FirmXRay: Detecting Bluetooth Link Layer Vulnerabilities From Bare-Metal Firmware

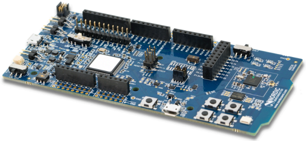
Haohuang Wen, Zhiqiang Lin, and Yinqian Zhang

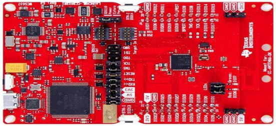
CCS 2020

Bluetooth Low Energy

Bluetooth™
4.0
Low Energy

Low Technical Barrier for IoT Development





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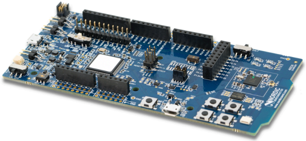

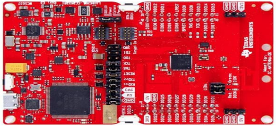

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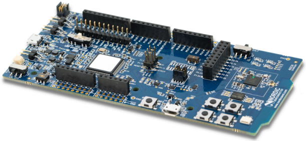
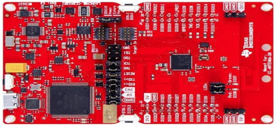
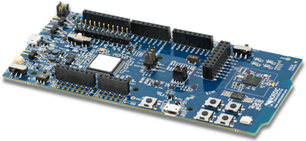


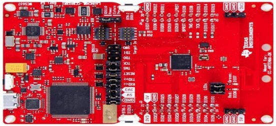


AWS IoT

Azure IoT Hub

Low Technical Barrier for IoT Development





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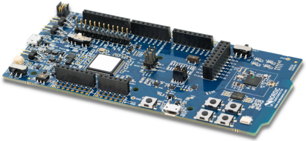

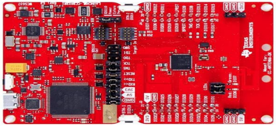

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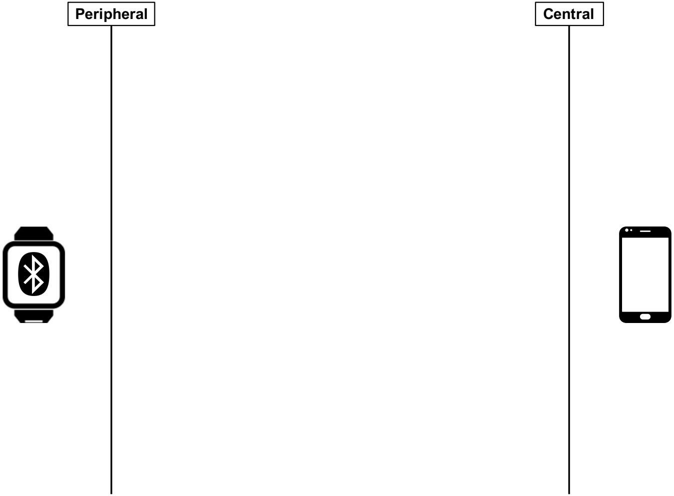
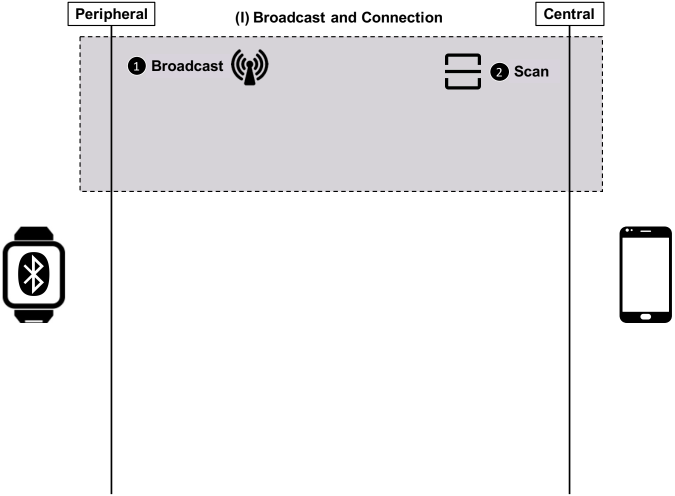
Are they secure?

