Wibbly Wobbly, Timey Wimey

What's Really Inside Apple's U1 Chip

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SEEMOO · TECHNISCHE UNIVERSITÄT DARMSTADT · ATHENE National Research Center for Applied Cybersecurity · emergenCITY

Ultra Wideband (UWB) U1 Chip

Nobody knows what
it is or does

Only available in the latest
generation of devices

Non-interceptable with
cheap SDRs

Must be
hacker-proof!

Ultra Wideband security in iOS

The new Apple-designed U1 chip uses Ultra Wideband technology for spatial awareness — allowing iPhone 11, iPhone 11 Pro and iPhone 11 Pro Max or later iPhone models to precisely locate other U1-equipped Apple devices. Ultra Wideband technology uses the same technology to randomise data found on other supported Apple devices:

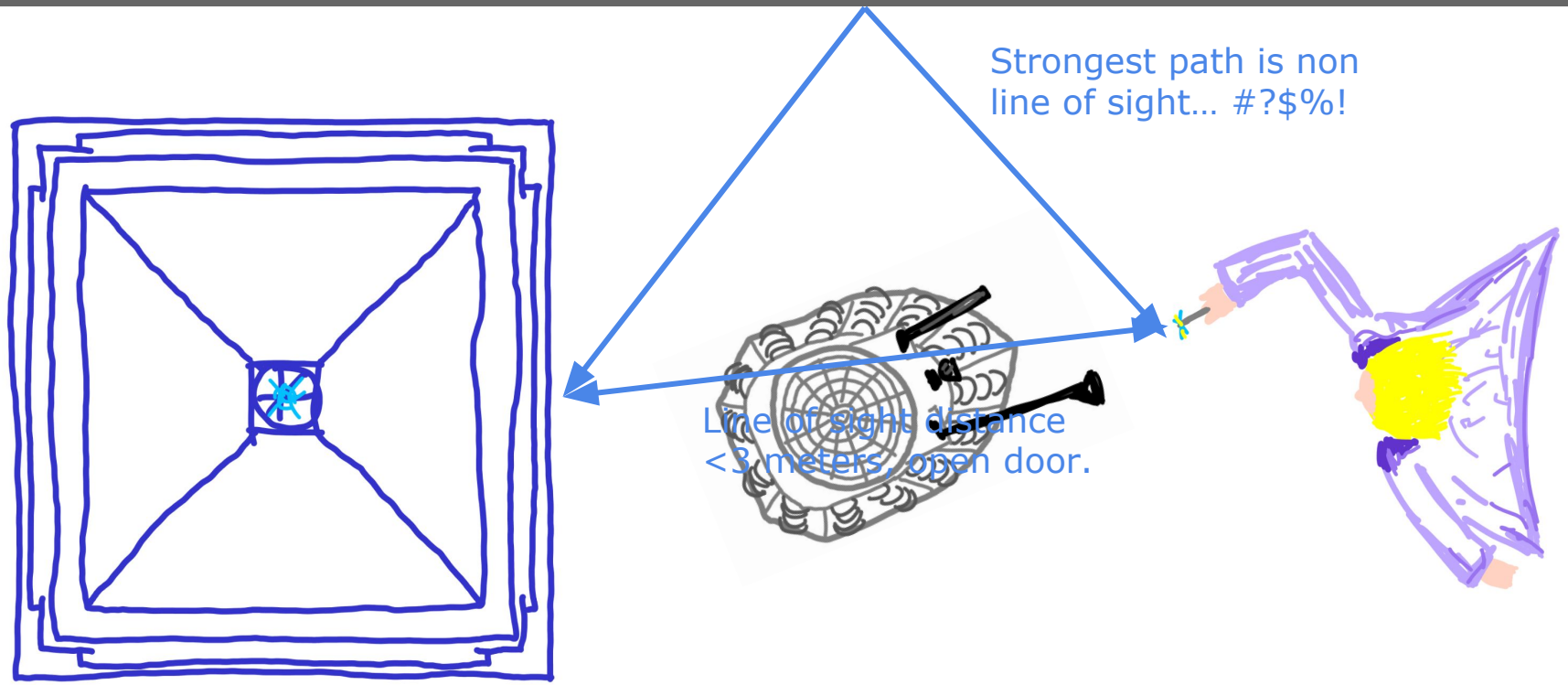
- MAC address randomisation
- Wi-Fi frame sequence number randomisation

Published Date: 18 February 2021

See also

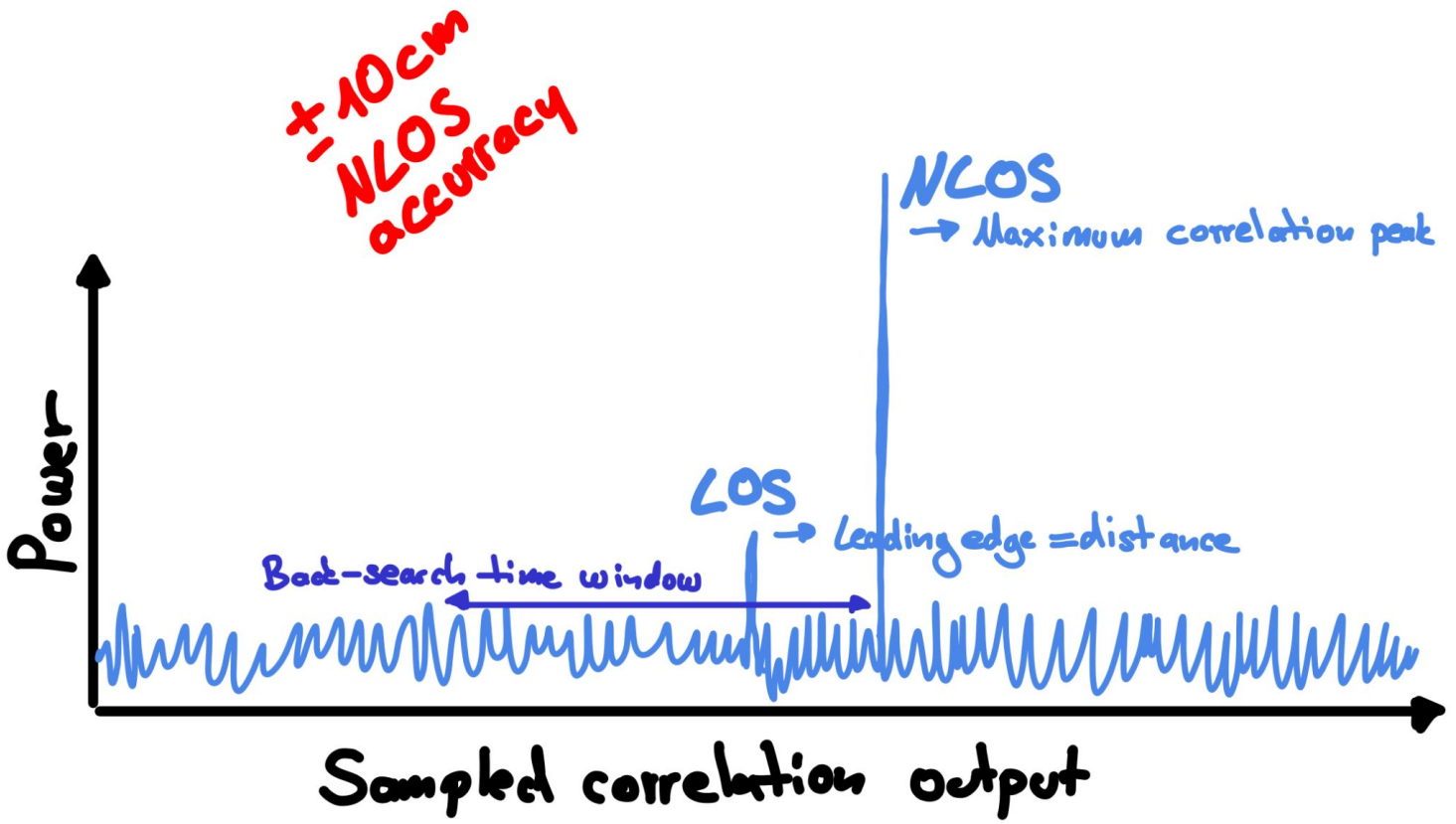
Wi-Fi privacy

UWB Secure Ranging & NLOS Distance Measurement



UWB Secure Ranging & NLOS Distance Measurement

Somewhat

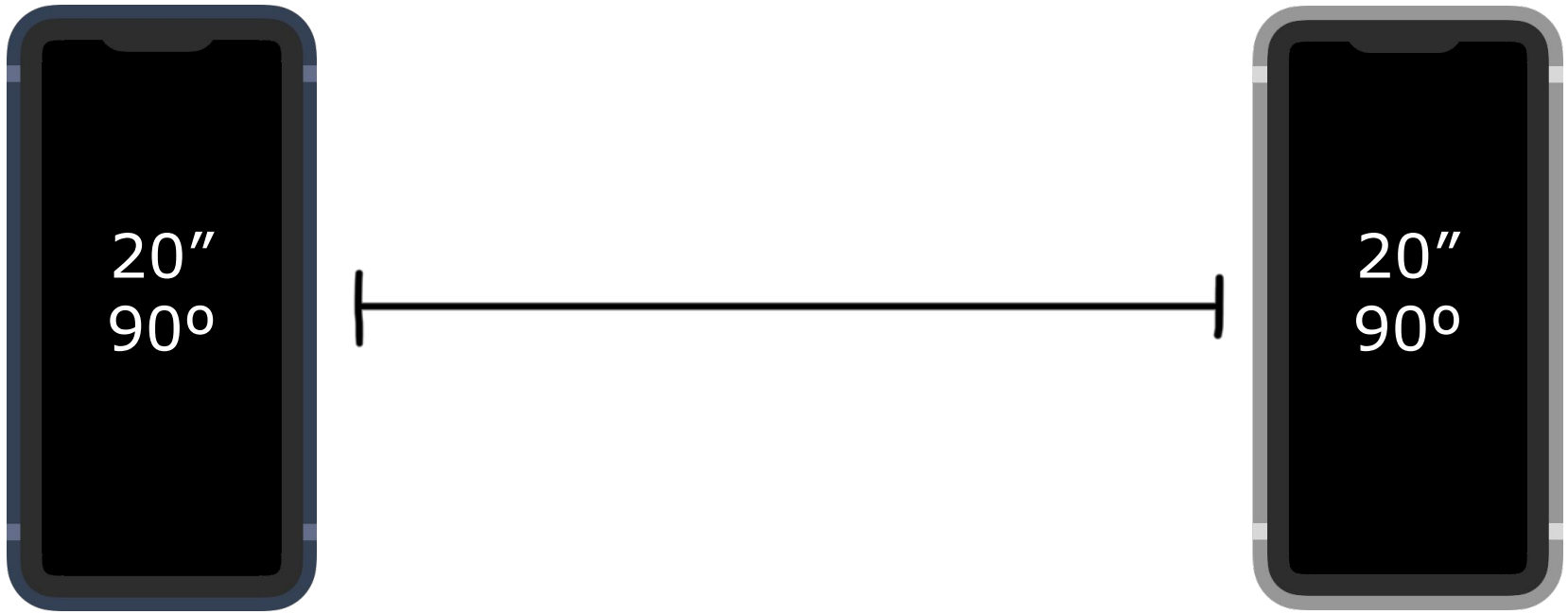


For more details, see WiSec 2021 paper "Security Analysis of IEEE 802.15.4z/HRP UWB Time-of-Flight Distance Measurement" by Singh et. al.

