All BLE guides are wrong

including this one

David Burnett, UC Berkeley, 2018 Mar 06
db@berkeley.edu

Preamble (1 byte)
Access address (4 bytes)
Header (2 bytes)
Advertising address (6 bytes)
Payload (0 to 31 bytes)
CRC (3 bytes)

All BLE guides are wrong

including this one

Preamble (1 byte, depends on access address)
Access address (4 bytes, but write out all 4 bytes and reverse them)
Header (2 bytes, first 4 bits are reversed from spec table, length is LSB first)
Advertising address (6 bytes, but write out all 6 bytes and reverse them)
Payload (0 to 31 bytes, individual bytes are LSB first)
CRC (3 bytes, MSB first but packet sniffers all calculate hex codes as if it was LSB first)
(and the most popular graphic about CRC has the wrong LFSR init code)

All BLE guides are wrong

including this one

Preamble (1 byte)
Access address (4 bytes)
Whiten:
Header (2 bytes)
-- 4 bits denoting type of packet (LSB first, so backward wrt spec)
-- 1 bits reserved for future use
-- 1 bit that does something new in BLE 5, don’t remember what, set it to 0
-- 1 bit about Tx address
-- 1 bit about Rx address
-- 8 bits length (as of BLE 5; LSB first)
Advertising address (6 bytes)
Payload (0 to 31 bytes), can contain multiple sub-payloads each with:
-- 1 byte length
-- 1 byte type, listed in “Supplement to the Bluetooth Core Specification”
-- N bytes data
CRC (3 bytes)
-- LFSR initialized to 0x555555

Preamble

- If first bit of access address 0
  - Preamble is 01010101
- If first bit of access address 1
  - Preamble is 10101010

Access address

```
>> dec2bin(hex2dec('8E89BED6'),32)
10001110100010011011111011010110
```

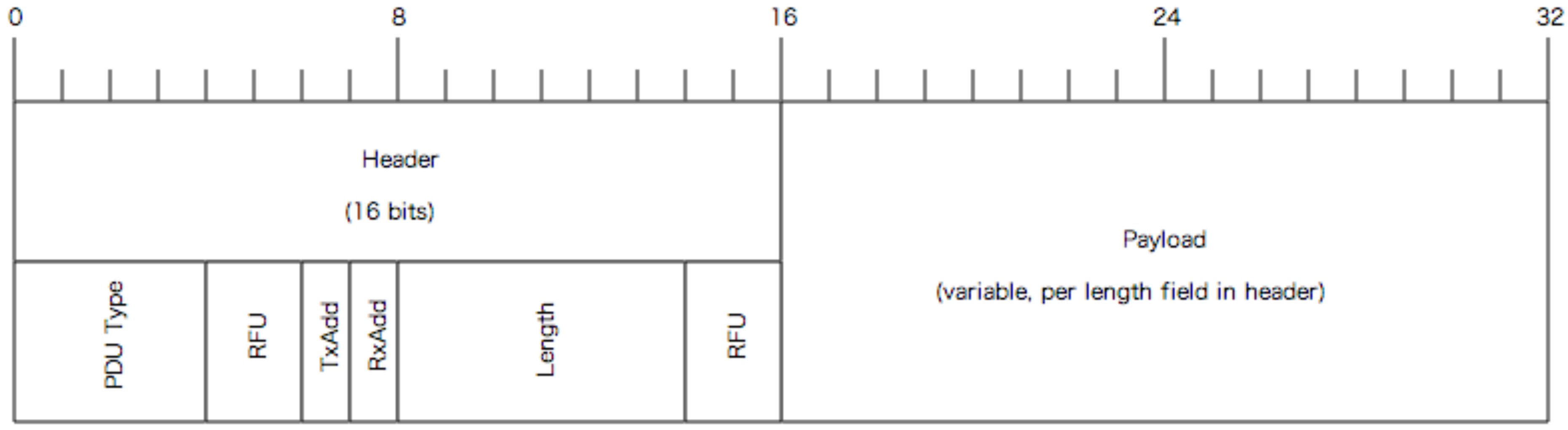
Access address

```
>> dec2bin(hex2dec('8E89BED6'),32)
10001110100010011011111011010110

preamble: 10101010

total: [10101010 10001110100010011011111011010110]
```

Access address

```
>> dec2bin(hex2dec('8E89BED6'),32)
10001110100010011011111011010110

preamble: 10101010

total: [10101010 10001110100010011011111011010110]

nope -- access address is transmitted LSB first
see BT core spec 5.0 Vol 6, Part B, section 1.2
(page 2,555)

>> fliplr(dec2bin(hex2dec('8E89BED6'),32))
01101011011111011001000101110001

preamble: 01010101

total: [01010101 01101011011111011001000101110001]
        ^first out of ant        last out of ant^
```

