time Location

Attack III: Tracking a Victim's Real-time Location w/ Tunneling

Active BAT Attacks: Tracking a Victim's Real-time Location



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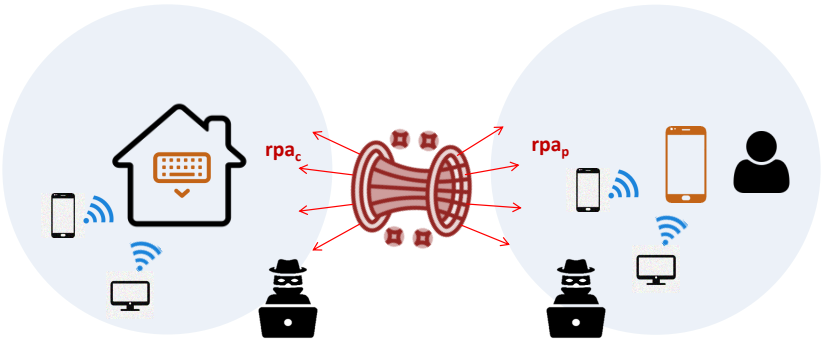
Active BAT Attacks: Tracking a Victim's Real-time Location

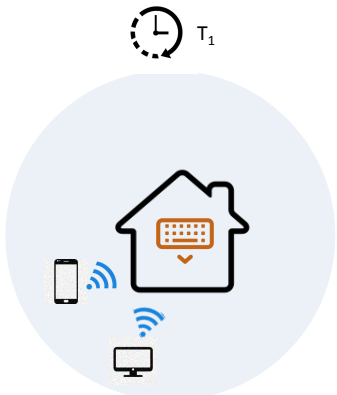


Attack III: Tracking a Victim's Real-time Location w/ Tunneling

Active BAT Attacks: Tracking a Victim's Real-time Location

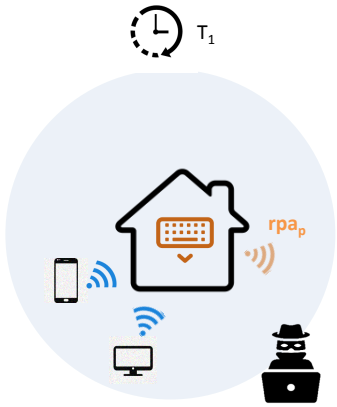
Attack IV: Tracking a Victim's Real-time Location w/o Tunneling

Active BAT Attacks: Tracking a Victim's Real-time Location



Attack IV: Tracking a Victim's Real-time Location w/o Tunneling

Active BAT Attacks: Tracking a Victim's Real-time Location



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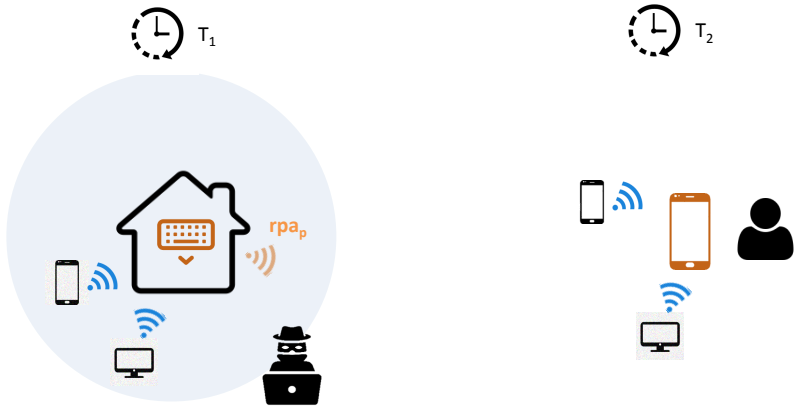

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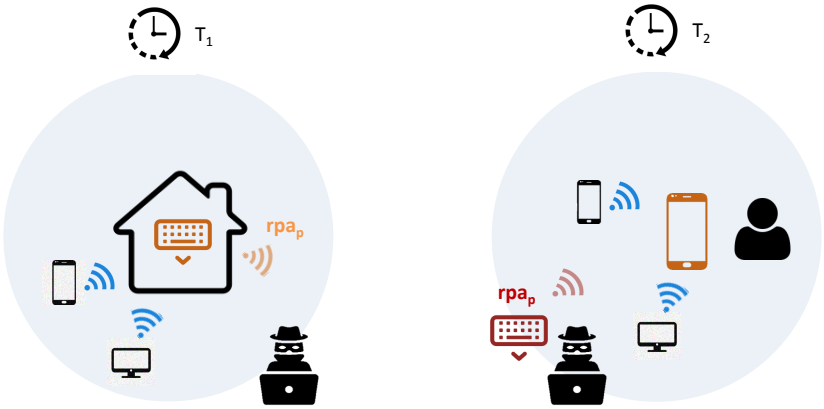