UWB Features

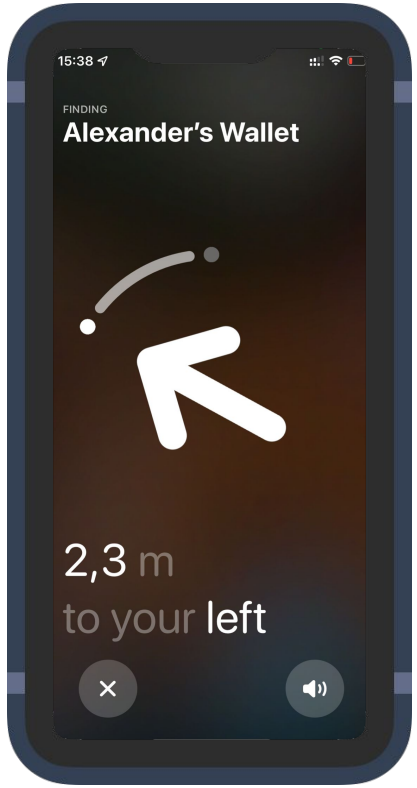

14:21
FaceTime
Calendar
Photos
Camera
Mail
Clock
Maps
Weather
Reminders
Notes
Stocks
Books
App Store
Podcasts
TV
Health
Home
Wallet
Settings
UWB
Distance 1"
Angle 0°
14:14
AirDrop
Done
A
Alexander
Tap to Share
People
A
Alexander

Nearby Interaction

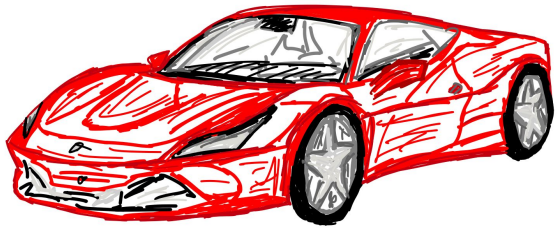


Find My

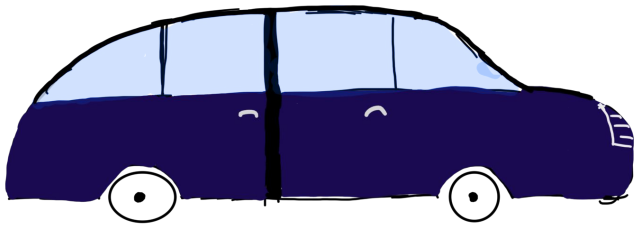

AirTag
Assembled in China
Designed by Apple in California

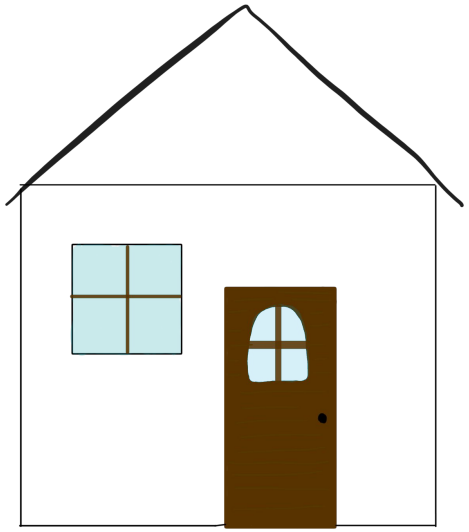

15:38
FINDING
Alexander's Wallet
2,3 m
to your left

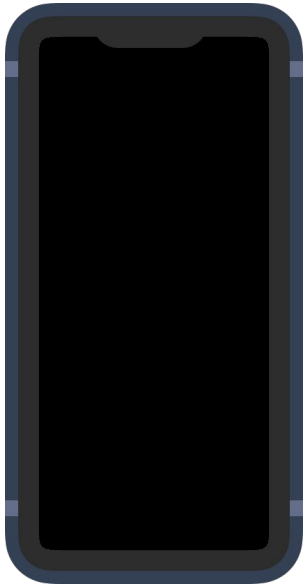
UWB to X



UWB to X

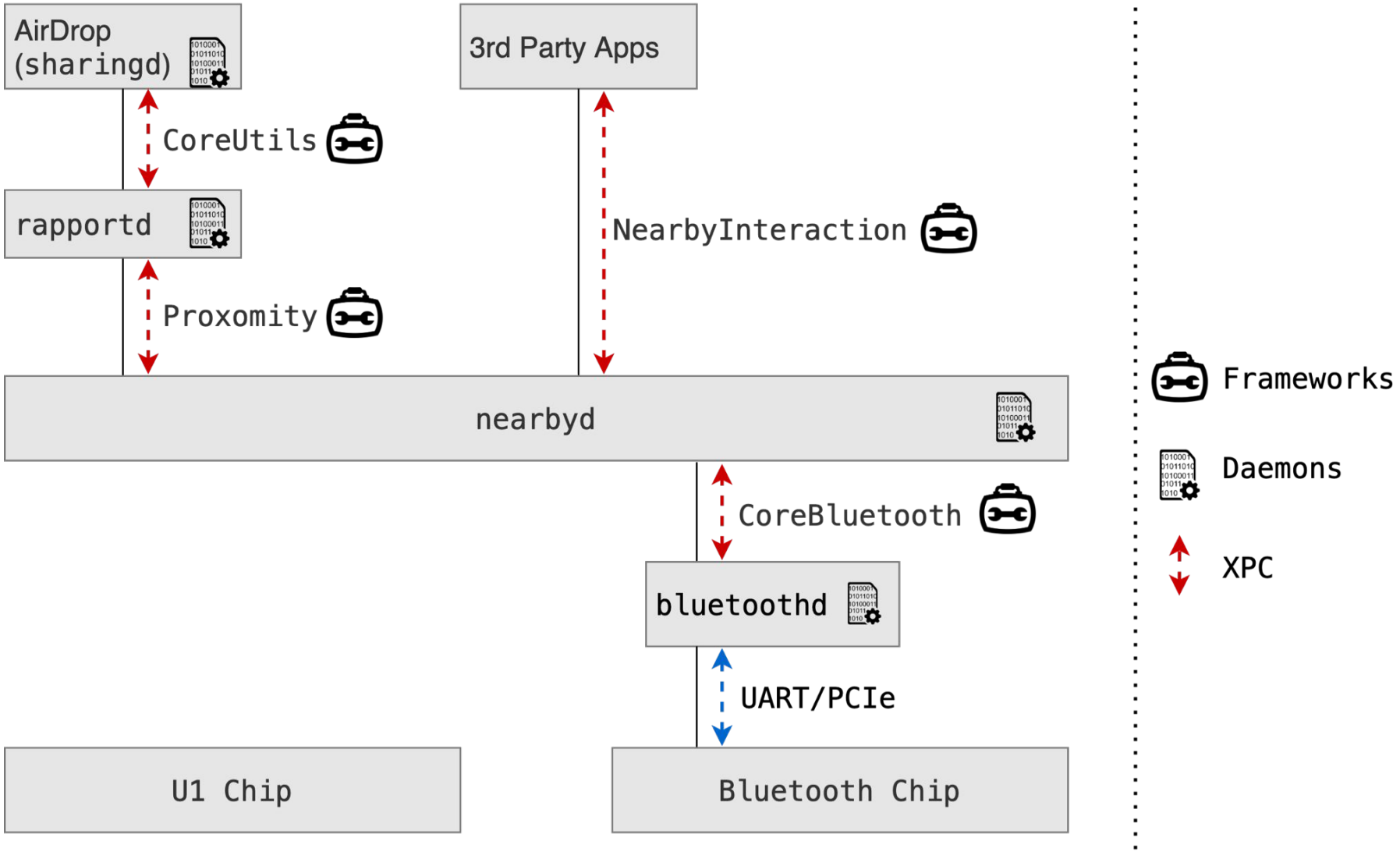






UWB Internals

UWB System Architecture



AirDrop

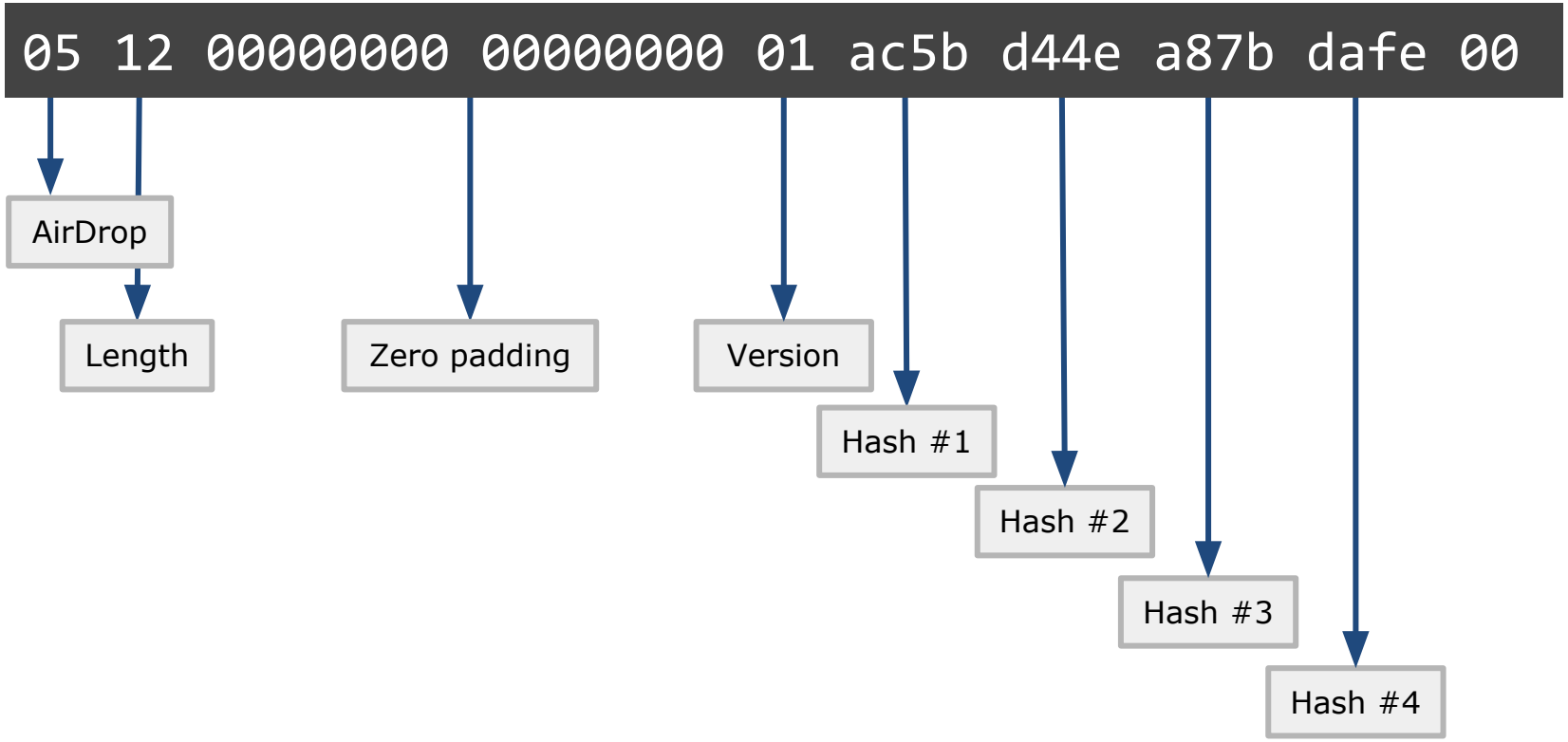
UWB Beaconing

+

AirDrop Protocol

AirDrop Bluetooth Discovery

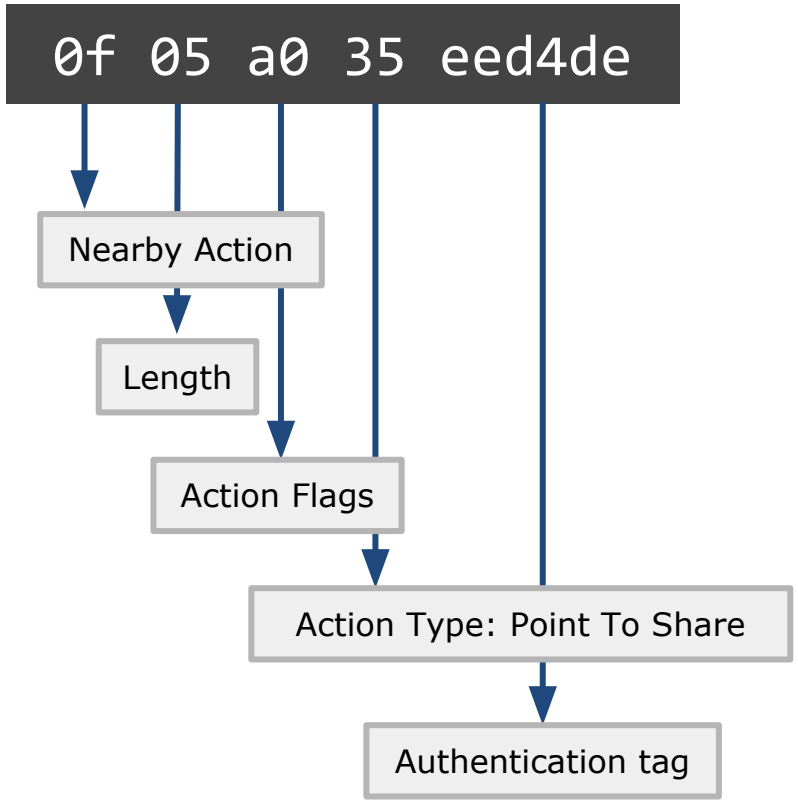
Random **non-resolvable**
MAC address



Stute et al. (2019). A Billion Open Interfaces for Eve and Mallory: MitM, DoS, and Tracking Attacks on iOS and macOS Through Apple Wireless Direct Link.
Celosia et al. (2020). Discontinued Privacy: Personal Data Leaks in Apple Bluetooth-Low-Energy Continuity Protocol