BLE 4 header & payload



Some reserved for future use (RFU) sections are in use for BLE 5

http://j2abro.blogspot.com/2014/06/understanding-bluetooth-advertising.html

Header: PDU type

```
%  PDU Types
%  b3b2b1b0 Packet Name
%  0000 ADV_IND connectable undirected advertising event
%  0001 ADV_DIRECT_IND connectable directed advertising event
%  0010 ADV_NONCONN_IND non-connectable undirected advertising event
%  0011 SCAN_REQ scan request
%  0100 SCAN_RSP scan response
%  0101 CONNECT_REQ connection request
%  0110 ADV_SCAN_IND scannable undirected advertising event
%  0111-1111 Reserved

Core spec 5.0 page 2567
```

- We used `ADV_NONCONN_IND` for our example packet
  - Transmitted LSB-first: 0100 in order of radio transmission

Header: RFU, TxAdd, RxAdd

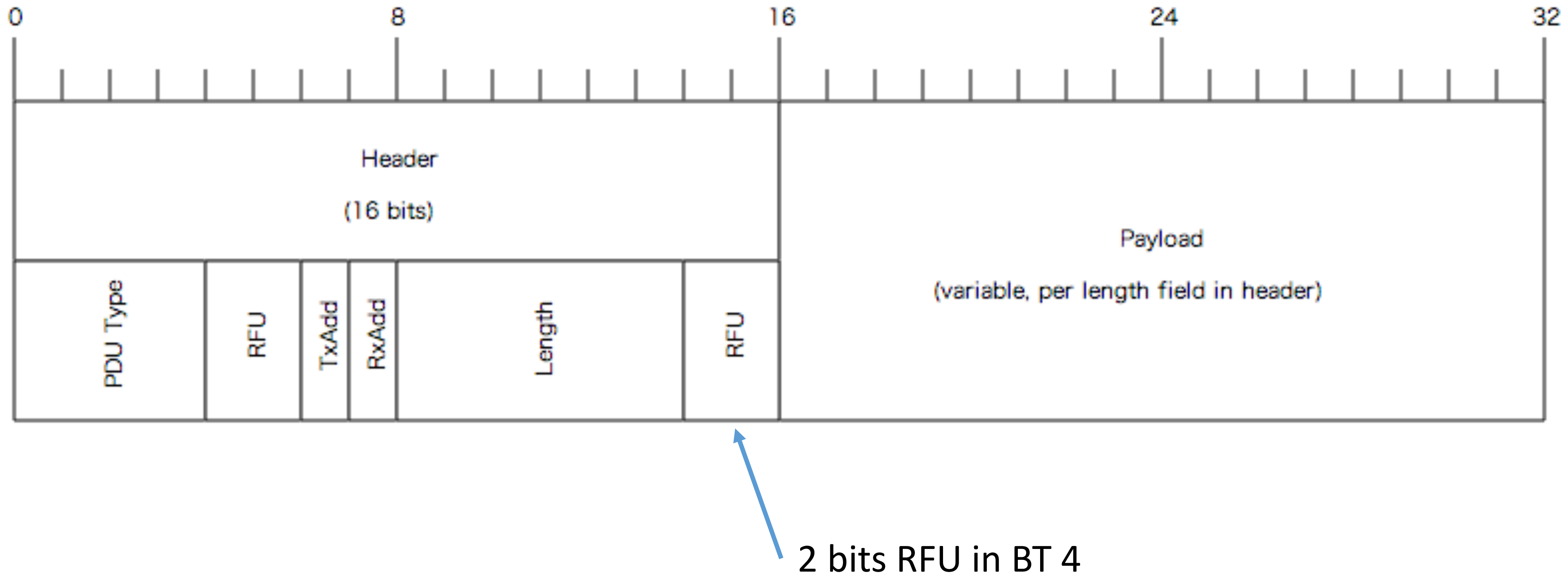
- Set both RFU bits to 0
- One of them has a new use in BT 5.0

- TxAdd, RxAdd:
  - 0 means public address, 1 means randomized address
  - Set both to 0 for this example

Header: length

- Size of payload in bytes/octets
- Length word is 6 bits long in BLE 4, 8 bits in BLE 5
- Length will be least 6 for advertiser address
  - I used an address from a prior packet capture
- At most 37 (typically)
- We used 16 in our example
- Transmitted LSB first, so length 16 is 00001000 in order of transmission

