Uncovering Vulnerabilities in Bluetooth Devices with Automated Binary Analysis

Zhiqiang Lin
zlin@cse.ohio-state.edu

03/26/2021
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
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
History of Bluetooth

Dr. Jaap Haartsen started a project named Bluetooth.

1994

Bluetooth Prototype
History of Bluetooth

- Bluetooth Prototype
- 1994
- Bluetooth SIG
- 1998
History of Bluetooth

- **1994**: Bluetooth Prototype
- **1998**: Bluetooth 1.0+1.0b
  - Many bugs
  - Bluetooth Basic Rate (~700KB/s)
- **1999**: Bluetooth SIG
History of Bluetooth

- **1994**: Bluetooth Prototype
- **1998**: Bluetooth SIG
- **1999**: Bluetooth 1.0+1.0b
- **2001**: Bluetooth 1.1

- (~700KB/s)
- (~700KB/s)

- Fixed security issues.
- First marketable product version.
History of Bluetooth

- **1994**: Bluetooth Prototype
- **1998**: Bluetooth SIG
- **1999**: Bluetooth 1.0+1.0b
- **2001**: Bluetooth 1.1 (~700KB/s)
- **2004**: Bluetooth 2.0/2.1 +EDR (~2.1MB/s)
- **2009**: (~700KB/s)

- Introduced EDR (Enhanced Data Rate)
- Secure simple pairing (SSP) is introduced
History of Bluetooth

1994: Bluetooth Prototype

1998: Bluetooth SIG

1999: Bluetooth 1.0+1.0b

2001: Bluetooth 1.1

2004: Bluetooth 2.0/2.1 +EDR

2009: Introduced High-speed channel

2009: Bluetooth 3.0+HS

(~700KB/s)

(~2.1MB/s)

(~24MB/s)
History of Bluetooth

- **1994**: Bluetooth Prototype
- **1998**: Bluetooth 1.0+1.0b
- **2001**: Bluetooth 2.0/2.1 +EDR
- **2004**: Bluetooth 3.0+HS
- **2009**: Bluetooth 4.0
- **2010**: Bluetooth 4.0

- **~700KB/s**
- **~2.1MB/s**
- **~24MB/s**

### Key Features
- Low energy (LE) protocol for IoT;
- 128-bit encryption/LE Privacy and Whitelisting
History of Bluetooth

1994 - Bluetooth Prototype
1998 - Bluetooth 1.0+1.0b
1999 - Bluetooth 1.1
2001 - Bluetooth 2.0/2.1 +EDR
2004 - Bluetooth 3.0+HS
2009 - Bluetooth 4.0
2010 - Bluetooth 4.1
2013 - (~700KB/s)
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• Low energy (LE) protocol for IoT;
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References

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## History of Bluetooth

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Speed</th>
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<tr>
<td>2013</td>
<td>Bluetooth 4.1</td>
<td>~24MB/s</td>
</tr>
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<td>2014</td>
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- 128-bit encryption/LE Privacy and Whitelisting
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- Bluetooth SIG
  (~700KB/s)

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- Bluetooth 3.0+HS
  (~24MB/s)

2009
- Bluetooth 4.0
  (~24MB/s)

2010
- Bluetooth 4.1

2013
- Bluetooth 4.2

2014
- Bluetooth 5.0
  (~50MB/s)

Significant increase in range and data transfer rate


History of Bluetooth

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2014: Bluetooth 5.0 (~50MB/s)
2016: Bluetooth 5.1/5.2 (~50MB/s)
2019: Bluetooth 5.0 (~50MB/s)
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- **2014**: Bluetooth 4.1 (~24MB/s)
- **2016**: Bluetooth 4.2
- **2019**: Bluetooth 5.0 (~50MB/s)
- **2020**: Bluetooth 5.1/5.2 (~50MB/s)
Total Annual Bluetooth Device Shipments [SIG20]
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Introduction

Background

BLESCOPE [ZWLZ19]

FirmXRay [WLZ20]

Future Work

Takeaway

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Total Annual Bluetooth Device Shipments [SIG20]
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Bluetooth IoT Devices and Companion Apps

BLE IoT Devices

Companion Mobile Apps

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Bluetooth IoT Devices and Companion Apps

BLE IoT Devices

Companion Mobile Apps
The General Workflow of Device Communication in TCP/IP Setting
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1. Listen to port 443
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2. \(<\text{Request, 192.168.1.1, port 443}>\)
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3. Connect
4. Authentication (Transport Layer Security / Secure Sockets Layer)
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5. Authentication (Application level)
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1. Request for scan
2. Notify
3. Identify target device
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1. Request for scan
2. Notify
3. Identify target device
4. Connect
5. Start pairing
6. Pairing feature exchange (Negotiate key entropy and elliptic curve)
7. Authentication and encryption
8. Key distribution (e.g. IRK)
9. Authentication (App level)
10. Communication

Authentication (Pairing)
The General Workflow of BLE IoT Devices and Companion Apps

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2. Notify
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10. Communication

Device

OS

App

Broadcast

Authentication (Pairing)
#### State-of-the-Art

**BLE-Guardian [KKS16]**

**Protecting Privacy of BLE Device Users.** In *USENIX Security 2016.*

- Defending against sensitive information leakage during broadcasting
State-of-the-Art

BlueShield [WNK+20a]

- Detecting spoofing BLE devices during broadcasting.
**State-of-the-Art**

**KNOB [ATR19]**


▶ An attacker forces victims to agree on an encryption key with only one byte of entropy.