UWB Bluetooth Discovery

Random **resolvable** MAC address

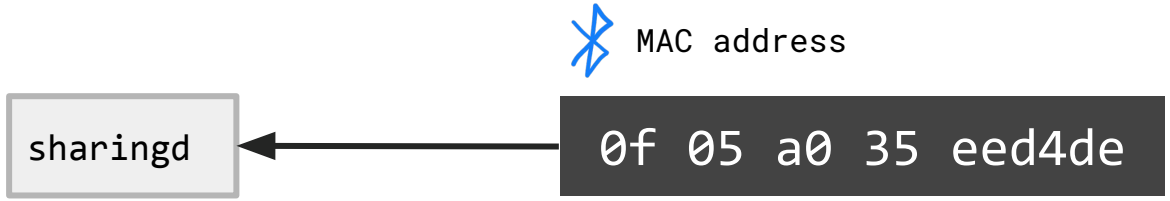


Martin et al. (2019). Handoff All Your Privacy – A Review of Apple's Bluetooth Low Energy Continuity Protocol
Celosia et al. (2020). Discontinued Privacy: Personal Data Leaks in Apple Bluetooth-Low-Energy Continuity Protocol

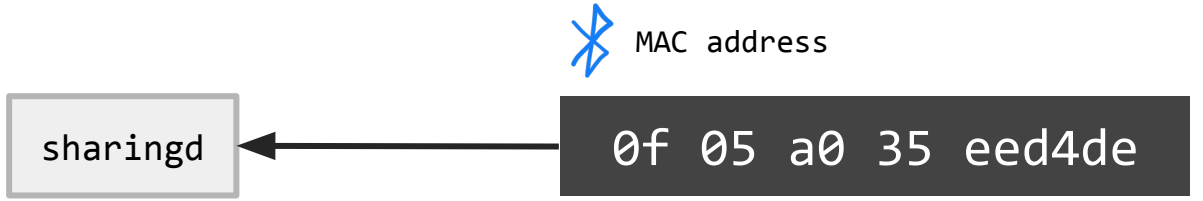
UWB Bluetooth Discovery

✅ Nearby device detected

✅ UWB Point To Share



Authentication Tag Validation



✅ Nearby device detected

✅ UWB Point To Share

✅ Validate Auth Tag

SipHash(MAC address , IRK) = Auth Tag

UWB Bluetooth Discovery

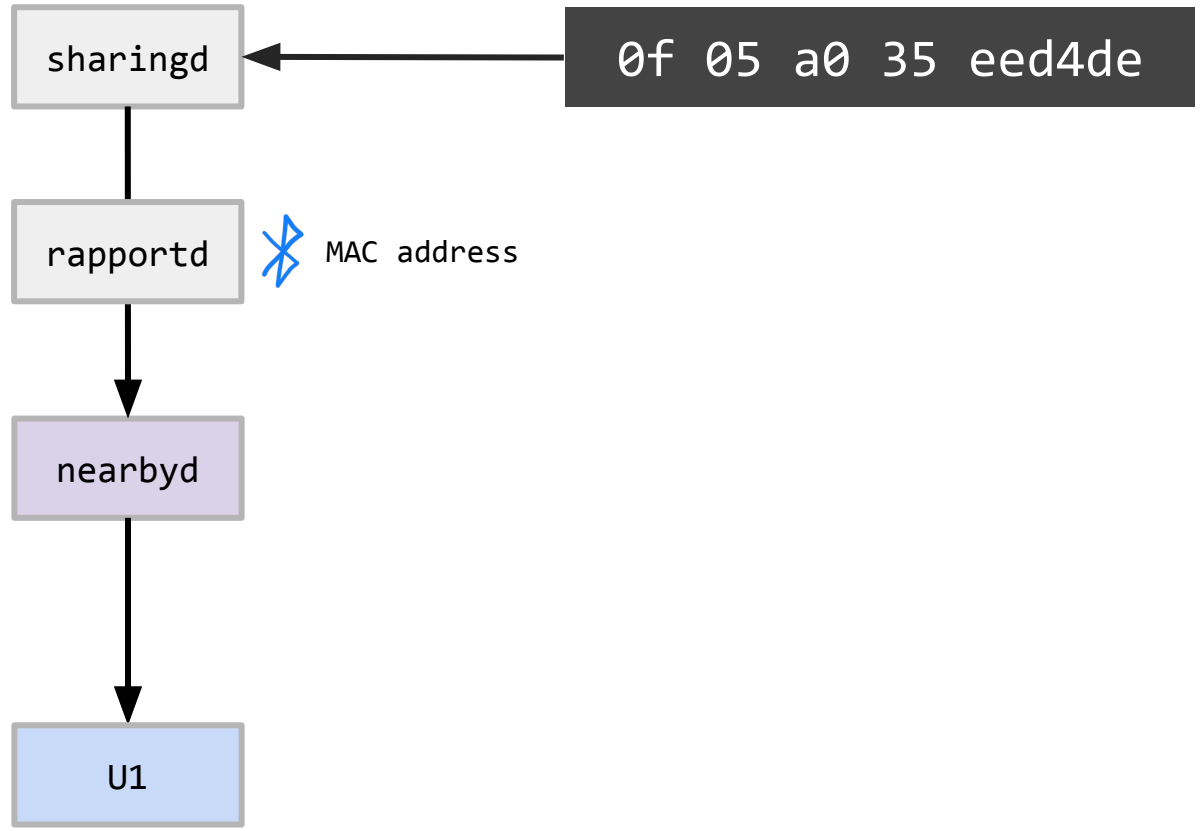
✅ Nearby device detected

✅ UWB Point To Share

✅ Validate Auth Tag

Initiate ranging

Whitelist UWB MAC address



AirDrop Ranging

UWB Ranging and Angle measurements

AirDrop Ranging

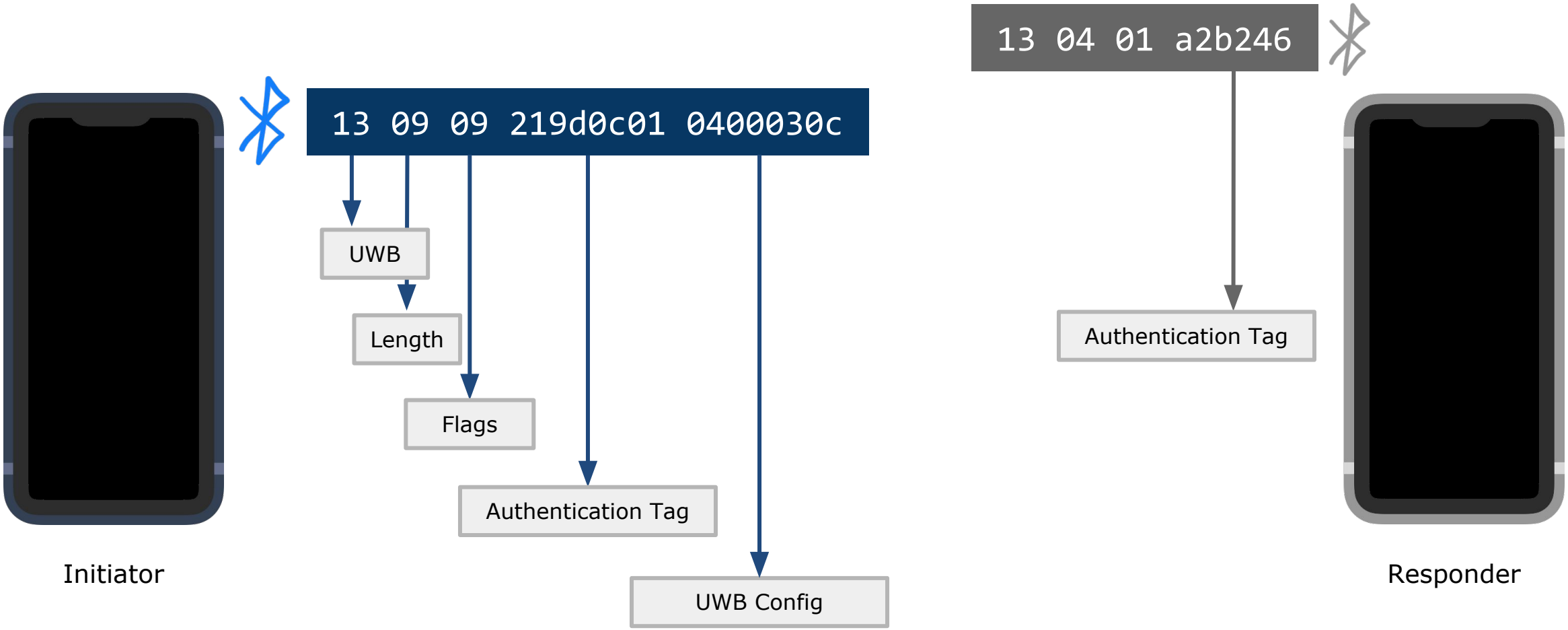
UWB Ranging and Angle measurements

Nearby Interaction Framework

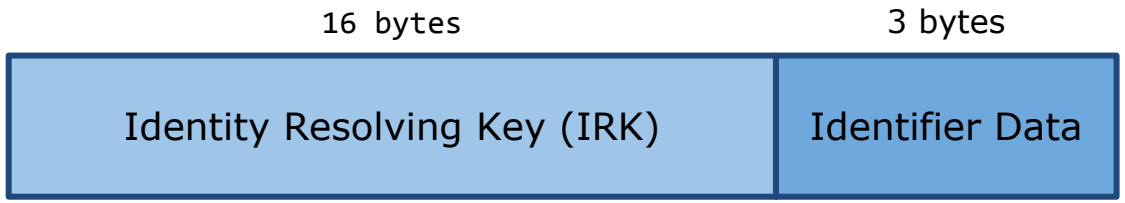
Initiator

Responder

Bluetooth discovery



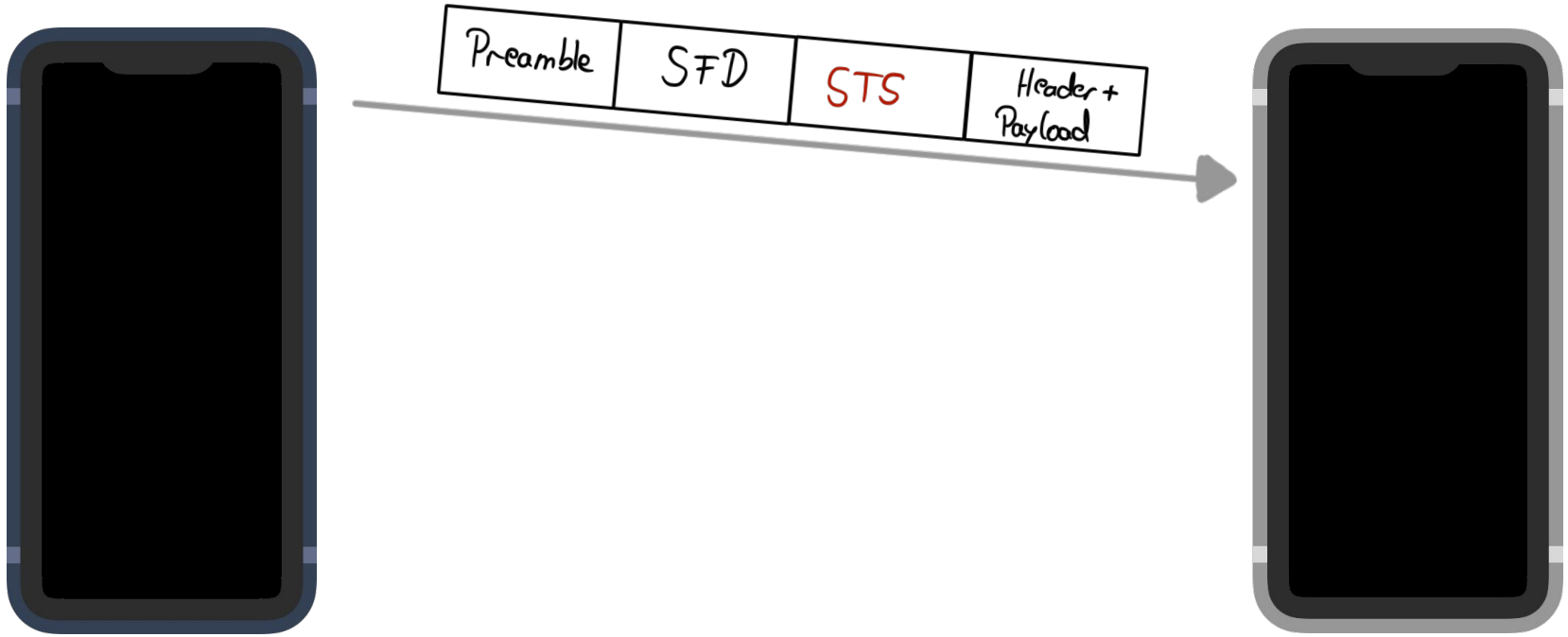
NIDiscoveryToken



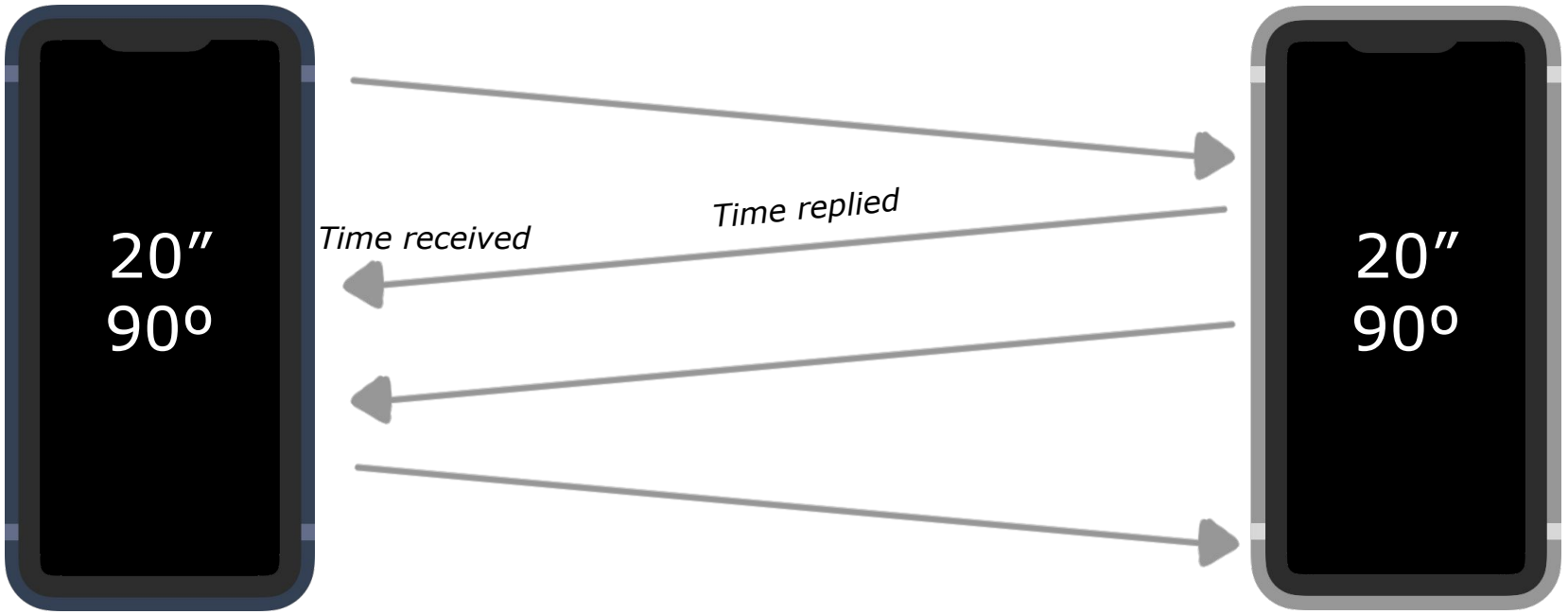
SipHash(MAC address , IRK) = Auth Tag

UWB Secure Ranging

Somewhat



UWB Ranging



Time of flight = Time received - Time replied - processing time

Sniffing UWB frames

```
nearbyd[1184] <Notice>: Built GR packet: {
                  ses_role: 0
                , tx_ant_mask : 2
                , rx_ant_mask : 11
                , rx_sync_search_ant_mask : 2
                , tx_preamble: 3
                , rx_preamble: 3
                , tx_pkt_type: 0
                , rx_pkt_type: 0
                , tx_mslot_sz_250us: 12
                , rx_mslot_sz_250us: 12
                , interval_min_ms: 30
                , naccess_slots_min: 1
                , naccess_slots_max: 32