BLE 4 header & payload



2 bits RFU in BT 4
Used for more length bits in BT 5

http://j2abro.blogspot.com/2014/06/understanding-bluetooth-advertising.html

Header: put it all together

```
PDU Type: 0100 (ADV_NONCONN_IND code expressed LSB-first)
RFU: 00
TxAdd: 0
RxAdd: 0
Length: 00001000 (0x10 expressed LSB-first)

Total header: 0100 00 0 0 00001000
              ^first out of antenna
```

Payload

- Advertiser address (6 bytes)
- 0 or more payload sections consisting of:
  - 1 byte length (not including self)
  - 1 byte GAP code describing this payload section
  - 0 to N bytes data
- For our example: 2 sections
  - First: 0x02 (length), 0x01 (“flags”), 0x05 (flag data)
  - See “Supplement to the Bluetooth Core Specification” part A section 1.3 at bluetooth.com/specifications/bluetooth-core-specification
  - Second: 0x06 (length), type 0x08 (“short name”), data 0x53 0x43 0x55 0x4D 0x33 (ASCII code for “SCUM3”)

Payload

- Advertiser address (6 bytes)
  - 0x90d7ebb19299, from TI packet capture*
  - Transmitted LSB first

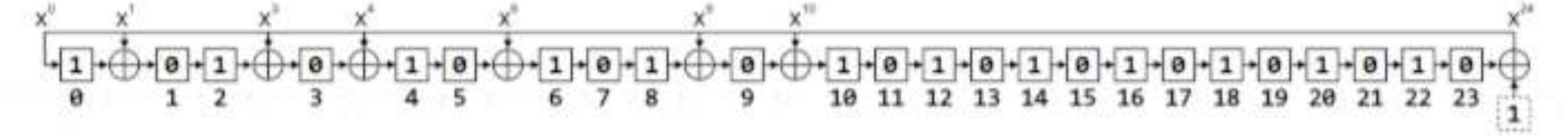
```
>> fliplr(dec2bin(hex2dec('90d7ebb19299'),48))
100110010100100110001101110101111110101100001001
```

- Data: transmitted LSB-first **per-byte**, e.g.,
  - 0x02 0x01 0x05 becomes
  - 01000000 10000000 10100000
  - ^ first bit out of antenna