▶ Windows/iOS have fixed it
State-of-the-Art

BIAS [ATR20]


- An attacker forces victims to use P-192 curve instead of using P-256 curve.
State-of-the-Art

BLESA [WNK\textsuperscript{+20b}]


- Fake BLE device attacks against mobiles.
- Android and iOS have fixed it
State-of-the-Art


▶ Brute force attacks against long term keys.
▶ Bluetooth after 4.1 is no longer vulnerable
Bluetooth Method Confusion [VTPFG21]

Method Confusion Attack on Bluetooth Pairing. In Oakland 2021

- Man in the middle attack (similar to the active attacks against DH)
- Attackers manipulates the pairing methods and target the ECDH key exchange process.
BadBluetooth [XDL+19]


- Fake devices manipulate BLE communication due to the lack of app-level authentication.
- Defense is up to the apps
Inside Job: Understanding and Mitigating the Threat of External Device Mis-Bonding on Android.
In NDSS 2014.

- Malicious apps manipulate BLE communication due to lack of app-level authentication.
- Defense is up to the devices
State-of-the-Art

Co-Located Attacks [SB19]


- Large-scale analysis of mis-bonding issues.
State-of-the-Art

Gattacking [Jas16]


- Poorly designed communication protocols are subject to various attacks (e.g., replay attacks).
State-of-the-Art

Frankenstein [RCGH20]


- BLE Fuzzing tool injects HCI traffic or Bluetooth frames into Bluetooth communication in order to uncover Remote Code Execution bugs.
Our Contributions

### BLEScope [ZWLZ19]

### FirmXRay [WLZ20]
FirmXRay: Detecting Bluetooth Link Layer Vulnerabilities From Bare-Metal Firmware. In CCS 2020.

### Downgrade Attacks [ZWD+20]
Our **BLEScope [ZWLZ19]** Work

**BLE-Guardian [KKS16]**

**BlueShield [WNK+20]**

**FirmXRay [WLZ20]**

**Future Work**

**Takeaway**

**References**

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**BLEScope [ZWLZ19]**

The Key Finding in **BLEScope** [ZWLZ19]

1. UUIDs are broadcasted by BLE IoT devices to nearby phones.
2. UUIDs are static.
3. Mobile apps contain UUIDs.
4. Mobile apps identify target BLE IoT devices based on their broadcasted UUIDs.
Attack: How to Fingerprint a BLE IoT Device with Static UUIDs
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1. Static Analysis
   - Sniff Advertised BLE Packets

2. Sniffed UUIDs

3. Static UUIDs

4. References

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BLEScope [ZWLZ19]

FirmXRay [WLZ20]

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Attack: How to Fingerprint a BLE IoT Device with Static UUIDs

Static Analysis → Static UUIDs → Fingerprinting

Sniff Advertised BLE Packets → Sniffed UUIDs → BLE IoT Device
Attack: How to Fingerprint a BLE IoT Device with Static UUIDs

1. Sniff Advertised BLE Packets
2. Sniffed UUIDs
3. Static Analysis
4. Static UUUIDs
5. Vulnerabilities
6. Fingerprinting

References

Google Play
Attack: How to Fingerprint a BLE IoT Device with Static UUIDs

Static Analysis

Static UUIDs

Vulnerabilities

Fingerprinting

Vulnerable Device

Sniff Advertised BLE Packets

Sniffed UUIDs

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Introducing BLEScope


1. **Novel Discovery.** We are the first to discover BLE IoT devices can be fingerprinted with static UUIDs.

2. **Effective Techniques.** We have implemented an automatic tool BLEScope to harvest UUIDs and detect vulnerabilities from mobile apps.

3. **Evaluation.** We have tested our tool with 18,166 BLE mobile apps from Google Play store, and found 168,093 UUIDs and 1,757 vulnerable BLE IoT apps.

4. **Countermeasures.** We present channel-level protection, app-level protection, and protocol-level protection (with dynamic UUID generation).
Overview of BLEScope
Overview of BLEScope

1. Android APKs
   → Value-set Analysis

2. Sniffed Advertisement UUIDs
   → UUID & Hierarchy
   → UUID Fingerprinting
   → Fingerprint-able Devices

- UUID Fingerprinting
- Value-set Analysis UUID & Hierarchy
- Android APKs
- Sniffed Advertisement UUIDs
Overview of BLEScope

1. Android APKs
   - Value-set Analysis
   - App-level Vulnerability Identification

2. UUID & Hierarchy
   - Sniffed Advertisement UUIDs
   - UUID Fingerprinting

3. Unauthorized Accessible Devices
   - Sniffable Devices
   - Fingerprint-able Devices
Overview of BLEScope

Challenges

1. How to extract UUIDs from mobile apps
2. How to reconstruct UUID hierarchy
3. How to identify flawed vulnerable authentication apps

Solutions: Using \textit{Automated Program Analysis}

1. Resolving UUIDs using context and \textit{value-set analysis}
2. Reconstructing UUID hierarchy with \textit{control dependence}
3. Identifying flawed authentication with \textit{data dependence}
Results from Google Play Store

**IoT Mobile App Collection**

1. We downloaded 2 million mobile apps from Google Play as of April 2019.
2. We identified BLE IoT apps by searching for after-connection BLE APIs.
3. 18,166 BLE IoT apps are found for our analysis.
Results from Google Play Store

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<td># Apps Support BLE</td>
<td>18,166</td>
<td>100.0</td>
</tr>
<tr>
<td># &quot;Just Works&quot; Pairing</td>
<td>11,141</td>
<td>61.3</td>
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<tr>
<td># Vulnerable Apps</td>
<td>1,757</td>
<td>15.8</td>
</tr>
<tr>
<td># Absent Cryptographic Usage</td>
<td>1,510</td>
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</tr>
<tr>
<td># Flawed Authentication</td>
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Table: Insecure app identification result.
Results from Google Play Store