                , access_slot_idx: 0
                , start_channel: 1
                , alternate_channel: 0
                , channel_hop_pattern_mask: 8
                , debug_flags: 7
                , start_time: 0
                , start_time_uncertainty: 0
                , interval_max_ms: 5000
                , local_addr: 0x0
                , peer_addr: 0x0
                , sts_blob: 128171129157185104203194128101126198143130668 4
     }
```

Sniffing UWB frames

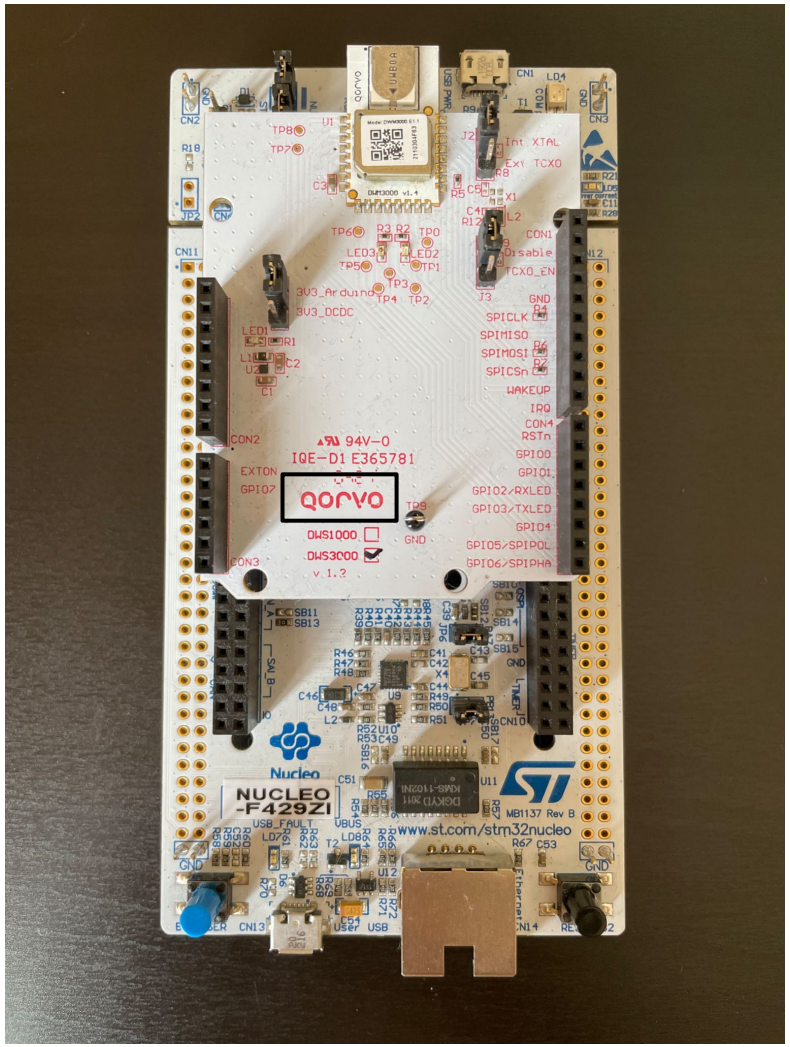
```
nearbyd[1184] <Notice>: Built GR packet: {
                    ses_role: 0
                  , tx_ant_mask : 2
                  , rx_ant_mask : 11
                  , rx_sync_search_ant_mask : 2
                  , tx_preamble: 3
                  , rx_preamble: 3
                  , tx_pkt_type: 0
                  , rx_pkt_type: 0
                  , tx_mslot_sz_250us: 12
                  , rx_mslot_sz_250us: 12
                  , interval_min_ms: 30
                  , naccess_slots_min: 1
                  , naccess_slots_max: 32
                  , access_slot_idx: 0
                  , start_channel: 1
                  , alternate_channel: 0
                  , channel_hop_pattern_mask: 8
                  , debug_flags: 7
                  , start_time: 0
                  , start_time_uncertainty: 0
                  , interval_max_ms: 5000
                  , local_addr: 0x0
                  , peer_addr: 0x0
                  , sts_blob: 128171129157185104203194128101126198143130668 4
      }
```

Supported *preambles codes* for 64MHz pulse repetition frequency

Channel 5: `[9, 10, 11, **12**]`
Channel 9: `[9, 10, 11, **12**]`

Channels supported by U1
`[5, **9**]`

The Right Hardware



Where can I find beta UWB development kits that interoperate with Apple U1?