*http://processors.wiki.ti.com/index.php/BLE_sniffer_guide

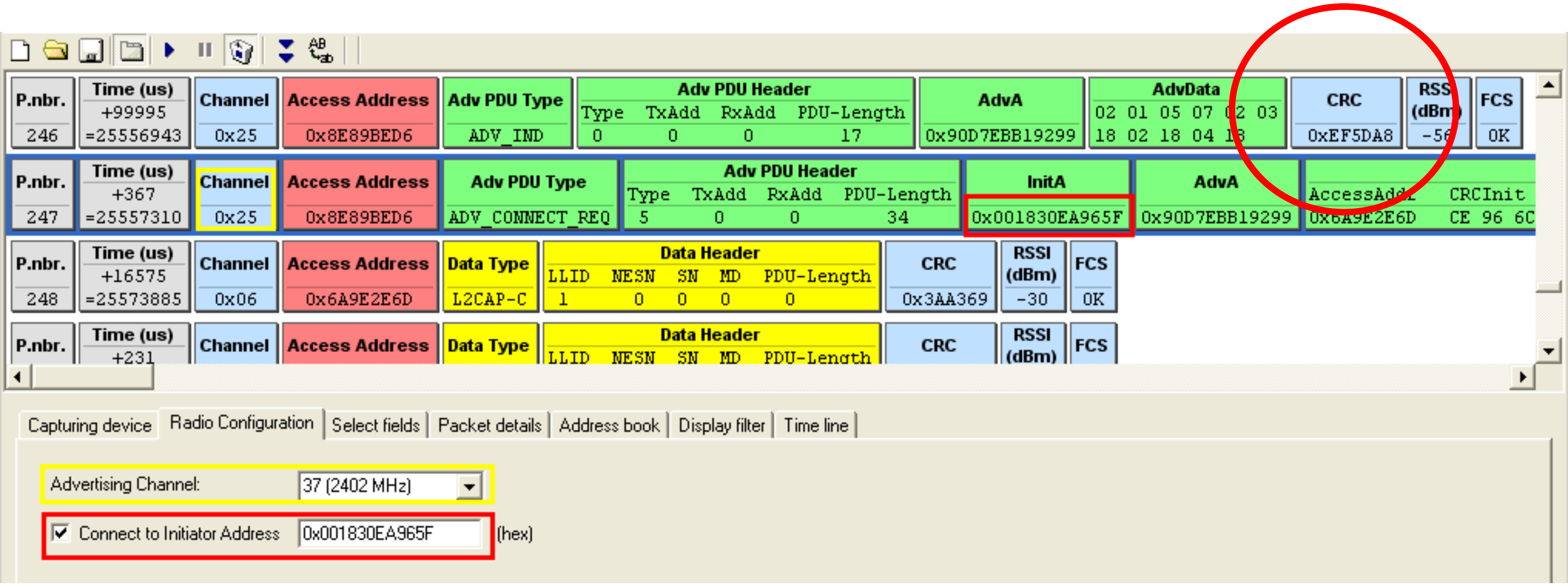
CRC

- 24-bit linear feedback shift register (LFSR) in spec



- Initialized to 0x555555 as shown above
- Feed data in LSB-first at far right
- Input data is header, adv. address, payload(s)
- Result is transmitted **MSB-first** (position 23 above)
  - Wireshark reports CRC values as if they were LSB-first!
- Could be calculated with very few (1?) clock cycles

https://www.allaboutcircuits.com/technical-articles/long-distance-bluetooth-low-energy-bit-data-paths/
Note “Example CRC encoding...” figure is initialized to the wrong value; corrected figure shown here



P.nbr.	Time (us)	Channel	Access Address	Adv PDU Type	Adv PDU Header Type	TxAdd	RxAdd	PDU-Length	AdvA	AdvData	CRC	RSSI (dBm)	FCS
246	+99995 =25556943	0x25	0x8E89BED6	ADV_IND	0	0	0	17	0x90D7EBB19299	02 01 05 07 02 03 18 02 18 04 18	0xEF5DA8	-56	OK

P.nbr.	Time (us)	Channel	Access Address	Adv PDU Type	Adv PDU Header Type	TxAdd	RxAdd	PDU-Length	InitA	AdvA	AccessAddr	CRCInit
247	+367 =25557310	0x25	0x8E89BED6	ADV_CONNECT_REQ	5	0	0	34	0x001830EA965F	0x90D7EBB19299	0x6A9E2E6D	CE 96 6C

P.nbr.	Time (us)	Channel	Access Address	Data Type	Data Header LLID	NESN	SN	MD	PDU-Length	CRC	RSSI (dBm)	FCS
248	+16575 =25573885	0x06	0x6A9E2E6D	L2CAP-C	1	0	0	0	0	0x3AA369	-30	OK
P.nbr.	Time (us) +231	Channel	Access Address	Data Type	Data Header LLID	NESN	SN	MD	PDU-Length	CRC	RSSI (dBm)	FCS

Capturing device | Radio Configuration | Select fields | Packet details | Address book | Display filter | Time line

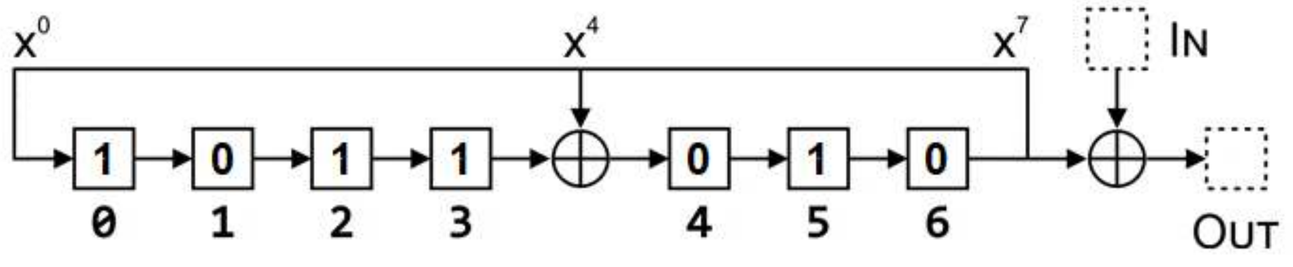
Advertising Channel: 37 (2402 MHz)

[✓] Connect to Initiator Address 0x001830EA965F (hex)

http://processors.wiki.ti.com/index.php/File:Using_radio_conf.png

Whitening

- Remove long strings of 0 or 1
  - Easier for the receiver to track center frequency and determine if bit is +df or -df
- 7-bit linear feedback shift register (LFSR) in spec