BLE Workflow



BLE Workflow



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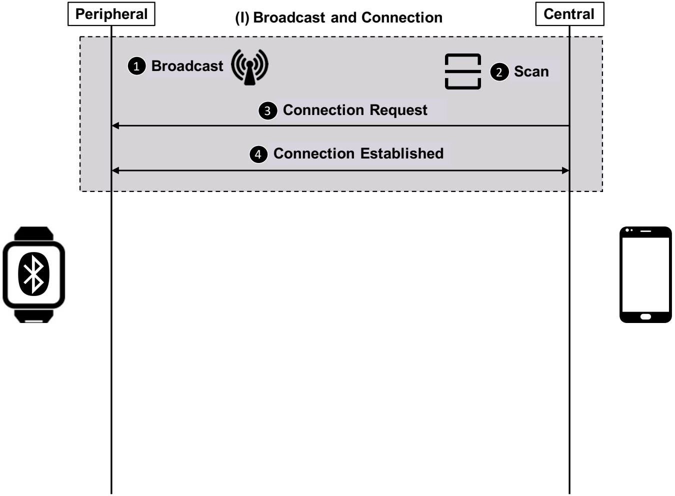

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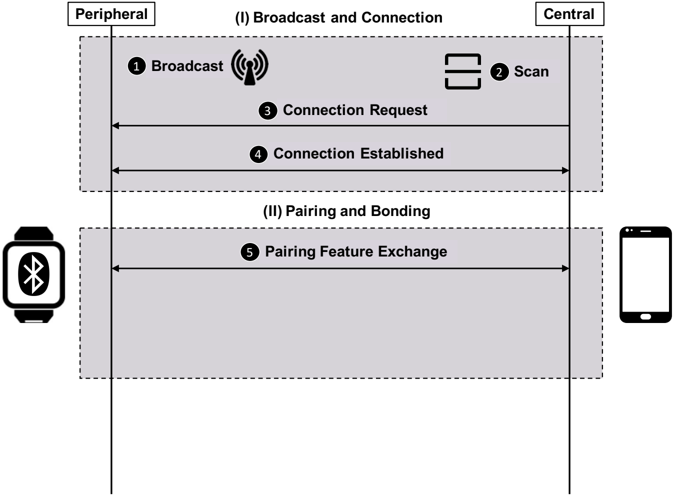

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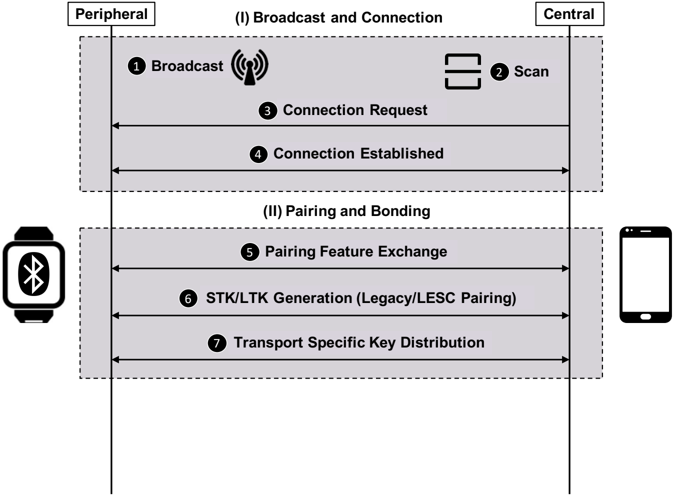