Approved beta UWB development kits are available from the following chipset manufacturers:

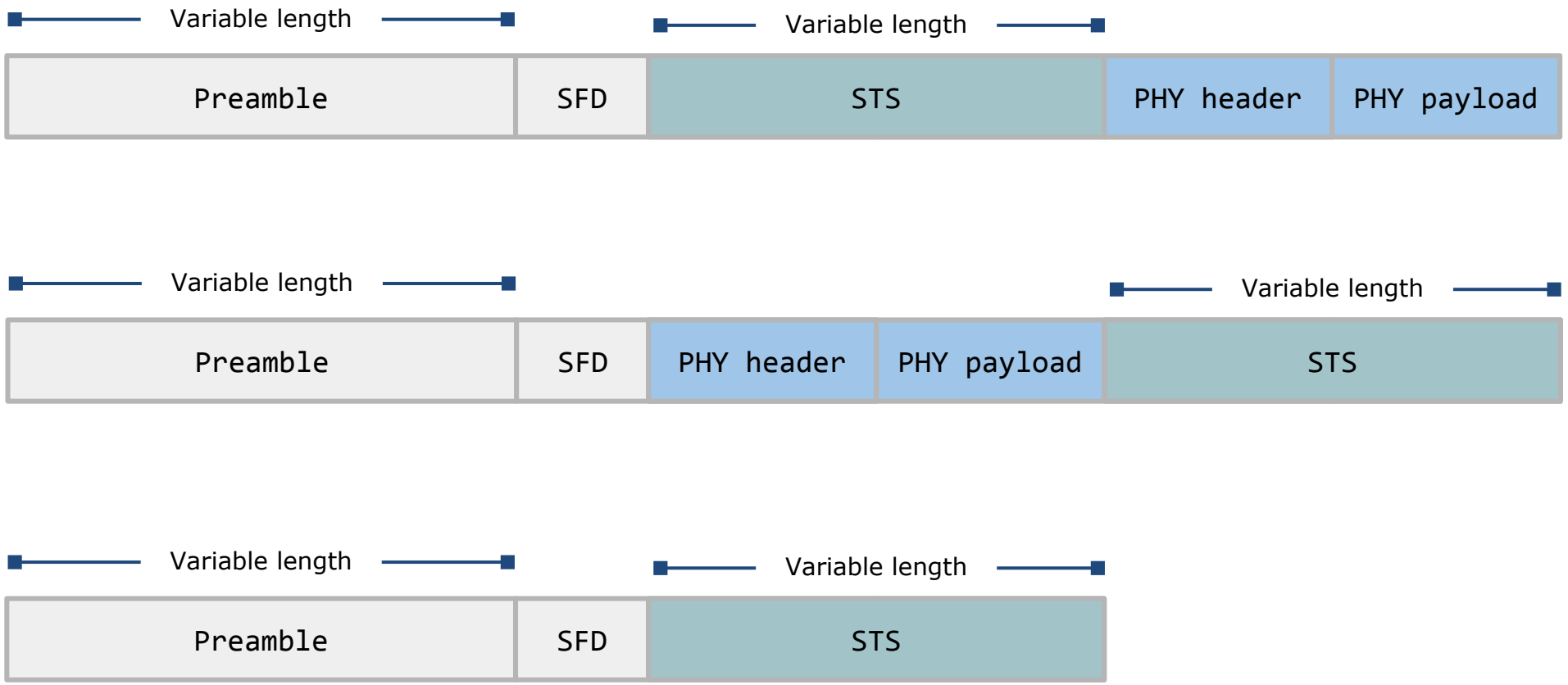
- NXP Semiconductors
- Qorvo

The Correct Configuration

Configuration:

Channel	9
Preamble code	12
Start of frame delimiter	likely 802.15.4z-2020
STS format	?
STS length	?

UWB Frame format



SFD = Start of frame delimiter

Issues

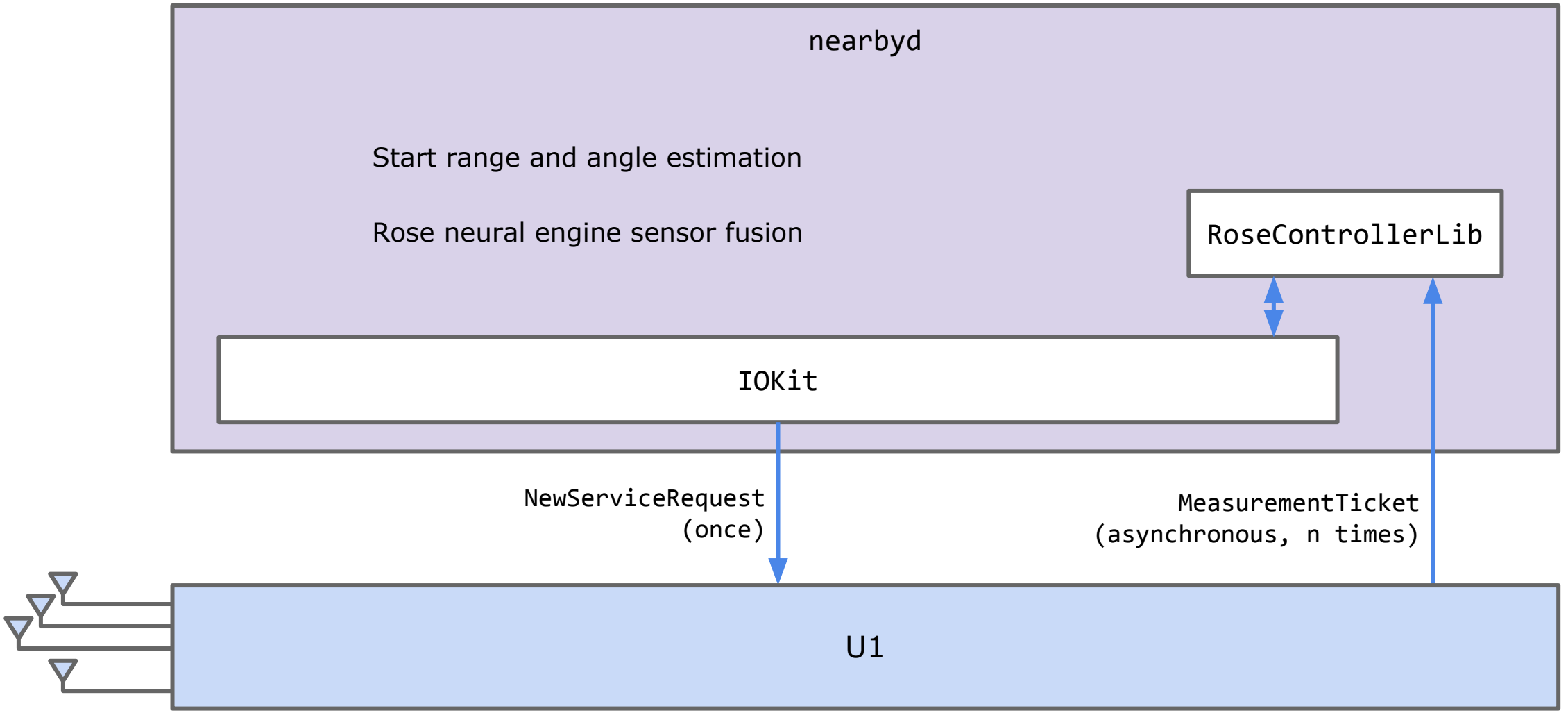
21	1.798144	IEEE 802.15.4	1	[Malformed Packet]
22	1.910204	IEEE 802.15.4	1	[Malformed Packet]
23	2.054215	IEEE 802.15.4	1	[Malformed Packet]
24	2.099162	IEEE 802.15.4	1	[Malformed Packet]
25	2.185221	IEEE 802.15.4	1	[Malformed Packet]
26	2.285248	IEEE 802.15.4	1	[Malformed Packet]
27	2.314213	IEEE 802.15.4	1	[Malformed Packet]
28	2.440272	IEEE 802.15.4	1	[Malformed Packet]
29	2.469252	IEEE 802.15.4	1	[Malformed Packet]
30	2.572254	IEEE 802.15.4	1	[Malformed Packet]

```
> Frame 52: 73 bytes on wire (584 bits), 73 bytes captured (584 bits) on interface 1
v IEEE 802.15.4 Data
  > Frame Control Field: 0x0149, Frame Type: Data, Security Enabled, PAN ID Compression, Sequence Numb
  > [Expert Info (Warning/Malformed): Sequence Number Suppression invalid for 802.15.4-2003 and 2006]
  > [Expert Info (Error/Malformed): Invalid Setting for PAN ID Compression]
```

```
49 01 0b f4 79 3f df fa  22 a4 c2 3a d5 22 66 1e   I···y?·· "··:·"f·
9b b7 b0 74 2f 34 6e 57  7a 97 90 1d f3 19 32 d6   ···t/4nW z·····2·
11 34 83 bb 9b 12 d3 48  8c 3e 69 2e 2c 67 00 62   ·4·····H ·>i.,g·b
4d d2 a9 e6 a4 56 53 2b  84 2a 60 90 86 5b c1 02   M····VS+ ·*`··[··
a1 a5 44 1a d0 57 44 08  56                        ··D··WD· V
```

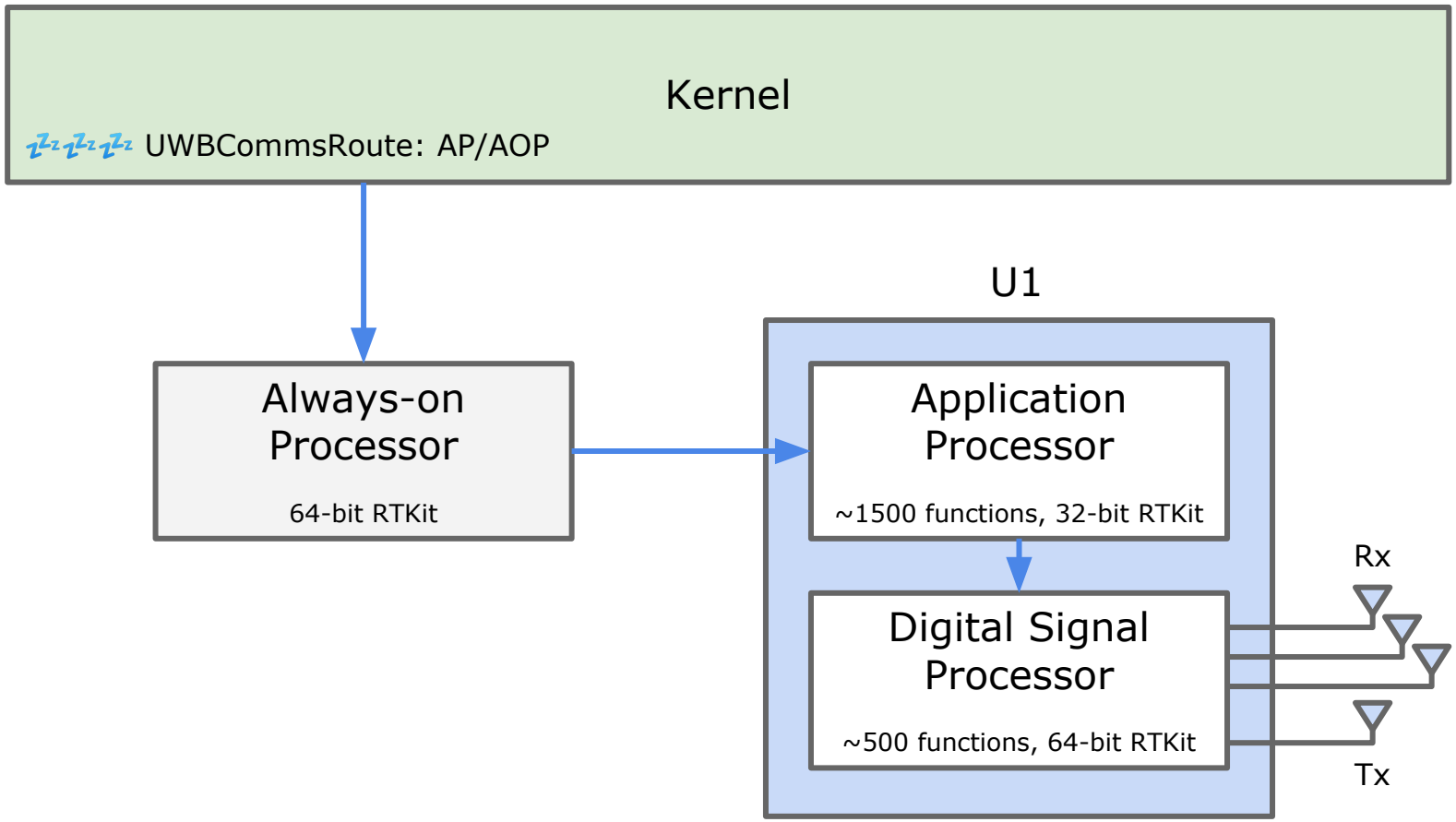
AirDrop	Nearby Interaction
One-to-many ranging	Peer-to-peer ranging
Single sided ranging	Double sided ranging
Likely no STS	Shared secret and STS