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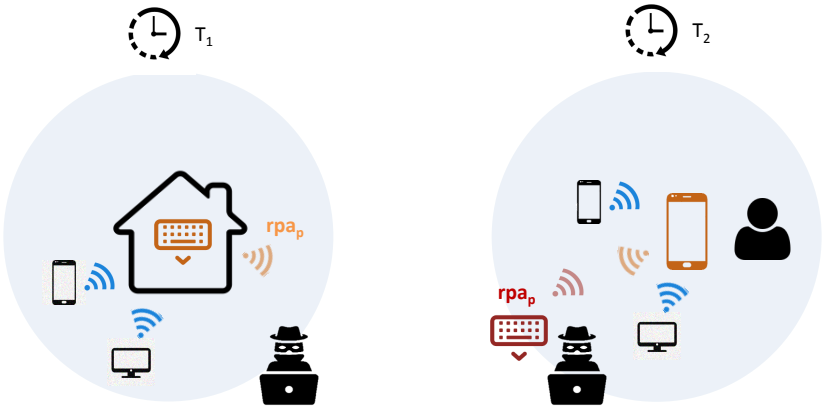
Active BAT Attacks: Tracking a Victim's Real-time Location



Attack IV: Tracking a Victim's Real-time Location w/o Tunneling

SABLE — Defense

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

SABLE — Defense

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || T || irk_p)$$

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(II) RPA Resolution

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$$rpa_c = prand_{24} || H_{24}(Prand_{24} || T || irk_c)$$

$irk_p = irk_c$ → $rpa_p = rpa_c$

Within a Threshold *Tx*

rpa_p

SABLE — Defense

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || T || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

No Identity Resolving Key

RPA Replay (rpa'$_p$)

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} || H_{24}(Prand_{24} || T || irk_c)$$

$irk_p = irk_c$ ➔ $rpa_p = rpa_c$

Within a Threshold *Tx*

rpa_p

SABLE — Defense

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)

(I) RPA Generation

$$rpa_p = prand_{24} || H_{24}(Prand_{24} || T || irk_p)$$

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

No Identity Resolving Key

RPA Replay (rpa'_p)

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

(II) RPA Resolution

Type	rand	Hash
01 (2bits)	0x00...3 (22bits)	0x00...04 (24bits)

$$rpa_c = prand_{24} || H_{24}(Prand_{24} || T || irk_c)$$

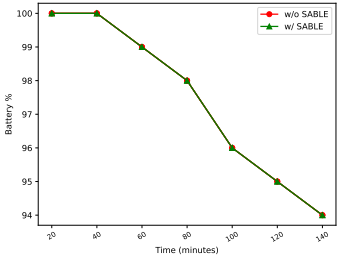
$irk_p = irk_c \rightarrow rpa_p = rpa_c$