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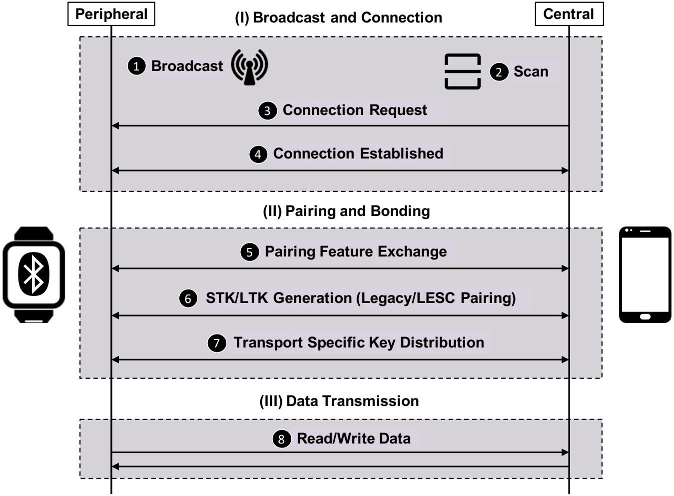
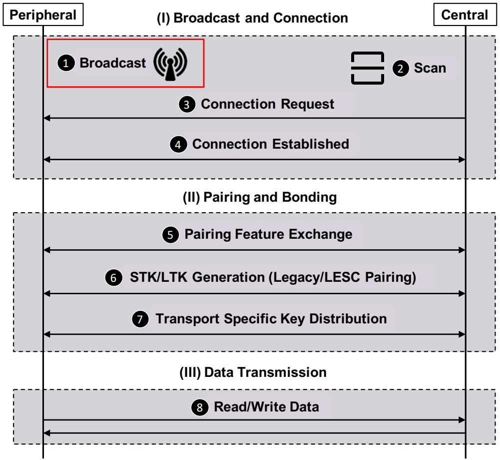


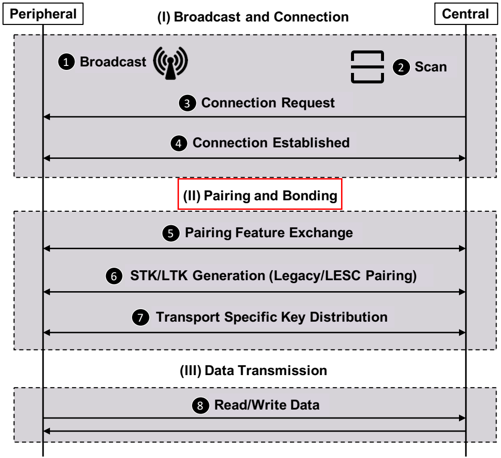
BLE Link Layer Vulnerabilities



Vulnerabilities

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

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.

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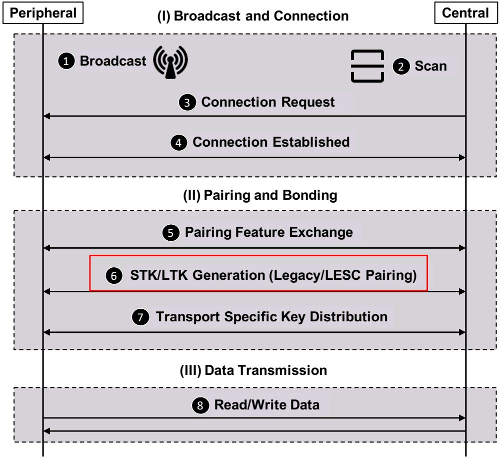
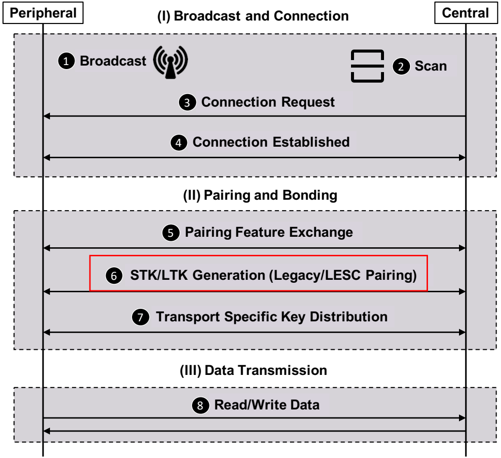


