When Wireless Malware Stays On After Turning Off iPhones

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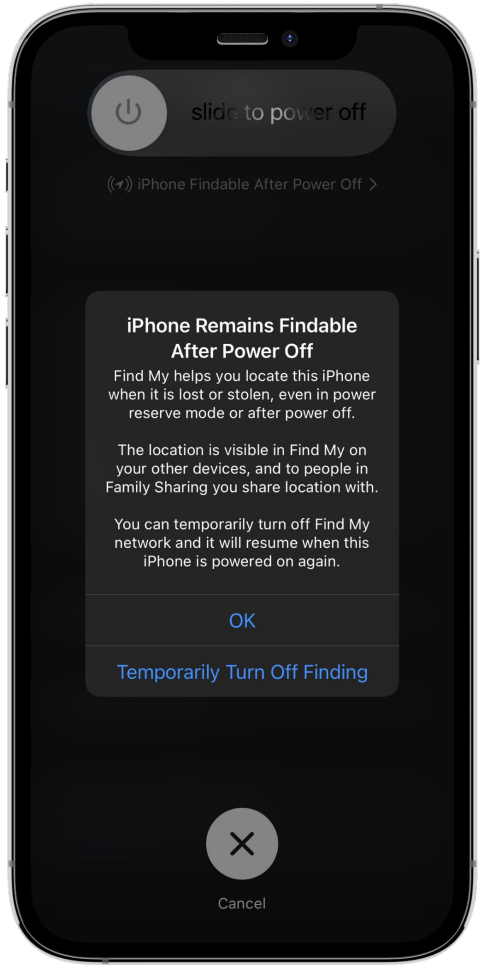
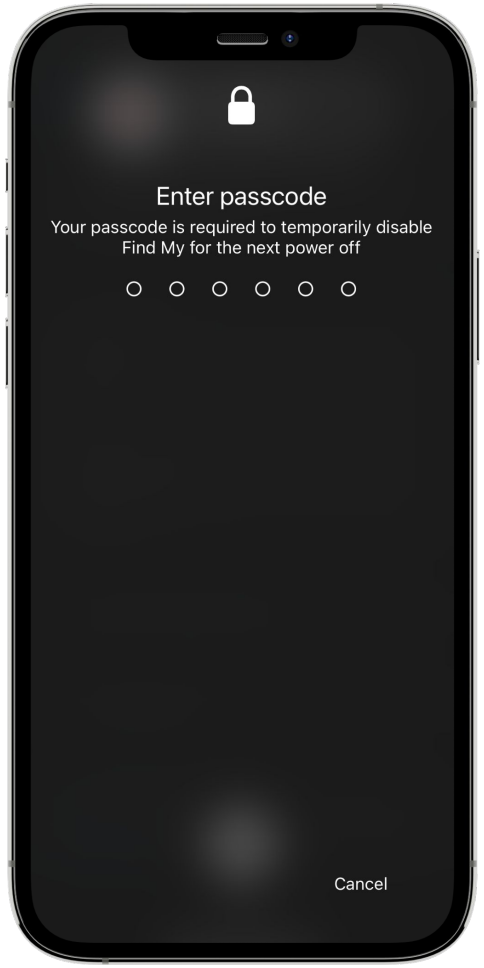
Find My
After Power Off

New “Security” Feature (iOS 15)





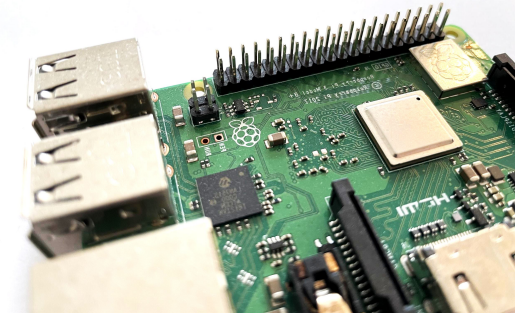
Is it a good anti-theft protection?

Observations

- Collect BLE advertisements (script by @Sn0wfreeze)
  - User-initiated shutdown.
  - Low battery automated shutdown.
  - Reboot, unlock, …
- Unexpected findings!
  - Advertisements roll every 15min, as with normal Find My.
  - Advertisements stop after 5h on low battery.
  - Advertisements stop after 24h on user-initiated shutdown.
  - Reboot won’t re-enable advertisements after 24h without unlock/Internet.
  - Find My dialogue might be shown even if activating Find My fails.

collect_advertisements.py

```
from bluepy.btle import Scanner,
DefaultDelegate, ScanEntry,
Peripheral, UUID, Service,
Characteristic, AssignedNumbers
import json
…
class BLEScanner(DefaultDelegate):
```



Technical Limitations

- Secure storage of Find My *Master Beacon Key* vs. promise of anti-theft…

- Master Beacon Key allows generating all past and future advertisements sent by a device.
  → Allows access to the device's location reports.

- On shutdown, 96 Find My advertisements for 15min (=24h) are generated.
  - Sent to the Bluetooth chip.
  - Stored in a database accessible before first unlock.

Is it a good anti-theft protection?