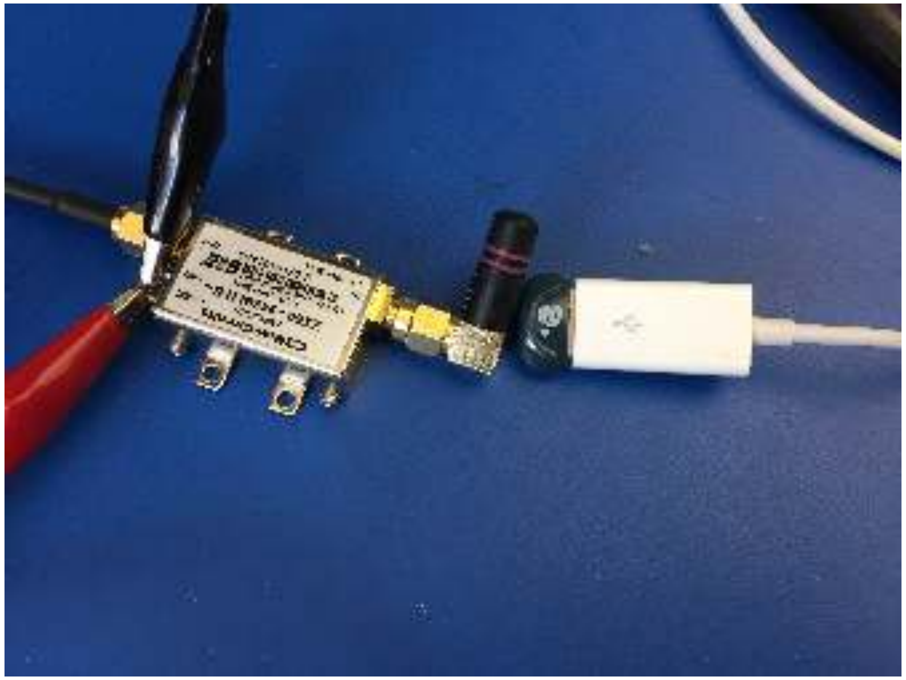
- Initialize to channel (37 in our example, not above) plus 1 added to LSB-side
- Feed in everything you fed into CRC, plus CRC, in transmit order

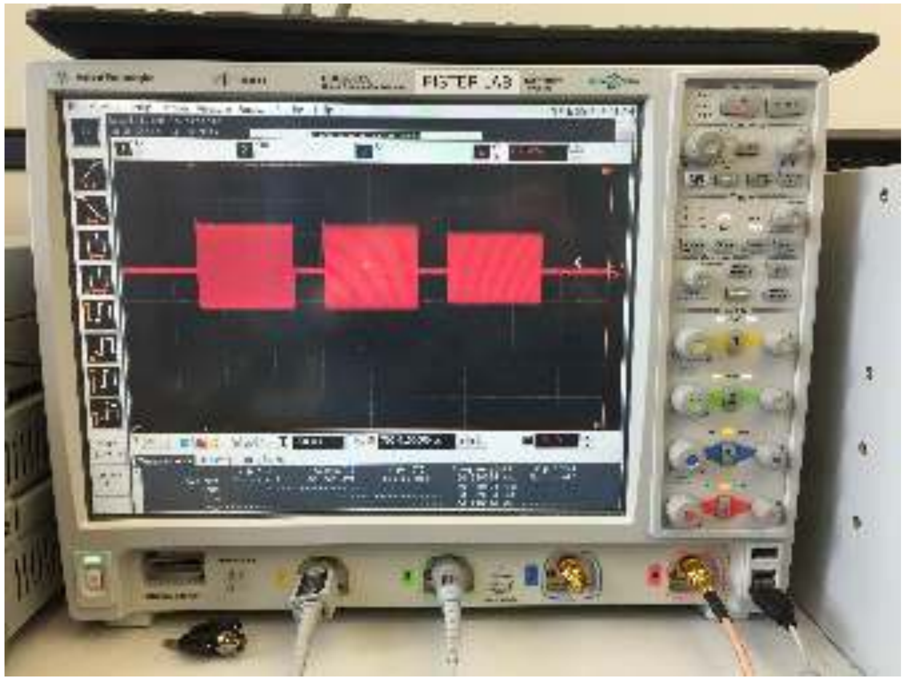
https://www.allaboutcircuits.com/technical-articles/long-distance-bluetooth-low-energy-bit-data-paths/
Note “Image illustrating logic inside the data whitening..” figure is not initialized to the claimed 19 value

