



Bluetooth Low Energy Protocol, Security & Attacks

Online Beer-Talk
07.05.2020 17:00



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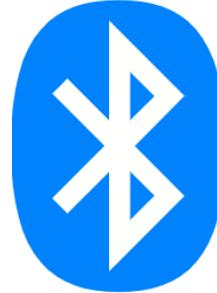
Speaker

- Emanuel Duss
- Bachelor Thesis @ HSR: «SAML Raider» Burp Extension in collaboration with Compass
- IT Security Analyst @ Compass Security since 2016
- Focus: Pentesting web apps, external/internal networks, mobile apps, hardening reviews, also a course teacher
- I like Linux, shells, CLI, networks, protocols, lockpicking and generally when things break 😊
- Bluetooth Low Energy: Research Topic 2019
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Agenda

- Introduction to Bluetooth Low Energy (BLE)
- BLE Security Mechanisms
- BLE Sniffing
- BLE Interaction
- BLE Man-in-the-Middle
- BLE Hijacking
- Example BLE Attacks
- BLE 5



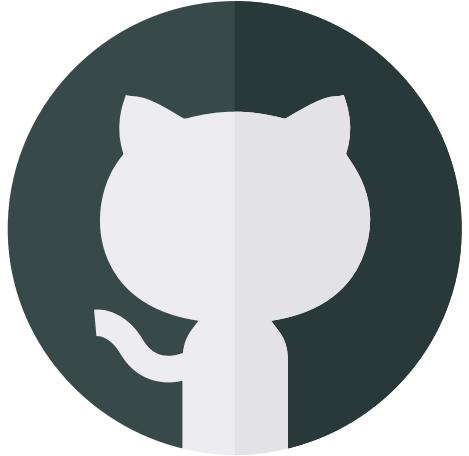
Bluetooth®

I'll skip some stuff in this Beer-Talk
so I can finish in $\leq 1\text{h}$ 😊.

Resources @ <https://github.com/CompassSecurity>



The screenshot shows a GitHub repository page for 'Bluetooth_Low_Energy_BLE_Beertalk'. The page includes a search bar, navigation links for Pull requests, Issues, Marketplace, and Explore, and a main content area with a 'Code' tab selected. It displays 6 commits, 0 issues, 0 pull requests, 0 actions, 0 projects, and a README file. A large watermark reading 'git.io/BLE' is overlaid on the page. A blue call-to-action button at the bottom right encourages users to 'Check out the GitHub repository!'. The URL in the browser address bar is https://github.com/CompassSecurity/Bluetooth_Low_Energy_BLE_Beertalk.



- Slides (full version!)
- Links to demo videos
- Links to this Beer-Talk video
- Links to software / hardware
- Example PCAPs
- Links to further resources

Introduction to Bluetooth Low Energy

Bluetooth

- Short-range wireless communication system intended to replace cables
- Key Features: Robustness, low power consumption, low cost
- Many features, many are optional
- Basic Rate (BR)
 - 721.2 kbit/s Basic Rate (BR) & 2.1 Mbit/s Enhanced Data Rate (EBR)
 - Up to 54 Mbit/s with 802.11 AMP
 - Up to 100 meter distance
- Low Energy (LE)
 - Not compatible with BR/EBR
 - High-level protocols are reused
- Both forms include device discovery, connection establishment & connection mechanisms

Standardized by
Bluetooth SIG (Special
Interest Group)



Bluetooth Low Energy

- Part of Bluetooth 4.0 core specification (2010)
 - Also known as Bluetooth Smart until 2016
- Low...
 - Lower complexity
 - Lower power consumption / duty cycles
 - Lower cost
 - Lower data rates (1 Mbit/s or 2 Mbit/s in BLE 5.0)
- But also up to 100 meter distance (400 m in BLE 5.0)
- Connectionless Model: Not necessarily a cable replacement
(short-term connections, fast connection setup)
- Versions
 - Version 4.2: More secure pairing
 - Version 5.0: 2 MB/s, longer range, changes in advertising
 - Version 5.1: GATT caching, changes in advertising

6 CHANGES FROM V3.0 + HS TO V4.0

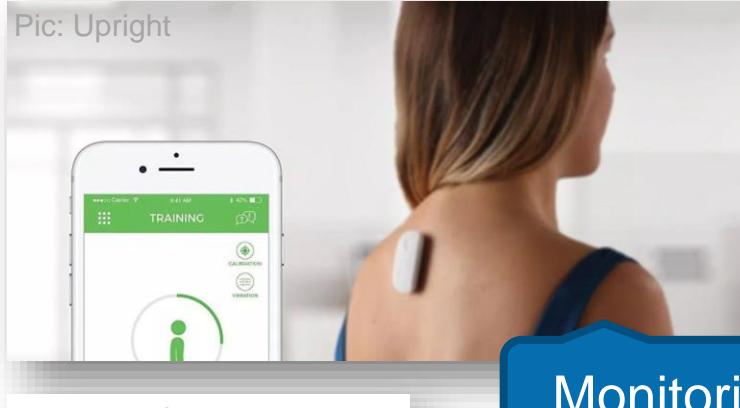
6.1 NEW FEATURES

Several new features are introduced in version 4.0. The major areas of improvement are:

- Bluetooth Low Energy including
 - Low Energy Physical Layer
 - Low Energy Link Layer
 - Enhancements to HCI for Low Energy
 - Low Energy Direct Test Mode
 - AES Encryption
 - Enhancements to L2CAP for Low Energy
 - Enhancements to GAP for Low Energy
 - Attribute protocol (ATT)
 - Generic Attribute profile (GATT)
 - Security Manager (SM)

Bluetooth 4.0 Core Specification

BLE Devices



Wearables



Smart Home

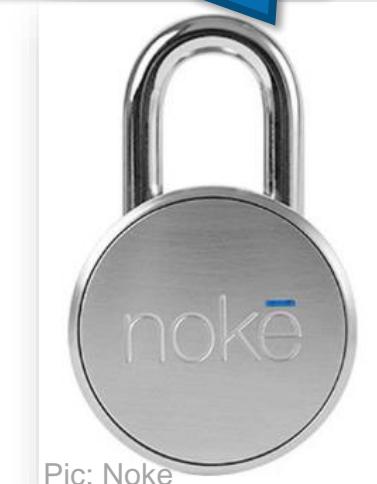


ESP32
BLE CTF Game



Monitoring

Smart Locks

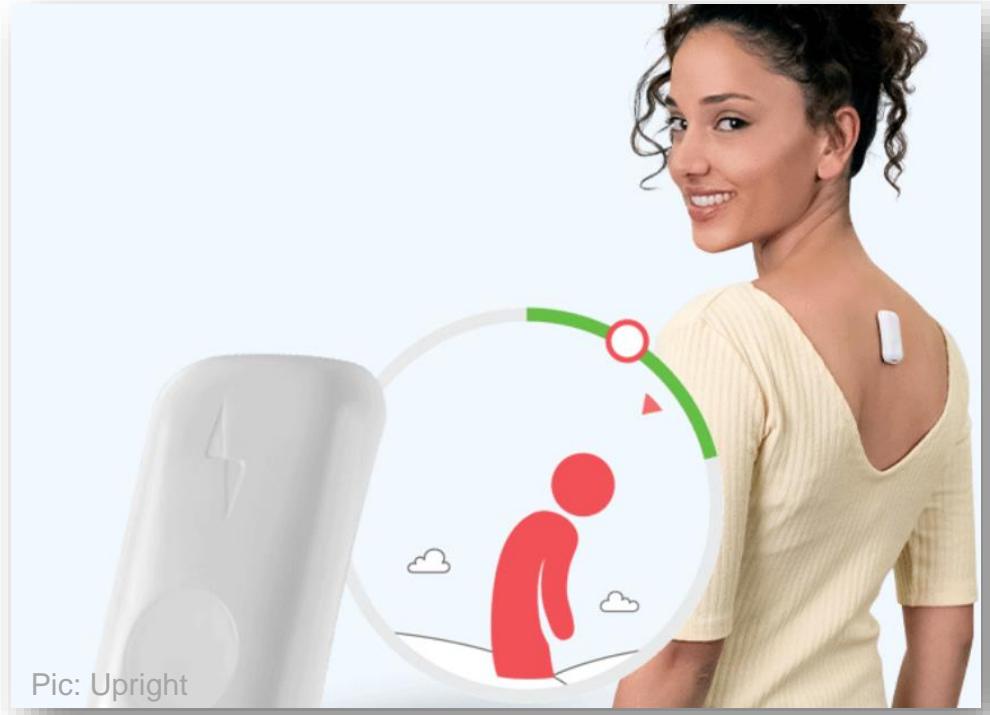


Conference Badges

Vehicles

Showcase: UprightGo

- This gadget can be attached to your neck
- It measures your posture and tells the phone via BLE
- The phone lets the device vibrate if your posture is bad
- Project Page: <https://www.uprightpose.com>



Bluetooth Low Energy Protocol Stack

GATT

ATT

L2CAP

Link Layer

Physical Layer

```
▶ Frame 16: 52 bytes on wire (416 bits), 52 bytes captured (416 bits)
└─ Nordic BLE Sniffer
    Board: 220
    └─ Header Version: 1, Packet counter: 0
        Length of packet: 28
    └─ Flags: 0x01
        Channel: 8
        RSSI (dBm): 0
        Event counter: 11
        Delta time (µs end to start): 0
        [Delta time (µs start to start): 144]
    └─ Bluetooth Low Energy Link Layer
        Access Address: 0xaf9a83d2
        [Master Address: 5b:e3:cc:ea:83:81 (5b:e3:cc:ea:83:81)]
        [Slave Address: ca:4d:10:ba:09:73 (ca:4d:10:ba:09:73)]
        └─ Data Header: 0x1a02
            [L2CAP Index: 10]
            CRC: 0x000000
    └─ Bluetooth L2CAP Protocol
        Length: 22
        CID: Attribute Protocol (0x0004)
    └─ Bluetooth Attribute Protocol
        └─ Opcode: Read By Group Type Response (0x11)
        Length: 20
        └─ Attribute Data, Handle: 0x0920, Group End Handle: 0xffff, UUID128: Unknown
            └─ Handle: 0x0920 (Unknown)
                Group End Handle: 0xffff
                UUID: 42234223422342234223422300022342
                [UUID: GATT Primary Service Declaration (0x2800)]
                [Request in Frame: 15]
```

These layers can
also be seen in
Wireshark 

Physical Layer

- Operates on the unlicensed 2.5 GHz ISM Band
- 40 times 2 MHz channels (2402 MHz to 2480 MHz)
- Access Scheme (Sharing the same medium)
 - Frequency Division Multiple Access (FDMA)
 - Time Division Multiple Access (TDMA)
- Different frequencies on different time slots



Physical Layer

- 3 Advertising Channels
 - 37, 38, 39
- 37 Data Channels
 - 0 to 36

Channel number

PHY Channel	RF Center Frequency	Channel Index	Physical Channel Type	
			Primary Advertising	All others
0	2402 MHz	37	•	
1	2404 MHz	0		•
2	2406 MHz	1		•
...
11	2424 MHz	10		•
12	2426 MHz	38	•	
13	2428 MHz	11		•
14	2430 MHz	12		•
...
38	2478 MHz	36		•
39	2480 MHz	39	•	

Table 1.2: Mapping of PHY channel to physical channel index and channel type

Link Layer

- Responsible for advertising, scanning, creating/maintaining connections
- Package format for LE Uncoded physical layer

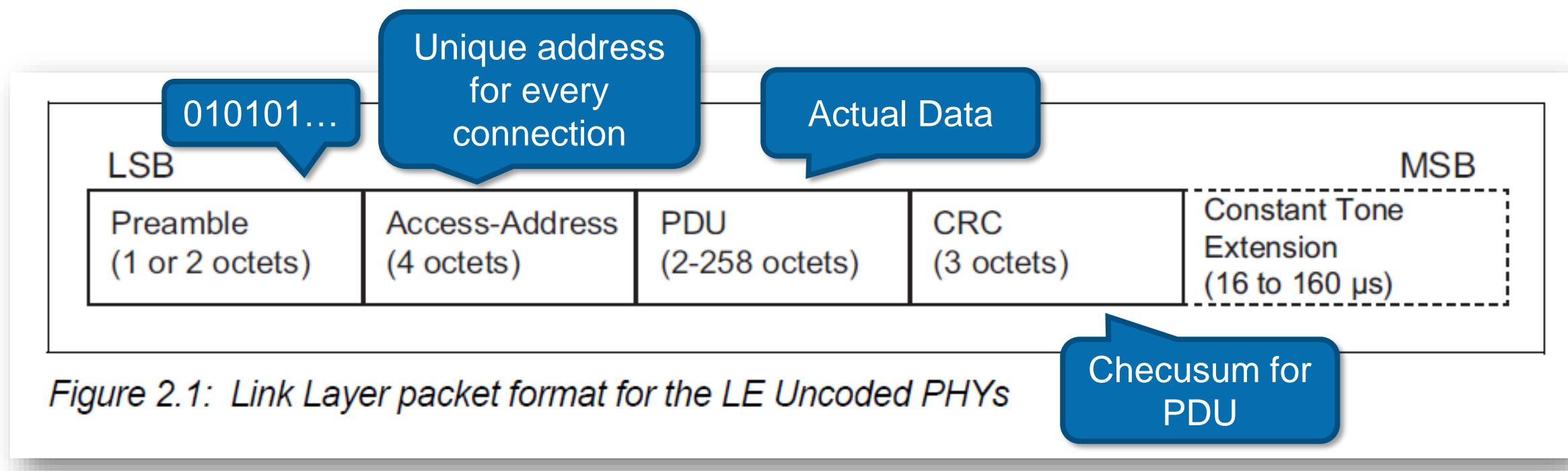


Figure 2.1: Link Layer packet format for the LE Uncoded PHYs

Link Layer

- Conflict if multiple devices send on the same channel at the same time
- Frequency hopping to combat interference and fading
- One data packet per channel at a given time
- Channel Selection Algorithm (CSA #1)
- Frequency hopping scheme (sent in connection request)
 - Channel Matrix: Which frequencies will be used? (e.g. use all 37 data channels)
 - Hop Increment: Next channel = Channel + Hop Increment (mod 37)
 - Hop Interval: Time between Hops



Passive Scanning

Scanner



Advertiser



Scanner



Advertisement

Advertisement

Advertisement

Advertisement

Advertisement

Advertisement

...

...

Active Scanning

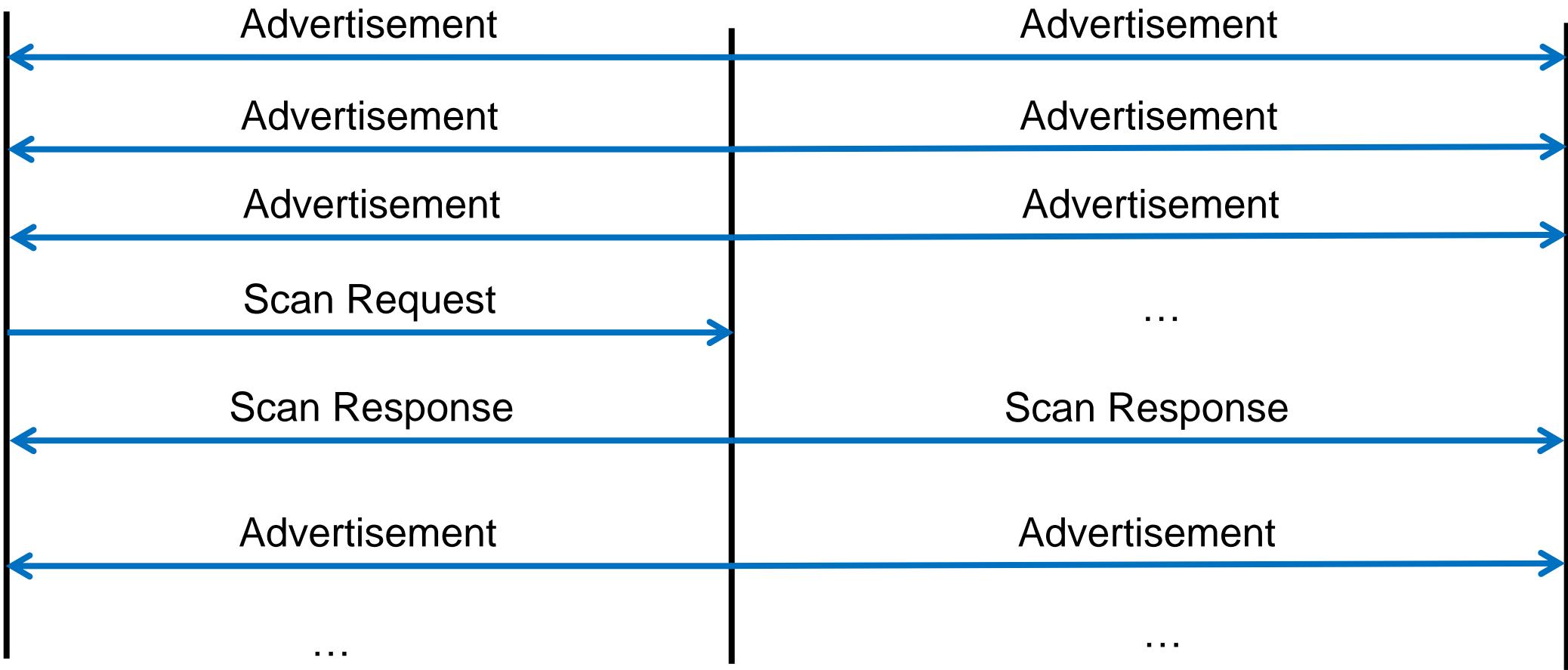
Scanner



Advertiser



Scanner



Packet: Scan Request

No.	Time	Source	Destination	Protocol	Length	Comment	Info
10498	365.649479	TexasIns_44:ee:30	Broadcast	LE LL	45		ADV_IND
10499	365.751589	TexasIns_44:ee:30	Broadcast	LE LL	45		ADV_IND
10500	365.756044	6d:89:e8:1e:29:ad	TexasIns_44:ee:30	LE LL	38		SCAN_REQ
10501	365.756802	TexasIns_44:ee:30	Broadcast	LE LL	52		SCAN_RSP

► Frame 10500: 38 bytes on wire (304 bits), 38 bytes captured (304 bits)
DLT: 157, Payload: nordic_ble (Nordic BLE Sniffer)
► Nordic BLE Sniffer
▼ Bluetooth Low Energy Link Layer
 Access Address: 0x8e89bed6

= Packet Header: 0x0c43 (PDU Type: SCAN_REQ, ChSel: #1, TxAdd: Random, RxAdd: Public)
.... 0011 = PDU Type: SCAN_REQ (0x3)
...0 = RFU: 0
..0 = Channel Selection Algorithm: #1
.1... = Tx Address: Random
0... = Rx Address: Public
Length: 12

Scanning Address: 6d:89:e8:1e:29:ad (6d:89:e8:1e:29:ad)
Advertising Address: TexasIns_44:ee:30 (30:45:11:44:ee:30)
CRC: 0x453ad6