No!

Low-Power Mode

LPM, LEPM, Power Reserve, …

Initial Reverse Engineering

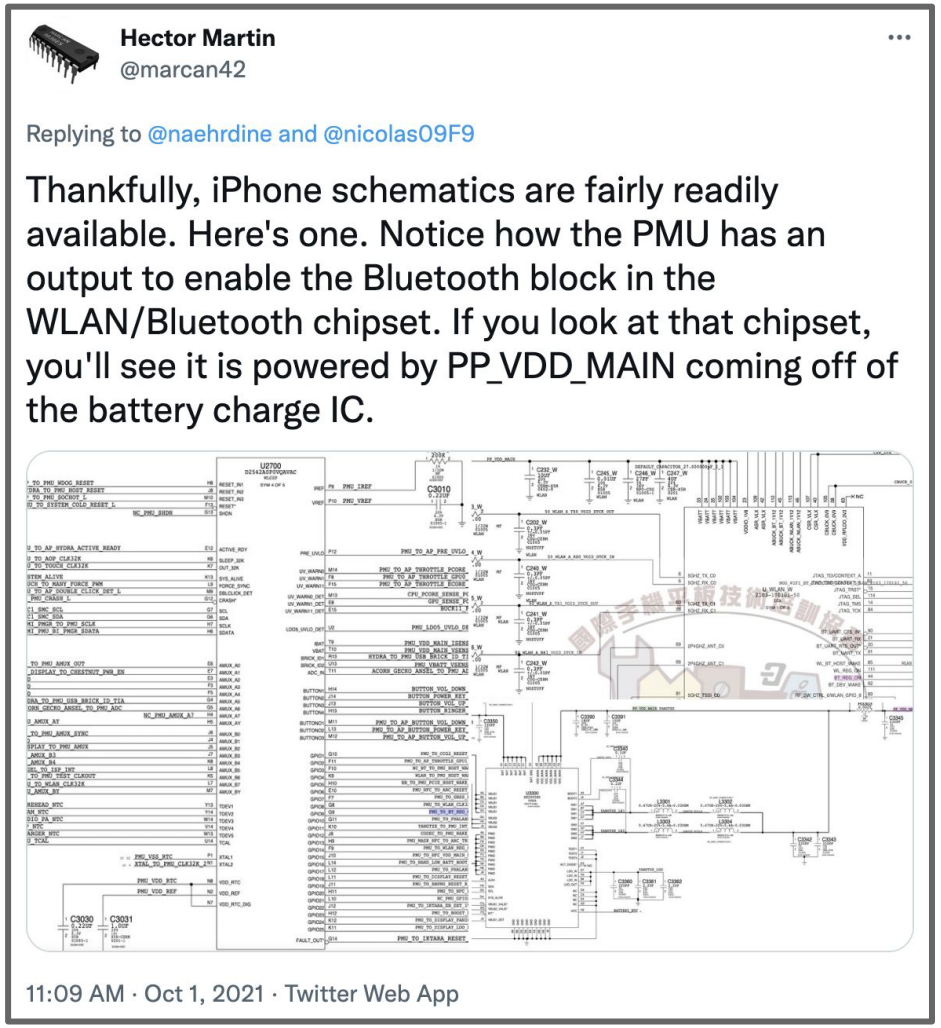
- Get latest iOS IPSW.
- Extract firmware…

```
% strings BCM4387C2_19.3.384.3994_PCIE_Hazelnut_CLPC_OS_USI_20211011.bin | grep Hazelnut
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/bcs/scheduler.o.patch2.c
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/bcs/isr.o.patch2.c
…
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/bcs/mpaf_layer_patch.o.patch2.c
…
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/mpaf/apps/lpm/lpm_app.o.patch2.c
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/mpaf/apps/lpm/lpm_app_gatt.o.patch2.c
tier2/Olympic/PCIE/Hazelnut_CLPC_OS/USI/bld/A_4387C2_ROM/tier2/patch/mpaf/apps/lpm/lpm_app_fsm.o.patch2.c
…
```

- **MPAF** is the name of a standalone thread, also used for IoT device development in the *Cypress Wiced SDK 6.2*.
- Not surprising at all.
- Reversing finished 🎉

How is the Bluetooth chip powered?

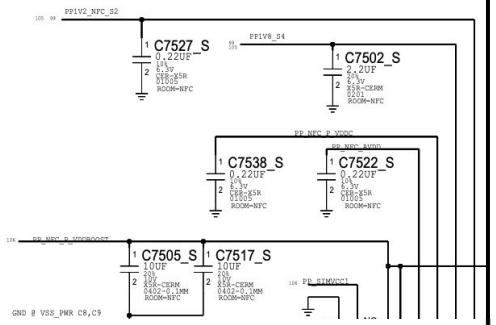
- No idea but Always-on Processor (AoP) firmware has some power module for Bluetooth…
- Publish blog post.
- If you're wrong on the Internet, people will correct you.