Putting it all together

- See ble_adv_scm3.mat

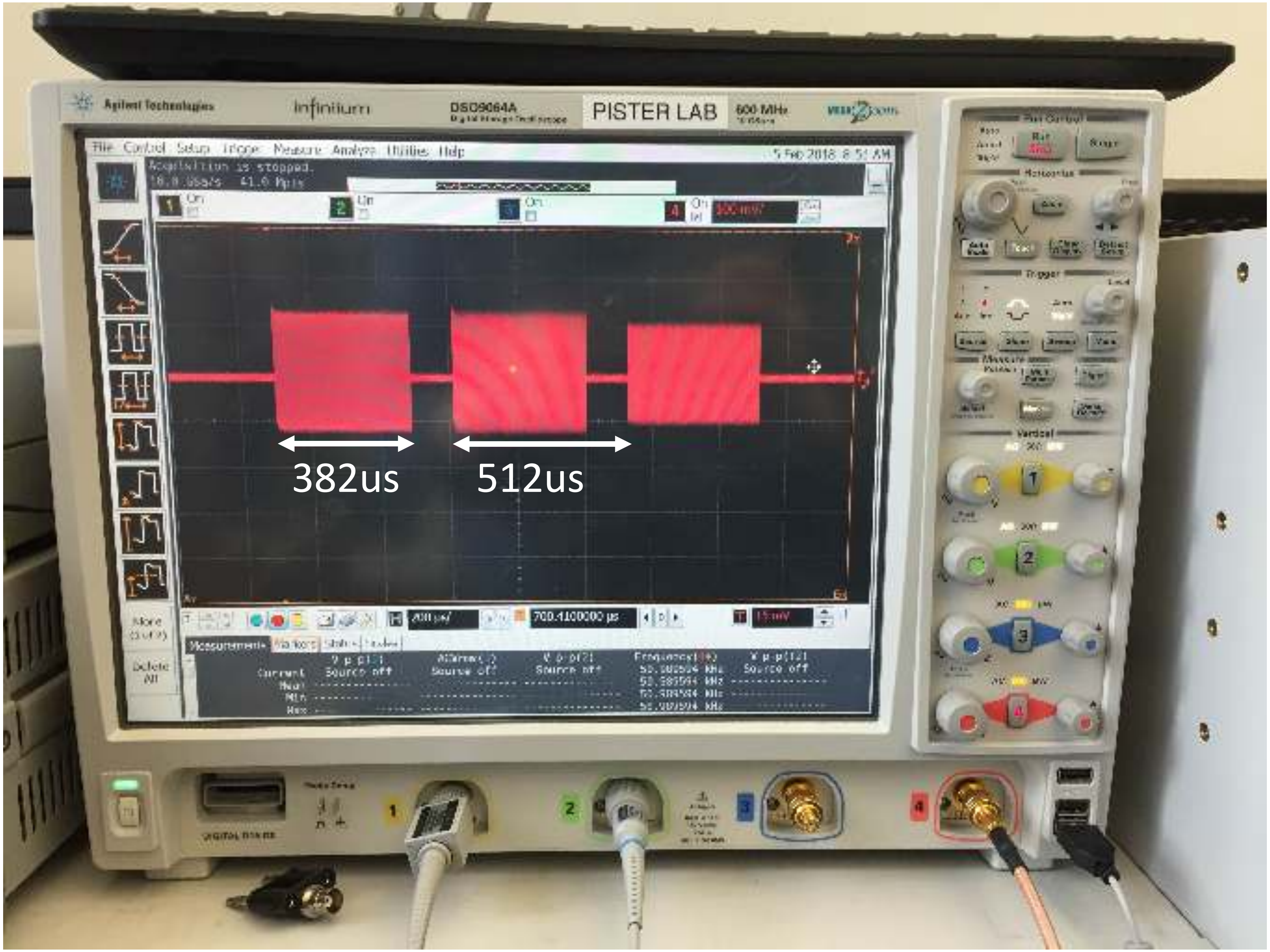
Recording commercial packets





BLE USB dongle producing ad packet
OpenMote antenna attached to LNA
Not pictured: mixer w/ 2.400GHz from Rohde