Fixed access address
for advertising packets

Bluetooth MAC
Address

Modern Bluetooth stacks
randomize the MAC address
for privacy reasons (user
tracking)

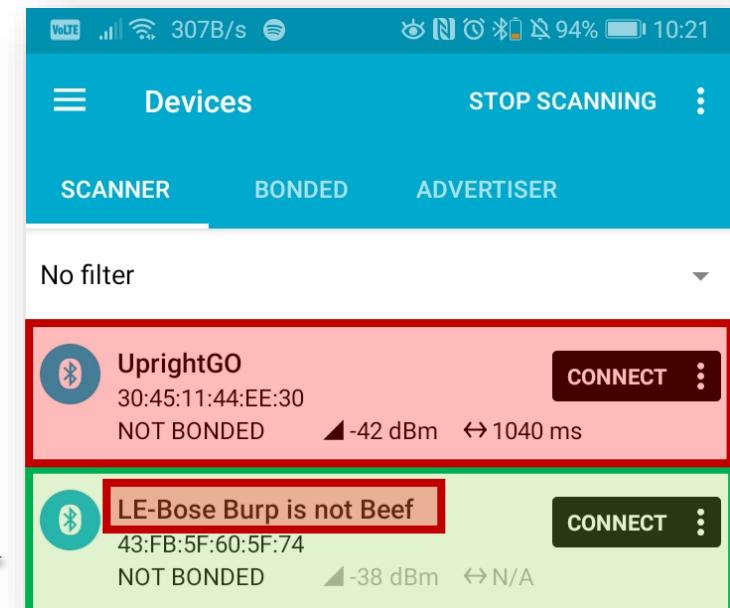
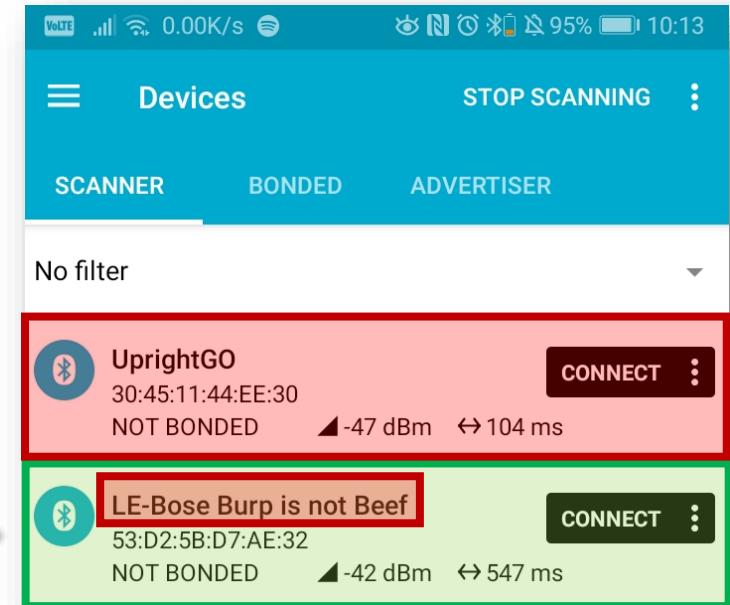
Bluetooth LE Privacy

- Bluetooth LE Privacy exists since Bluetooth 4.0
- Implemented to avoid user tracking
- Random MAC address is used
- Changes the MAC address at a time interval specified by the manufacturer
- Identity Resolution Key (IRK) is exchanged during pairing / bonding process
- Paired devices can convert random MAC addresses back to real MAC address

nRF Connect App

Bose headphones
can be controlled
via BLE

Other information could be used for
user tracking like the device name.



Packet: Scan Response

No.	Time	Source	Destination	Comment	Info
10499	365.751589	TexasIns_44:ee:30	Broadcast		ADV_IND
10500	365.756044	6d:89:e8:1e:29:ad	TexasIns_44:ee:30	LE LL	SCAN_REQ
10501	365.756802	TexasIns_44:ee:30	Broadcast	LE LL	52 SCAN_RSP
10502	365.757418	TexasIns_44:ee:30	Broadcast	LE LL	45 ADV_IND

▶ Frame 10501: 52 bytes on wire (416 bits), 52 bytes captured (416 bits)
DLT: 157, Payload: nordic_ble (Nordic BLE Sniffer)

▶ Nordic BLE Sniffer

▼ Bluetooth Low Energy Link Layer

- Access Address: 0x8e89bed6
- ▼ Packet Header: 0x1a04 (PDU Type: SCAN_RSP, ChSel: #1, TxAdd: Public)
 - 0100 = PDU Type: SCAN_RSP (0x4)
 - ...0 = RFU: 0
 - ..0. = Channel Selection Algorithm: #1
 - .0... = Tx Address: Public
 - 0.... = Reserved: False
- Length: 26
- Advertising Address: TexasIns_44:ee:30 (30:45:11:44:ee:30)
- ▼ Scan Response Data: 0a0955707269676874474f05120a000a00020a00
 - ▼ Advertising Data
 - ▼ Device Name: UprightGO
 - Length: 10
 - Type: Device Name (0x09)
 - Device Name: UprightGO
 - ▼ Slave Connection Interval Range: 12.5 - 12.5 msec
 - Length: 5
 - Type: Slave Connection Interval Range (0x12)
 - Connection Interval Min: 10 (12.5 msec)
 - Connection Interval Max: 10 (12.5 msec)
 - ▼ Tx Power Level
 - Length: 2
 - Type: Tx Power Level (0x0a)
 - Power Level (dBm): 0
- CRC: 0x85a949

Broadcast

That's how your phone knows
the name of your \$GADGET.

Connection Establishment

Advertiser



Scanner



Advertiser



Advertisement

Advertisement

Advertisement

Master

Connection Request

Data

Data

Slave

Connection Request

Data

...

A master can establish multiple connections.

No advertisements are sent anymore.

Packet: Connection Request

No.	Time	Source	Destination	Protocol	Length	Comment	Info
10656	407.794530	TexasIns_44:ee:30	Broadcast	LE LL	45	ADV_IND	
10657	407.906622	TexasIns_44:ee:30	Broadcast	LE LL	45	ADV_IND	
10658	407.907744	6d:89:e8:1e:29:ad	TexasIns_44:ee:30	LE LL	26	CONNECT REQ	
10659	407.908525	Master_0xaf9a9c24	Slave_0xaf9a9c24	LE LL	26	Empty PDU	
10660	407.947269	Master_0xaf9a9c24	Slave_0xaf9a9c24	LE LL	26	Empty PDU	

► Frame 10658: 60 bytes on wire (480 bits), 60 bytes captured (480 bits)
DLT: 157, Payload: nordic_ble (Nordic BLE Sniffer)

► Nordic BLE Sniffer

▼ Bluetooth Low Energy Link Layer

Access Address: 0x8e89bed6

Packet Header: 0x2245 (PDU Type: CONNECT_REQ, ChSel: #1, TxAdd: Random, RxAdd: Public)

- 0101 = PDU Type: CONNECT_REQ (0x5)
- ...0 = RFU: 0
- ..0. = Channel Selection Algorithm: #1
- .1.. = Tx Address: Random
- 0... = Rx Address: Public

Length: 34

Initiator Address: 6d:89:e8:1e:29:ad (6d:89:e8:1e:29:ad)

Advertising Address: TexasIns_44:ee:30 (30:45:11:44:ee:30)

▼ Link Layer Data

Access Address: 0xaf9a9c24

CRC Init: 0xdceebf

Window Size: 3 (3.75 msec)

Window Offset: 1 (1.25 msec)

Interval: 39 (48.75 msec)

Latency: 0

Timeout: 500 (5000 msec)

Channel Map: ffffffff1f

...0 0111 = Hop: 7

001. = Sleep Clock Accuracy (1)

CRC: 0xe91210

Unicast

Access Address

Hop Interval

Channel Map

Hop Increment

Frequency Hopping Scheme



Packet: Data (Empty)

No.	Time	Source	Destination	Protocol	Length	Comment	Info
10656	407.794530	TexasIns_44:ee:30	Broadcast	LE LL	45		ADV_IND
10657	407.906622	TexasIns_44:ee:30	Broadcast	LE LL	45		ADV_IND
10658	407.907744	6d:89:e8:1e:29:ad	TexasIns_44:ee:30	LE LL	60		CONNECT_REQ
10659	407.908525	Master_0xaf9a9c24	Slave_0xaf9a9c24	LE LL	26		Empty PDU
10660	407.947269	Master_0xaf9a9c24	Slave_0xaf9a9c24	LE LL	26		Empty PDU
10661	407.947714	Slave_0xaf9a9c24	Master_0xaf9a9c24	LE LL	26		Empty PDU

► Frame 10659: 26 bytes on wire (208 bits), 26 bytes captured (208 bits)

DLT: 157, Payload: nordic_ble (Nordic BLE Sniffer)

► Nordic BLE Sniffer

▼ Bluetooth Low Energy Link Layer

Access Address: 0xaf9a9c24

[Master Address: 6d:89:e8:1e:29:ad (6d:89:e8:1e:29:ad)]

[Slave Address: TexasIns_44:ee:30 (30:45:11:44:ee:30)]

▼ Data Header: 0x0001

.... .01 = LLID: Continuation fragment of an L2CAP message, or an Empty PDU (0x1)

.... .0.. = Next Expected Sequence Number: 0

.... 0... = Sequence Number: 0 [OK]

.00 = More Data: False

000 = RFU: 0

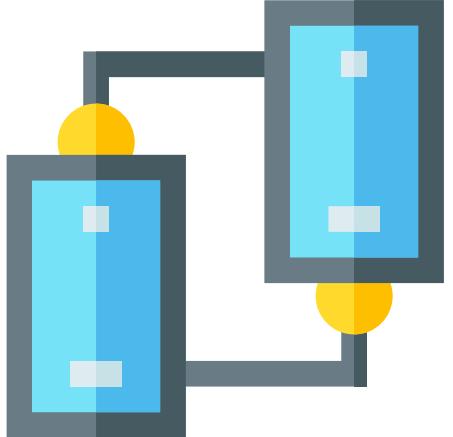
Length: 0

CRC: 0x059579

Access Address is used for further communication.

Attribute Protocol (ATT)

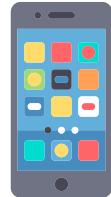
- Peer-to-peer protocol between attribute server and attribute client
- The master is the ATT client
 - The ATT client can send ATT commands, requests and confirmations
- The slave is the ATT server
 - The ATT server can send ATT sends responses, notifications and indications
- Based on attributes
 - Attribute Type (16 or 128 bit UUID)
 - 16 bit handle
 - Length + Value



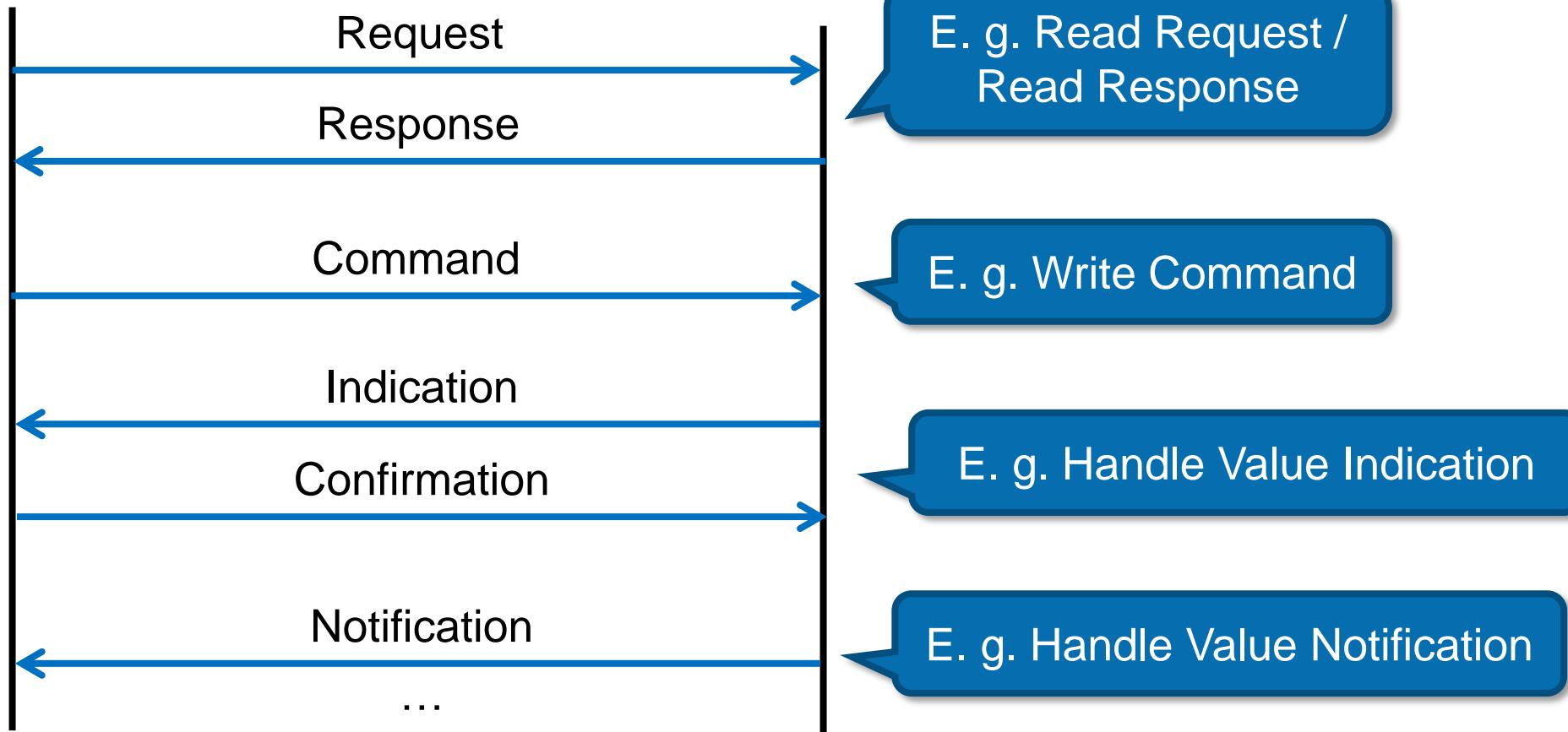
The handle is used to address an attribute

Attribute Protocol (ATT)

Master (ATT Client)

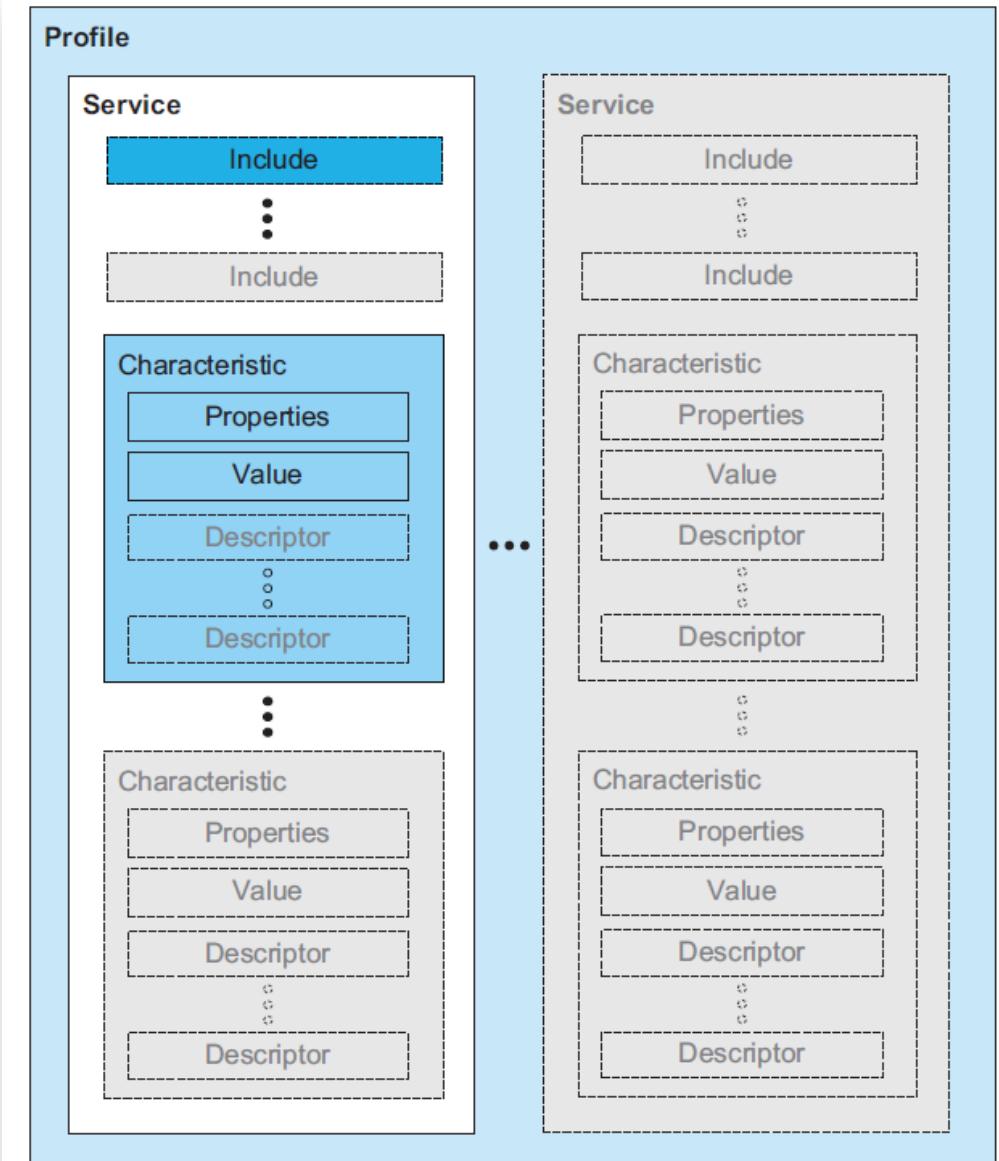


Slave (ATT Server)