Schematics

STOCKHOLM

PRIMARY NFC



I2C_BT_TO_NFC_SCL E4

I2C_BT_TO_NFC_SDA F4

Stockholm
(NFC)

NFC_I2C_SCL
NFC_I2C_SDA

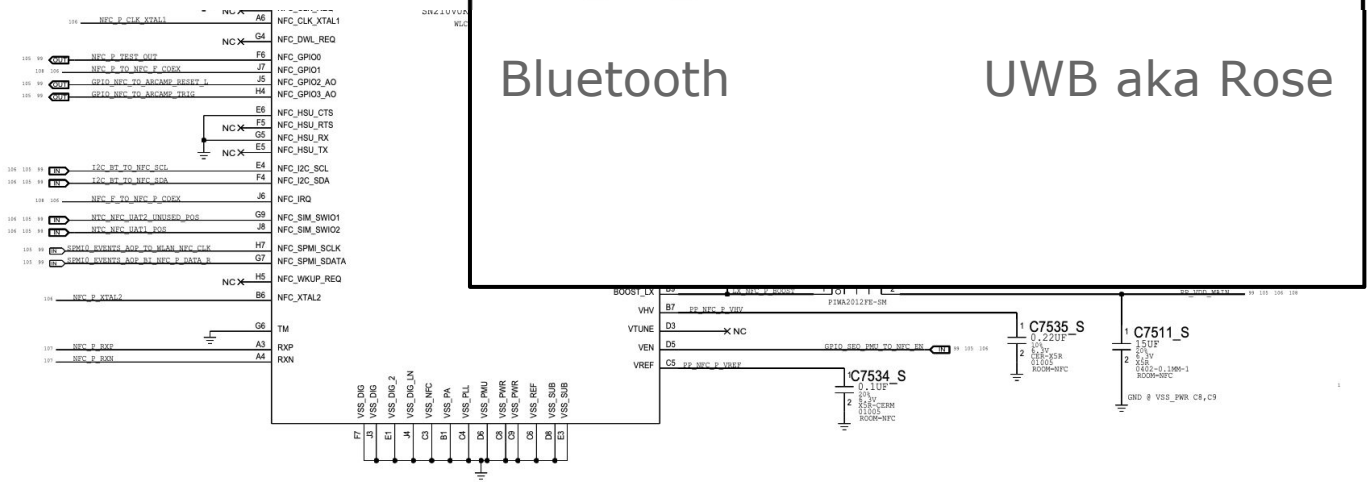
Bluetooth

SE_I2C_SCL
SE_I2C_SDA

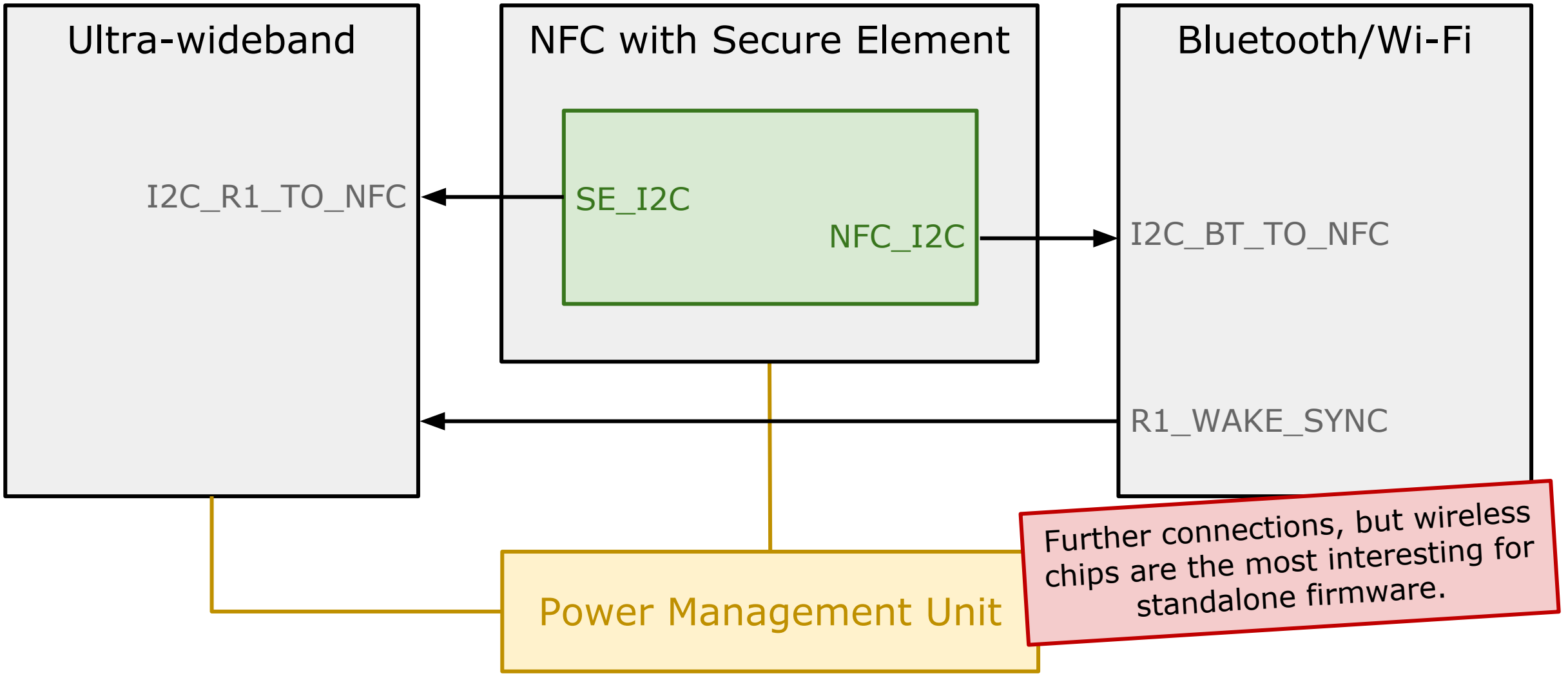
UWB aka Rose

G1 I2C_R1_TO_NFC_SCL

H1 I2C_R1_TO_NFC_SDA



Hardware Changes (iPhone 11 and Newer)



iPhone Insomnia

What is all this doing while the iPhone is “off”?

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Express Cards with power reserve

If iOS isn't running because iPhone needs to be charged, there may still be enough power in the battery to support Express Card transactions. Supported iPhone devices automatically support this feature with:

- A payment or transit card designated as the Express Transit card
- Student ID cards with Express Mode turned on
- Car keys with Express Mode turned on
- Home keys with Express Mode turned on
- Hospitality or Corporate access cards with Express Mode turned on

Pressing the side button (or on iPhone SE 2nd generation, the Home button) displays the low-battery icon as well as text indicating that Express Cards are available to use. The