AoA and Distance Measurement Ticket Processing

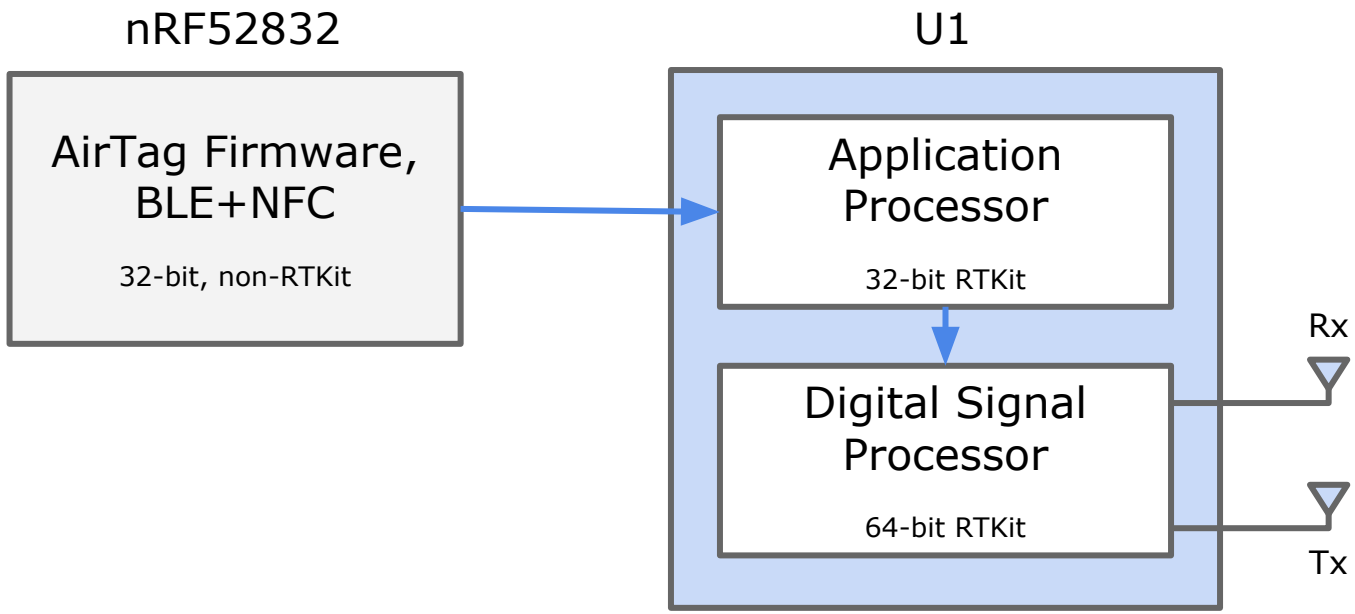


Hardware Interaction

Hardware Components



Hardware Components - AirTag

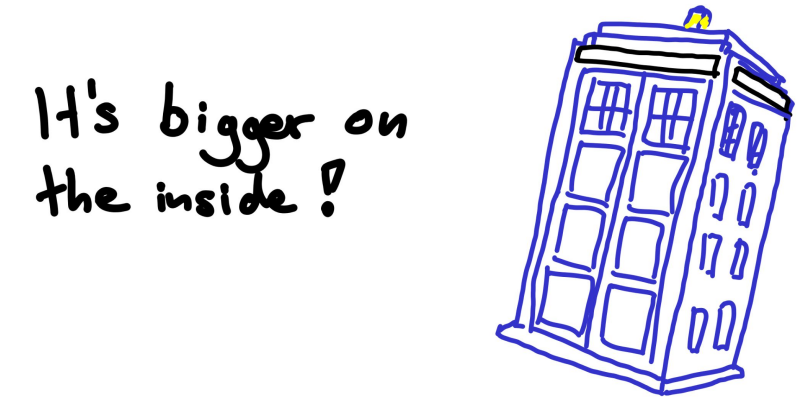


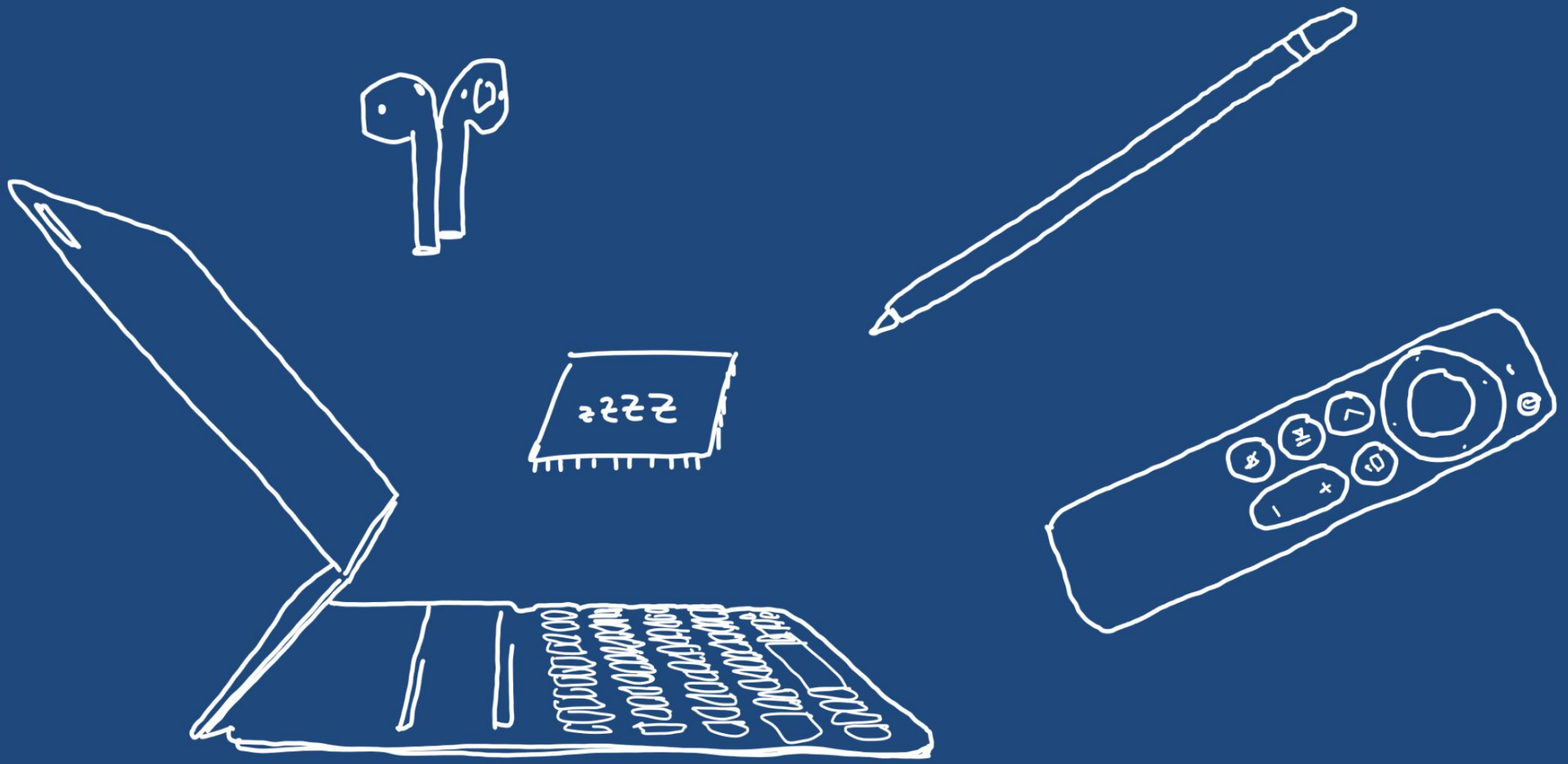
"Hacking the Apple AirTags", DEF CON 29 talk by Thomas Roth.

RTKit Operating System

- RTKitOS runs on almost every Apple chip or embedded device.
  - 64-bit variant comes with ASLR. 
  - Lightweight, ~100 functions.
  - Even logging is implemented differently in every RTKitOS firmware.

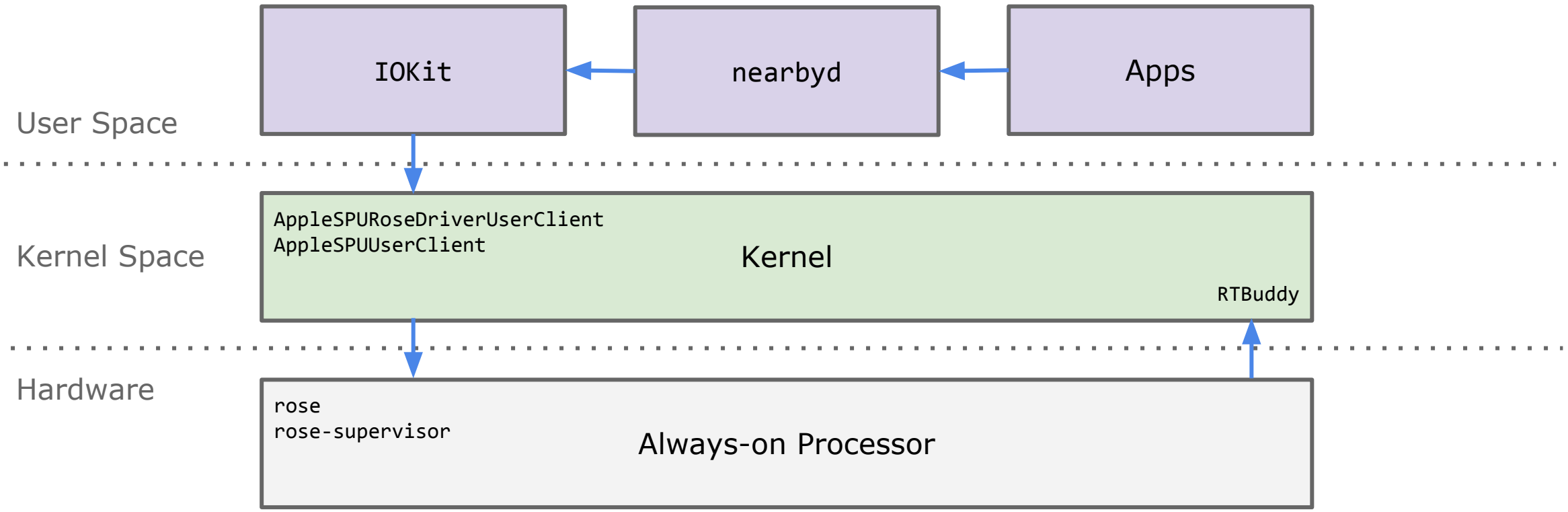
- RTKitOS debug builds support additional logging.
  - U1 debug builds: iOS 13.3 on iPhone 11 & initial AirTag firmware 🎉





More details about RTKitOS in Apple’s Bluetooth chip and peripherals are documented in Dennis Heinze’s thesis (https://github.com/seemoo-lab/toothpicker).

Duplicate User Clients



`IOKit UserClients` for RTKit-based chips have equivalents in the AOP.
Same principle for other wireless chips by Apple, e.g., the audioOS AOP implements `marconi-bluetooth` and `aop-marconi-bt-control` to communicate with Apple's Bluetooth chip.

RTKit-based chips communicate with an `RTBuddy` for logging etc.