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<th>Flawed Auth.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health &amp; Fitness</td>
<td>3,849</td>
<td>2,639</td>
<td>221</td>
<td>207</td>
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<tr>
<td>Tools</td>
<td>2,833</td>
<td>1,895</td>
<td>385</td>
<td>362</td>
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<td>Lifestyle</td>
<td>2,173</td>
<td>1,081</td>
<td>147</td>
<td>141</td>
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<td>Business</td>
<td>1,660</td>
<td>972</td>
<td>90</td>
<td>85</td>
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<tr>
<td>Travel &amp; Local</td>
<td>967</td>
<td>582</td>
<td>90</td>
<td>87</td>
</tr>
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</table>

Table: Top 5 category of the IoT apps.
Results from Our Field Test

**BLE Sniffer**
- Raspberry-Pi
- Parani-UD100 (Bluetooth adapter)
- Antenna RP-SMA-R/A (1km range)
- SIM7000A GPS module (GPS sensor)
Results from Our Field Test
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<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td># Unique BLE Device</td>
<td>30,862</td>
<td></td>
</tr>
<tr>
<td># Unique BLE Device w. UUID</td>
<td>5,822</td>
<td>18.9</td>
</tr>
<tr>
<td># Fingerprintable</td>
<td>5,509</td>
<td>94.6</td>
</tr>
<tr>
<td># Vulnerable</td>
<td>431</td>
<td>7.4</td>
</tr>
<tr>
<td># Sniffable</td>
<td>369</td>
<td>6.7</td>
</tr>
<tr>
<td># Unauthorized Accessible</td>
<td>342</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table: Experimental result of our field test.
Results from Our Field Test

<table>
<thead>
<tr>
<th>Company Name</th>
<th># Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Google</td>
<td>2,436</td>
</tr>
<tr>
<td>Tile, Inc.</td>
<td>441</td>
</tr>
<tr>
<td>-</td>
<td>243</td>
</tr>
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<td>208</td>
</tr>
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<td>Logitech International SA</td>
<td>131</td>
</tr>
<tr>
<td>Nest Labs Inc.</td>
<td>114</td>
</tr>
<tr>
<td>Google</td>
<td>92</td>
</tr>
<tr>
<td>Hewlett-Packard Company</td>
<td>74</td>
</tr>
<tr>
<td>-</td>
<td>46</td>
</tr>
<tr>
<td>-</td>
<td>44</td>
</tr>
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Table: Top 10 devices in the field test.
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<td>7</td>
</tr>
<tr>
<td>Car Dongle</td>
<td>6</td>
</tr>
<tr>
<td>Key Finder A</td>
<td>6</td>
</tr>
<tr>
<td>Smart Lamp</td>
<td>5</td>
</tr>
<tr>
<td>Key Finder B</td>
<td>5</td>
</tr>
<tr>
<td>Smart Toy A</td>
<td>4</td>
</tr>
<tr>
<td>Smart VFD</td>
<td>4</td>
</tr>
<tr>
<td>Air Condition Sensor</td>
<td>4</td>
</tr>
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<td>Smart Toy B</td>
<td>4</td>
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<td>Accessibility Device</td>
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Table: Top 10 vulnerable devices.
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![Field Test Results](image)
Our FirmXRay [WLZ20] Work

BLE Link Layer Vulnerabilities

- **Identity Tracking**: Configure static MAC address during broadcast [DPCM16].
BLE Link Layer Vulnerabilities

1. Identity Tracking. Configure static MAC address during broadcast [DPCM16].
2. Active MITM. Just Works is adopted as the pairing method.
BLE Link Layer Vulnerabilities

Vulnerabilities

1. **Identity Tracking.** Configure static MAC address during broadcast [DPCM16].

2. **Active MITM.** Just Works is adopted as the pairing method.

3. **Passive MITM.** Legacy pairing is used during key exchange [ble14].
BLE Link Layer Vulnerabilities

**Vulnerabilities**

1. **Identity Tracking.** Configure static MAC address during broadcast [DPCM16].
2. **Active MITM.** Just Works is adopted as the pairing method.
3. **Passive MITM.** Legacy pairing is used during key exchange [ble14].

**Identification**

1. Traffic analysis
2. Mobile app analysis
BLE Link Layer Vulnerabilities

Vulnerabilities

1. **Identity Tracking**: Configure static MAC address during broadcast [DPCM16].
2. **Active MITM**: Just Works is adopted as the pairing method.
3. **Passive MITM**: Legacy pairing is used during key exchange [ble14].

Identification

1. Traffic analysis
2. Mobile app analysis
3. Firmware analysis
An Example of a Just Works Pairing Vulnerability

Read Only Memory

```
1 243a8    mov    r2, #0x0
2 243aa   orr r2, #0x1
3  243ac   and    r2, #0xe1
4  243ae   add    r2, #0xc
5  243b0     and   r2, #0xdf
6  243b2   ldr    r1, [0x260c8]
7  243b4   str    r2, [r1, #0x0]
...
8 25f44   ldr    r2, [0x260c8]
9 25f46   mov    r1, #0x0
10 25f48   svc   0x7f
  // SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8  0x20003268
    // ble_gap_secParms_t*
```

Register Values

- r1 = 0x0
- r2 = 0x0
An Example of a Just Works Pairing Vulnerability

Read Only Memory

1 243a8  mov    r2, #0x0
2 243aa  orr    r2, #0x1
3 243ac  and    r2, #0xe1
4 243ae  add    r2, #0xc
5 243b0  and    r2, #0xdf
6 243b2  ldr    r1, [0x260c8]
7 243b4  str    r2, [r1, #0x0]
8 25f44  ldr    r2, [0x260c8]
9 25f46  mov    r1, #0x0
10 25f48  svc   0x7f

// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8  0x20003268

// ble_gap_sec_parms_t*

Register Values

r1 = 0x0
r2 = 0xD
An Example of a Just Works Pairing Vulnerability

Read Only Memory

1 243a8   mov    r2, #0x0
2 243aa   orr r2, #0x1
3  243ac   and    r2, #0xe1
4 243ae   add  r2, #0xc
5 243b0   and  r2, #0xdf
6 243b2  ldr  r1, [0x260c8]
7 243b4  str  r2, [r1, #0x0]
8 25f44  ldr  r2, [0x260c8]
9 25f46  mov  r1, #0x0
10 25f48  svc  0x7f

// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8  0x20003268
// ble_gap_sec_parms_t*

Random Access Memory

Struct ble_gap_sec_params_t

20003268  uint8 pairing_feature

20003269  uint8 min_key_size
20003270  uint8 max_key_size
20003271  ble_gap_sec_kdist_t kdist_own
20003275  ble_gap_sec_kdist_t kdist_peer

Register Values

r1 = 0x20003268
r2 = 0xD
An Example of a Just Works Pairing Vulnerability

Read Only Memory

1 243a8  mov r2, #0x0
2 243aa  orr r2, #0x1
3 243ac  and r2, #0xe1
4 243ae  add r2, #0xc
5 243b0  and r2, #0xdf
6 243b2  ldr r1, [0x260c8]
7 243b4  str r2, [r1, #0x0]

Random Access Memory

Struct ble_gap_sec_params_t

20003268  uint8 pairing_feature = 0xD

20003269  uint8 min_key_size
20003270  uint8 max_key_size
20003271  ble_gap_sec_kdist_t kdist_own
20003275  ble_gap_sec_kdist_t kdist_peer

Register Values

r1 = 0x20003268
r2 = 0xD

r1 = 0x20003268
r2 = 0xD
An Example of a Just Works Pairing Vulnerability

Read Only Memory

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<tbody>
<tr>
<td>1</td>
<td>243a8</td>
<td>mov</td>
<td>r2, #0x0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>243aa</td>
<td>orr</td>
<td>r2, #0x1</td>
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</tr>
<tr>
<td>3</td>
<td>243ac</td>
<td>and</td>
<td>r2, #0xe1</td>
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<td></td>
<td></td>
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<tr>
<td>4</td>
<td>243ae</td>
<td>add</td>
<td>r2, #0xc</td>
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</tr>
<tr>
<td>5</td>
<td>243b0</td>
<td>and</td>
<td>r2, #0xdf</td>
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<tr>
<td>6</td>
<td>243b2</td>
<td>ldr</td>
<td>r1, [0x260c8]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>243b4</td>
<td>str</td>
<td>r2, [r1, #0x0]</td>
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<td>...</td>
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<tr>
<td>8</td>
<td>25f44</td>
<td>ldr</td>
<td>r2, [0x260c8]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>25f46</td>
<td>mov</td>
<td>r1, #0x0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>25f48</td>
<td>svc</td>
<td>0x7f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>// SD_BLE_GAP_SEC_PARAMS_REPLY</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>260c8</td>
<td>0x20003268</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>// ble_gap_secParms_t</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Random Access Memory

```
struct ble_gap_sec_params_t

uint8 pairing_feature = 0xD
20003268
uint8 min_key_size
20003269
uint8 max_key_size
20003270
ble_gap_sec_kdist_t kdist_own
20003271
ble_gap_sec_kdist_t kdist_peer
20003275
```

Register Values

- `r1 = 0x0`
- `r2 = 0x20003268`
An Example of a Just Works Pairing Vulnerability

Read Only Memory

```
1 243a8 mov r2, #0x0
2 243aa orr r2, #0x1
3 243ac and r2, #0xe1
4 243ae add r2, #0xc
5 243b0 and r2, #0xdf
6 243b2 ldr r1, [0x260c8]
7 243b4 str r2, [r1, #0x0]
8 25f44 ldr r2, [0x260c8]
9 25f46 mov r1, #0x0
10 25f48 svc 0x7f
```

// SD_BLE_GAP_SEC_PARAMS_REPLY

Random Access Memory

```
Struct ble_gap_sec_params_t

20003268 uint8 pairing_feature = 0xD

<table>
<thead>
<tr>
<th>BOND</th>
<th>MITM</th>
<th>IO</th>
<th>OOB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

// BOND = 1, MITM = 0
// IO   = 3, OOB = 0

20003269 uint8 min_key_size
20003270 uint8 max_key_size
20003271 ble_gap_sec_kdist_t kdist_own
20003275 ble_gap_sec_kdist_t kdist_peer
```

Register Values

```
r1 = 0x0
r2 = 0x20003268
```

References

- ZWLZ19
- WLZ20
An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling

Read Only Memory

```
1  243a8  mov r2, #0x0
2  243aa  orr r2, #0x1
3  243ac  and r2, #0xe1
4  243ae  add r2, #0xc
5  243b0  and r2, #0xdf
6  243b2  ldr r1, [0x260c8]
7  243b4  str r2, [r1, #0x0]
...
8  25f44  ldr r2, [0x260c8]
9  25f46  mov r1, #0x0
10 25f48  svc 0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8  0x20003268
// ble_gap_sec_params_t*
```

Random Access Memory

```
Struct ble_gap_sec_params_t

20003268  uint8 pairing_feature = 0xD

<table>
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<tr>
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<th>MITM</th>
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<th>OOB</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
// BOND = 1, MITM = 0
// IO   = 3, OOB = 0
20003269  uint8 min_key_size
20003270  uint8 max_key_size
20003271  ble_gap_sec_kdist_t kdist_own
20003275  ble_gap_sec_kdist_t kdist_peer
```

Register Values

- r1 = 0x0
- r2 = 0x20003268
An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling

Read Only Memory

1 243a8  mov r2, #0x0
2 243aa  orr r2, #0x1
3 243ac  and r2, #0xe1
4 243ae  add r2, #0xc
5 243b0  and r2, #0xdf
6 243b2  ldr r1, [0x260c8]
7 243b4  str r2, [r1, #0x0]
...  
8 25f44  ldr r2, [0x260c8]
9 25f46  mov r1, #0x0
10 25f48  svc 0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...  
11 260c8  0x20003268
// ble_gap_sec_parms_t*

Recognize data structures

Random Access Memory

Struct ble_gap_sec_params_t

20003268  uint8 pairing_feature = 0xD

<table>
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<th>MITM</th>
<th>IO</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
// BOND = 1, MITM = 0
// IO   = 3, OOB  = 0

20003269  uint8 min_key_size
20003270  uint8 max_key_size
20003271  ble_gap_sec_kdist_t kdist_own
20003275  ble_gap_sec_kdist_t kdist_peer

Register Values

r1 = 0x0
r2 = 0x20003268
An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling

Read Only Memory

1 243a8 mov r2, #0x0
2 243aa orr r2, #0x1
3 243ac and r2, #0xe1
4 243ae add r2, #0xc
5 243b0 and r2, #0xdf
6 243b2 ldr r1, [0x260c8]
7 243b4 str r2, [r1, #0x0]
...
8 25f44 ldr r2, [0x260c8]
9 25f46 mov r1, #0x0
10 25f48 svc 0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8 0x20003268
// ble_gap_sec_parms_t

Random Access Memory

Struct ble_gap_sec_params_t

20003268 uint8 pairing_feature = 0xD

<table>
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<th>MITM</th>
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<th>OOB</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

20003269 uint8 min_key_size
20003270 uint8 max_key_size
20003271 ble_gap_sec_kdist_t kdist_own
20003275 ble_gap_sec_kdist_t kdist_peer

Value computation

Register Values

r1 = 0x0
r2 = 0x20003268
FirmXRay Overview

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Detection Policies

Constraints

Disassembler

$X = \text{argmax}_{x \in R} N(x)$
Robust Firmware Disassembling

Correct Base 0x1B000

Function Foo()
push {r3, r4, r5, lr}

(1) Absolute Function Pointer

(2) Absolute String Pointer
Robust Firmware Disassembling

Incorrect Base 0x0

05452  ldr  r0, \texttt{pc+0x72}
05454  blx  r0\rightarrow 0x22A90
...
054c4  0x22A90
...
Function Foo()
07a90  push  \{r3, r4, r5, lr\}

Correct Base 0x1B000

20452  ldr  r0, \texttt{pc+0x72}
20454  blx  r0\rightarrow 0x22A90
...
204c4  0x22A90
...
Function Foo()
22a90  push  \{r3, r4, r5, lr\}

(1) Absolute Function Pointer

04e52  ldr  r0, \texttt{pc+0x146}
04e54  ldmia  r0\rightarrow 0x23058, \{r4, r5, r6\}
...
04f98  0x23058
...
08058  "KinsaHealth"

(2) Absolute String Pointer
Robust Firmware Disassembling

Base
0x0

05452 ldr r0, pc+0x72
05454 blx r0=>0x22A90
...
054c4 0x22A90
...
Function Foo()
07a90 push {r3, r4, r5, lr}

04e52 ldr r0, pc+0x146
04e54 ldmia r0=>0x23058, {r4, r5, r6}
...
04f98 0x23058
...
08058 "KinsaHealth"
Robust Firmware Disassembling

05452  ldr  r0, pc+0x72
05454  blx  r0=>0x22A90
...  
054C4  0x22A90
...  
Function Foo()
07A90  push  {r3, r4, r5, lr}

Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058
Robust Firmware Disassembling

Base 0x0

Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058

N(0x1B000) = 2
Robust Firmware Disassembling

Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058

N(0x1B000) = 2
Precise Data Structure Recognition

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Read Only Memory

1 243a8 mov r2, #0x0
2 243aa orr r2, #0x1
3 243ac and r2, #0xe1
4 243ae add r2, #0xc
5 243b0 and r2, #0xdf
6 243b2 ldr r1, [0x260c8]
7 243b4 str r2, [r1,#0x0]
8 25f44 ldr r2, [0x260c8]
9 25f46 mov r1, #0x0
10 25f48 svc 0x7f
   // SD_BLE_GAP_SEC_PARAMS_REPLY(r0, r1, r2)
11 260c8 0x20003268
   // ble_gap_sec_parms_t*
Configuration Value Resolution

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Read Only Memory

1 243a8 mov r2, #0x0
2 243aa orr r2, #0x1
3 243ac and r2, #0xe1
4 243ae add r2, #0xc
5 243b0 and r2, #0xdf
6 243b2 ldr r1, [0x260c8]
7 243b4 str r2, [r1, #0x0]

... 8 25f44 ldr r2, [0x260c8]
9 25f46 mov r1, #0x0
10 25f48 svc 0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8 0x20003268
// ble_gap_sec_parms_t*

Program Path
Configuration Value Resolution

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Read Only Memory

1 243a8  mov  r2, #0x0
2 243aa  orr r2, #0x1
3 243ac  and r2, #0xe1
4 243ae  add r2, #0xc
5 243b0  and r2, #0xdf
6 243b2  ldr r1, [0x260c8]
7 243b4  str r2, [r1, #0x0]
8 25f44  ldr  r2, [0x260c8]
9 25f46  mov r1, #0x0
10 25f48  svc 0x7f
   // SD_BLE_GAP_SEC_PARAMS_REPLY
11 260c8 0x20003268
   // ble_gap_sec_Parms_t*