Vulnerabilities

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



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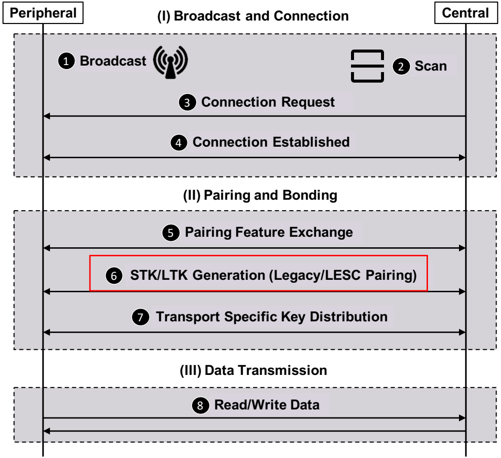
Identification

1. Traffic analysis
2. Mobile app analysis

BLE Link Layer Vulnerabilities



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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

```
243a8  mov  r2, #0x0
243aa  orr  r2, #0x1
243ac  and  r2, #0xe1
243ae  add  r2, #0xc
243b0  and  r2, #0xdf
243b2  ldr  r1, [0x260c8]
243b4  str  r2, [r1,#0x0]
...
25f44  ldr  r2, [0x260c8]
25f46  mov  r1, #0x0
25f48  svc  0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
260c8  0x20003268
       // ble_gap_sec_parms_t*
```

Register Values

r1 = 0x0
r2 = 0x0

An Example of a Just Works Pairing Vulnerability

Read Only Memory

```
243a8   mov   r2, #0x0
243aa   orr   r2, #0x1
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Register Values

```
r1 = 0x0
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260c8   0x20003268
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```

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
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```

An Example of a Just Works Pairing Vulnerability

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r1 = 0x20003268
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Random Access Memory

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20003268   uint8 pairing_feature  = 0xD
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BOND	MITM	IO	OOB

```
           // BOND  = 1, MITM  = 0
           // IO    = 3, OOB   = 0
20003269   uint8 min_key_size
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An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling

Read Only Memory

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243a8   mov   r2, #0x0
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```

Register Values

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r1 = 0x0
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```

An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling → **Recognize data structures**

Read Only Memory

```
243a8   mov    r2, #0x0
243aa   orr    r2, #0x1
243ac   and    r2, #0xe1
243ae   add    r2, #0xc
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Random Access Memory

Struct ble_gap_sec_params_t

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Register Values

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

An Example of a Just Works Pairing Vulnerability

Correct Firmware Disassembling → **Read Only Memory**

```
243a8   mov   r2, #0x0
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// SD_BLE_GAP_SEC_PARAMS_REPLY
...
260c8   0x20003268
        // ble_gap_sec_parms_t*
```

Recognize data structures → **Random Access Memory**

Struct **ble_gap_sec_params_t**

```
20003268   uint8 pairing_feature  = 0xD
```

BOND	MITM	IO	OOB

```
           // BOND = 1, MITM = 0
           // IO   = 3, OOB  = 0
20003269   uint8 min_key_size
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20003271   ble_gap_sec_kdist_t  kdist_own
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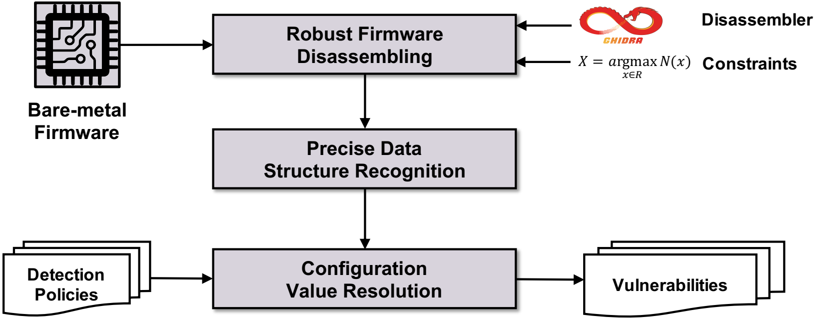
```