Checking RTKit-based Driver Dependencies

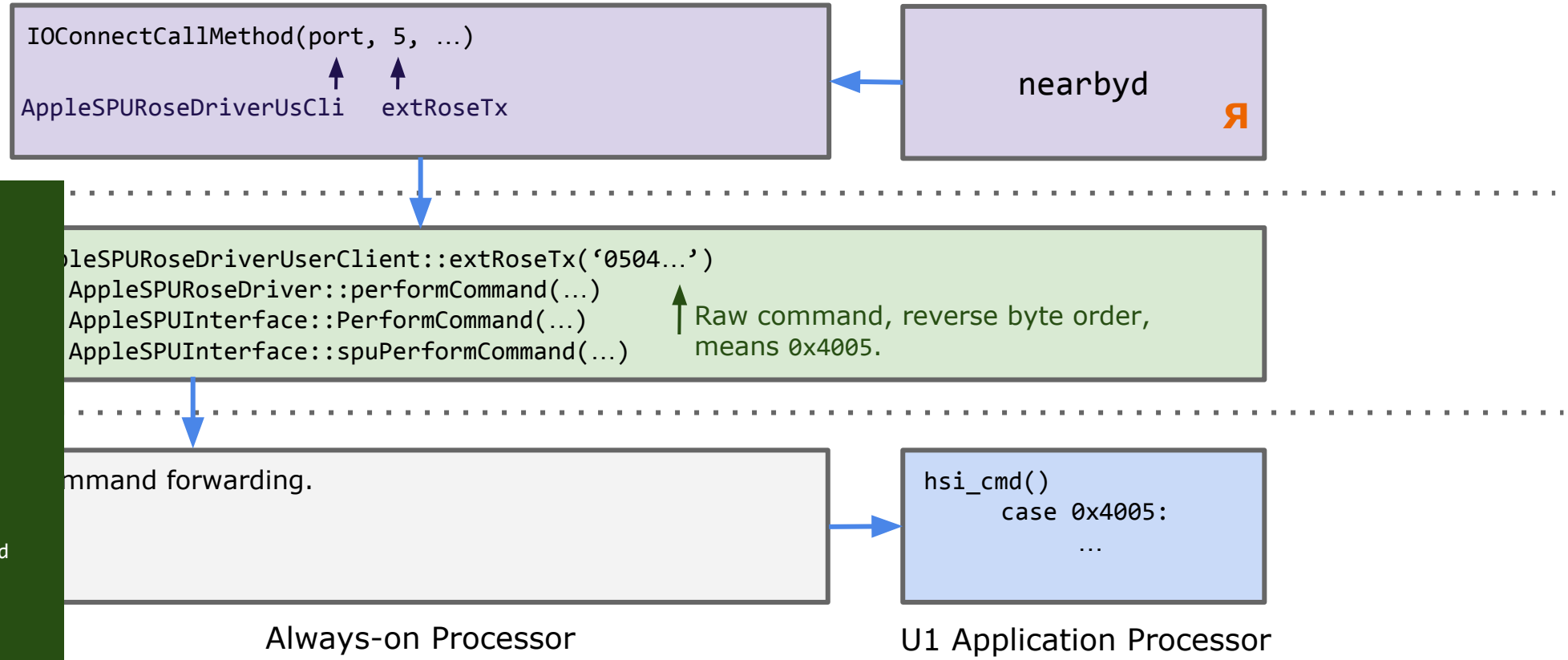
```
# ioreg -rtc IOUserClient

+-o Root  <class IORegistryEntry, id 0x100000100, retain 184>
  +-o N104AP  <class IOPlatformExpertDevice, id 0x10000020f, ... >
    +-o AppleARMPE  <class AppleARMPE, id 0x100000210, ... >
      +-o arm-io@10F00000  <class IOPlatformDevice, id 0x100000118, ... >
      ...         +-o RTBuddyV2  <class RTBuddyV2, id 0x100000374, ... >
                    +-o AOPEndpoint17  <class RTBuddyEndpointService, id 0x1000003a0, ... >
                      +-o AppleSPU@10000014  <class AppleSPU, id 0x1000003dc, ... >
                        +-o rose  <class AppleSPUAppInterface, id 0x100000142, ... >
                          +-o AppleSPURoseDriver  <class AppleSPURoseDriver, id 0x1000004e4... >
                            +-o AppleSPURoseDriverUserClient  <class AppleSPURoseDriverUserClient, id 0x100000aa3, ... >
                                {
                                  "IOUserClientCreator" = "pid 549, nearbyd"
                                }
...
                     +-o AppleSPU@10000020  <class AppleSPU, id 0x1000003e2, ... >
                        +-o rose-supervisor  <class AppleSPUHIDInterface, id 0x10000049e, ... >
                          +-o AppleSPUUserClient  <class AppleSPUUserClient, id 0x100000aa4, ... >
                              {
                                "IOUserClientCreator" = "pid 549, nearbyd"
                                "IOUserClientDefaultLocking" = Yes
                              }
```

Find detailed `ioreg` outputs from current devices on https://github.com/robre/ioreg-archive.

Sending Commands directly to Rose

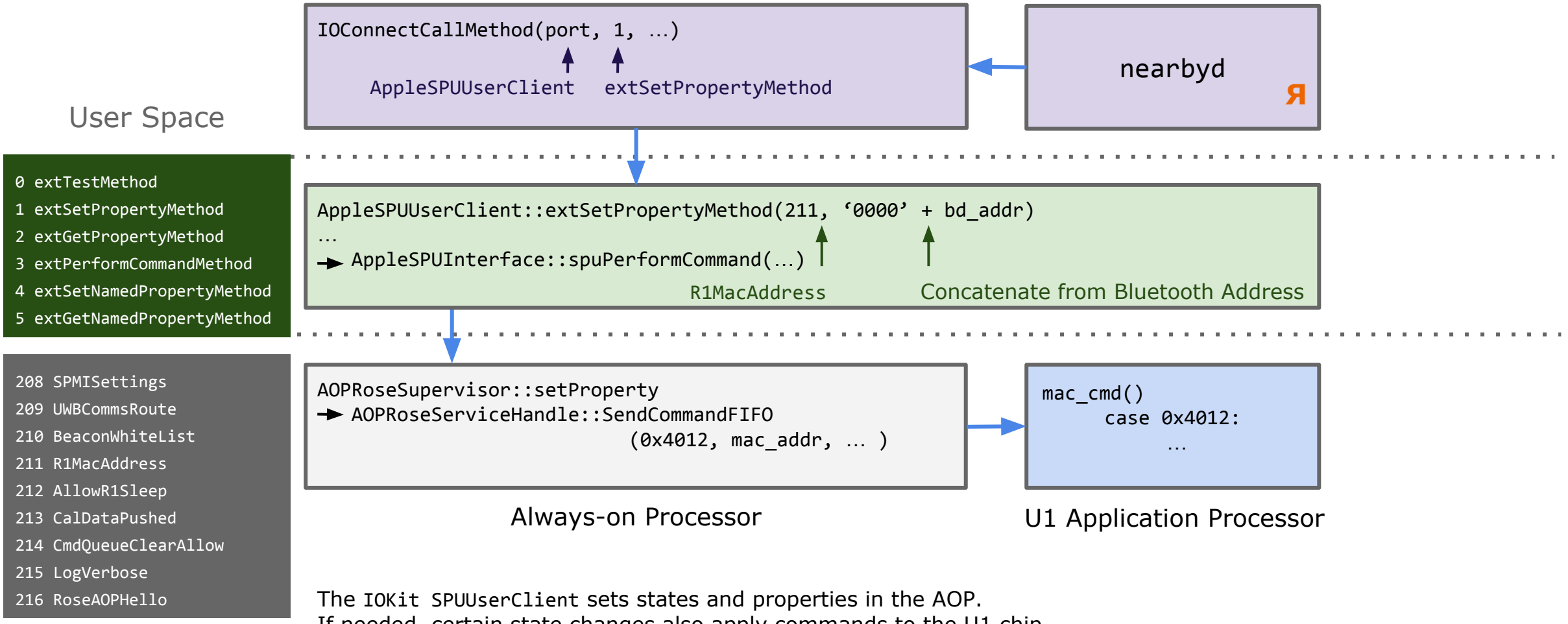
User Space

```
 0 extRoseLoadFirmware
 1 extRoseGetInfo
 2 extRoseReset
 3 extRoseEnterCommandMode
 4 extRosePing
 5 extRoseTx
 6 extRoseTimeSync
 7 extRoseGetSyncedTime
 8 extRoseGetProperty
 9 extRoseSetProperty
10 extRosePerformInternalCommand
11 extRoseCacheFirmwareLogs
12 extRoseDequeueFirmwareLogs
13 extRoseTriggerCoredump
14 extRoseDequeueCoredump
15 extRoseCoredumpInfo
16 extRosePowerOn
17 extRoseReadPowerState
18 extRoseConfigureFirmwareLogCache
```



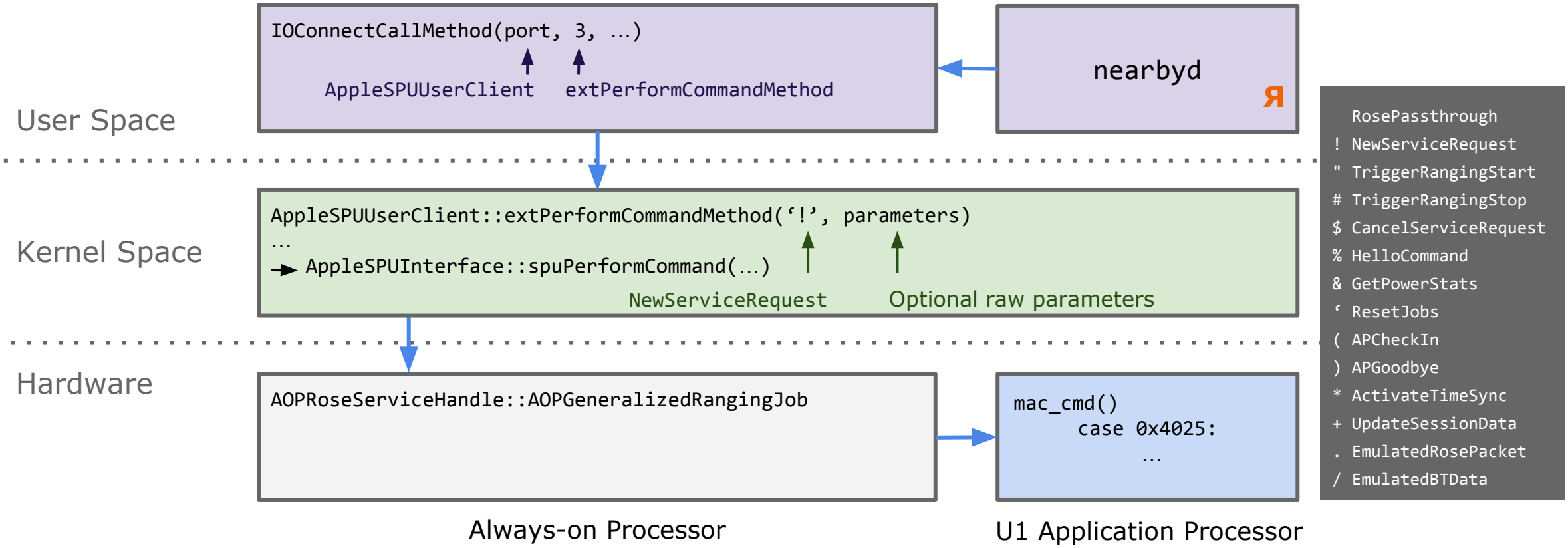
e IOKit RoseDriverUserClient exports various functions, but in the end they call leSPUInterface::spuPerformCommand(…) within the kernel, similar to the SPUUserClient.

Sending Commands via the AOP to Rose



The `IOKit SPUUserClient` sets states and properties in the AOP.
If needed, certain state changes also apply commands to the U1 chip.

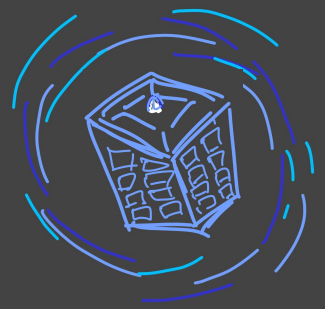
Sending Commands via the AOP to Rose



Demo: Frida script that decodes interaction
-> NewServiceRequest etc.