Program Path

1dr  r2, [0x260c8]
str  r2, [r1, #0x0]
Configuration Value Resolution

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Read Only Memory

1 243a8  mov    r2, #0x0
2 243aa  orr    r2, #0x1
3 243ac  and   r2, #0xe1
4 243ae  add   r2, #0xc
5 243b0  and   r2, #0xdf
6 243b2  ldr   r1, [0x260c8]
7 243b4  str   r2, [r1, #0x0]
8 25f44  ldr   r2, [0x260c8]
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10 25f48  svc  0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
11 260c8  0x20003268
// ble_gap_sec_parms_t*

Program Path

1  ldr  r2, [0x260c8]
2  str  r2, [r1, #0x0]
3  ldr  r1, [0x260c8]
4  and  r2, #0xdf
5  add  r2, #0xc
6  and  r2, #0xe1
7  orr  r2, #0x1
8  mov  r2, #0x0
Configuration Value Resolution

Robust Firmware Disassembling

Precise Data Structure Recognition

Configuration Value Resolution

Program Path

```
ldr r2, [0x260c8]
str r2, [r1, #0x0]
ldr r1, [0x260c8]
and r2, #0xdf
add r2, #0xc
and r2, #0xe1
orr r2, #0x1
mov r2, #0x0
r2 = 0x20003268
```

Read Only Memory

```
1 243a8  mov    r2, #0x0
2 243aa  orr    r2, #0x1
3  243ac  and    r2, #0xe1
4  243ae  add    r2, #0xc
5  243b0  and    r2, #0xdf
6  243b2  ldr    r1, [0x260c8]
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...  
8 25f44   ldr    r2, [0x260c8]
9 25f46   mov    r1, #0x0
10 25f48  svc   0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...  
11 260c8  0x20003268
// ble_gap_sec_parms_t*
```
### Configuration Value Resolution

<table>
<thead>
<tr>
<th>Policy</th>
<th>SDK Function Name</th>
<th>Reg. Index</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>SD_BLE_GAP_ADDR_SET</td>
<td>0</td>
<td>Configure the MAC address</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_GAP_APPEARANCE_SET</td>
<td>0</td>
<td>Set device description</td>
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<tr>
<td></td>
<td>SD_BLE_GATTS_SERVICE_ADD</td>
<td>0, 1</td>
<td>Add a BLE GATT service</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_GATTS_CHARACTERISTIC_ADD</td>
<td>2</td>
<td>Add a BLE GATT characteristic</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_UUID_VS_ADD</td>
<td>0</td>
<td>Specify the UUID base</td>
</tr>
<tr>
<td></td>
<td>GAP_ConfigDeviceAddr*</td>
<td>0</td>
<td>Setup the address type</td>
</tr>
<tr>
<td></td>
<td>GATTServApp_RegisterService*</td>
<td>0</td>
<td>Register BLE GATT service</td>
</tr>
<tr>
<td>(i)</td>
<td>SD_BLE_GAP_SEC_PARAMS_REPLY</td>
<td>2</td>
<td>Reply peripheral pairing features</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_GAP_AUTH</td>
<td>1</td>
<td>Reply central pairing features</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_GAP_AUTH_KEY_REPLY</td>
<td>1, 2</td>
<td>Reply with an authentication key</td>
</tr>
<tr>
<td></td>
<td>SD_BLE_GATTS_CHARACTERISTIC_ADD</td>
<td>2</td>
<td>Add a BLE GATT characteristic</td>
</tr>
<tr>
<td></td>
<td>GAPBondMgr_SetParameter*</td>
<td>2</td>
<td>Setup pairing parameters</td>
</tr>
<tr>
<td></td>
<td>GATTServApp_RegisterService*</td>
<td>0</td>
<td>Register BLE GATT service</td>
</tr>
<tr>
<td>(ii)</td>
<td>SD_BLE_GAP_LESC_DHKEY_REPLY</td>
<td>0</td>
<td>Reply with a DH key</td>
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<tr>
<td></td>
<td>GAPBondMgr_SetParameter*</td>
<td>2</td>
<td>Setup pairing parameters</td>
</tr>
<tr>
<td>(iii)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Robust Firmware Disassembling**

**Precise Data Structure Recognition**

**Configuration Value Resolution**
Firmware Collection
Firmware Collection

2M Free Apps
Firmware Collection

2M Free Apps ➔ Filter ➔ 13K BLE Apps
Firmware Collection

2M Free Apps → Filter → 13K BLE Apps → Unpack → Extract → 793 Firmware
Firmware Collection

2M Free Apps

13K BLE Apps

793 Firmware

768 Nordic

25 TI
Firmware Categorization

- Firmware categorization
Firmware Categorization

▶ Firmware categorization
  ▶ Descriptive APIs (e.g., SD_BLE_GAP_APPEARANCE_SET)
Firmware Categorization

- Firmware categorization
  - Descriptive APIs (e.g., SD_BLE_GAP_APPEARANCE_SET)
  - Mobile app descriptions
Firmware Categorization

- Firmware categorization
  - Descriptive APIs (e.g., SD_BLE_GAP_APPEARANCE_SET)
  - Mobile app descriptions

### Table: Top categories of firmware.

<table>
<thead>
<tr>
<th>Category</th>
<th># Firmware</th>
<th># Device</th>
<th>Avg. Size (KB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nordic-based Firmware</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wearable</td>
<td>204</td>
<td>138</td>
<td>98.2</td>
</tr>
<tr>
<td>Others</td>
<td>76</td>
<td>22</td>
<td>223.5</td>
</tr>
<tr>
<td>Sensor</td>
<td>67</td>
<td>51</td>
<td>80.9</td>
</tr>
<tr>
<td>Tag (Tracker)</td>
<td>58</td>
<td>41</td>
<td>84.2</td>
</tr>
<tr>
<td>Robot</td>
<td>41</td>
<td>21</td>
<td>117.7</td>
</tr>
<tr>
<td>Medical Devices</td>
<td>41</td>
<td>21</td>
<td>138.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>793</td>
<td>538</td>
<td>102.7</td>
</tr>
<tr>
<td><strong>TI-based Firmware</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>19</td>
<td>19</td>
<td>132.9</td>
</tr>
<tr>
<td>Smart Lock</td>
<td>2</td>
<td>2</td>
<td>46.3</td>
</tr>
<tr>
<td>Smart Toy</td>
<td>2</td>
<td>2</td>
<td>47.8</td>
</tr>
<tr>
<td>Medical Devices</td>
<td>1</td>
<td>1</td>
<td>70.2</td>
</tr>
<tr>
<td>Others</td>
<td>1</td>
<td>1</td>
<td>76.7</td>
</tr>
</tbody>
</table>