NFC controller performs Express Card transactions under the same conditions as when iOS is running, except that transactions are indicated only with haptic notification (no visible notification is shown). On iPhone SE 2nd generation, completed transactions may take a few seconds to appear on screen. This feature isn't available when a standard user-initiated shutdown is performed.

https://support.apple.com/guide/security/express-cards-with-power-reserve-sec90cd29d1f/web

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Digital Car Key 3.0 supports power reserve and is based on Bluetooth & Ultra-wideband

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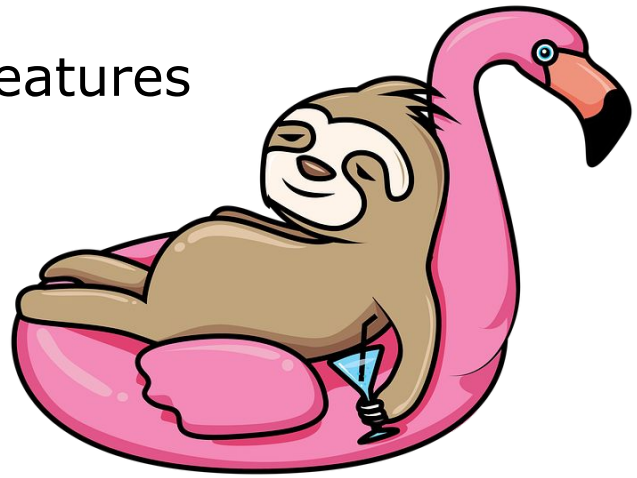
https://support.apple.com/guide/security/express-cards-with-power-reserve-sec90cd29d1f/web
https://developer.apple.com/videos/play/wwdc2021/10084/ (at 6:08)

“Find My After Power Off” is likely a byproduct of Digital Car Key 3.0.

Entering Low-Power Mode

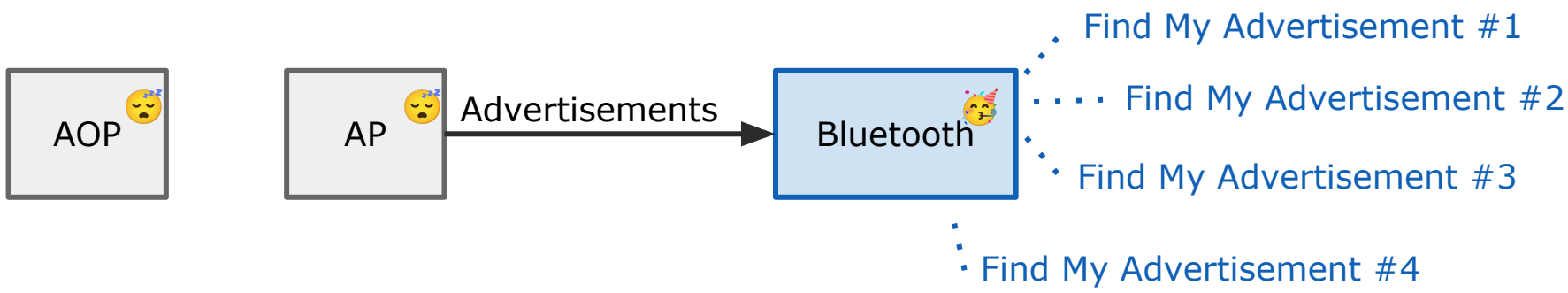
☐ User-initiated
- Find My (24h)
- Find My dialogue is shown
- User can opt out during each shutdown
- Pressing power button turns on phone