Value computation →

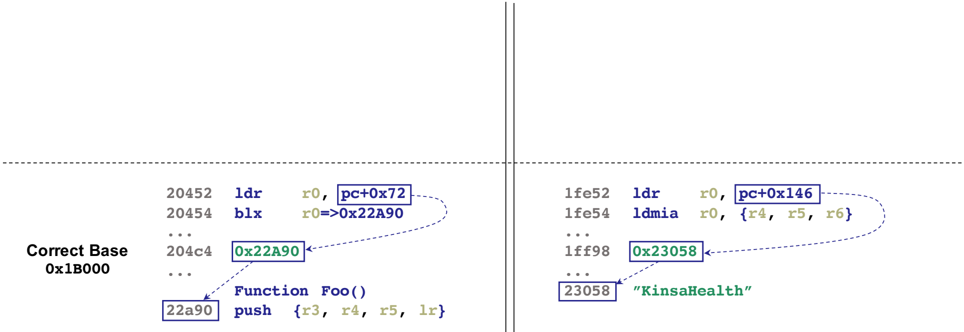
Register Values

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

FirmXRay Overview



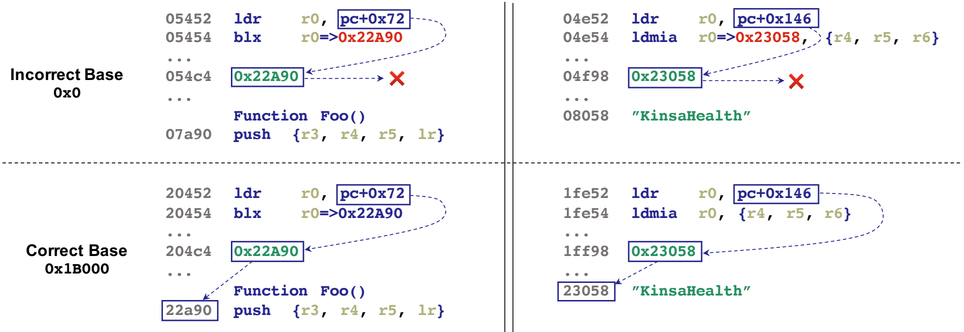
Robust Firmware Disassembling



(1) Absolute Function Pointer

(2) Absolute String Pointer

Robust Firmware Disassembling



(1) Absolute Function Pointer

(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

Base
0x0

```
05452  ldr    r0, pc+0x72
05454  blx    r0=>0x22A90
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Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058

Robust Firmware Disassembling

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05452  ldr    r0, pc+0x72
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Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058

N(0x1B000) = 2

Robust Firmware Disassembling

Base
0x0

```
05452  ldr    r0, pc+0x72
05454  blx    r0=>0x22A90
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...
04f98  0x23058
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```