Table: Top categories of firmware.
Firmware Categorization

- Firmware categorization
  - Descriptive APIs (e.g., SD_BLE_GAP_APPEARANCE_SET)
  - Mobile app descriptions

- Firmware aggregation
  - Aggregate different versions of firmware of the same device
  - The 793 firmware represent 538 real devices

<table>
<thead>
<tr>
<th>Category</th>
<th># Firmware</th>
<th># Device</th>
<th>Avg. Size (KB)</th>
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<td>Total</td>
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<td>538</td>
<td>102.7</td>
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</table>

Table: Top categories of firmware.
Identity Tracking Vulnerability Identification

Among the 538 devices, nearly all of them (98.1%) have configured random static addresses that do not change periodically.
 Experiment Results

Identity Tracking Vulnerability Identification

Among the 538 devices, nearly all of them (98.1%) have configured random static addresses that do not change periodically.

<table>
<thead>
<tr>
<th>Firmware Name</th>
<th>Mobile App</th>
<th>Category</th>
<th># Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>cogobeacon</td>
<td>com.aegismobility.guardian</td>
<td>Car Accessory</td>
<td>4</td>
</tr>
<tr>
<td>sd_bl</td>
<td>fr.solem.solemwf</td>
<td>Agricultural Equip.</td>
<td>2</td>
</tr>
<tr>
<td>LRFL_nRF52</td>
<td>fr.solem.solemwf</td>
<td>Agricultural Equip.</td>
<td>2</td>
</tr>
<tr>
<td>orb</td>
<td>one.shade.app</td>
<td>Smart Light</td>
<td>1</td>
</tr>
<tr>
<td>sd_bl</td>
<td>com.rainbird</td>
<td>Agricultural Equip.</td>
<td>1</td>
</tr>
</tbody>
</table>

Table: Firmware using private MAC address.
Active MITM Vulnerability Identification

385 (71.5%) devices use Just Works pairing, which essentially does not provide any protection against active MITM attacks at the BLE link layer.
Active MITM Vulnerability Identification

385 (71.5%) devices use Just Works pairing, which essentially does not provide any protection against active MITM attacks at the BLE link layer.

<table>
<thead>
<tr>
<th>Item</th>
<th>N</th>
<th>T</th>
<th>Total</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td># Total Device</td>
<td>513</td>
<td>25</td>
<td>538</td>
<td>100</td>
</tr>
<tr>
<td># Device w/ active MITM vulnerability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># Device w/ Just Works pairing only</td>
<td>317</td>
<td>1</td>
<td>318</td>
<td>59.1</td>
</tr>
<tr>
<td># Device w/ flawed Passkey implementation</td>
<td>37</td>
<td>0</td>
<td>37</td>
<td>6.9</td>
</tr>
<tr>
<td># Device w/ flawed OOB implementation</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>5.6</td>
</tr>
<tr>
<td># Device w/ secure pairing</td>
<td>6</td>
<td>24</td>
<td>30</td>
<td>3.8</td>
</tr>
<tr>
<td># Device w/ correct Passkey implementation</td>
<td>3</td>
<td>24</td>
<td>27</td>
<td>3.4</td>
</tr>
<tr>
<td># Device w/ correct OOB implementation</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table: Pairing configurations of devices (N:Nordic, T:TI).
Experiment Results

Passive MITM Vulnerability Identification

98.5% of the devices fail to enforce LESC pairing, and thus they can be vulnerable to passive MITM attacks if there is no application-layer encryption.
Passive MITM Vulnerability Identification

98.5% of the devices fail to enforce LESC pairing, and thus they can be vulnerable to passive MITM attacks if there is no application-layer encryption.

<table>
<thead>
<tr>
<th>Firmware Name</th>
<th>Mobile App</th>
<th>Category</th>
<th>#</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>DogBodyBoard</td>
<td>com.wowwee.chip</td>
<td>Robot</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>BW_Pro</td>
<td>com.ecomm.smart_panel</td>
<td>Tag</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Smart_Handle</td>
<td>com.exitec.smartlock</td>
<td>Smart Lock</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sma05</td>
<td>com.smalife.watch</td>
<td>Wearable</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>CPRmeter</td>
<td>com.laerdal.cprmeter2</td>
<td>Medical Device</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>WiJumpLE</td>
<td>com.wesssrl.wijumble</td>
<td>Sensor</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>nRF Beacon</td>
<td>no.nordicsemi.android.nrfbeacon</td>
<td>Beacon</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Hoot Bank</td>
<td>com.qvivr.hoot</td>
<td>Debit Card</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table: Firmware that enforce LESC pairing.
Attack Case Studies

nRF52840 DK

Vulnerable BLE Devices
# Attack Case Studies

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Category</th>
<th>Attacks (A1, A2, A3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuband Activ+</td>
<td>Wearable</td>
<td>✓</td>
</tr>
<tr>
<td>Kinsa Smart</td>
<td>Thermometer</td>
<td>✓</td>
</tr>
<tr>
<td>Chipolo ONE</td>
<td>Tag</td>
<td>✓</td>
</tr>
<tr>
<td>SwitchBot Button Pusher</td>
<td>Smart Home</td>
<td>✓</td>
</tr>
<tr>
<td>XOSS Cycling Computer</td>
<td>Sensor</td>
<td>✓ ✓</td>
</tr>
</tbody>
</table>