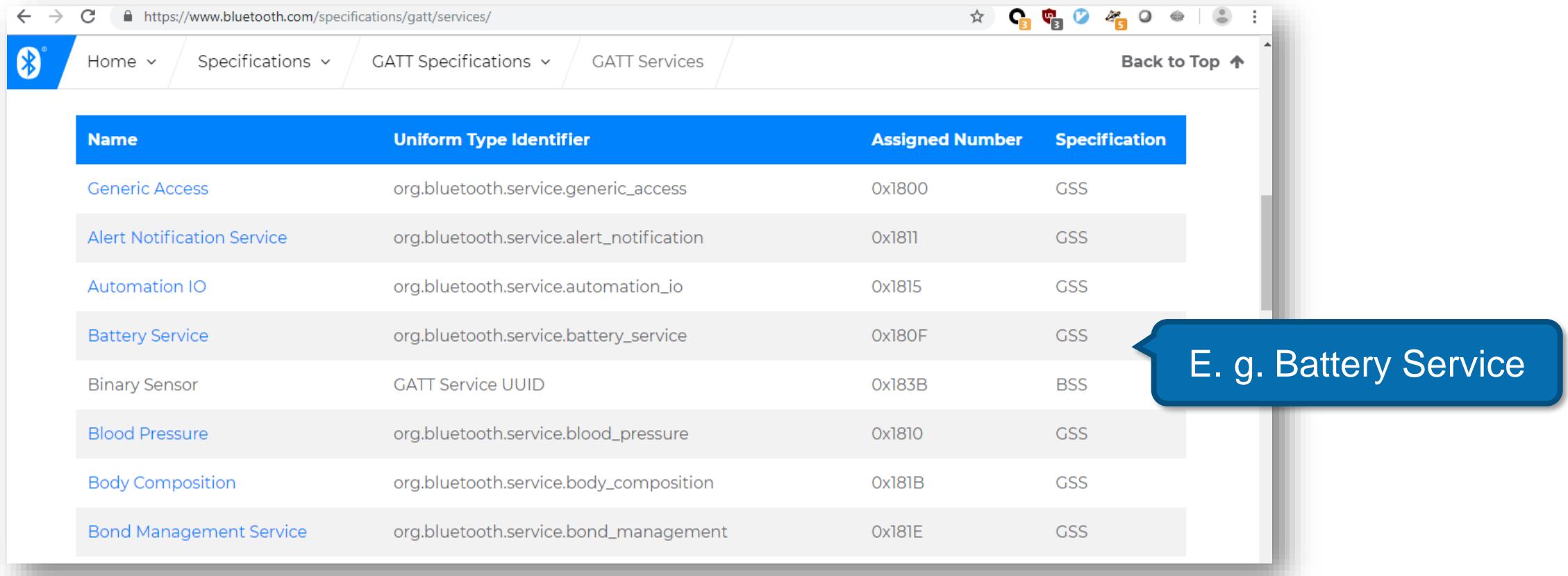
Generic Attribute Profile (GATT)

- Functionality of the ATT server and optionally the ATT client
- Hierarchy of services & characteristics
- Interface for discovering, reading, writing and indicating services
- Multiple services containing multiple characteristics
- Think of a «web service»
 - Profile / Service ≈ Description
 - Characteristics ≈ Webservice Endpoints



GATT Services

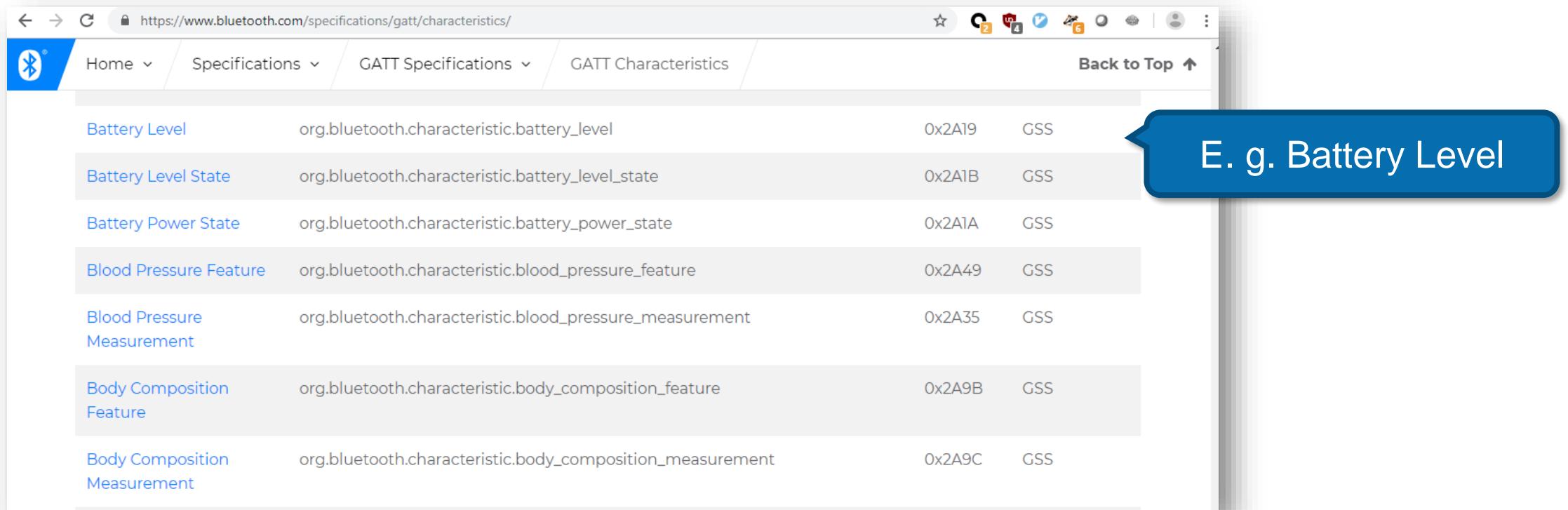
- Collection of characteristics (think of «categories»)
- Identified by a UUID (Standardised services: 16 bit; custom services: 128 bit)
- Standardised services: <https://www.bluetooth.com/specifications/gatt/services>



Name	Uniform Type Identifier	Assigned Number	Specification
Generic Access	org.bluetooth.service.generic_access	0x1800	GSS
Alert Notification Service	org.bluetooth.service.alert_notification	0x1811	GSS
Automation IO	org.bluetooth.service.automation_io	0x1815	GSS
Battery Service	org.bluetooth.service.battery_service	0x180F	GSS
Binary Sensor	GATT Service UUID	0x183B	BSS
Blood Pressure	org.bluetooth.service.blood_pressure	0x1810	GSS
Body Composition	org.bluetooth.service.body_composition	0x181B	GSS
Bond Management Service	org.bluetooth.service.bond_management	0x181E	GSS

GATT Characteristics

- Actual data
- Read/Write/...
- Identified by a UUID (Standardised characteristics: 16 bit; custom characteristics: 128 bit)
- Defined in the service specification



The screenshot shows a web browser displaying the Bluetooth specifications page for GATT Characteristics. The page lists several standard characteristics:

Battery Level	org.bluetooth.characteristic.battery_level	0x2A19	GSS
Battery Level State	org.bluetooth.characteristic.battery_level_state	0x2A1B	GSS
Battery Power State	org.bluetooth.characteristic.battery_power_state	0x2A1A	GSS
Blood Pressure Feature	org.bluetooth.characteristic.blood_pressure_feature	0x2A49	GSS
Blood Pressure Measurement	org.bluetooth.characteristic.blood_pressure_measurement	0x2A35	GSS
Body Composition Feature	org.bluetooth.characteristic.body_composition_feature	0x2A9B	GSS
Body Composition Measurement	org.bluetooth.characteristic.body_composition_measurement	0x2A9C	GSS

A blue callout bubble points to the first row, labeled "E. g. Battery Level".

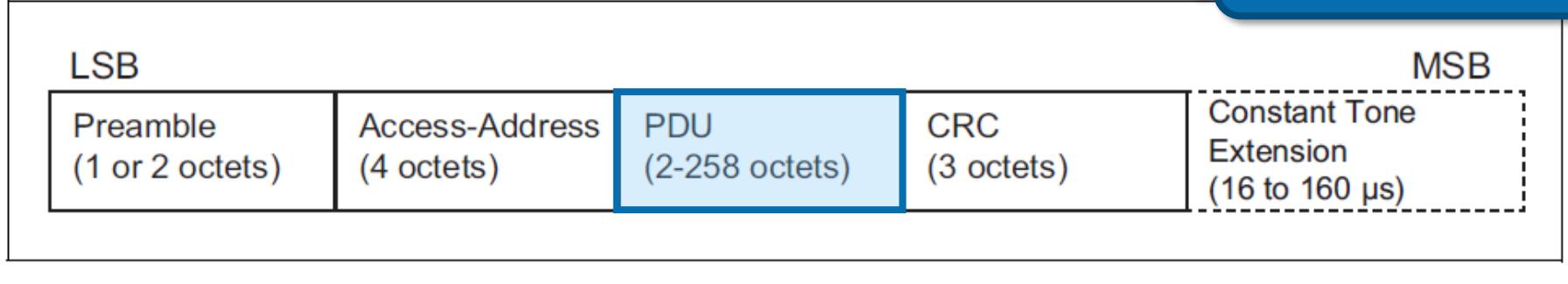
BLE Security Mechanisms

BLE Security

- Security is optional!
 - By default, there is no authentication & no encryption!
- Authentication & encryption is possible
- Authentication
 - Used to ensure that the connection is established to the correct device
 - Protects against active Man-in-the-Middle attacks
- Encryption
 - Used to ensure that noone can read the transmitted data
 - Protects against passive Man-in-the-Middle attacks



AES-128 CCM
(Counter mode with CBC-MAC)



Security Manager (SM)

- Defines pairing, authentication, encryption, key exchange/distribution, ...
- Security Manager Protocol (SMP): Peer-to-peer protocol used to generate encryption keys
- Custom Key Exchange Protocol (3 phases)

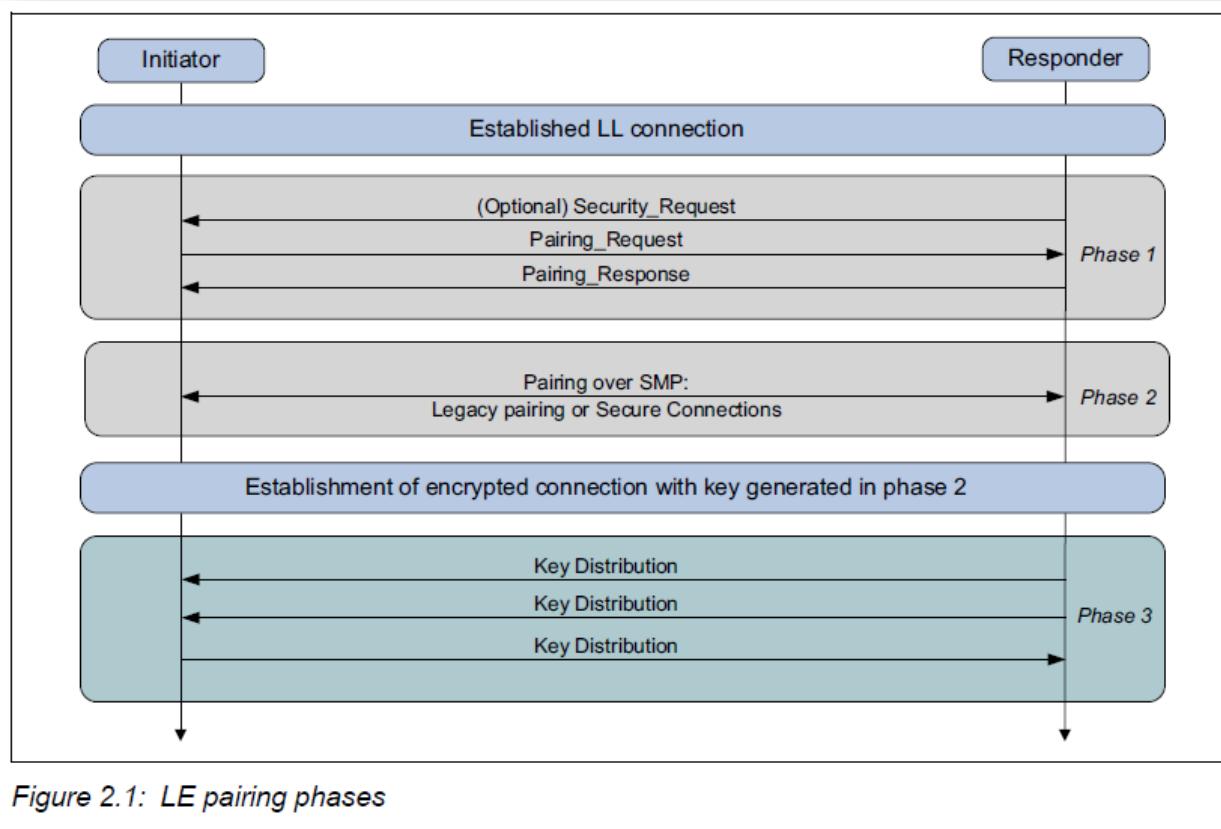
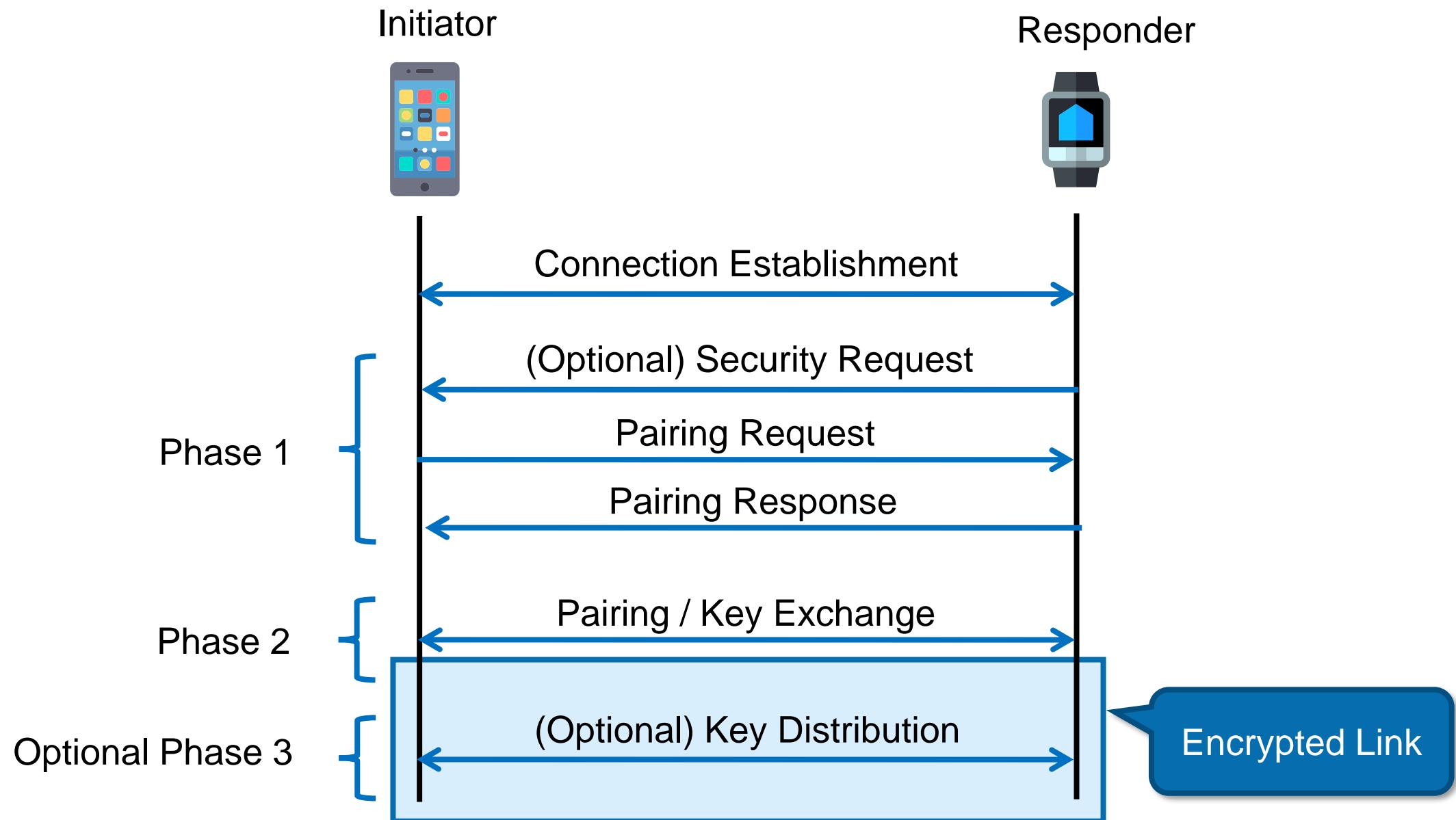


Figure 2.1: LE pairing phases

Pairing = Key Exchange Mechanisms

Pairing Phases



Pairing Phases

- Phase 1
 - Which key generation / pairing method is used?
- Phase 2
 - Key Generation
 - «LE Legacy Pairing»
 - Both devices generate a Short Term Key (STK)
 - Key generation method depends on the pairing method
 - «LE Secure Connections»
 - Long Term Key (LTK) Generation
- Phase 3 (Optional)
 - Transport Specific Key Distribution
 - Used for Bonding



Since Bluetooth
4.2 (2014)

Pairing Phase 1: Pairing Feature Exchange

The devices tell each other which pairing features they support.