☐ Automated (aka “Power Reserve”)
- Find My + Express Cards and Keys (5h)
- No dialogue, opt out via disabling features in settings
- Pressing power button shows empty battery and enabled features



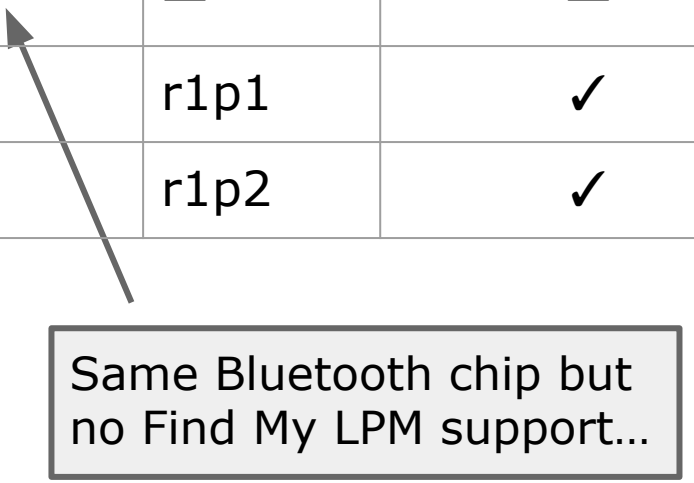
Basic Principle

- iOS initializes firmware on LPM-enabled chips.
- iOS application processor (and always-on processor) shut down.
- Power Management Unit (PMU) powers chips to run standalone firmware.



Supported Devices

Series	NFC+SE	NFC LPM	Bluetooth/Wi-Fi	UWB	Find My LPM
iPhone XR	NXP SN100	✓	BCM4347B1	—	—
iPhone X□	NXP SN100	✓	BCM4377B2	—	—
iPhone 11	NXP SN200	✓	BCM4378B1	r1p0	✓
iPhone SE 2020	NXP SN200	✓	BCM4378B1	—	—
iPhone 12	NXP SN210	✓	BCM4387C2	r1p1	✓
iPhone 13	NXP SN210	✓	BCM4387C2	r1p2	✓



Analysis & Attack Vectors

- **NFC/SE** firmware is encrypted and signed.
  - Previous hacking attempts on PN553, but SN100/200/210 is not vulnerable to the same attack.
    https://www.pentestpartners.com/security-blog/breaking-the-nfc-chips-in-tens-of-millions-of-smart-phones-and-a-few-pos-systems/

- **UWB** firmware is only signed.
  - We did lots of static analysis, some of our U1 driver interface reversing published at Black Hat 2021.
  - Florian Kosterhon even fuzzed the interface into chip direction, emulated the firmware for fuzzing, etc. but no vulnerabilities found.
  - UWB has no data transfer, requires activation via BLE, limited attack surface.

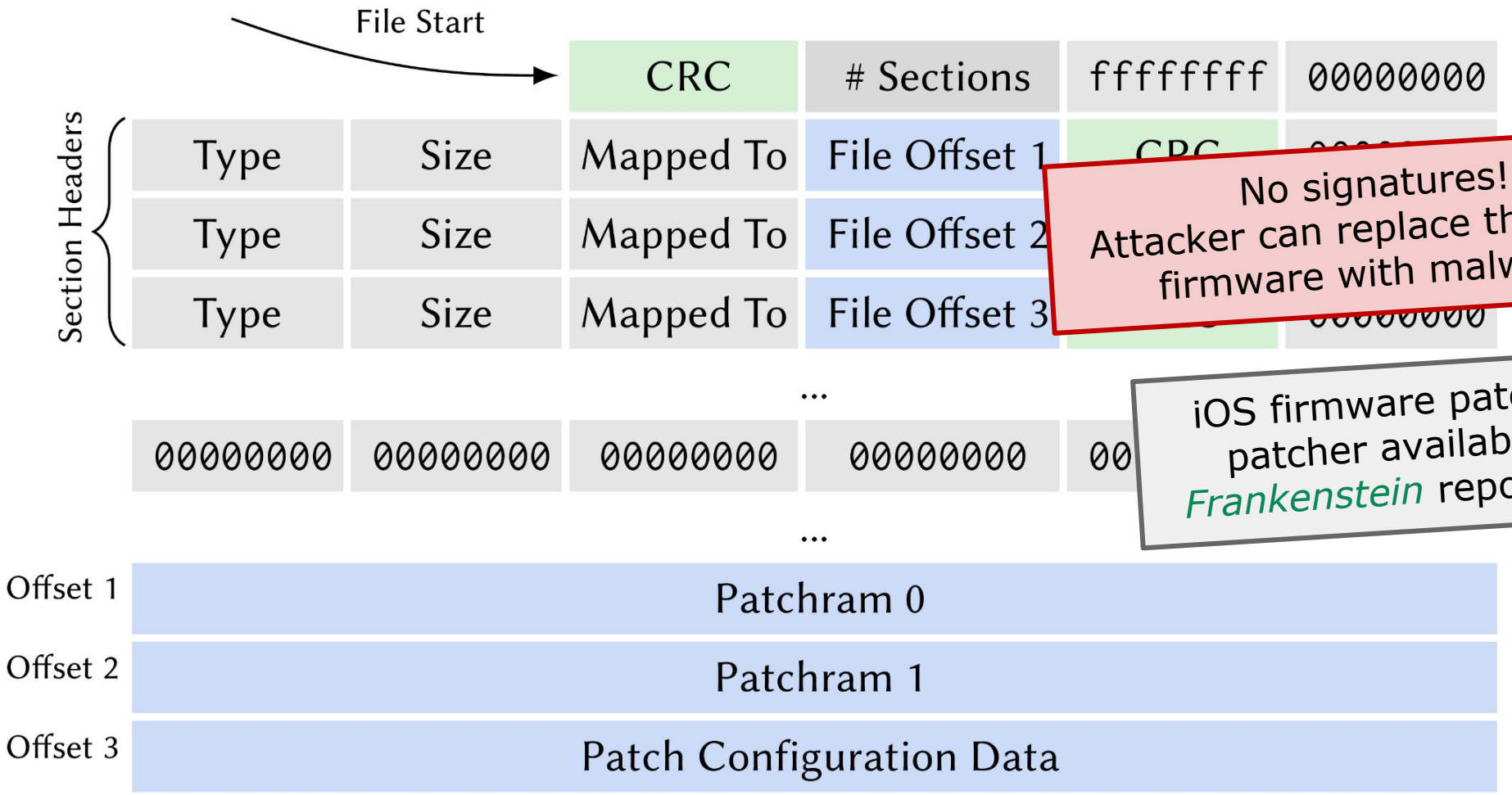
- **Bluetooth** firmware??
  - Lots of experience with that in our team!
  - @r0bre wrote an iPhone X☐+ firmware patcher for his thesis.