## A1: User Tracking
## Attack Case Studies

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Category</th>
<th>Attacks</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Kinsa Smart</td>
<td>Thermometer</td>
<td></td>
</tr>
<tr>
<td>Chipolo ONE</td>
<td>Tag</td>
<td>✓</td>
</tr>
<tr>
<td><strong>SwitchBot Button Pusher</strong></td>
<td><strong>Smart Home</strong></td>
<td>✓</td>
</tr>
<tr>
<td>XOSS Cycling Computer</td>
<td>Sensor</td>
<td>✓</td>
</tr>
</tbody>
</table>

A2: Unauthorized Control
## Attack Case Studies

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Category</th>
<th>Attacks</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuband Activ+</td>
<td>Wearable</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Kinsa Smart</td>
<td>Thermometer</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Chipolo ONE</td>
<td>Tag</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>SwitchBot Button Pusher</td>
<td>Smart Home</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>XOSS Cycling Computer</td>
<td>Sensor</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

A3: Sensitive Data Eavesdropping
Near Term

OS Defense: OS-level defense to patch multiple security issues.
Near Term

1. **OS Defense**: OS-level defense to patch multiple security issues.
2. **Scanning Defense**: Defending against malicious scanning.
Near Term

1. **OS Defense**: OS-level defense to patch multiple security issues.
2. **Scanning Defense**: Defending against malicious scanning.
3. **Notification Fingerprinting**: Exploring notification fingerprinting against BLE devices.
Near Term

1. OS Defense: OS-level defense to patch multiple security issues.
Other New Security Features. New security features (e.g., Cross-Transport Key Derivation) are keeping introducing, bringing new security attack surfaces.

Privacy-preserving Protocols. BLE Privacy-preserving protocols such as identity resolution protocol may be vulnerable, and further understanding is needed.
Other Directions

1. **Other New Security Features.** New security features (e.g., Cross-Transport Key Derivation) are keeping introducing, bringing new security attack surfaces.

2. **Privacy-preserving Protocols.** BLE Privacy-preserving protocols such as identity resolution protocol may be vulnerable, and further understanding is needed.

Recent Papers of Bluetooth Research with COVID-19


2. Haohuang Wen, Qingchuan Zhao, Zhiqiang Lin, Dong Xuan, and Ness Shroff. **A Study of the Privacy of COVID-19 Contact Tracing Apps.** In SECURECOMM’20, October 2020.
The Landscape of Bluetooth Security and Privacy

1. Request for scan
2. Notify
3. Identify target device
4. Connect
5. Start pairing
6. Pairing feature exchange (Negotiate key entropy and elliptic curve)
7. Authentication and encryption
8. Key distribution (e.g., IRK)
9. Authentication (App level)
10. Communication

Device
- BLE-Guardian [KKS16]
- BlueShield [WNK+20]
- FirmXRay [WLZ20]

OS
- BLEScope [ZWLZ19]
- BlueShield [WNK+20]
- BLE-Guardian [KKS16]

App
- BLEScope [ZWLZ19]
- BlueShield [WNK+20]
- BLE-Guardian [KKS16]

Broadcast
- Mis-Bonding [NZD+14]; Co-Located Attacks [SB19]
- BadBluetooth [XDL+19]
- Crackle [Rya13]
- Downgrade Attack [ZWD+20]
- Authentication (Pairing)
- Authentication and encryption
- Key distribution (e.g., IRK)
- Pairing feature exchange (Negotiate key entropy and elliptic curve)
- Start pairing
- Connect
- Identify target device
- Notify
- Request for scan

References
- BLEScope [ZWLZ19]
- BlueShield [WNK+20]
- BLE-Guardian [KKS16]
- FirmXRay [WLZ20]
- Future Work
- Takeaway
- References
BLEScope [CCS 2019]

BLEScope

- Automatic UUID extraction and hierarchy reconstruction from mobile apps
- Identify app-level vulnerabilities by directly analyzing mobile apps

App Analysis and Field Test Result

- We analyzed 18,166 apps and discovered 168,093 UUIDs and 1,757 vulnerable apps
- 5,822 BLE devices were discovered in the field test, and 94.6% can be fingerprinted
**FirmXRay [CCS 2020]**

**BLEScope**

- A static analysis tool based on Ghidra for detecting BLE link layer vulnerabilities from bare-metal firmware.
- A scalable approach to efficiently collect bare-metal firmware images from only mobile apps.
- Vulnerability discovery and attack case studies.

The source code is available at [https://github.com/OSUSecLab/FirmXRay](https://github.com/OSUSecLab/FirmXRay).
Future Directions

1. **OS Defense**: OS-level defense to patch multiple security issues.
2. **Scanning Defense**: Defending against malicious scanning.
3. **Notification Fingerprinting**: Exploring notification fingerprinting against BLE devices.
4. **Connection Security**: Exploring a defense for jamming attacks.
Uncovering Vulnerabilities in Bluetooth Devices with Automated Binary Analysis

Zhiqiang Lin
zlin@cse.ohio-state.edu

03/26/2021


Jianliang Wu, Yuhong Nan, Vireshwar Kumar, Mathias Payer, and Dongyan Xu, *Blueshield: Detecting spoofing attacks in bluetooth low energy networks*.

Jianliang Wu, Yuhong Nan, Vireshwar Kumar, Dave Jing Tian, Antonio Bianchi, Mathias Payer, and Dongyan Xu, *Blesa: Spoofing attacks against reconnections in bluetooth low energy*.