Capability Flags	Description
No input	No method to indicate yes or no
Yes / No	There is a method to indicate yes or no
Keyboard	There is a keyboard with the number 0 to 9 and a method to indicate yes or no
No output	Not possible to display a 6 digit number
Numeric output	Possible to display a 6 digit number

Other Flags	Description
OOB	Flag whether out-of-band authentication data is present or not
Bonding	Flag whether long-term key should be saved for later use
MITM	Flag whether man-in-the-middle protection is requested or not (request Authenticated security property for the legacy pairing STK / Secure Connection LTK)
SC	Flag whether LE Secure Connections can be used
KC	Keypress flag used for the Passkey Entry pairing method (generate keypress notifications and send via SMP)

Pairing Phase 1: Pairing Method Selection

- Choose key generation method

LE Legacy Pairing

		Initiator			
		OOB Set	OOB Not Set	MITM Set	MITM Not Set
Responder	OOB Set	Use OOB	Check MITM		
	OOB Not Set	Check MITM	Check MITM		
	MITM Set			Use IO Capabilities	Use IO Capabilities
	MITM Not Set			Use IO Capabilities	Use Just Works

Table 2.6: Rules for using Out-of-Band and MITM flags for LE legacy pairing

LE Secure Connections

		Initiator			
		OOB Set	OOB Not Set	MITM Set	MITM Not Set
Responder	OOB Set	Use OOB	Use OOB		
	OOB Not Set	Use OOB	Check MITM		
	MITM Set			Use IO Capabilities	Use IO Capabilities
	MITM Not Set			Use IO Capabilities	Use Just Works

Table 2.7: Rules for using Out-of-Band and MITM flags for LE Secure Connections pairing

Pairing Phase 1: Pairing Method Selection

		Initiator				
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display	
Display Only	Just Works Unauthenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	
	Just Works Unauthenticated	Just Works (For LE Legacy Pairing) Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing): responder displays, initiator inputs Authenticated	
Display YesNo	Just Works Unauthenticated	Numeric Comparison (For LE Secure Connections) Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Numeric Comparison (For LE Secure Connections) Authenticated	

Table 2.8: Mapping of IO capabilities to key generation method

		Initiator				
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display	
Keyboard Only	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator and responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	
NoInput NoOutput	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated	
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Numeric Comparison (For LE Secure Connections) Authenticated	
Keyboard Display	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated	
	Numeric Comparison (For LE Secure Connections) Authenticated	Numeric Comparison (For LE Secure Connections) Authenticated	Authenti- cated	Authenti- cated	Numeric Comparison (For LE Secure Connections) Authenticated	

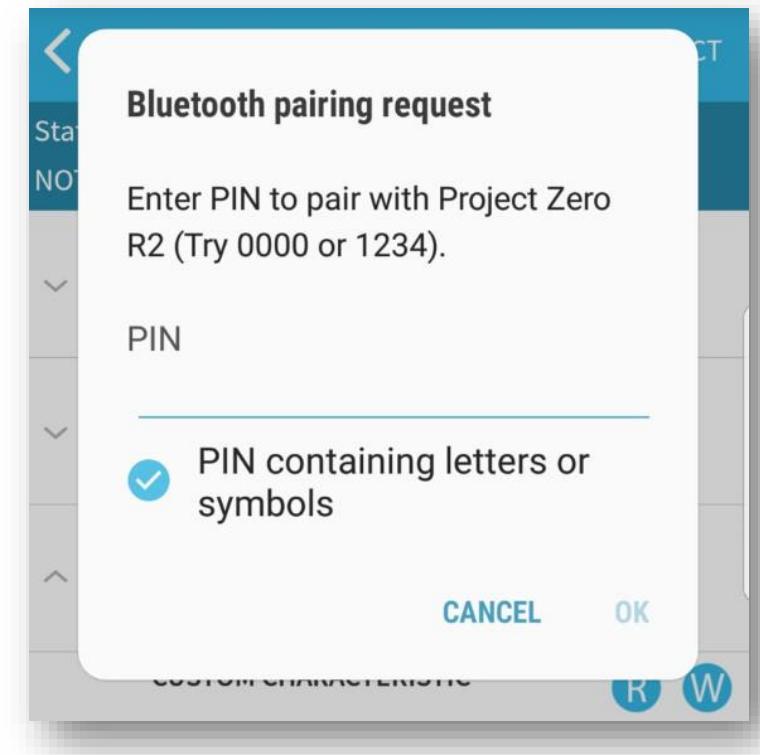
Table 2.8: Mapping of IO capabilities to key generation method

Pairing Methods

- Just Works
 - It just works, no user interaction needed
 - Unauthenticated!
 - No protection against active MITM



- Passkey Entry
 - One device generates and displays a number between 000000 and 999999
 - This number must be entered on the other device
 - Protects against active MITM (0.000001 succeeding probability)



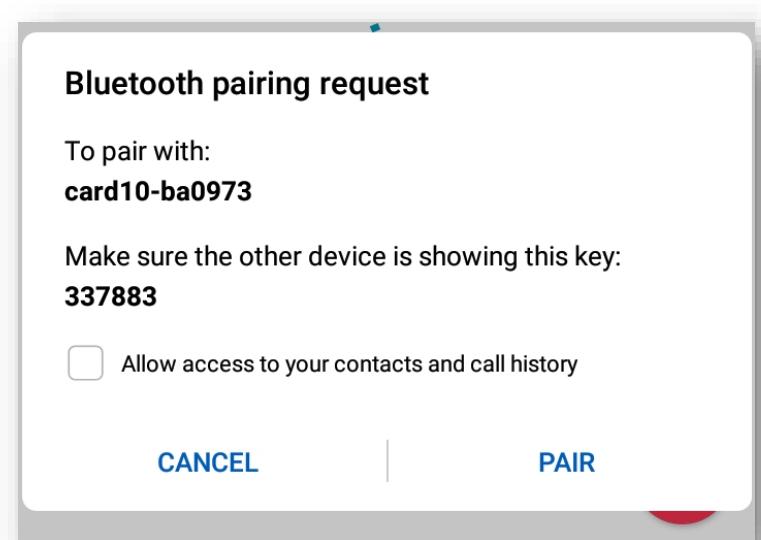
Pairing Methods

- Out of Band
 - Exchange of the key material out of band
 - E.g. via NFC, QR Codes, ...
 - Protects against active MITM if the OOB mechanism is also MITM resistant

- Numeric Comparison
 - Only for LE Secure Connections
 - Both devices display the same agreed number that has to be acknowledged on both devices
 - Protects against active MITM



Pic: Bose



Pairing Phase 1: Example #1

- ▶ Frame 8: 37 bytes on wire (296 bits), 37 bytes captured (296 bits)
- ▶ Nordic BLE Sniffer
- ▶ Bluetooth Low Energy Link Layer
- ▶ Bluetooth L2CAP Protocol
- ▼ Bluetooth Security Manager Protocol
 - Opcode: Pairing Request (0x01)
 - [IO Capability: Keyboard, Display (0x04)]
 - OOB Data Flags: OOB Auth. Data Not Present (0x00)
 - AuthReq: 0x05, MITM Flag, Bonding Flags: Bonding
 - 000. = Reserved: 0x0
 - ...0 = Keypress Flag: False
 - 0... = Secure Connection Flag: False
 -1.. = MITM Flag: True
 -01 = Bonding Flags: Bonding (0x1)
 - Max Encryption Key Size: 16
 - ▶ Initiator Key Distribution: 0x07, Signature Key (CSRK), Id Key (IRK), Encryption Key (LTK)
 - ▶ Responder Key Distribution: 0x07, Signature Key (CSRK), Id Key (IRK), Encryption Key (LTK)

Initiator

IO Capability: Keyboard, Display
Secure Connection: False
MITM Flag: True
Bonding Flag: True

- ▶ Frame 10: 37 bytes on wire (296 bits), 37 bytes captured (296 bits)
- ▶ Nordic BLE Sniffer
- ▶ Bluetooth Low Energy Link Layer
- ▶ Bluetooth L2CAP Protocol
- ▼ Bluetooth Security Manager Protocol
 - Opcode: Pairing Response (0x02)
 - [IO Capability: No Input, No Output (0x03)]
 - OOB Data Flags: OOB Auth. Data Not Present (0x00)
 - AuthReq: 0x01, Bonding Flags: Bonding
 - 000. = Reserved: 0x0
 - ...0 = Keypress Flag: False
 - 0... = Secure Connection Flag: False
 -0.. = MITM Flag: False
 -01 = Bonding Flags: Bonding (0x1)
 - Max Encryption Key Size: 16
 - ▶ Initiator Key Distribution: 0x06, Signature Key (CSRK), Id Key (IRK)
 - ▶ Responder Key Distribution: 0x03, Id Key (IRK), Encryption Key (LTK)

Responder

IO Capability: No Input, No Output
Secure Connection: False
MITM Flag: False
Bonding Flag: True

Pairing Phase 1: Example #1

		Initiator			
		OOB Set	OOB Not Set	MITM Set	MITM Not Set
Responder	OOB Set	Use OOB	Check MITM		
	OOB Not Set	Check MITM	Check MITM		
	MITM Set			Use IO Capabilities	Use IO Capabilities
	MITM Not Set			Use IO Capabilities	Use Just Works

Table 2.6: Rules for using Out-of-Band and MITM flags for LE legacy pairing

Selected Key
Generation Method:
Just Works

		Initiator			
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display
Keyboard Only	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator and responder inputs Authenticated	Just Works Unauthenticated	Passkey Entry: initiator displays, responder inputs Authenticated
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated
NoInput NoOutput	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated
	Numeric Comparison (For LE Secure Connections) Authenticated	Authenticated			Numeric Comparison (For LE Secure Connections) Authenticated
Keyboard Display	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing): initiator displays, responder inputs Authenticated
	Numeric Comparison (For LE Secure Connections) Authenticated	Authenticated			Numeric Comparison (For LE Secure Connections) Authenticated

Table 2.8: Mapping of IO capabilities to key generation method

Pairing Phase 1: Example #1



In fact, our machine does not require any pairing at all 😞.

Unauthenticated
0xc0ffee!



Pairing Phase 1: Example #2

No.	Time	Source	Destination	Protocol	Length	Comment	Info
1	0.000000	5b:e3:cc:ea:83:81	ca:4d:10:ba:09:73	LE LL	60		CONNECT_REQ
2	0.018635	Slave_0xaf9a83d2	Master_0xaf9a83d2	SMP	32	Rcvd Security Request: AuthReq: Bonding, SecureConnection	
3	0.070730	Master_0xaf9a83d2	Slave_0xaf9a83d2	LE LL	25	Control Opcode: LL FEATURE_REQ	
4	0.070730	ca:4d:10:ba:09:73	5b:e3:cc:ea:83:81	SMP	26		

Frame 2: 32 bytes on wire (256 bits), 32 bytes captured (256 bits)

► Nordic BLE Sniffer

► Bluetooth Low Energy Link Layer

Access Address: 0xaf9a83d2

[Master Address: 5b:e3:cc:ea:83:81 (5b:e3:cc:ea:83:81)]

[Slave Address: ca:4d:10:ba:09:73 (ca:4d:10:ba:09:73)]

► Data Header: 0x0606

[L2CAP Index: 0]

CRC: 0x000000

► Bluetooth L2CAP Protocol

► Bluetooth Security Manager Protocol

 Opcode: Security Request (0x0b)

 AuthReq: 0x09, Secure Connection Flag, Bonding Flags: Bonding

 000. = Reserved: 0x0

 ...0 = Keypress Flag: False

 1... = Secure Connection Flag: True

 0.. = MITM Flag: False

 01 = Bonding Flags: Bonding (0x1)

Security Request
→ Device needs pairing

Pairing Phase 1: Example #2

```
▶ Frame 120: 37 bytes on wire (296 bits), 37 bytes captured (296 bits)
▶ Nordic BLE Sniffer
▶ Bluetooth Low Energy Link Layer
▶ Bluetooth L2CAP Protocol
└ Bluetooth Security Manager Protocol
    └ Opcode: Pairing Request (0x01)
        IO Capability: Keyboard, Display (0x04)
        OOB Data Flags: OOB Auth. Data Not Present (0x00)
        └ AuthReq: 0x2d. Secure Connection Flag, MITM Flag, Bonding Flags: Bonding
            001. .... = Reserved: 0x1
            ...0 .... = Keypress Flag: False
            .... 1... = Secure Connection Flag: True
            .... .1.. = MITM Flag: True
            .... ..01 = Bonding Flags: Bonding (0x1)
        Max Encryption Key Size: 16
        └ Initiator Key Distribution: 0x0f, Link Key, Signature Key (CSRK), Id Key (IRK), Encryption Key (LTK)
        └ Responder Key Distribution: 0x0f, Link Key, Signature Key (CSRK), Id Key (IRK), Encryption Key (LTK)
```

Initiator

IO Capability: Keyboard, Display
Secure Connection: True
MITM Flag: True
Bonding Flag: True

```
▶ Frame 122: 37 bytes on wire (296 bits), 37 bytes captured (296 bits)
▶ Nordic BLE Sniffer
▶ Bluetooth Low Energy Link Layer
▶ Bluetooth L2CAP Protocol
└ Bluetooth Security Manager Protocol
    └ Opcode: Pairing Response (0x02)
        IO Capability: Display Yes/No (0x01)
        OOB Data Flags: OOB Auth. Data Not Present (0x00)
        └ AuthRes: 0x00, Secure Connection Flag, Bonding Flags: Bonding
            000. .... = Reserved: 0x0
            ...0 .... = Keypress Flag: False
            .... 1... = Secure Connection Flag: True
            .... .0.. = MITM Flag: False
            .... ..01 = Bonding Flags: Bonding (0x1)
        Max Encryption Key Size: 16
        └ Initiator Key Distribution: 0x02, Id Key (IRK)
        └ Responder Key Distribution: 0x01, Encryption Key (LTK)
```

Responder

IO Capability: Display Yes/No
Secure Connection: True
MITM Flag: False
Bonding Flag: True

Pairing Phase 1: Example #2

		Initiator			
		OOB Set	OOB Not Set	MITM Set	MITM Not Set
Responder	OOB Set	Use OOB	Use OOB		
	OOB Not Set	Use OOB	Check MITM		
	MITM Set			Use IO Capabilities	Use IO Capabilities
	MITM Not Set			Use IO Capabilities	Use Just Works

Table 2.7: Rules for using Out-of-Band and MITM flags for LE Secure Connections pairing

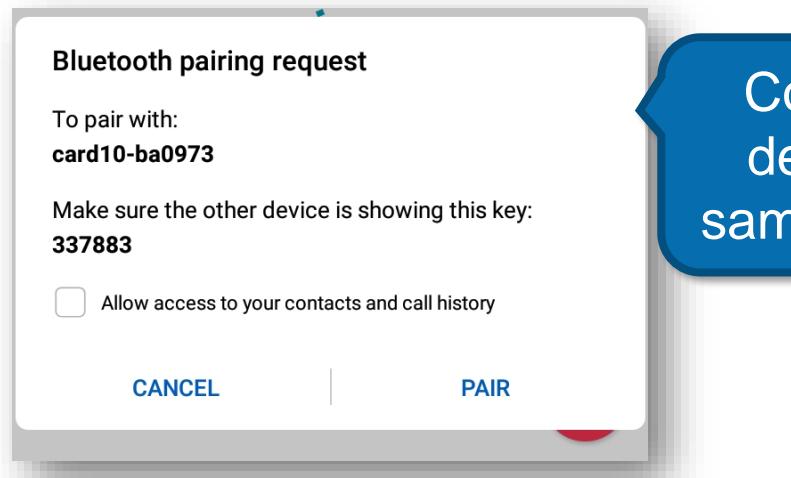
		Initiator			
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display
Display Only	Just Works Unauthenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated
		Just Works (For LE Legacy Pairing) Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing): responder displays, initiator inputs Authenticated
Display YesNo	Just Works Unauthenticated				Numeric Comparison (For LE Secure Connections) Authenticated
		Just Works (For LE Legacy Pairing) Unauthenticated			
					Authenticated

Table 2.8: Mapping of IO capabilities to key generation method

Selected:
Numeric Comparison

LE Secure
Connections

Pairing Phase 1: Example #2



Confirm on both devices that the same key is shown!



Implementation may be incomplete 🤷

Emanuel Duss
@mindfuckup

You can use this nRF Connect macro to let other's [#card10 @card10badge](#) badges vibrate and turn on all LEDs via Bluetooth LE:
gist.github.com/mindfuckup/7d5... (you have to enable maximum MTU for the top LED rainbow). 😊
[#CCCamp19](#) [#CCCamp2019](#)

The screenshot shows the nRF Connect app interface. At the top, it displays "Devices" and the device ID "CARD10-BA0973". Below this, it lists service details:

- Generic Access (UUID: 0x1800, PRIMARY SERVICE)
- Generic Attribute (UUID: 0x1801, PRIMARY SERVICE)
- Device Information (UUID: 0x180A, PRIMARY SERVICE)

In the "Macros" section, there is a macro named "Card10Fun" with three buttons: a blue one with a plus sign, a green one with a downward arrow, and a red one with a circle.

9:47 PM · Aug 24, 2019 · Twitter Web App

Pairing Phase 2: Key Generation

LE Legacy Pairing

- Temporary Key (TK) → Short Term Key (STK) → Long Term Key (LTK) → Session Key (SK)
- TK is generated from the selected key exchange method
 - Just Works: TK = 0
 - Passcode Entry: TK = Entered PIN (000000-999999)
 - Out of Band: TK = OOB Exchanged Key (128 bits)

The arrows «→» mean
«some cryptographic algorithm
defined in the spec».

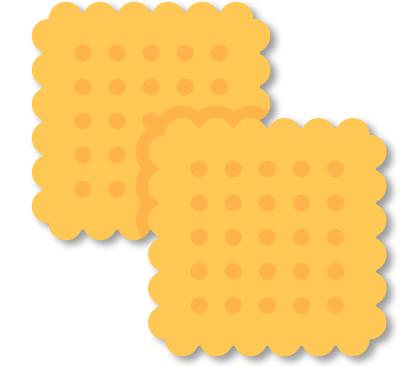
LE Secure Connections

- No Temporary Keys (TK) or Short Term Key (STK)
- Long Term Key (LTK) generated using Elliptic Curve Diffie-Hellman (ECDH)
- Long Term Key (LTK) → Session Key (SK)

Key Cracking

LE Legacy Pairing is easy to crack:

- Just Works
 - TK is always 0 → Always the same static key
- Passkey Entry: 6 digits = 1'000'000 possibilities
 - Provides 20 bits of security ($\log_2(1000000) \approx 20$) → Can be cracked immediately
- Out of Band
 - Depends on the generated key → this can be strong!



LE Secure Connections cannot be cracked:

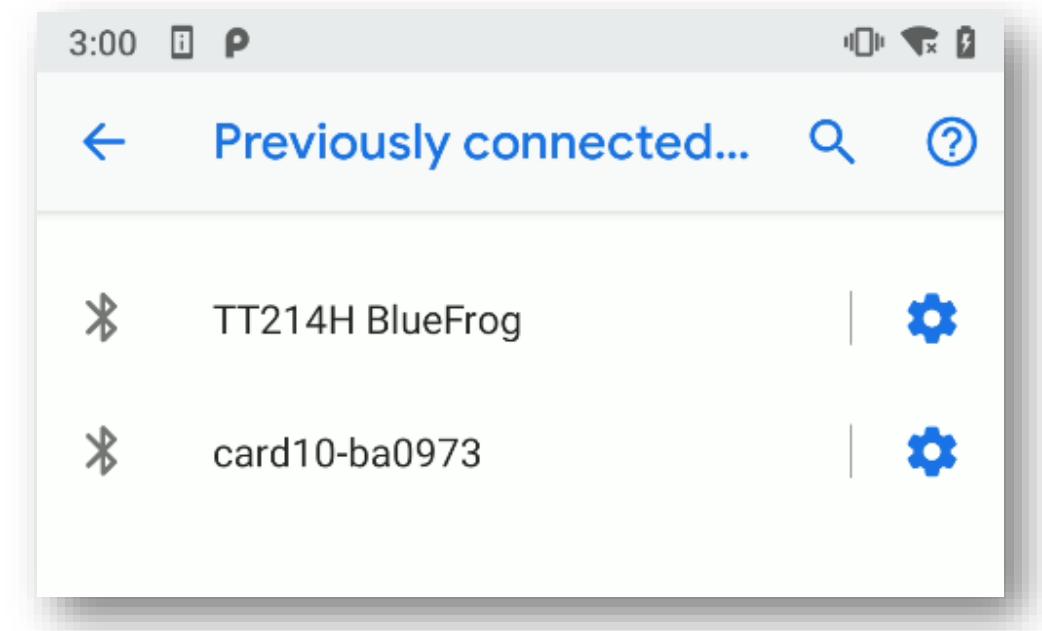
- Elliptic Curve Diffie-Hellman (ECDH) key exchange is used.