Bluetooth Firmware Analysis

LPM Initialization

- Initialization commands observed from logs (non-jailbroken iOS 15).
- Static and dynamic firmware analysis to confirm semantics.

Bluetooth Firmware Patch Format



No signatures!
Attacker can replace the whole firmware with malware.

iOS firmware patch file patcher available in *Frankenstein* repository.

File Edit Jump Search View Debugger Lumina Options Windows Help

No debugger

Library function | Regular function | Instruction | Data | Unexplored | External symbol | Lumina function

Functions | Names | IDA View-A | Structures | Hex View-2 | Strings | Segments | Hex View-1 | Imports

Name	Address
lets_config_fun_2BDB08	002BDB08
lpm_printf	**002BDB32**
j_debug_2BDB88	002BDB88
bthci_event_Send_0x62_CommandCompl...	002BDB8C
bthci_event_Send_0x62_CommandCompl...	002BDBC8
lpm_i2c_write_via_hci_command_complete	002BDC18
lpm_i2c_hci_2BDCA0	002BDCA0
lpm_i2c_hci_2BDCC8	002BDCC8
lpm_fsm_sth_2BDCE4	002BDCE4
lpm_l2cWrite_N	002BDD54
lpm_l2cRead_N	002BDE24
lpm_le_encrypt_cback	002BDF50
lpm_gattc_discover_2BDFC0	002BDFC0
lpm_get_gatt_cb_by_bdaddr_2BE034	002BE034
lpm_gatt_discovery	002BE070
lpm_gattc_read_char	002BE0AC
lpm_gatt_read_complete	002BE118
lpm_app_gattc_callback	002BE1A8
jpt_2BE1BC	002BE1C0
def_2BE1BC	002BE1F6
lpm_le_open_connect	002BE200
lpm_app_l2c_disconnet_ind_cb	002BE22C
lpm_app_l2c_disconnet_cfm_cb	002BE2C0
lpm_l2cap_le_data_write	002BE354
lpm_L2CA_LeRegisterConnect	002BE3C0
lpm_send	002BE428
lpm_send_protocol_event_response	002BE4E0
lpm_send_timesync_message	002BE520
tim_2BE654	002BE654
lpm_app_l2c_connect_cfm_cb	002BE658
lpm_send_some_msg	002BE6F4
lpm_fsm_alloc_message_1_2_7_2BE72C	002BE72C
sep_2BE878	
failed_alloc_2BE880	
lpm_sep2_ssr_sth_2BE88	
sep_2BE924	
lpm_2BE928	
lpm_suspendRQ	
lpm_funcid_funcstatus_fs	
lpm_transaction_print_hd	
jpt_2BECB6	
def_2BECB6	002BED14
lpm_app_l2c_data_ind_cb	002BEDC0
init_i2c_session_with_timer_2BEDF8	002BEDF8
lpm_fsm_timer_sth_2BEE5C	002BEE5C
jpt_2BEE6C	002BEE70