IF on scope showing ad packets on each BLE ad channel: 2MHz, 26MHz, 80MHz pulses

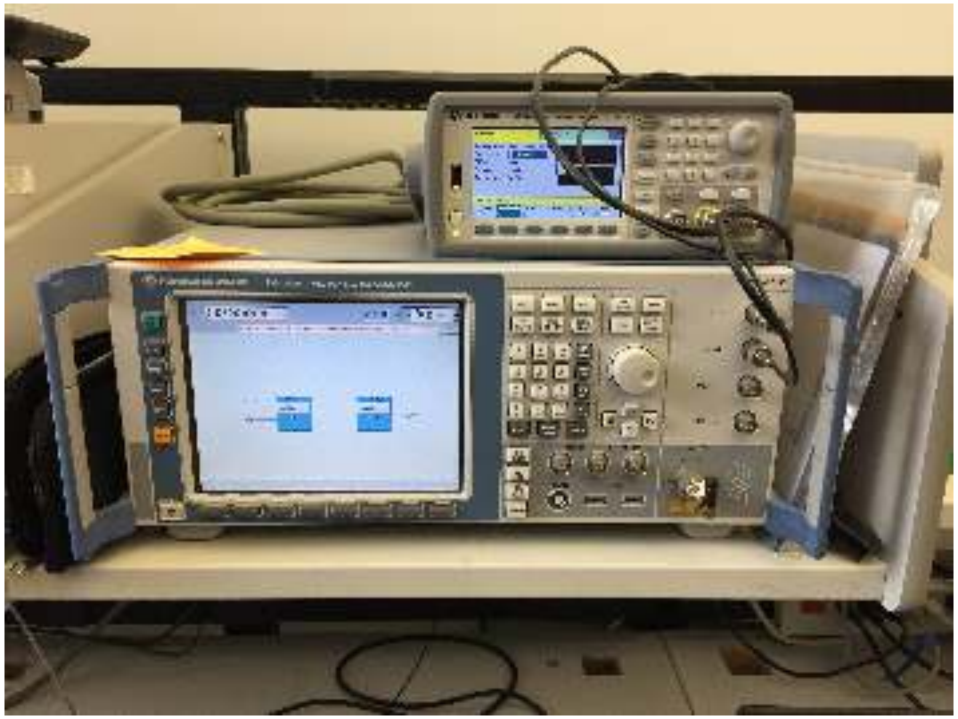


382us
512us
PISTER LAB
Agilent Technologies
Infiniium
DSO9064A
600 MHz
Acquisition is stopped.
5 Feb 2018
200 µs/
700.4100000 µs

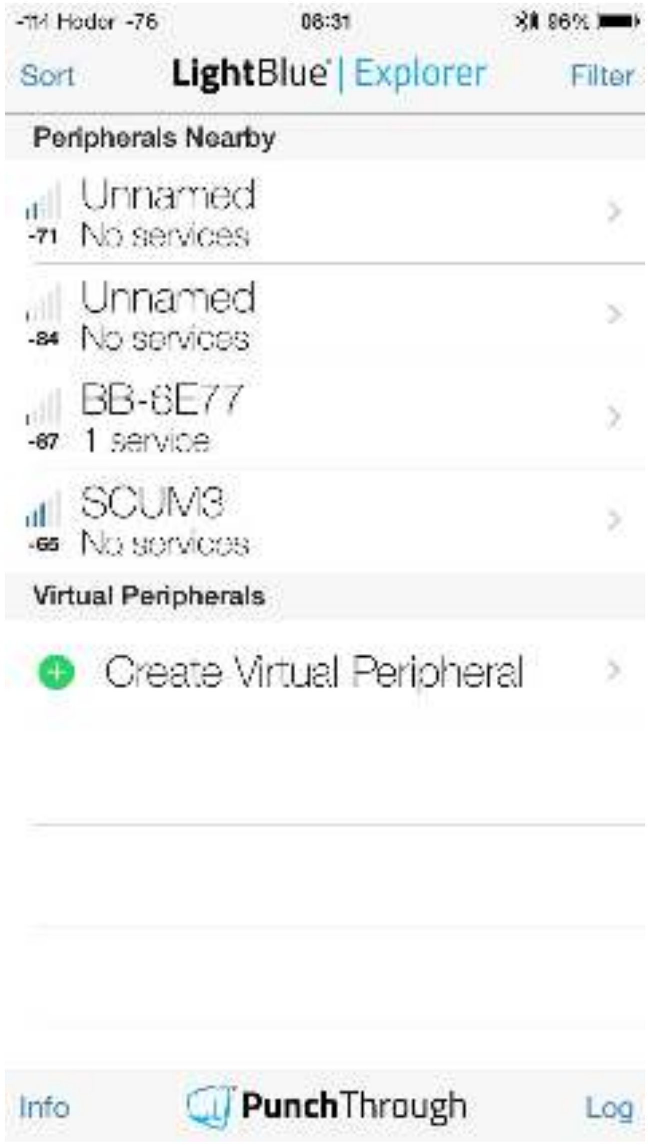
Recording commercial packets

- hcitool:
  - linux app, only works with some BLE dongles
  - Can specify custom payload in hex
- Pre-preamble 000111
- Length is 37 even if payload isn’t
  - Remaining space is filled with extra sub-payload w/ 0x00 for length, 0x00 for type and garbage (?) data