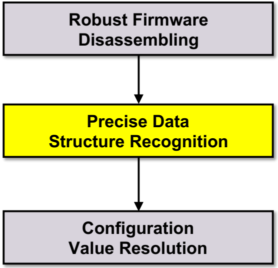
Absolute Pointers: 0x22A90, 0x23058

Gadgets: 0x07A90, 0x08058

0x1B000 = 0x22A90 − 0x07A90
= 0x23058 − 0x08058

N(0x1B000) = 2

Precise Data Structure Recognition



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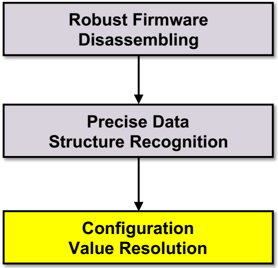
243b0    and    r2, #0xdf
243b2    ldr    r1, [0x260c8]
243b4    str    r2, [r1,#0x0]
...
25f44    ldr    r2, [0x260c8]
25f46    mov    r1, #0x0
25f48    svc    0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY(r0, r1, r2)
...
260c8    0x20003268
         // ble_gap_sec_parms_t*
```

Configuration Value Resolution



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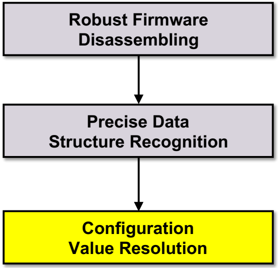
```

Program Path

Configuration Value Resolution



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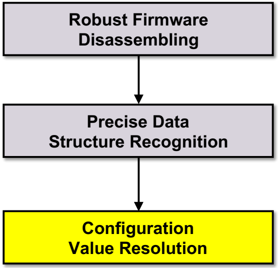
...
260c8   0x20003268
        // ble_gap_sec_parms_t*
```

Program Path

```
ldr r2, [0x260c8]
str r2, [r1, #0x0]
```

Configuration Value Resolution



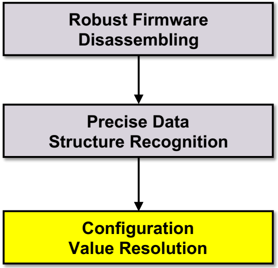
Read Only Memory

```
243a8   mov   r2, #0x0
243aa   orr   r2, #0x1
243ac   and   r2, #0xe1
243ae   add   r2, #0xc
243b0   and   r2, #0xdf
243b2   ldr   r1, [0x260c8]
243b4   str   r2, [r1,#0x0]
...
25f44   ldr   r2, [0x260c8]
25f46   mov   r1, #0x0
25f48   svc   0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
260c8   0x20003268
        // ble_gap_sec_parms_t*
```

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
```

Configuration Value Resolution



Read Only Memory

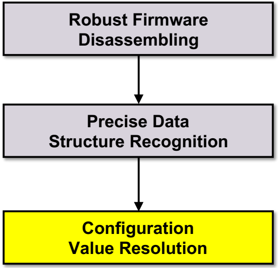
```
243a8  mov  r2, #0x0
243aa  orr  r2, #0x1
243ac  and  r2, #0xe1
243ae  add  r2, #0xc
243b0  and  r2, #0xdf
243b2  ldr  r1, [0x260c8]
243b4  str  r2, [r1,#0x0]
...
25f44  ldr  r2, [0x260c8]
25f46  mov  r1, #0x0
25f48  svc  0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
260c8  0x20003268
       // ble_gap_sec_parms_t*
```