Phase 3: Bonding / Transport Specific Key Distribution

- Bonding is the exchange of a Long Term Key (LTK) after pairing
- No pairing is required for the next session
- Exchanged in Pairing Phase 3
- Creates relationship and permanent security between two devices
- Link key as an identifier
- Link key stored on both devices
- Link key used for further authentication
- Long Term Key (LTK) stored on both devices

The bonded devices can be seen in Android in the Bluetooth menu



BLE Sniffing

BLE Sniffing

- Blackbox Approach: Capture the packets in the air
 - Ubertooth
 - Adafruit Bluefruit LE Sniffer
 - Micro:Bit / BtleJack
- Whitebox Approach: Sniff directly on the used BLE interface
 - Android HCI Snoop Log
 - Linux HCI Snoop Log



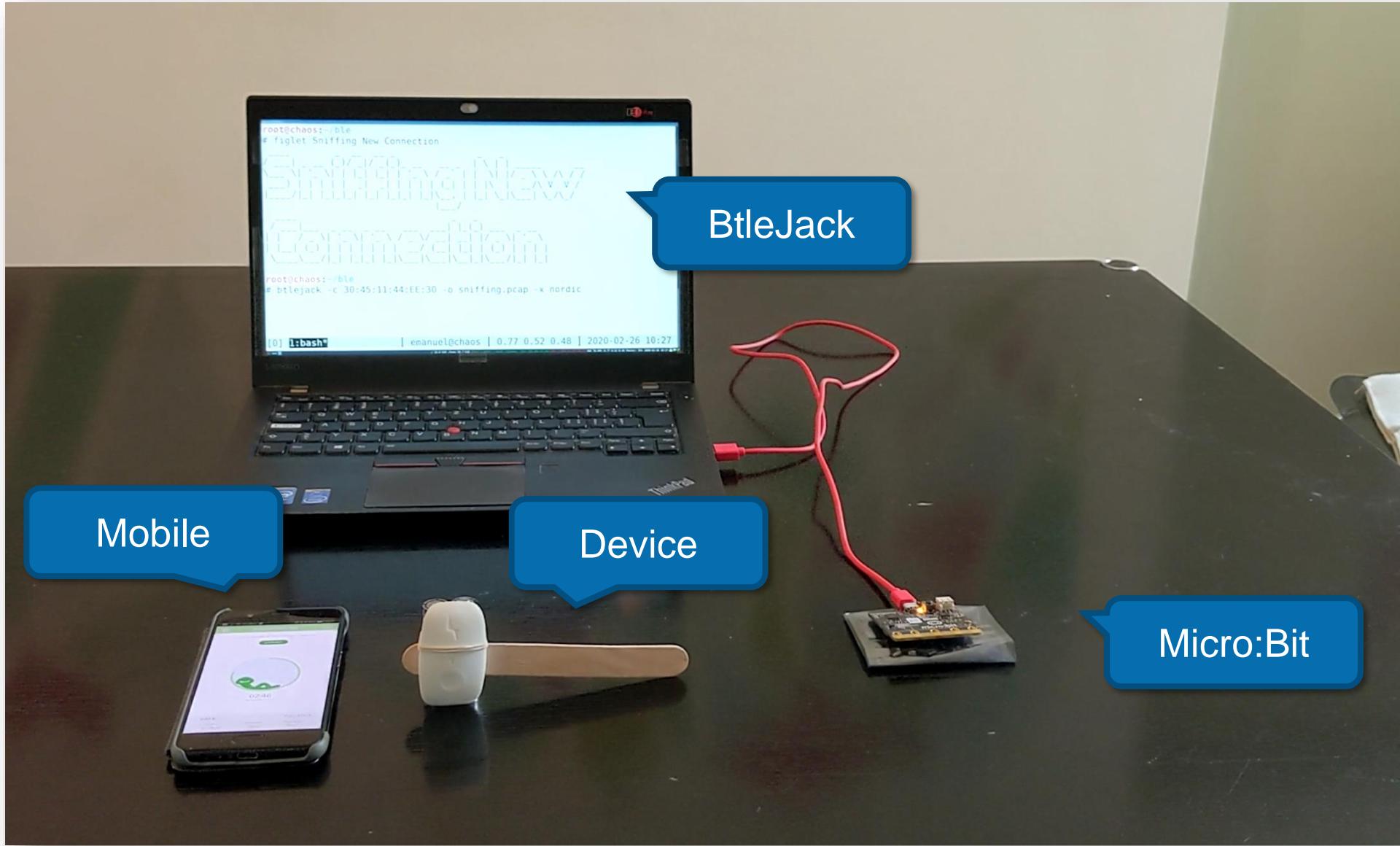
BtleJack

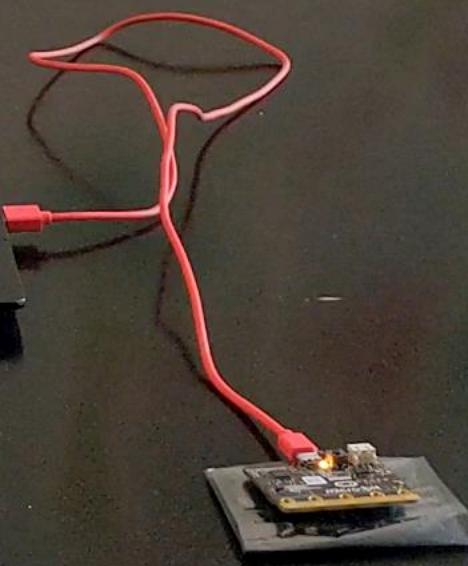
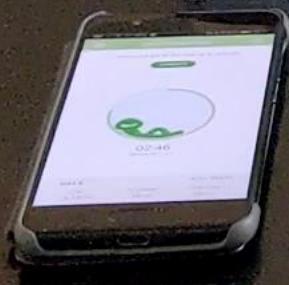
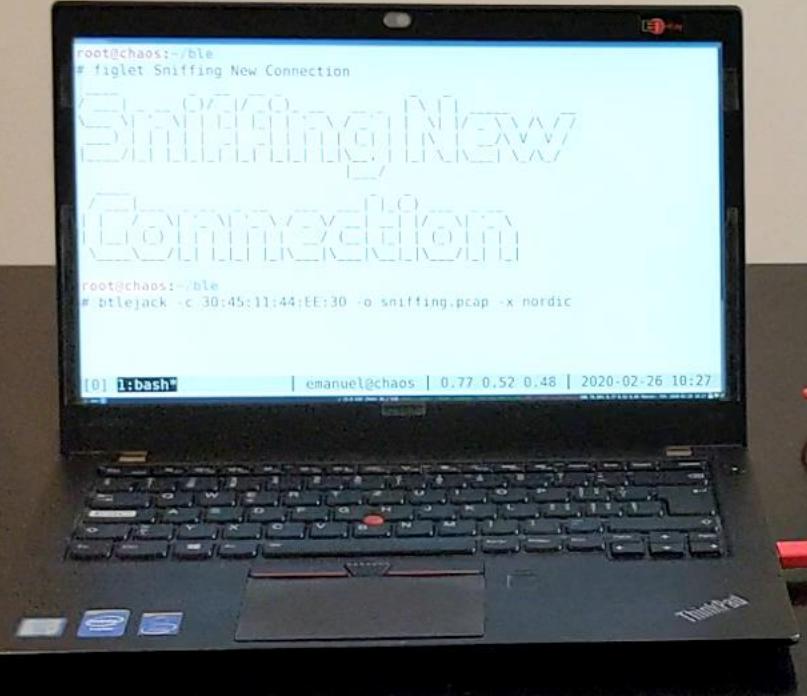
- Bluetooth LE Swiss-Army Knife Software by Damien Cauquil
- Firmware for various devices: BBC Micro:Bit, Adafruit Bluefruit LE sniffer, nRF51822 Eval Kit
- Micro:Bit is an OpenSource ARM Hardware created for teaching programming
- It has an Nordic nRF51822 chip → Bluetooth Low Energy
- Features: Sniffing, Jamming, Hijacking
- Supports multiple devices to sniff all 3 advertisement channels
- Respects the channel map
- More reliable than Adafruit Bluefruit LE Sniffer
- Project Page: <https://github.com/virtualabs/btlejack>

The way to go!



Demo Time: Sniffing New Connection





PCAP Analysis

No.	Time	Source	Destination	Protocol	Length	Value	Info
394	44.824232	Slave_0x50657412	Master_0x50657412	ATT	35	8900	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)
395	45.330332	Slave_0x50657412	Master_0x50657412	ATT	35	5d00	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)
396	45.432084	Slave_0x50657412	Master_0x50657412	ATT	35	4b00	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)
397	45.938163	Slave_0x50657412	Master_0x50657412	ATT	35	7600	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)
398	46.039331	Slave_0x50657412	Master_0x50657412	ATT	35	9100	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)
399	46.646395	Slave_0x50657412	Master_0x50657412	ATT	35	a300	Rcvd Handle Value Notification, Handle: 0x004b (Unknown: Unknown)

+ Frame 396: 35 bytes on wire (280 bits), 35 bytes captured (280 bits)
+ Nordic BLE Sniffer
+ Bluetooth Low Energy Link Layer
+ Bluetooth L2CAP Protocol
- Bluetooth Attribute Protocol
 - Opcode: Handle Value Notification (0x1b)
 0... = Authentication Signature: False
 .0... = Command: False
 ..01 1011 = Method: Handle Value Notification (0x1b)
 - Handle: 0x004b (Unknown: Unknown)
 [Service UUID: Unknown (0xaac0)]
 [UUID: Unknown (0xaaca)]
 Value: 4b00

Notification for
device angle

PCAP Analysis

No.	Time	Source	Destination	Protocol	Length	Info
420	53.723458	Slave_0x50657412	Master_0x50657412	ATT	38	Rcvd Read Response, Handle: 0x0016 (Device Information: Firmware Revision String)
421	56.309847	Master_0x50657412	Slave_0x50657412	ATT	36	Sent Write Request, Handle: 0x0028 (Unknown: Unknown)
422	56.344767	Slave_0x50657412	Master_0x50657412	ATT	31	Rcvd Write Response, Handle: 0x0028 (Unknown: Unknown)
423	56.411022	Master_0x50657412	Slave_0x50657412	ATT	33	Sent Read Request, Handle: 0x0016 (Device Information: Firmware Revision String)

+ Frame 421: 36 bytes on wire (288 bits), 36 bytes captured (288 bits)
+ Nordic BLE Sniffer
+ Bluetooth Low Energy Link Layer
+ Bluetooth L2CAP Protocol
- Bluetooth Attribute Protocol
 - Opcode: Write Request (0x12)
 0... = Authentication Signature: False
 0... ... = Command: False
 ..01 0010 = Method: Write Request (0x12)
 - Handle: 0x0028 (Unknown: Unknown)
 [Service UUID: Unknown (0xaaaa0)]
 [UUID: Unknown (0xaaa5)]
 Value: 030001

Write Request

Change Vibration Mode:

- Handle: 0x0028
- Value: 0x030001
- UUID: 0xaaa5

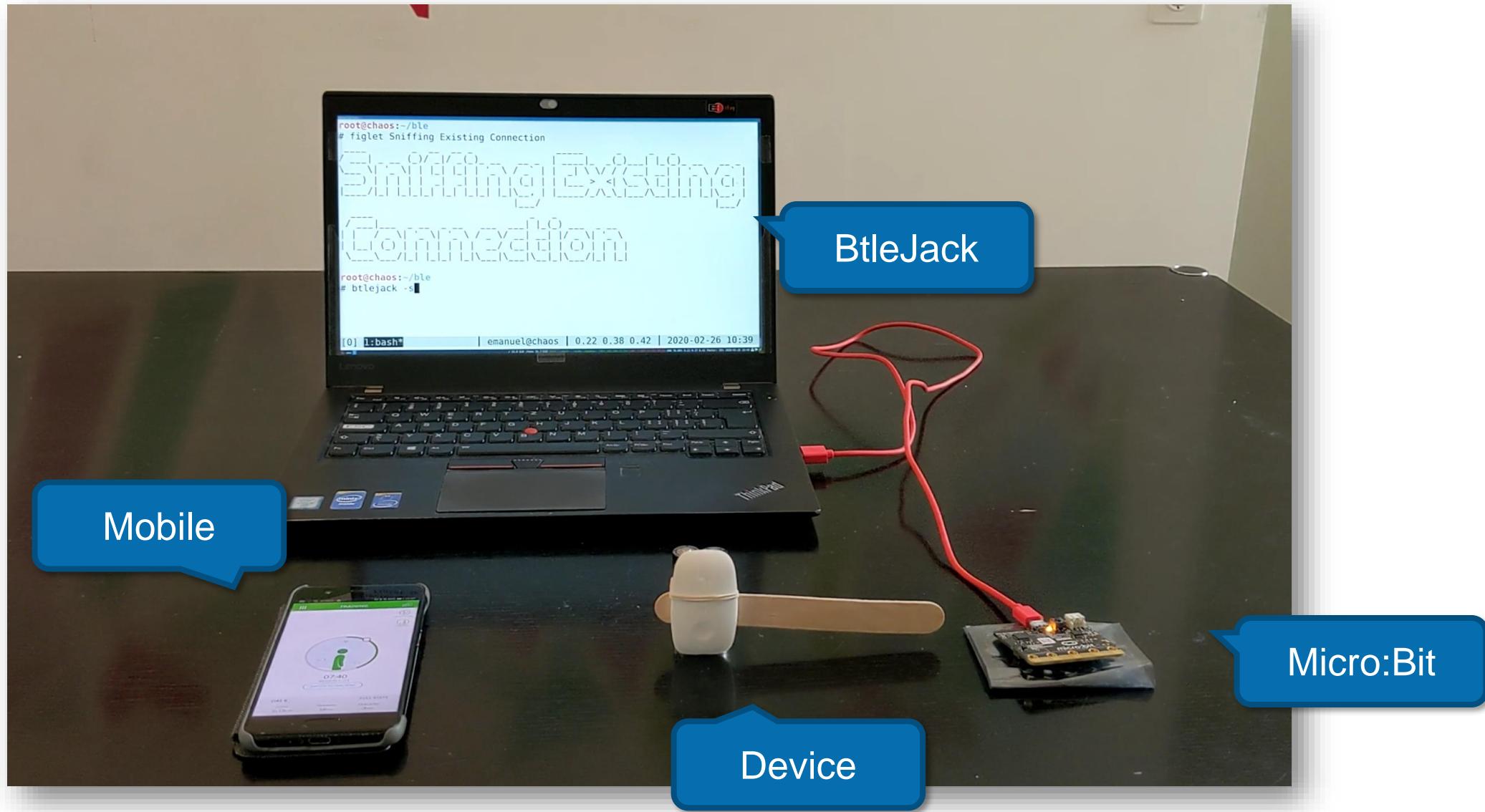


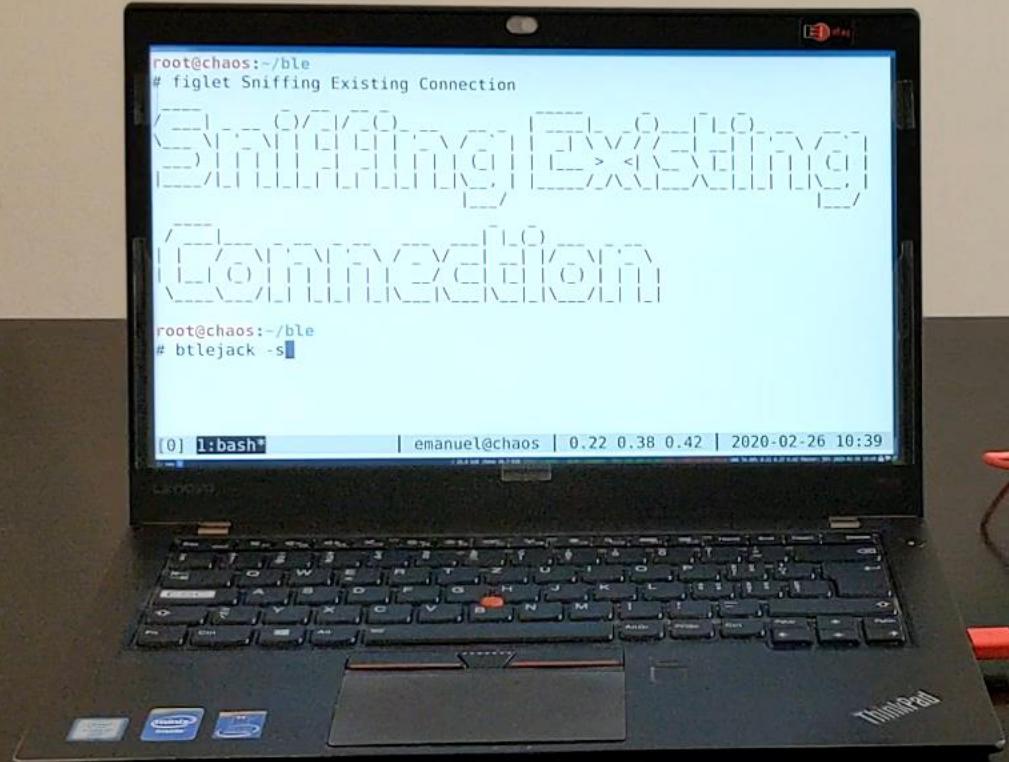
Encrypted Connections

- Crackle brute forces the TK used during BLE Legacy Pairing
- 6 digit PIN (Pinentry Pairing) or 000000 (JustWorks Pairing) is used as a TK (added to 128 Bits)
- Easy to brute force
- Pairing handshake must be captured
- BtleJack's II_phdr format is supported
- Project Page: <https://github.com/mikeryan/crackle>

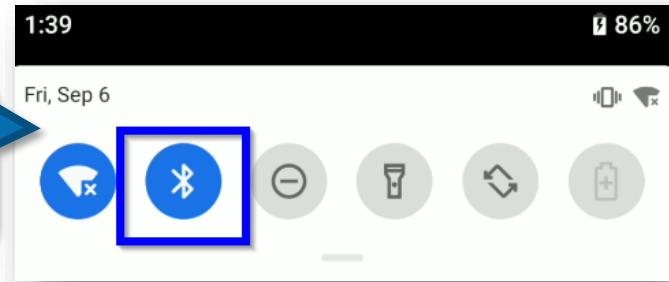
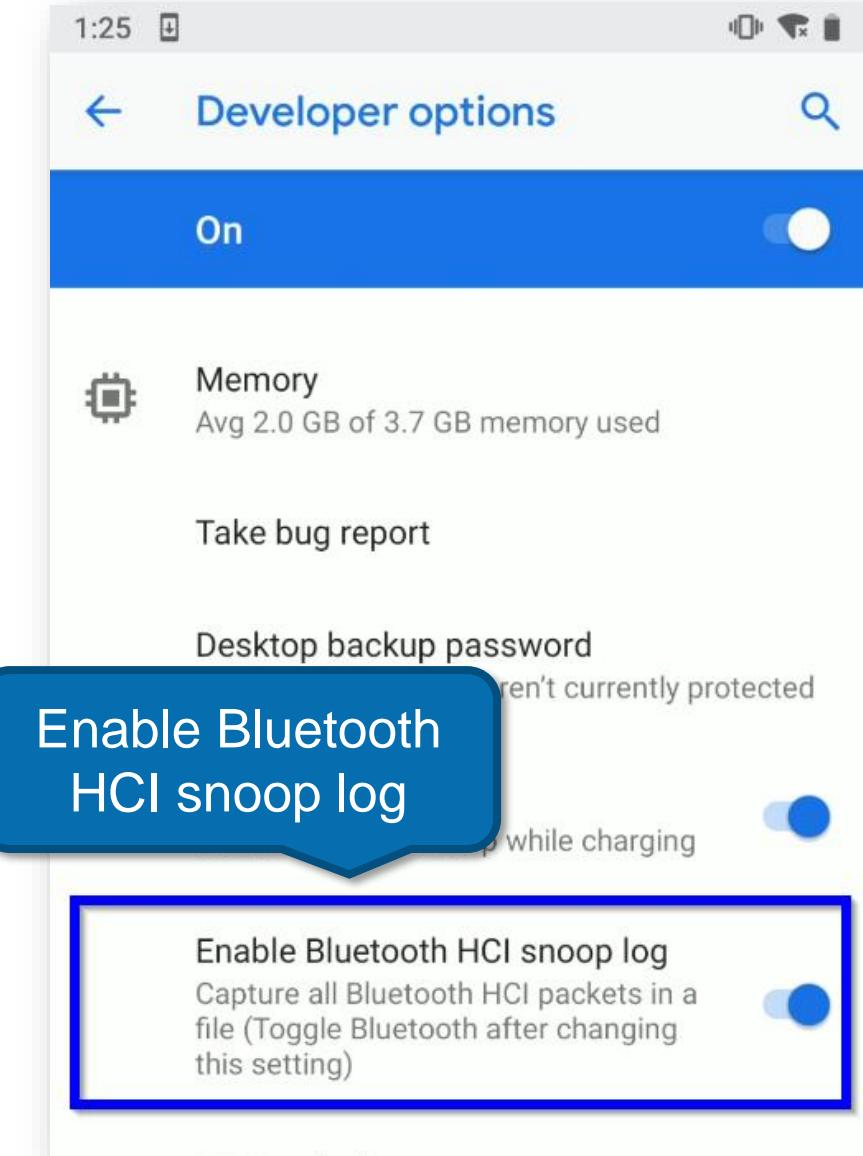