Line 5417 of 9362

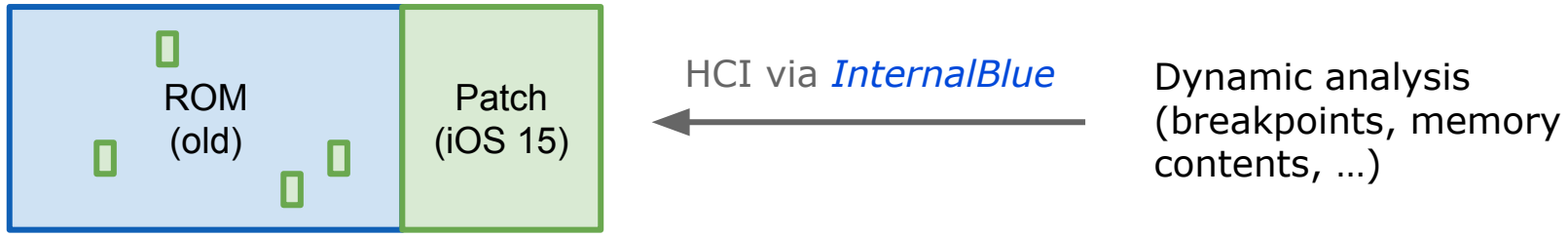
Exported function names to *Frankenstein* repository.
Write firmware patches in C!

```
patch1:002BD92E            ; ---------------------------------------------------------------------------
patch1:002BD92E
patch1:002BD92E            loc_2BD92E                              ; CODE XREF: lpm_app_stack_event_handler+18↑j
patch1:002BD92E 02 79                  LDRB    R2, [R0,#4]
patch1:002BD930 C3 78                  LDRB    R3, [R0,#3]
patch1:002BD932 03 EB 02 23            ADD.W   R3, R3, R2,LSL#8
patch1:002BD936 9B B2                  UXTH    R3, R3
patch1:002BD938 42 F2 05 02            MOVW    R2, #0x2005
patch1:002BD93C 93 42                  CMP     R3, R2
patch1:002BD93E 00 F1 05 05            ADD.W   R5, R0, #5
patch1:002BD942 23 D1                  BNE     loc_2BD98C
patch1:002BD944 33 68                  LDR     R3, [R6]
patch1:002BD946 99 06                  LSLS    R1, R3, #0x1A
patch1:002BD948 20 D4                  BMI     loc_2BD98C
patch1:002BD94A 43 F0 20 03            ORR.W   R3, R3, #0x20
patch1:002BD94E 33 60                  STR     R3, [R6]
patch1:002BD950 68 4B                  LDR     R3, =lpm_module_data_0xa0
patch1:002BD952 1B 68                  LDR     R3, [R3]
patch1:002BD954 93 F8 59 30            LDRB.W  R3, [R3,#0x59]
patch1:002BD958 01 2B                  CMP     R3, #1
patch1:002BD95A 02 D1                  BNE     loc_2BD962
patch1:002BD95C 66 48                  LDR     R0, =(AdvTxOffload_start+1) ; start find my advertisements
patch1:002BD95E 64 F5 21 FC            BL      mpaf_thread_PostMessage
patch1:002BD962
patch1:002BD962            loc_2BD962                              ; CODE XREF: lpm_app_stack_event_handler+4A↑j
patch1:002BD962 14 F7 05 F9            BL      sub_1D1B70
patch1:002BD966 65 4A                  LDR     R2, =byte_219C68
patch1:002BD968 DF F8 84 91            LDR.W   R9, =LPM_FSM_S
patch1:002BD96C 04 21                  MOVS    R1, #4
patch1:002BD96E 08 20                  MOVS    R0, #8
patch1:002BD970 02 F0 52 FD            BL      read_gpio_value
patch1:002BD974 33 68                  LDR     R3, [R6]
                                       LSLS    R2, R3, #0x19
                                       BPL     loc_2BD98C
                                       LDR     R0, =(Init_Scan_Start+1) ; also start scanning
                 12 FC                 BL      mpaf_thread_PostMessage
                 00 30                 LDR.W   R3, [R9]
                 80 03                 BIC.W   R3, R3, #0x80
                 00 30                 STR.W   R3, [R9]
patch1:002BD98C            loc_2BD98C                              ; CODE XREF: lpm_app_stack_event_handler+1C↑j
patch1:002BD98C                                                    ; lpm_app_stack_event_handler+32↑j ...
patch1:002BD98C 33 68                  LDR     R3, [R6]
patch1:002BD98E 9B 06                  LSLS    R3, R3, #0x1A
patch1:002BD990 36 D5                  BPL     loc_2BDA00
patch1:002BD992 23 78                  LDRB    R3, [R4]
patch1:002BD994 3E 2B                  CMP     R3, #0x3E ; '>'
002BD97A 002BD97A: lpm_app_stack_event_handler+6A (Synchronized with Hex View-1)
```

Static reversing and diffing of >2000 functions…

Firmware Analysis Workflow

- Dump Bluetooth ROM of iPhone 12 on any (jailbreakable) iOS version with *InternalBlue*.
- Apply iOS 15 firmware patches.
- Perform static analysis to locate functions of interest.
  Modify functions in patch file if needed (e.g., allow `Write_RAM`, `Launch_RAM`).
- Load patches to jailbroken iPhone for dynamic analysis.