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

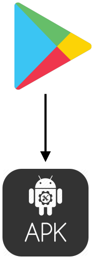
Configuration Value Resolution



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

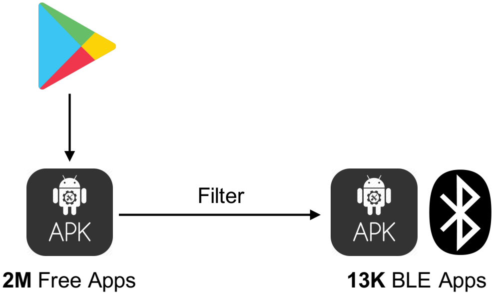
Firmware Collection

Firmware Collection

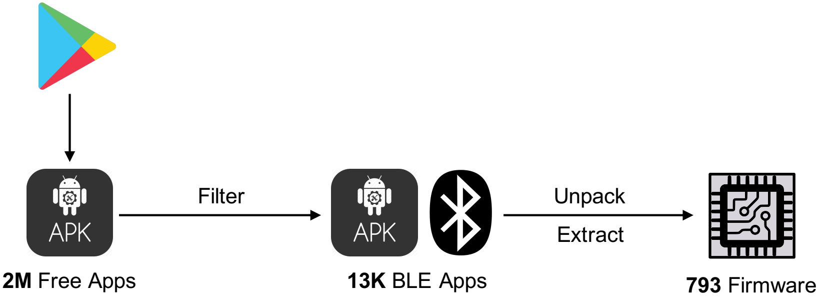


2M Free Apps

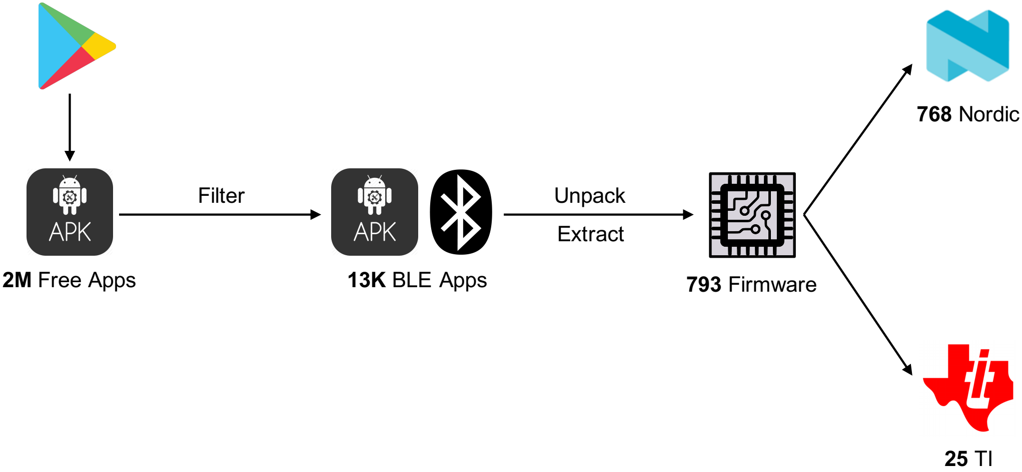
Firmware Collection



Firmware Collection



Firmware Collection



Firmware Categorization

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

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

Category	# Firmware	# Device	Avg. Size (KB)
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Table: Top categories of firmware.

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.

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Firmware Name	Mobile App	Category	# Device
cogobeacon	com.aegismobility.guardian	Car Accessory	4
sd_bl	fr.solem.solemwf	Agricultural Equip.	2
LRFL_nRF52	fr.solem.solemwf	Agricultural Equip.	2
orb	one.shade.app	Smart Light	1
sd_bl	com.rainbird	Agricultural Equip.	1

Table: Firmware using private MAC address.

Experiment Results

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.

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Item	N	T	Total	%
# Total Device	513	25	538	100
# Device w/ active MITM vulnerability	384	1	385	71.5
# Device w/ Just Works pairing only	317	1	318	59.1
# Device w/ flawed Passkey implementation	37	0	37	6.9
# Device w/ flawed OOB implementation	30	0	30	5.6
# Device w/ secure pairing	6	24	30	3.8
# Device w/ correct Passkey implementation	3	24	27	3.4
# Device w/ correct OOB implementation	3	0	3	0.4

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.

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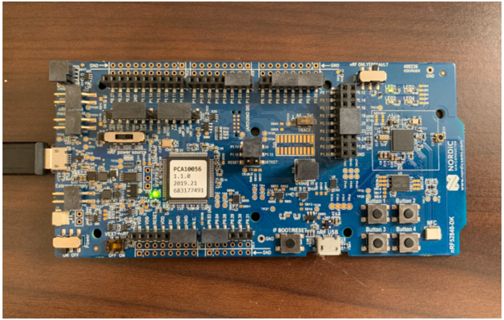
Firmware Name	Mobile App	Category	# Version
DogBodyBoard	com.wowwee.chip	Robot	16
BW_Pro	com.ecomm.smart_panel	Tag	1
Smart_Handle	com.exitec.smartlock	Smart Lock	1
Sma05	com.smalife.watch	Wearable	1
CPRmeter	com.laerdal.cprmeter2	Medical Device	4
WiJumpLE	com.wesssrl.wijumple	Sensor	1
nRF Beacon	no.nordicsemi.android.nrfbeacon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

Table: Firmware that enforce LESC pairing.