Demo Time: Sniffing Existing Connection

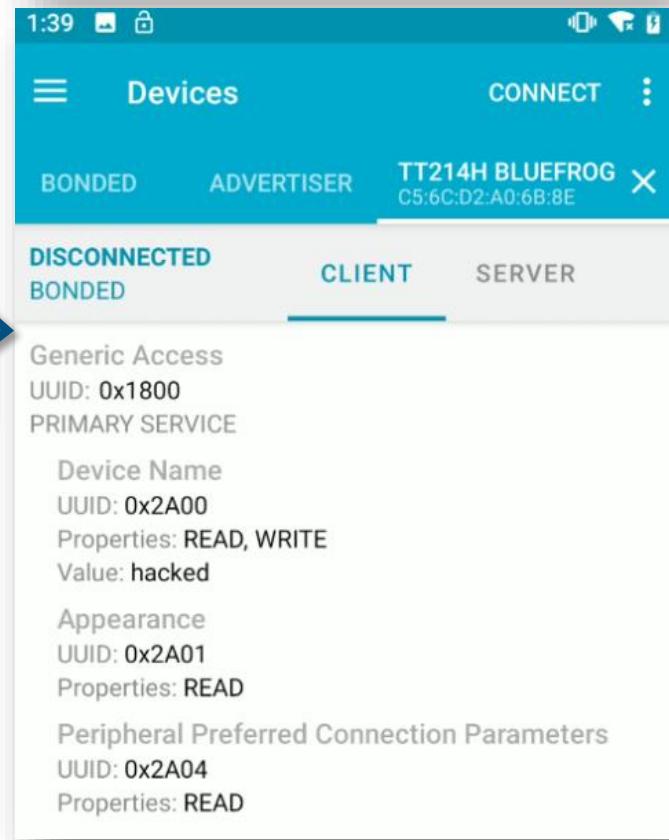




Android Bluetooth HCI Snoop Log



Toggle the
Bluetooth adapter



Start device
interaction

HCI = Host
Controller Interface

Android Bluetooth Snoop Log

```
# adb shell su -c cat /data/misc/bluetooth/logs/btsnoop_hci.log > btsnoop_hci.log
# file btsnoop_hci.log
btsnoop_hci.log: BTSSnoop version 1, HCI UART (H4)
```

Location for Pixel 3,
Android 9

No.	Time	Source	Destination	Protocol	Length	Comment	Info
553	23.320193	Google_1c:cc:92 (Pixel 3)	ca:4d:10:ba:09:73 (card10-ba0973)	SMP	26	Sent	Pairing DHKey Check
554	23.335610	controller	host	HCI_EVT	8	Rcvd	Number of Completed Packets
555	23.447688	ca:4d:10:ba:09:73 (card10-ba0973)	Google_1c:cc:92 (Pixel 3)	SMP	26	Rcvd	Pairing DHKey Check
→ 556	23.448338	host	controller	HCI_CMD	32	Sent	LE Start Encryption
← 557	23.449112	controller	host	HCI_EVT	7	Rcvd	Command Status (LE Start Encryption)
← 558	23.492703	controller	host	HCI_EVT	7	Rcvd	Encryption Change
559	23.493329	Google_1c:cc:92 (Pixel 3)	ca:4d:10:ba:09:73 (card10-ba0973)	SMP	26	Sent	Identity Information
560	23.493648	Google_1c:cc:92 (Pixel 3)	ca:4d:10:ba:09:73 (card10-ba0973)	SMP	17	Sent	Identity Address Information
561	23.993756	host	controller	HCI_CMD	43	Sent	LE Add Device to Resolving List

```
▶ Frame 556: 32 bytes on wire (256 bits), 32 bytes captured (256 bits)
▶ Bluetooth
▶ Bluetooth HCI H4
└ Bluetooth HCI Command - LE Start Encryption
  ▶ Command Opcode: LE Start Encryption (0x2019)
  Parameter Total Length: 28
  Connection Handle: 0x0002
  Random Number: 0000000000000000
  Encrypted Diversifier: 0x0000
  Long Term Key: a867626cc70c5f516e9c921af871c6f9
  [Pending in frame: 557]
  [Command-Pending Delta: 0.774ms]
  [Response in frame: 558]
  [Command-Response Delta: 44.365ms]
```

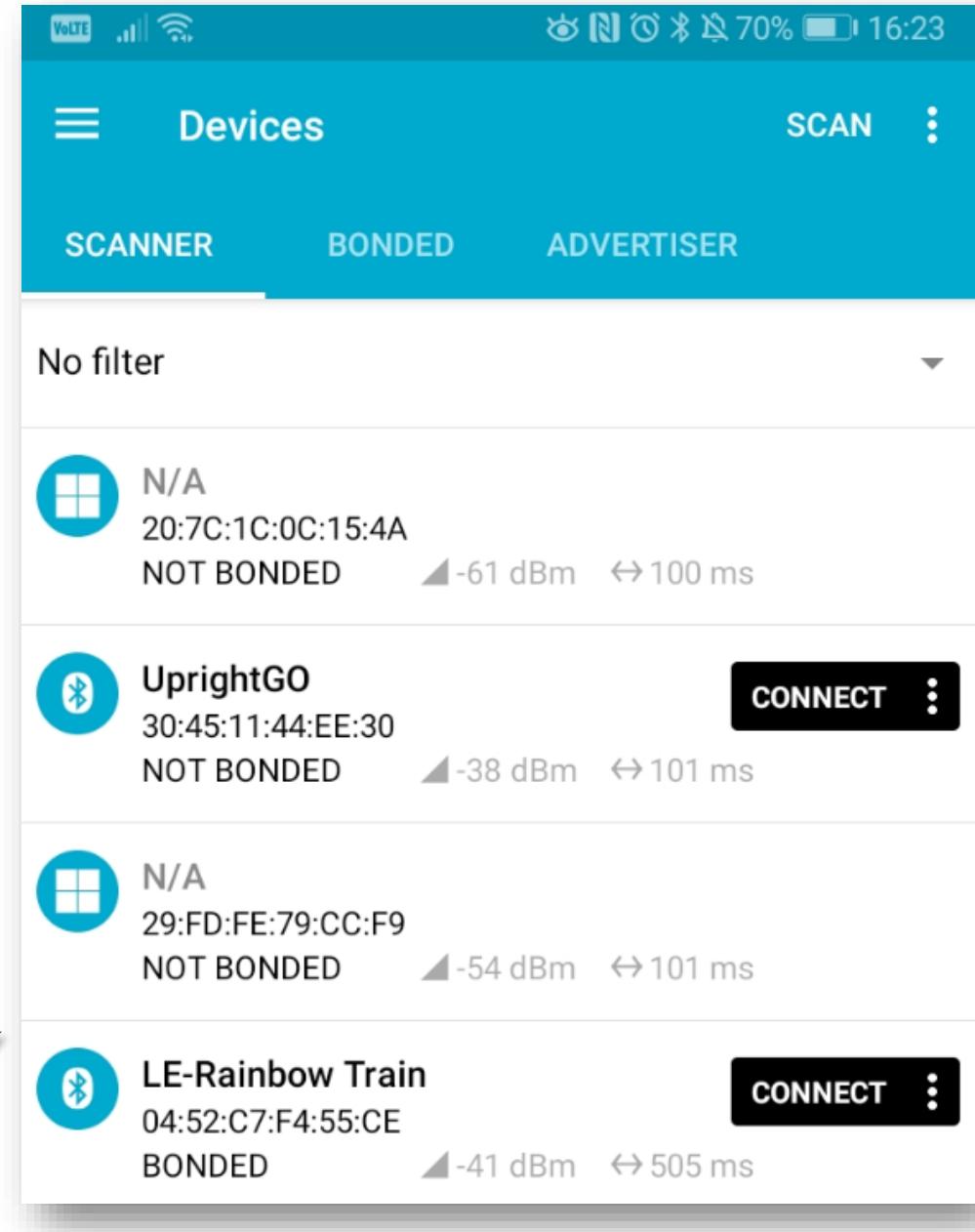
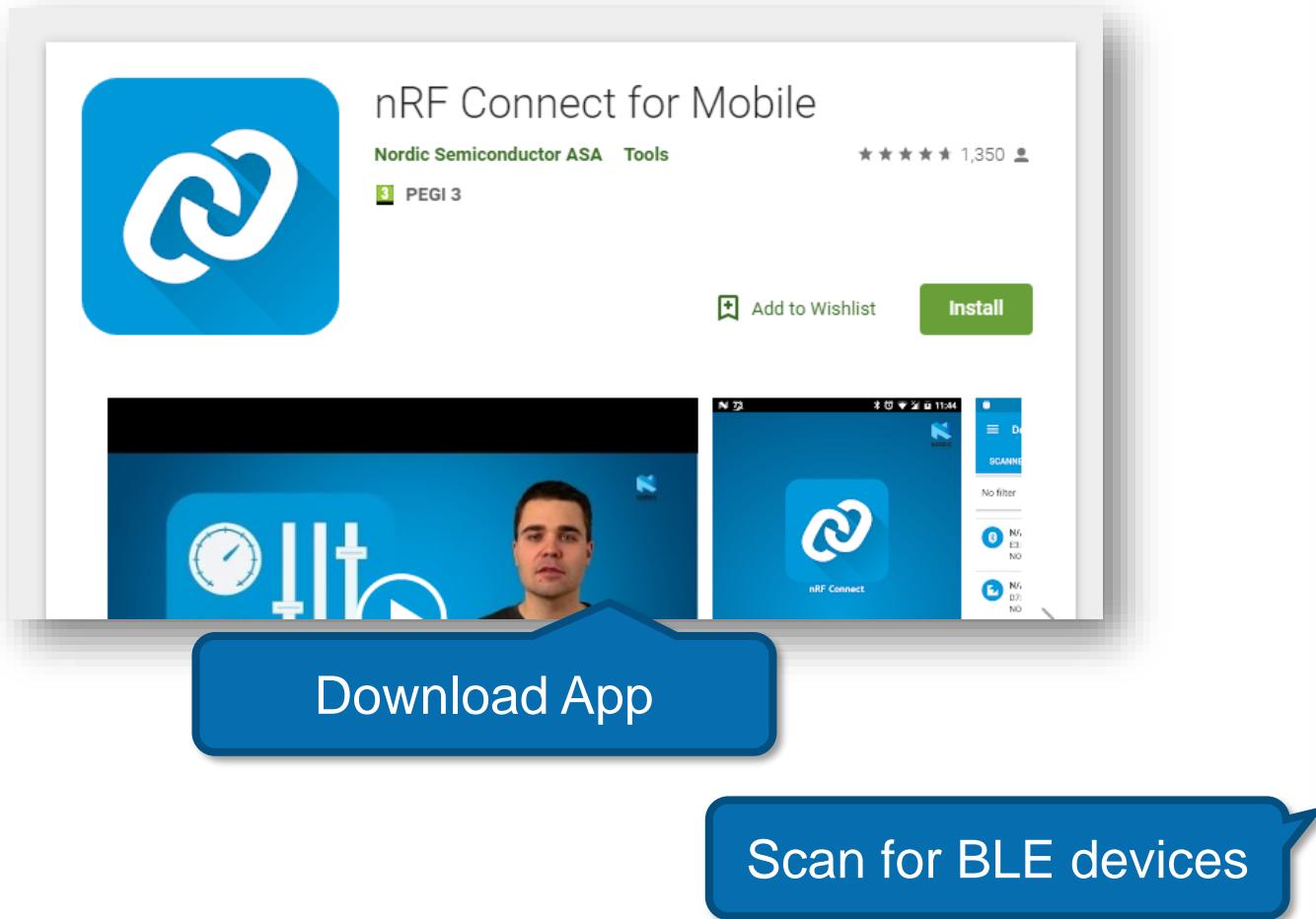
Encrypted Link

Read Encrypted Data,
e.g. Long Term Key

BLE Interaction

Android App

- nRF Connect for Mobile



Android App

The image consists of three side-by-side screenshots of an Android application interface, likely a Bluetooth debugger or monitor. Each screenshot shows a list of services and characteristics with various properties and descriptors.

Known and unknown Services:

- Generic Access**: UUID: 0x1800, PRIMARY SERVICE
- Generic Attribute**: UUID: 0x1801, PRIMARY SERVICE
- Device Information**: UUID: 0x180A, PRIMARY SERVICE
- Unknown Service**: UUID: 0000aaa0-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE
- Unknown Service**: UUID: 0000aab0-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE
- Unknown Service**: UUID: 0000aac0-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE
- Unknown Service**: UUID: 0000aae0-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE
- Unknown Service**: UUID: 0000acca-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE

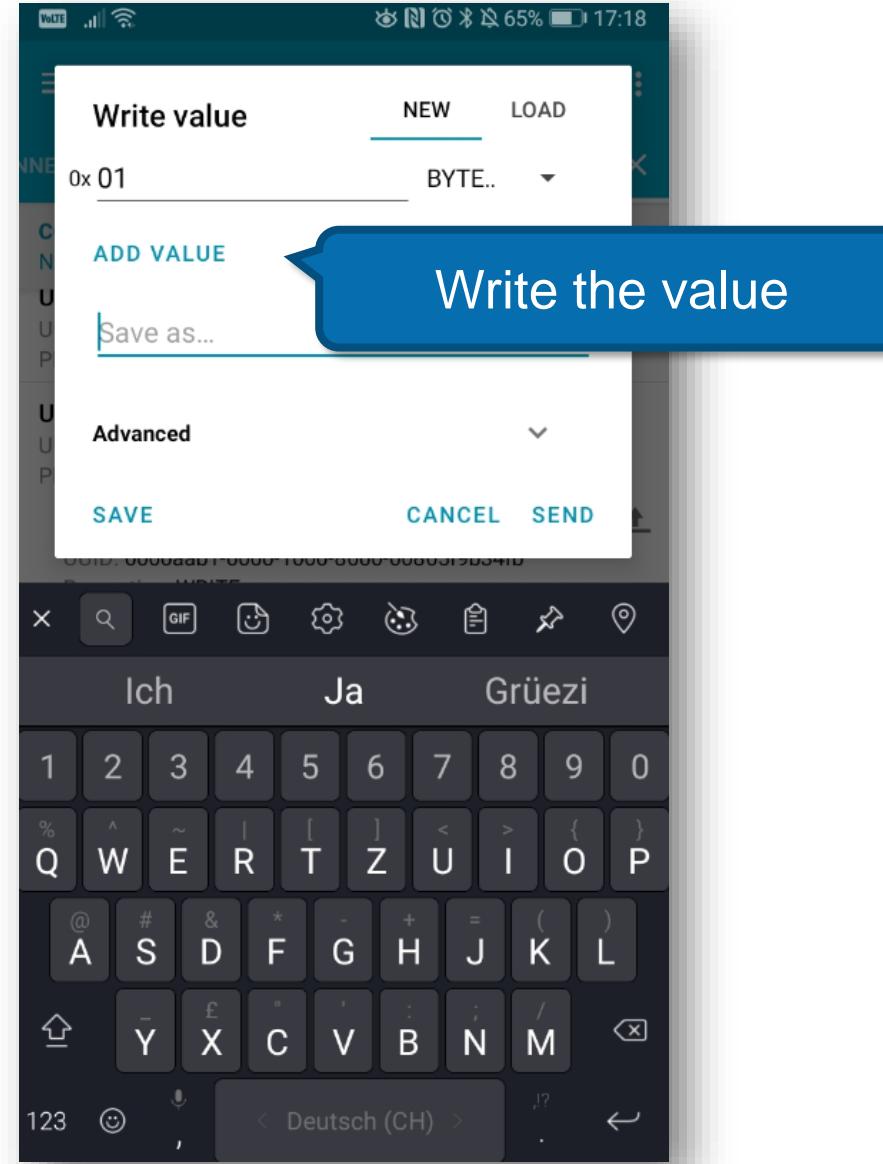
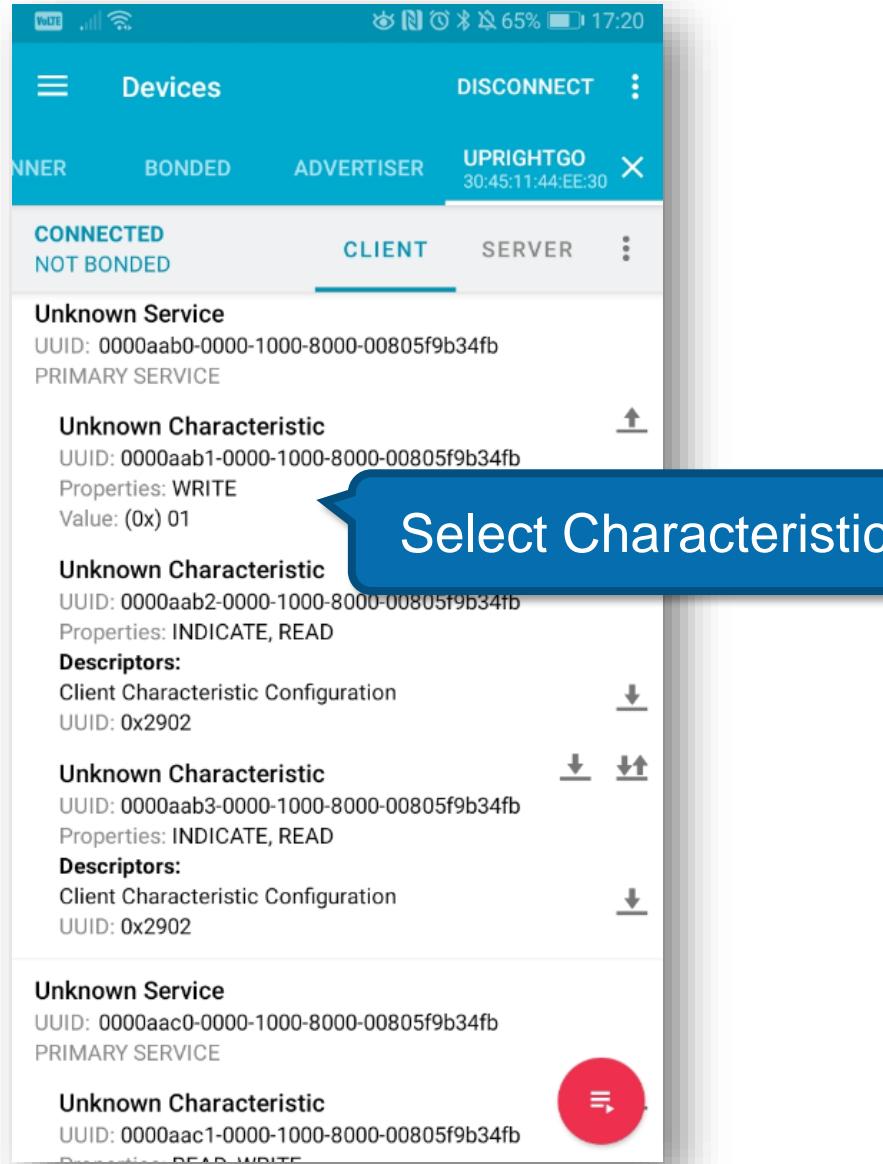
Known Characteristics:

- Device Name**: UUID: 0x2A00, Properties: READ, WRITE, WRITE NO RESPONSE
- Appearance**: UUID: 0x2A01, Properties: READ
- Peripheral Privacy Flag**: UUID: 0x2A02, Properties: READ, WRITE
- Reconnection Address**: UUID: 0x2A03, Properties: WRITE
- Peripheral Preferred Connection Parameters**: UUID: 0x2A04, Properties: READ
- Generic Attribute**: UUID: 0x1801, PRIMARY SERVICE
- Device Information**: UUID: 0x180A

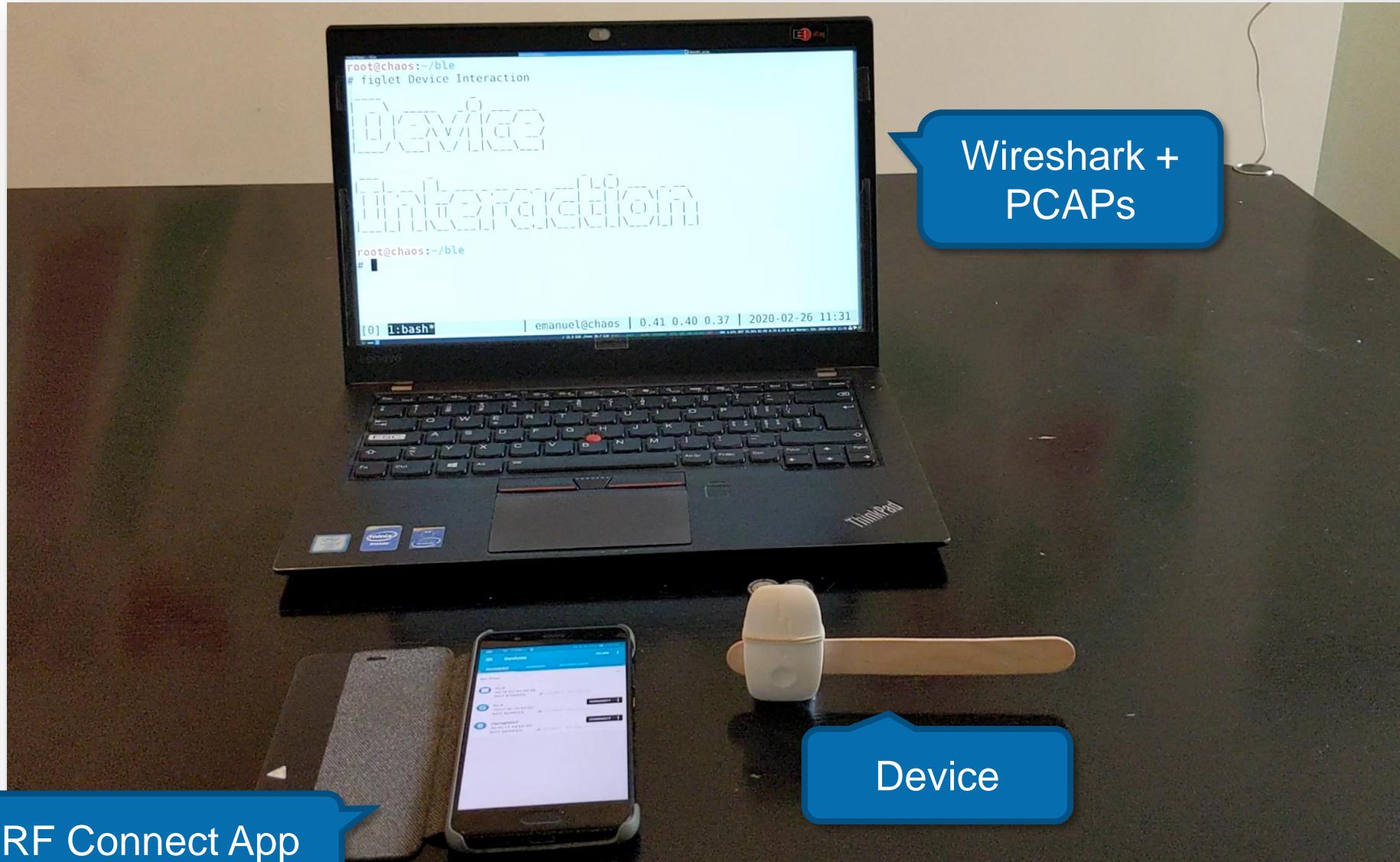
Unknown Characteristics:

- Unknown Service**: UUID: 0000aac1-0000-1000-8000-00805f9b34fb, PRIMARY SERVICE
 - Unknown Characteristic**: UUID: 0000aac1-0000-1000-8000-00805f9b34fb, Properties: READ, WRITE
 - Unknown Characteristic**: UUID: 0000aac2-0000-1000-8000-00805f9b34fb, Properties: READ, WRITE
 - Unknown Characteristic**: UUID: 0000aac3-0000-1000-8000-00805f9b34fb, Properties: INDICATE, READ
 - Descriptors:**
 - Client Characteristic Configuration
 - UUID: 0x2902
 - Unknown Characteristic**: UUID: 0000aac4-0000-1000-8000-00805f9b34fb, Properties: NOTIFY, READ
 - Descriptors:**
 - Client Characteristic Configuration
 - UUID: 0x2902
 - Unknown Characteristic**: UUID: 0000aac5-0000-1000-8000-00805f9b34fb, Properties: READ

Android App

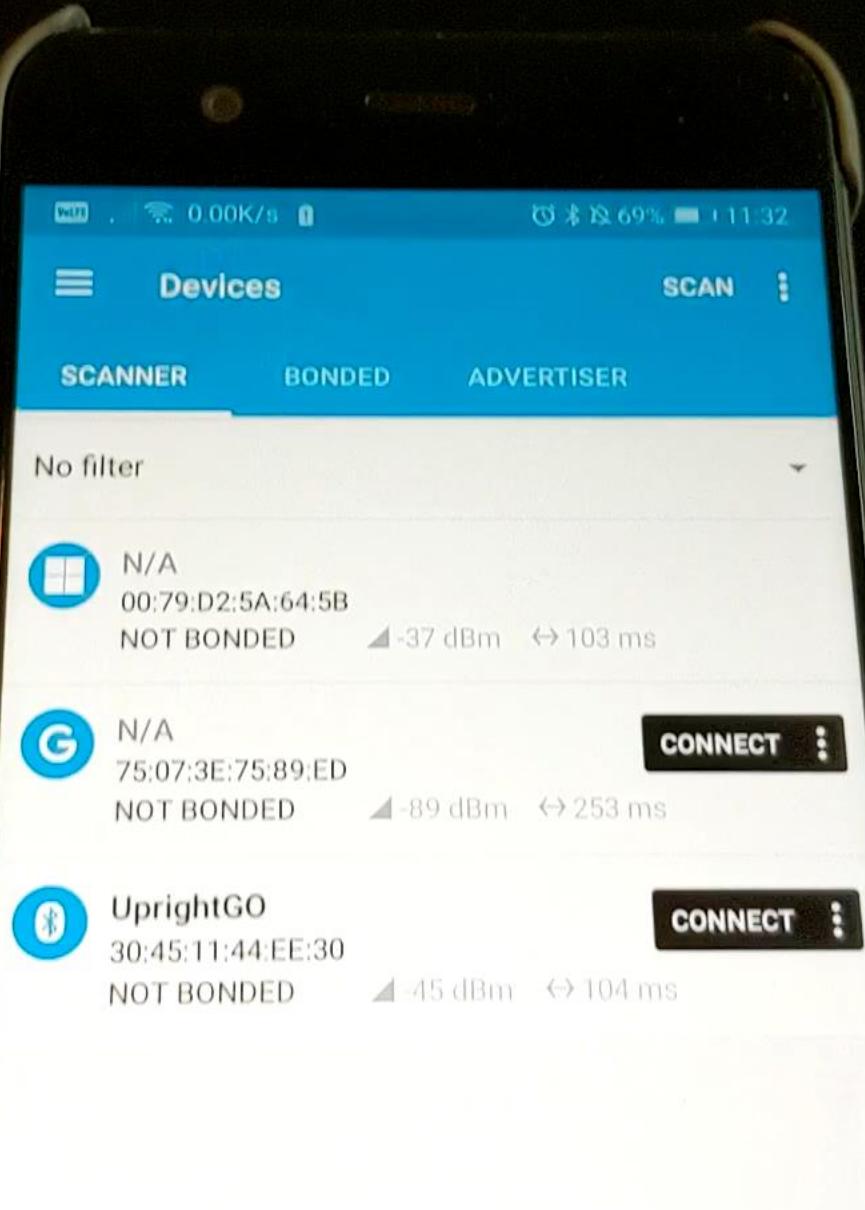


Demo Time: Device Interaction



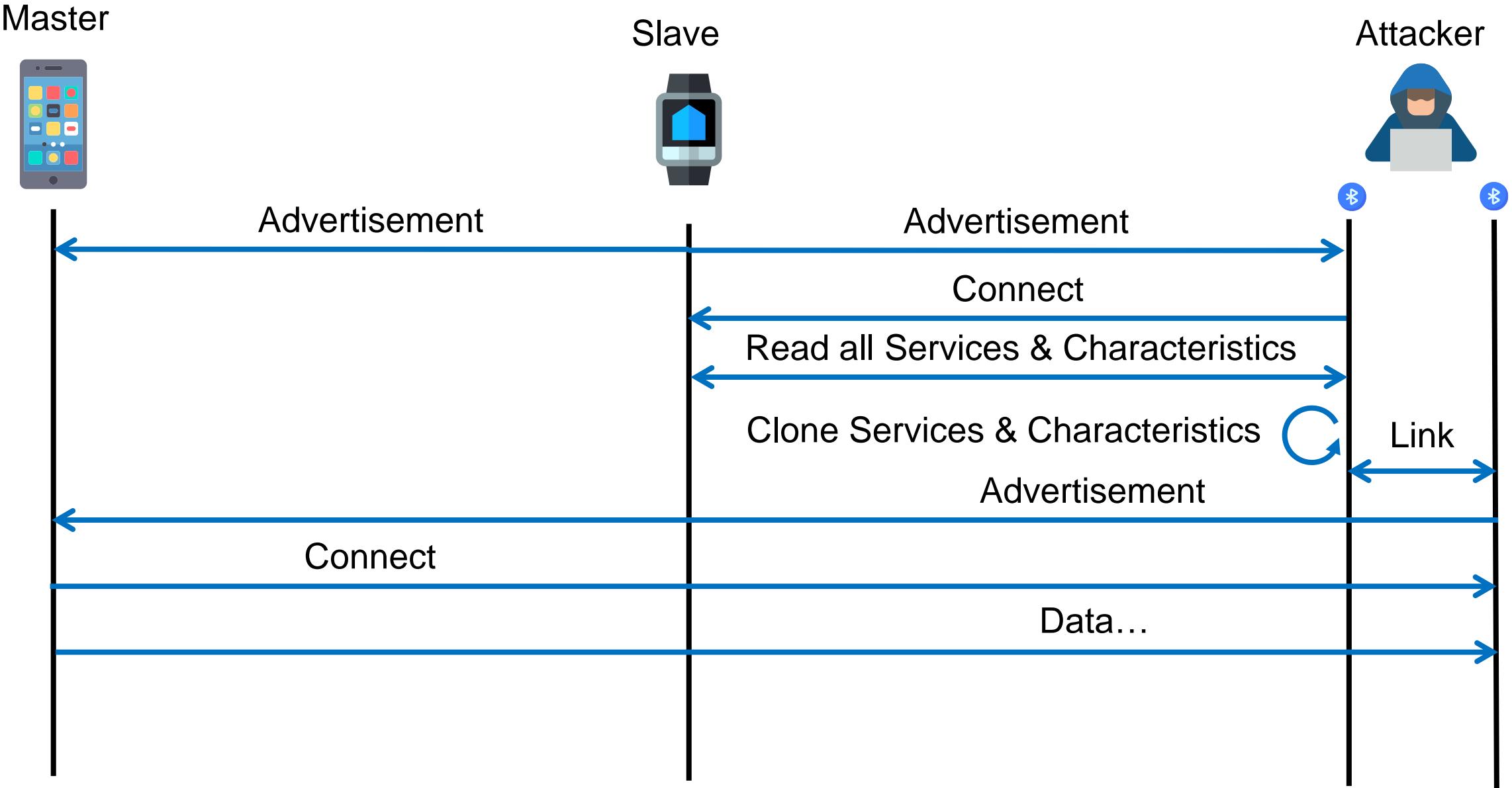
nRF Connect App

Device

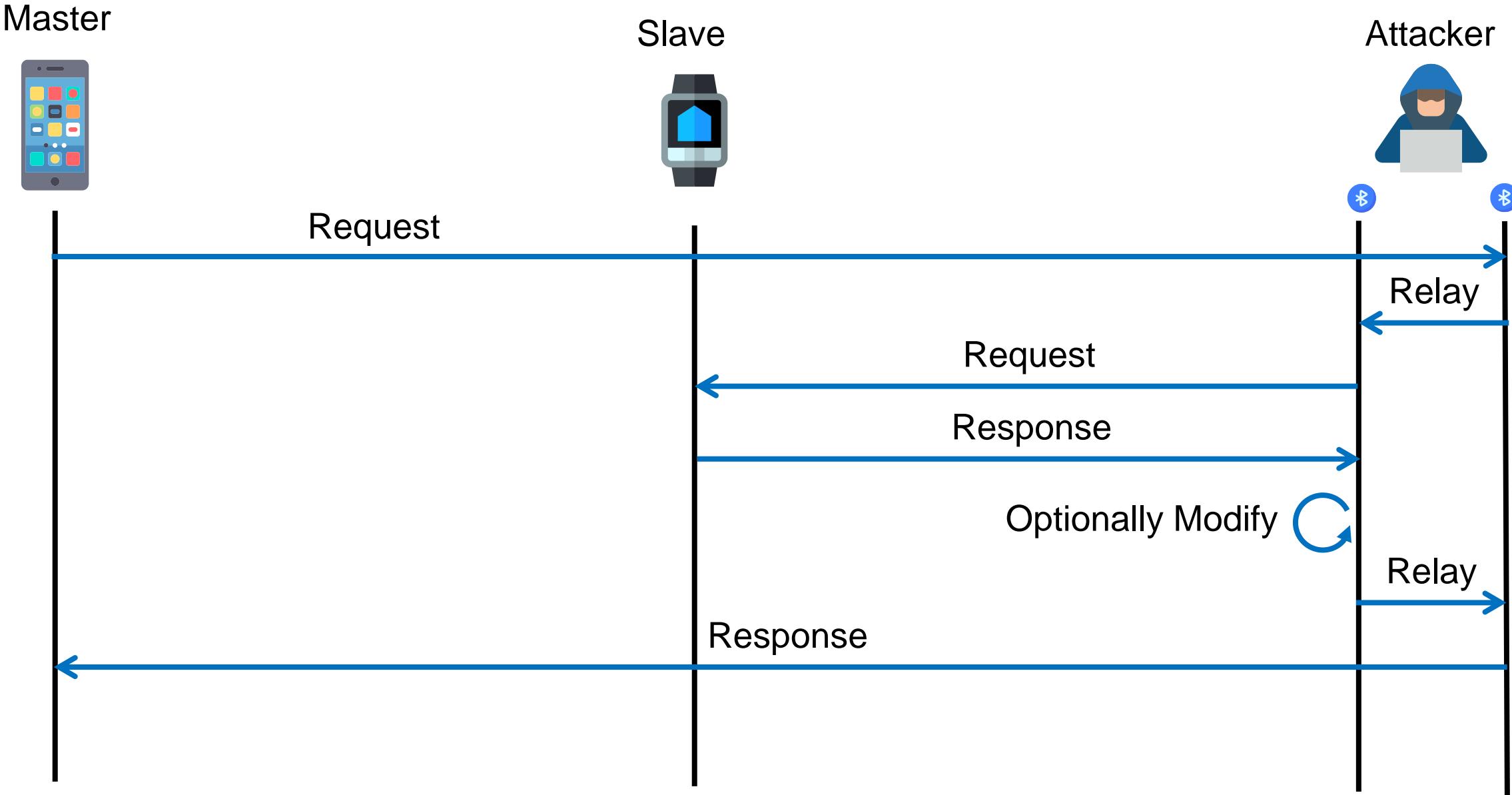


BLE Man-in-the-Middle

BLE Man-in-the-Middle



BLE Man-in-the-Middle



MITM Software

- GATTacker by Slawomir Jasek
 - Project Page: <https://github.com/securing/gattacker>
 - Console tools to perform the attacks
 - Writing hooks for manipulating the traffic
- BtleJuice by Econocom Digital Security
 - Project Page: <https://github.com/DigitalSecurity/btlejuice>
 - Webinterface to perform the attacks
- Both tools work in the same way:
 - 2 VMs: Master (central) and Slave (peripheral) with each one Bluetooth adapter
 - VM 1 (Master): Central connects to peripheral
 - VM 2: WebSocket to VM 1 and clone/advertise the same GATT services
 - Sniff, intercept and modify, replay
- Downsides
 - Complex setup, they don't work properly, no pairing support



I invested a lot of work and time
in getting the tools to work. It was
not worth the time 😞

Feature Requirements for active MITM Protection

		Initiator				
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display	
Display Only	Just Works Unauthenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	
	Just Works Unauthenticated	Just Works (For LE Legacy Pairing) Unauthenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing)	
Display YesNo	Just Works Unauthenticated	Numeric Comparison (For LE Secure Con- nections) Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Numeric Comparison (For LE Secure Con- nections) Authenticated	
	Just Works Unauthenticated					

This means, both devices need a keyboard AND/OR a display!