Test



Keysight waveform generator producing I/Q of packet
Rohde combining & upconverting to BLE ch 37 (2.402GHz)



-114 Hodor -76 08:31 96%

Sort LightBlue | Explorer Filter

Peripherals Nearby

-71	Unnamed	No services
-84	Unnamed	No services
-67	BB-6E77	1 service
-65	SCUM3	No services

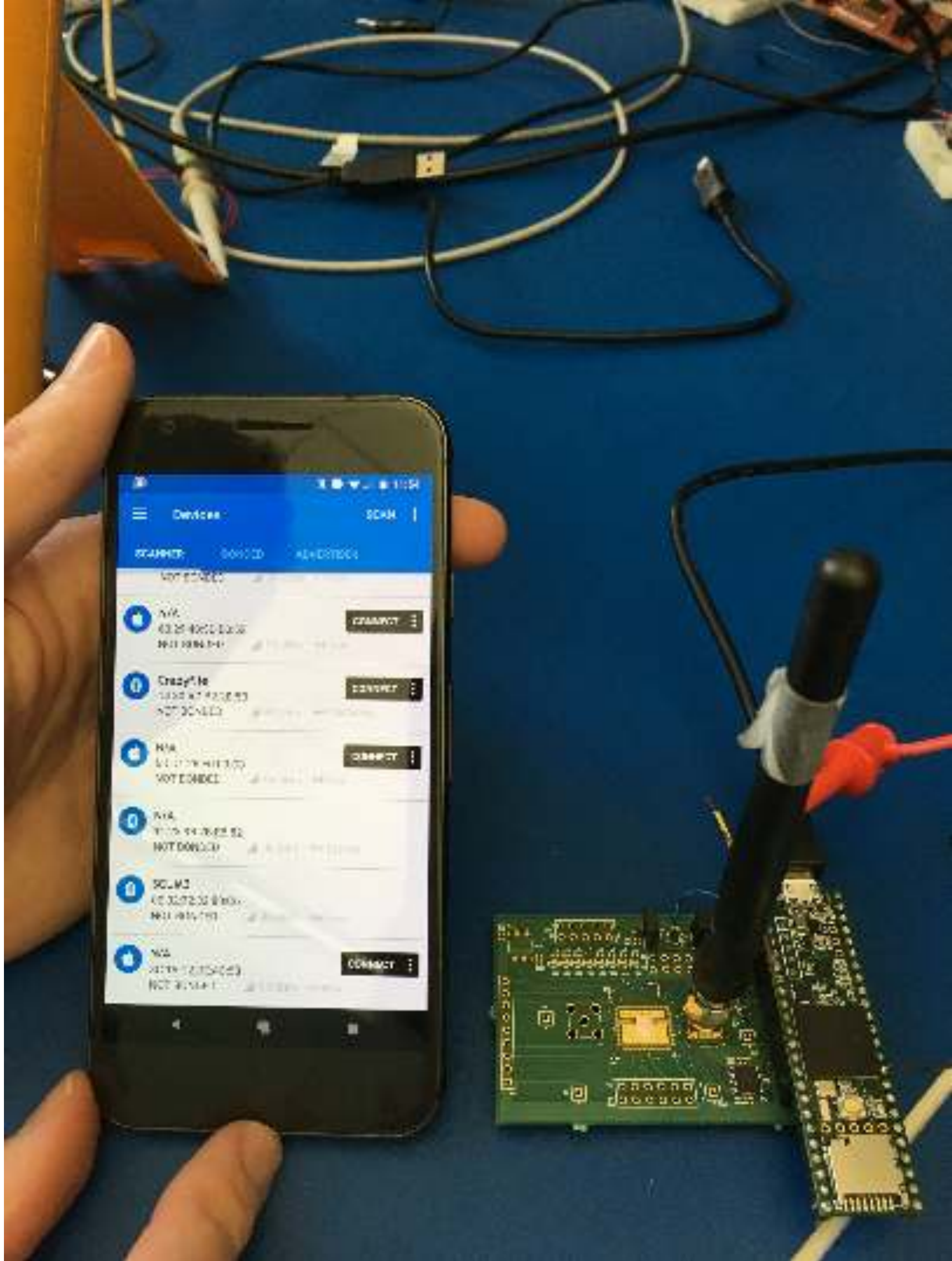
Virtual Peripherals

Create Virtual Peripheral

Info PunchThrough Log

iphone w/ BLE scanner app

Test: 12:30pm


Devices
SCAN
SCANNER
BONDED
ADVERTISER
Crazyflie
CONNECT
NOT BONDED