Attack Case Studies



nRF52840 DK

Vulnerable BLE Devices

Attack Case Studies

Device Name	Category	Attacks		
		A1	A2	A3
Nuband Activ+	Wearable	✓		✓
Kinsa Smart	Thermometer			✓
Chipolo ONE	Tag	✓		
SwitchBot Button Pusher	Smart Home		✓	
XOSS Cycling Computer	Sensor	✓		✓

A1: User Tracking

Attack Case Studies

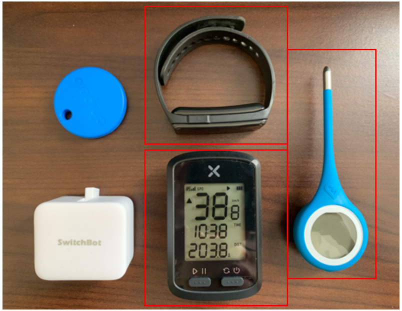
Device Name	Category	Attacks		
		A1	A2	A3
Nuband Activ+	Wearable	✓		✓
Kinsa Smart	Thermometer			✓
Chipolo ONE	Tag	✓		
SwitchBot Button Pusher	Smart Home		✓	
XOSS Cycling Computer	Sensor	✓		✓

A2: Unauthorized Control

Attack Case Studies

Device Name	Category	Attacks		
		A1	A2	A3
Nuband Activ+	Wearable	✓		✓
Kinsa Smart	Thermometer			✓
Chipolo ONE	Tag	✓		
SwitchBot Button Pusher	Smart Home		✓	
XOSS Cycling Computer	Sensor	✓		✓

A3: Sensitive Data Eavesdropping



Discussion

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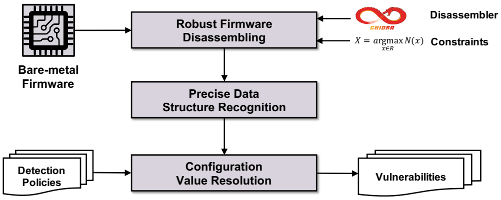
Discussion

- **Effectiveness**. Source of FP/FN: incorrect base address and fundamental limitations of program analysis.
- **Exploitation**. Not all the vulnerabilities can be exploited in practice.
- **Root Cause**. Lack of hardware capabilities and misconfiguration by the developers are the two major root causes.
- **Future Work**.
  - Extract more embedded firmware from apps (e.g., those downloaded from server).
  - Adapt FirmXRay to other SDKs and architectures.
  - Enable dynamic analysis and firmware emulation [CGS+20] [CWBE16] [FML20].

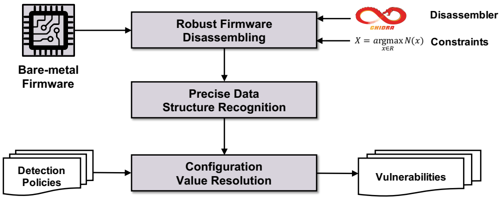
Takeaway



FirmXRay

- 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.

Takeaway



FIRMXRAY

- 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`.

References I

- *Bluetooth specification version 4.2*, https://www.bluetooth.org/DocMan/handlers/DownloadDoc.ashx?doc_id=286439, 2014.
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- Bo Feng, Alejandro Mera, and Long Lu, *P2im: Scalable and hardware-independent firmware testing via automatic peripheral interface modeling*, Proceedings of the 29th USENIX Security Symposium (USENIX Security 20), USENIX Association, 2020.