GR Packet to Initiate Secure Ranging

```
nearbyd[1184] <Notice>: RoseScheduler::handleNewServiceRequestInternal
nearbyd[1184] <Notice>: [AP Scheduler] Servicing dequeued service request.
             Passing message to AOP scheduler.
nearbyd[1184] <Notice>: Request: [Role]: Initiator, [MacMode]: GR
nearbyd[1184] <Notice>: Built GR packet: {
                    ses_role: 0
                  , tx_ant_mask : 2
                  , rx_ant_mask : 11
                  , rx_sync_search_ant_mask : 2
                  , tx_preamble: 3
                  , rx_preamble: 3
                  , tx_pkt_type: 0
                  , rx_pkt_type: 0
                  , tx_mslot_sz_250us: 12
                  , rx_mslot_sz_250us: 12
                  , interval_min_ms: 30
                  , naccess_slots_min: 1
                  , naccess_slots_max: 32
                  , access_slot_idx: 0
                  , start_channel: 1
                  , alternate_channel: 0
                  , channel_hop_pattern_mask: 8
                  , debug_flags: 7
                  , start_time: 0
                  , start_time_uncertainty: 0
                  , interval_max_ms: 5000
                  , local_addr: 0x0
                  , peer_addr: 0x0
                  , sts_blob: 128171129157185104203194128101126198143130668 4
    }
```



0x80=128, 0xab=171, …, 0x54=84

```
   - AppleSPUUserClient::extPerformCommandMethod()
       > connection      0xa503
       > selector        0x3
       > input
         v
          0  1  2  3  4  5  6  7  8  9  A  B  C  D  E  F  0123456789ABCDEF
00000000  21                                              !
    + NewServiceRequest
          v---- IOKit input struct ----
          0  1  2  3  4  5  6  7  8  9  A  B  C  D  E  F  0123456789ABCDEF
00000000  30 00 16 00 00 00 04 00 01 13 01 02 00 00 00 00  0...............
00000010  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000020  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000030  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000040  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000050  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000060  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000070  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000080  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000090  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
000000a0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
000000b0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
000000c0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
000000d0  00 00 00 00 00 25 40 00 00 00 00 01 04 02 0b 02 01  ....%@.........
000000e0  00 08 03 03 00 00 00 00 00 00 0c 0c 00 00 1e 00  ................
000000f0  88 13 01 20 ff 80 ab 81 9d b9 68 cb c2 80 65 7e  ... ......h...e~
00000100  c6 8f 82 42 54 00 00 00 00 00 07 00 00 00 00 00  ...BT...........
00000110  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000120  00 00 00 00 00 00 00 00                          ........
```

Firmware Format

U1 Firmware Extraction

Contained in every iOS/audioOS IPSW, watchOS OTA image, or AirTag firmware image.

`/Firmware/Rose/[type]/ftab.bin`

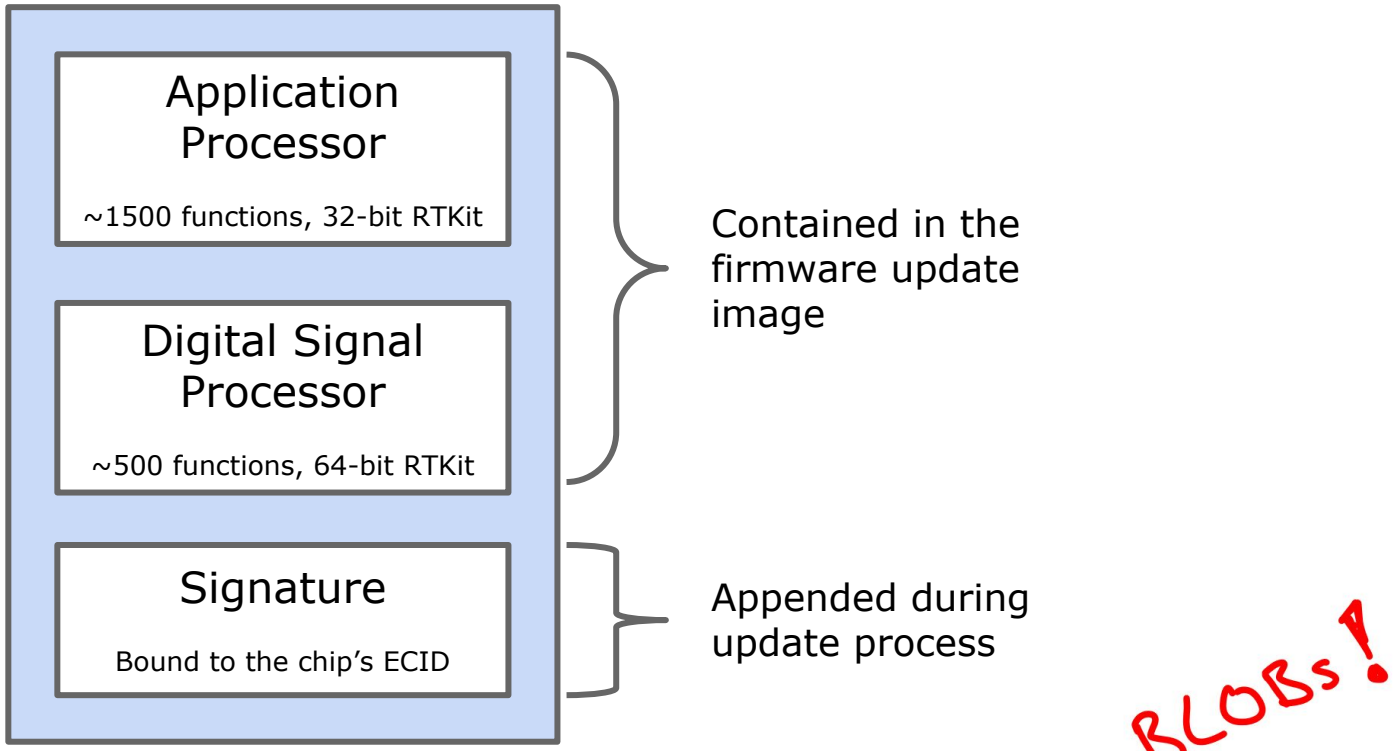
Types as of now:

- iPhone 11 (r1p0)
- iPhone 12 (r1p1)
- Apple Watch 6 (r1w0)
- HomePod mini (r1hp0)
- AirTag (b389)

```
00000000  01 00 00 00 ff ff ff ff  00 00 00 00 00 00 00 00  ................
00000010  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000020  72 6b 6f 73 66 74 61 62  03 00 00 00 00 00 00 00  rkosftab........
00000030  72 6b 6f 73 60 00 00 00  e0 98 04 00 00 00 00 00  rkos`...........
00000040  73 62 64 31 40 99 04 00  60 39 04 00 00 00 00 00  sbd1@...`9......
00000050  62 76 65 72 a0 d2 08 00  26 00 00 00 00 00 00 00  bver....&.......
…
000786b0  00 00 00 00 00 00 00 00  00 00 00 00 20 00 00 00  ............ ...
000786c0  52 54 4b 69 74 5f 69 4f  53 2d 31 32 36 34 2e 36  RTKit_iOS-1264.6
000786d0  30 2e 36 2e 30 2e 31 2e  64 65 62 75 67 00 00 00  0.6.0.1.debug...
000786e0  06 00 00 80 04 00 00 00  00 00 00 00 00 00 00 00  ................
000786f0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
```

The ftab format is also used for other firmware, split it using https://gist.github.com/matteyeux/c1018765a51bcac838e26f8e49c6e9ce.

Firmware Segments



Demo: Show system messages how the chip boots, maybe also an invalid boot

Obtaining Logs

Trigger Rose Error Handling (#1)

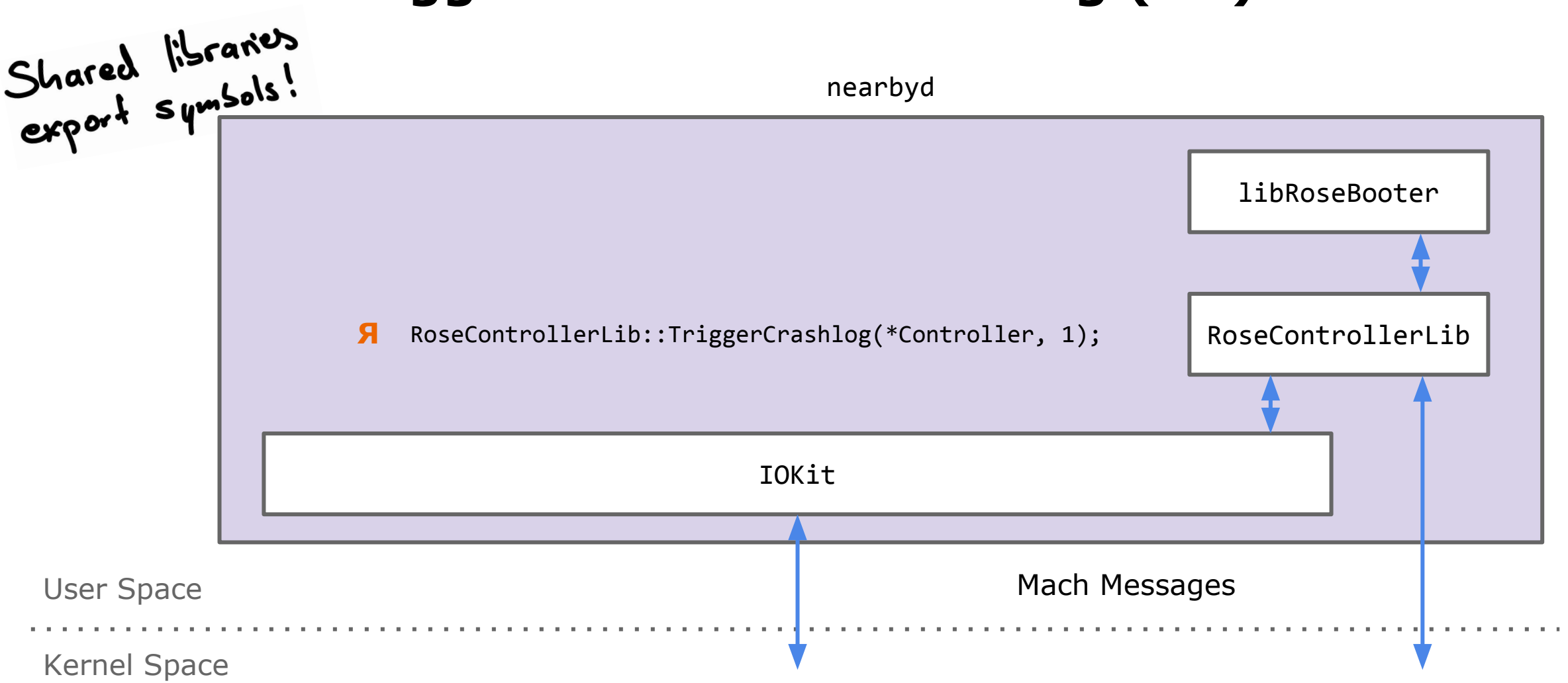
Can we interact with the firmware without modifying it?

`SystemOff` is executed when entering flight mode, switch this with the implementation of `TriggerFatalErrorHandling`.

Get full crash logs and packet logs by setting `isInternalBuild` and a few other properties.

```
case 7:
   _os_log_impl( …,
     "PRRoseProvider::relayCommandMessage -- SystemOff",
     buf_full_packet,
     2LL);
 …
case 8:
  …
     "PRRoseProvider::relayCommandMessage -- RefreshConfiguration",
  …
 PRRoseProvider::relayCommandMessage_RefreshConfiguration_104F70484(a1 + 19);
 …
case 9:
   …
     "PRRoseProvider::relayCommandMessage -- TriggerFatalErrorHandling",
   …
 log_rose_r1_msg_1021139CC(buf_full_packet, "AOPRoseFatalError");
 PRRoseProvider::relayCommandMessage_TriggerFatalErrorHandling_104F72654(…)
 …
```

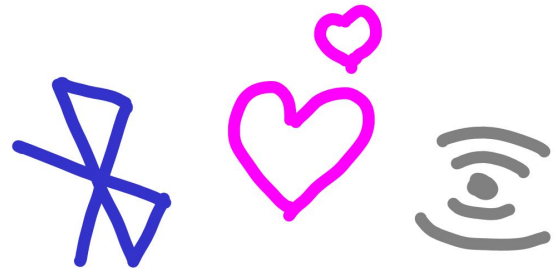
Trigger Rose Error Handling (#2)



Demo: Show Crash Logs & iOS 13.3 Packet Logs

Conclusion

Lessons Learned



- Bluetooth and Ultra Wideband are tightly coupled on iOS.
- Apple’s own RTKit-based wireless chips have an interesting architecture with many security features like secure boot and ASLR.
- Many features in the chip can be instrumented from user space.

Q&A

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