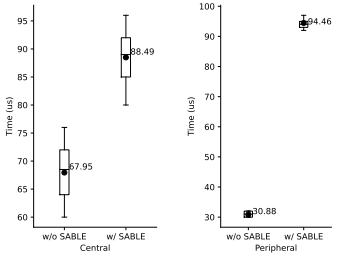
Within a Threshold *Tx*

rpa_p

rpa'_p

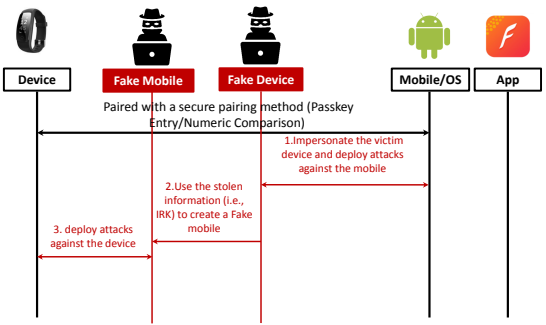
Performance of SABLE





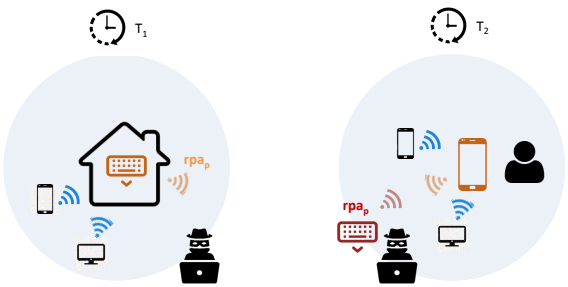
"When Good Becomes Evil: Tracking Bluetooth Low Energy Devices via Allowlist-based Side Channel and Its Countermeasure". Yue Zhang, and Zhiqiang Lin. *In Proceedings of the 29th ACM Conference on Computer and Communications Security (CCS 2022)*. November 2022

Lesson Learned (1/3): BLE Communication Can Be Downgraded



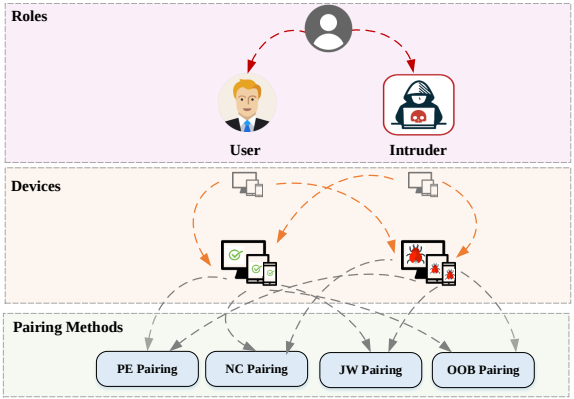
- Bluetooth low energy (BLE) pairing can be **downgraded**
- There are many stages that are not part of the pairing process, but they are, in fact, closely related to pairing security.
- A systematic analysis of the pairing process, including the **error handling** of BLE communication, is needed.

Lesson Learned (2/3): New Features Need Re-examinations



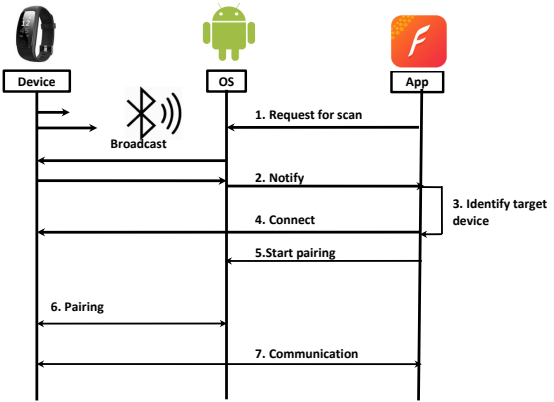
- BLE introduces multiple new features, some of which may **violate existing assumptions**
- Simliar to allowlist, those new features need to be **scrunitized**. For example, Cross-transport key derivation (CTKD); Authorization; The Connection Signature Resolving Key (CSRK).

Lesson Learned (3/3): Formal Method Can Help Improve BLE Security



- The specification (3,000+ pages) is often confusing and inconsistent across chapters.
- The confusion may lead to different vendors implement BLE protocols in quite different ways, for example, for error handling, and IRK use.
- Converting the Bluetooth specification to formal model (e.g., using NLP), and formally verify the entire protocol would help.
- See our NDSS'23 paper.

Bluetooth Security and Privacy



1. ~~BLEScope: Automatic Fingerprinting of Vulnerable BLE IoT Devices with Static UUIDs from Mobile Apps. In ACM CCS 2019~~
2. ~~FirmXRay: Detecting Bluetooth Link Layer Vulnerabilities From Bare-Metal Firmware. In ACM CCS 2020.~~
3. **Breaking Secure Pairing of Bluetooth Low Energy in Mobile Devices Using Downgrade Attacks**. In USENIX Security 2020
4. **When Good Becomes Evil: Tracking Bluetooth Low Energy Devices via Allowlist-based Side Channel and Its Countermeasure**". In ACM CCS 2022.
5. ~~Extrapolating Formal Analysis to Uncover Attacks in Bluetooth Passkey Entry Pairing. In NDSS 2023~~

Thank You

Rethinking the Security and Privacy of Bluetooth Low Energy

Zhiqiang Lin
Distinguished Professor of Engineering
zlin@cse.ohio-state.edu

10/25/2022