Running Backported Firmware

- Run iOS 15 LPM firmware on jailbroken iPhone with iOS 14, load it with `BlueTool`.

```
power off
device -D
bcm -w /tmp/fw.bin
```

- Send the same LPM initialization commands to the firmware.

- Entering LPM (`fe 62 04`) terminates HCI communication with the host.
  - We can no longer debug what's going on.
  - `bluetoothd` will immediately restart the Bluetooth chip upon timeouts.
  - Would require lots of firmware patching for analysis…

- Dumping Bluetooth RAM with *InternalBlue* just before entering LPM.
  - See all structures in RAM.
  - Cross-reference their access in functions.
  - Analyze and name functions, e.g., the one rolling advertisements.

```
int bthci_cmd_0xfe62_set_advertisements(int input, int a2, byte* a3) {
...
 if ( lpm_module_data_0xa0 ) {
   switch (input + 12) { // get LPM opcode from HCI command
     case 1:
       r = bthci_cmd_lmp_0xfe62_0x01(input + 9);
       break;
     case 2:
       r = bthci_cmd_lmp_0xfe62_0x02(input + 9);
       break;
     case 3:
       r = bthci_cmd_lmp_0xfe62_0x03(input + 9);
       break;
     case 4:  // Enter LPM
       r = bthci_cmd_lmp_0xfe62_finally_activate_0x04(input + 9, a2, a3, v4);
       ...
       break;
     case 5:  // Find My configuration
       r = bthci_cmd_lmp_0xfe62_0x05_set_advertisement_config(input + 9);
       break;
     case 6:  // Set advertisements
       r = bthci_cmd_lmp_0xfe62_0x06_add_advertisements(input + 9);
       break;
     case 7:  // Final step
       r = bthci_cmd_lmp_0xfe62_0x07_after_advertisements(input + 9, a2, a3, v4);
       break;
     default: // Error code: HCI command disallowed
       r = 18;
       break;
   }
...
```

Some LPM initialization functions not used by iOS Find My setup.

Name functions starting from here.

Enable `Write_RAM` for Dynamic Analysis

- iOS applies Bluetooth firmware patch to RAM.
- Firmware patch then disables `Write_RAM` command.
- Statically remove check, calculate new CRCs.
- Patched firmware available in *InternalBlue* repository.

```
patch1:002C57D2                 disallow_fwupdate                       ; CODE XREF: bthci_cmd_HandleCommand+1D6↑j
patch1:002C57D2 2E 2A                           CMP     R2, #0x2E       ; VSC_HandleDownload_Minidriver
patch1:002C57D4 00 F0 C3 81                     BEQ.W   command_disallowed
patch1:002C57D8 4C 2A                           CMP     R2, #0x4C       ; VSC_Write_RAM
patch1:002C57D8                                                         ; -> disallows writing to RAM via HCI
patch1:002C57DA 00 F0 C0 81                     BEQ.W   command_disallowed
patch1:002C57DE 0B E2                           B       call_default_command_handler
```

Interesting Functions in LPM Firmware

- MPAF thread calls into multiple BLE functions known from leaked symbols (CYW20735 etc. from *Wiced Studio 6.2*).
  - BLE advertisements for Find My.
  - Scanning for other devices, GATT service, … likely all used for Digital Car Key.

- Analyzing Digital Car Key 3.0?
  - Dynamic analysis would require to also backport NFC + UWB firmware.
  - At the same time also requires the NFC SE applet and various user-space daemon updates introduced in iOS 15.
  - …waiting for an iOS 15 jailbreak.

Impact of Firmware Modification

- Malicious Bluetooth firmware could be installed. 🐛
  - Only protection is CRC, no signature checks.
  - Code execution on system → code execution after “power off”.

- Use jailbroken iOS 14.x iPhones for dynamic Bluetooth security analysis. 🔍
  - Modify firmware, e.g., install your own patches for testing.
  - We bring back *Frankenstein* and *InternalBlue* support to the iPhone X☐, 11, 2020 SE, 12, and 13 Bluetooth chips!

https://github.com/seemoo-lab

Conclusions

Security Impact

- New *“Find My After Power Off”* feature markets LPM for anti-theft.
  Current implementation makes false promises and does not prevent theft. 🔓
- Turning off the main processor 😴 no longer turns off all chips.
  High-value targets can no longer trust iPhones that off means off. 🥳
- Direct connections between wireless technologies.
  Chips might extract each other’s secrets or even execute code. 💥
  (Code execution has been shown for Bluetooth→Wi-Fi…)

Q&A

https://github.com/seemoo-lab/{frankenstein,internalblue}

Twitter: @naehrdine

jclassen@seemoo.de

https://arxiv.org/abs/2205.06114

24h Limitation in Find My LPM Module

- No real limitation why LPM should only run 24h.

- Generate more advertisements?
  Quite some memory usage and Bluetooth memory is very limited.

- Master Beacon Key protections…
  Copy key to NFC Secure Element, request more advertisements when empty? (Not implemented as of now.)