Table 2.8: Mapping of IO capabilities to key generation method

		Initiator				
Responder	DisplayOnly	Display YesNo	Keyboard Only	NoInput NoOutput	Keyboard Display	
Keyboard Only	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: initiator and responder inputs Authenticated	Just Works Unauthenti- cated	Passkey Entry: initiator displays, responder inputs Authenticated	
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	
NoInput NoOutput	Passkey Entry (For LE Legacy Pairing): initiator dis- plays, responder inputs Authenticated	Passkey Entry: initiator displays, responder inputs Authenticated	Passkey Entry: responder displays, initiator inputs Authenticated	Just Works Unauthenticated	Passkey Entry (For LE Legacy Pairing): initiator dis- plays, responder inputs Authenticated	
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	
Keyboard Display	Numeric Comparison (For LE Secure Con- nections) Authenticated	Numeric Comparison (For LE Secure Con- nections) Authenticated	Numeric Comparison (For LE Secure Con- nections) Authenticated	Just Works Unauthenticated	Numeric Comparison (For LE Secure Con- nections) Authenticated	
	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	Just Works Unauthenticated	

Table 2.8: Mapping of IO capabilities to key generation method

Which Pairing Methods are Secure?

- Use pairing methods which use strong key generation mechanisms and support authentication!

Security Type	Pairing Method	Passive Sniffing	Active MitM
No Pairing	-	FAIL	FAIL
LE Legacy Pairing	Just Works	FAIL	FAIL
LE Legacy Pairing	Passkey Entry	FAIL	PASS
LE Legacy Pairing	Out-of-Band	PASS	PASS
LE Secure Connection	Just Works	PASS	FAIL
LE Secure Connection	Passkey Entry	PASS	PASS
LE Secure Connection	Out-of-Band	PASS	PASS
LE Secure Connection	Numeric Comparison	PASS	PASS

BLE Hijacking

BLE Hijacking

Master



Slave



Attacker



Data / Keep Alive

Listens to determine
frequency hopping
pattern.

Jamming on same frequency

Jamming on same frequency

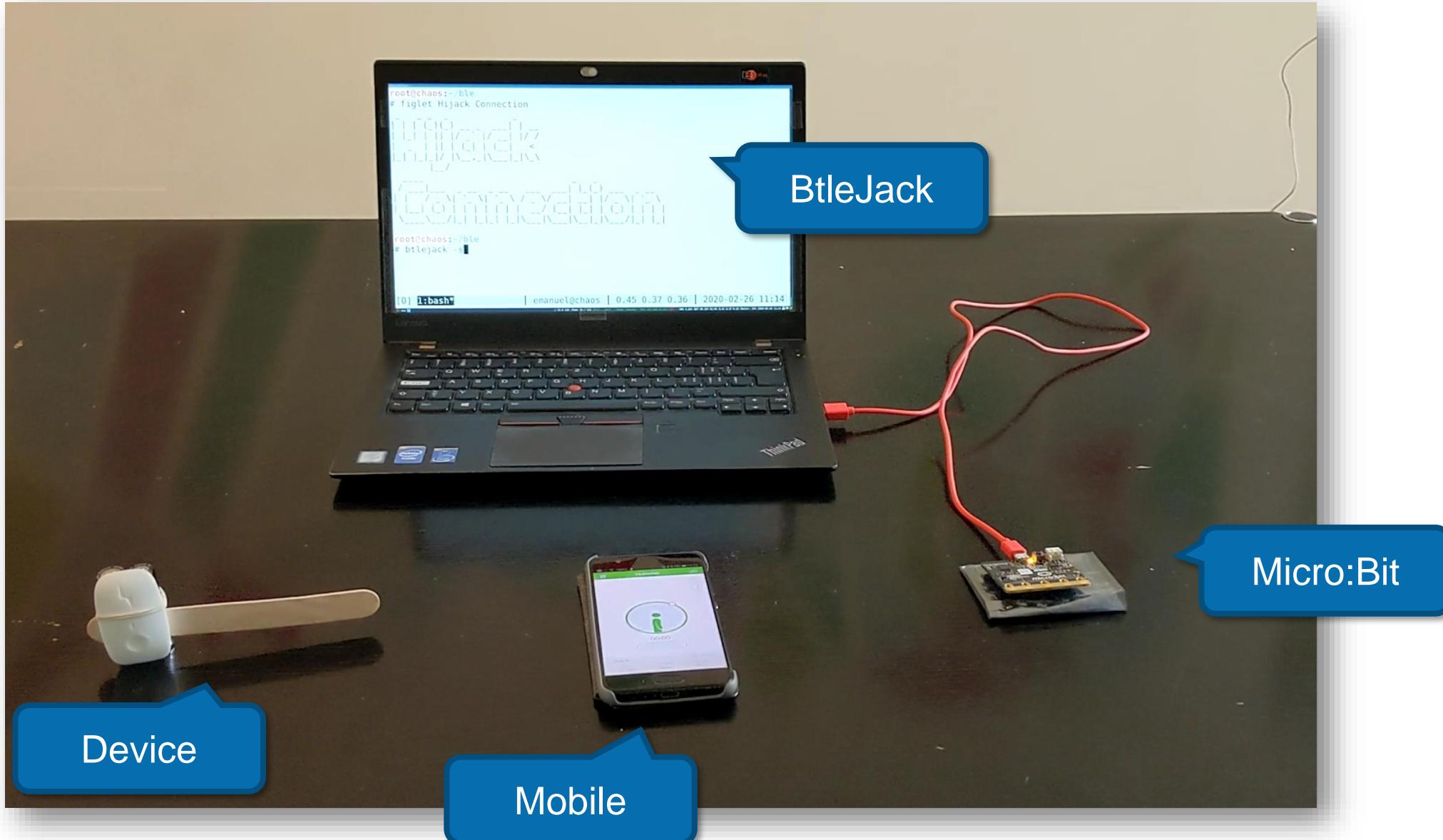
Jamming on same frequency

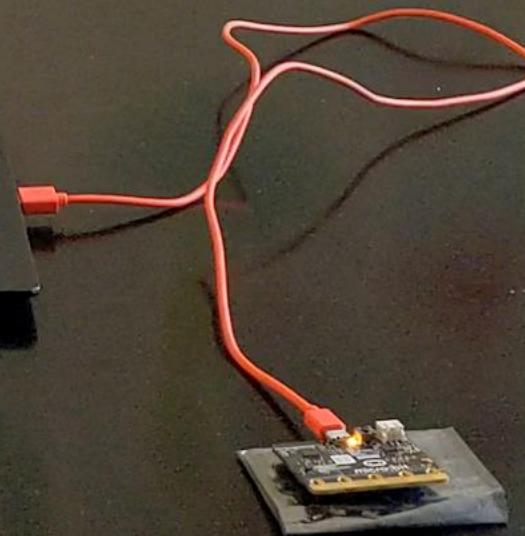
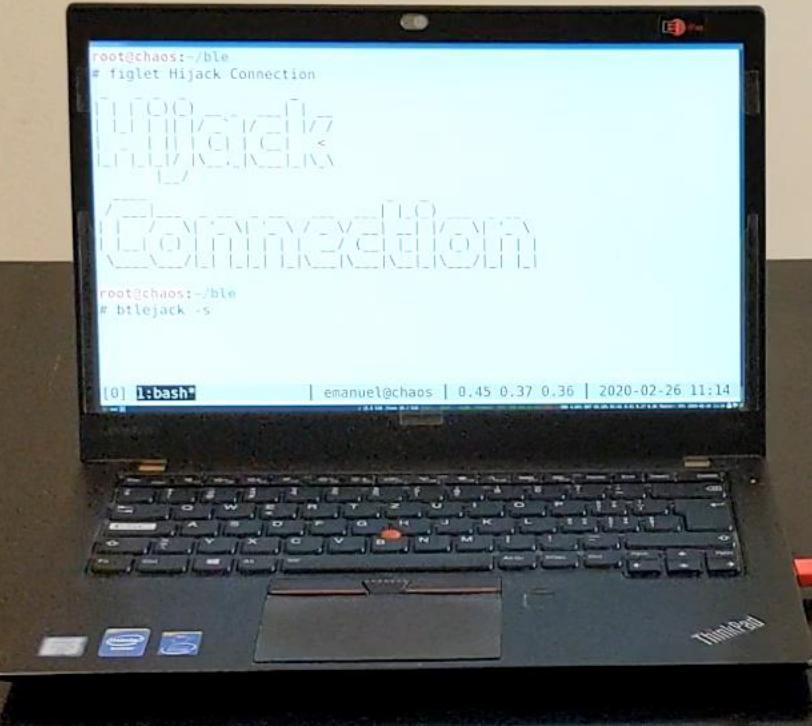


Timeout! Connection Lost!

Data: Communication Hijacked!

Demo Time: Hijacking

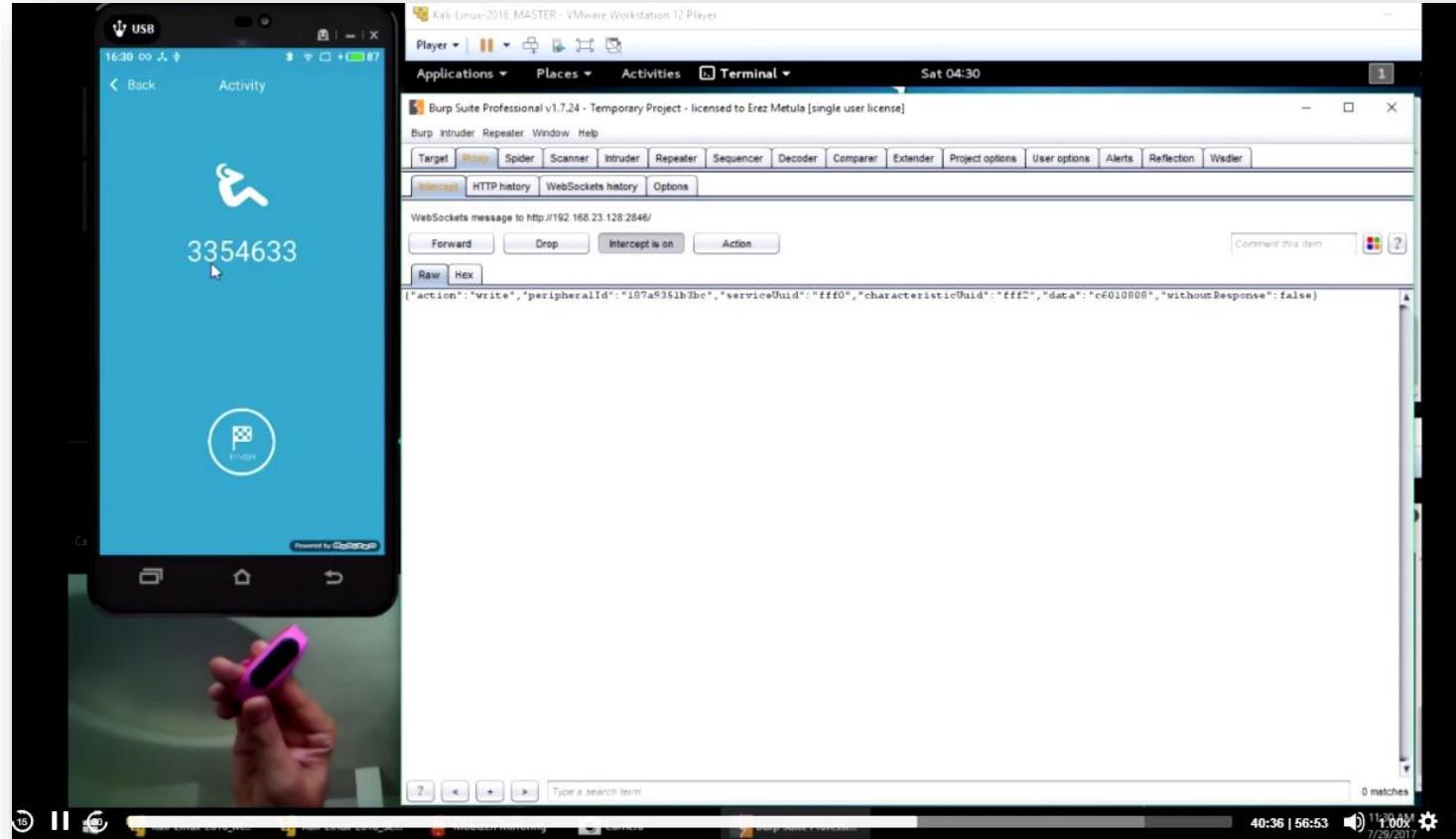




Example BLE Attacks

SHA2017 – Hack-a-ble

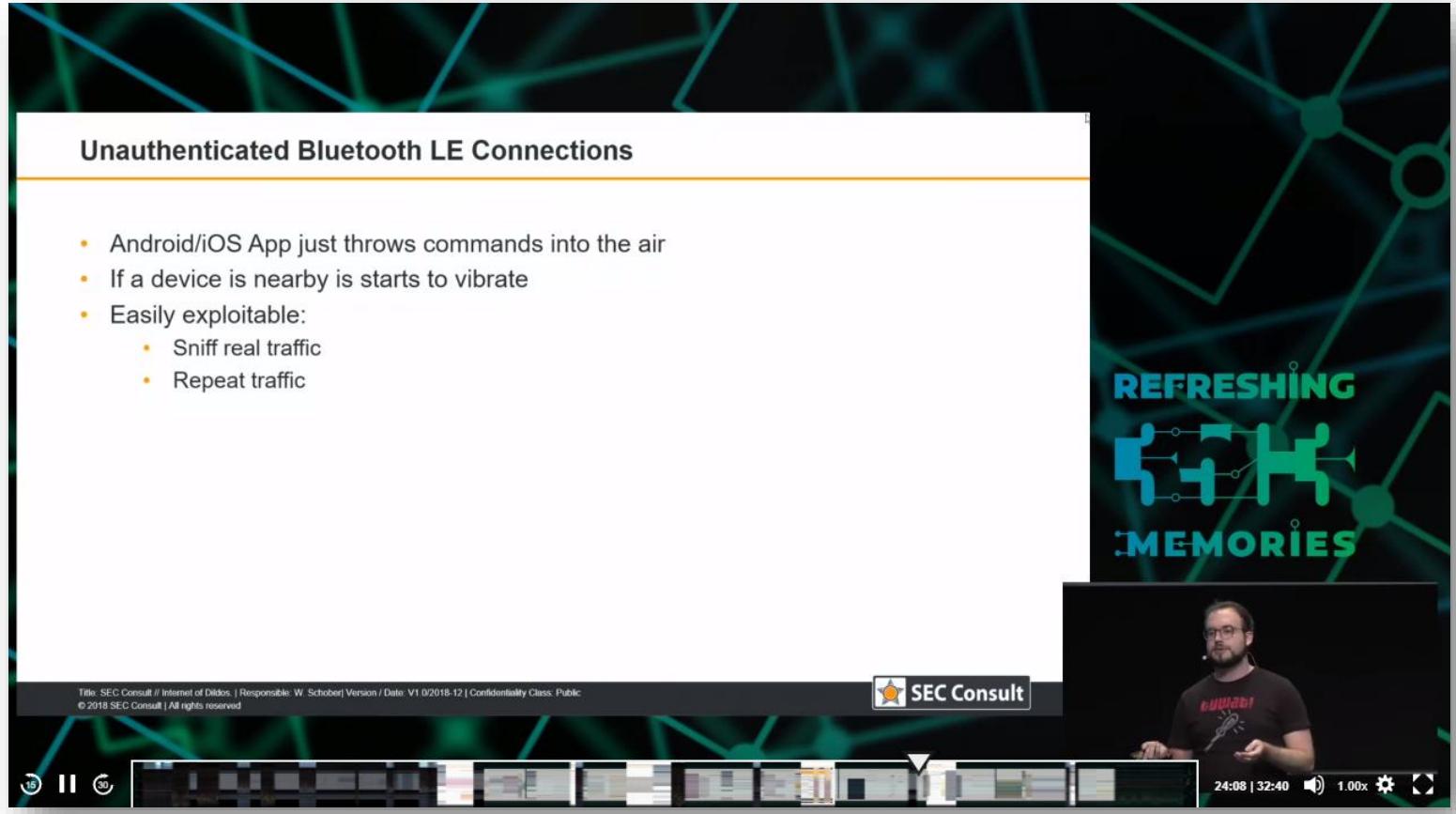
- General BLE security talk by Tal Melamed
- Example: Man-in-the Middle of a fitness watch



<https://media.ccc.de/v/SHA2017-230-hack-a-ble>

35c3 – Internet of Dongs

- Sex toy research that also covers BLE by Werner Schober
- No pairing at all (= no authentication): Let other's sex toys vibrate



https://media.ccc.de/v/35c3-9523-internet_of_dongs

CCCamp2019 – Taking Bluetooth lockpicking to the next level

▪ BLE SmartLocks Lockpicking talk by Ray and mh

ANBOUD PWNED

- Bluetooth Attribute Protocol
 - Opcode: Write Request (0x12)
 - Handle: 0x0029 (Unknown: Unknown)
 - Value: 55410~~027dbe8~~
- HEX 0x~~027db~~ = 010203 decimal
- That's the code I set on the lock
- Original app can now be used to open lock with sniffed code

cccamp 2019 - Zehdenick, Germany 

No pairing, lock code transmitted in cleartext

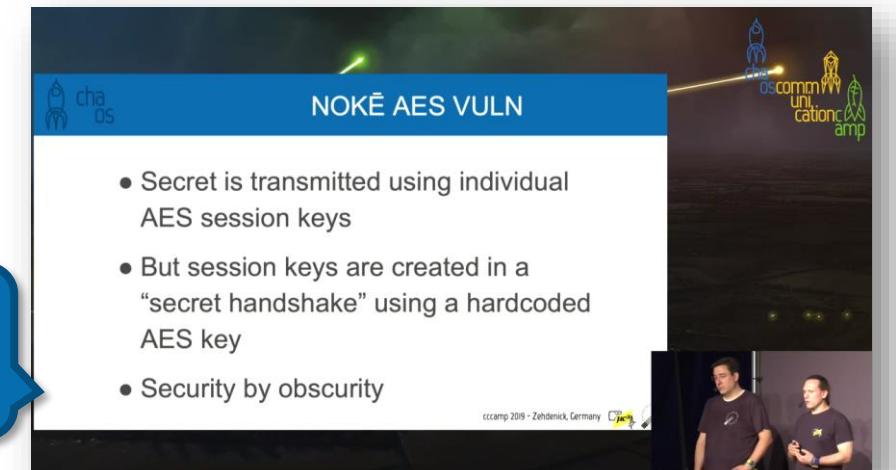
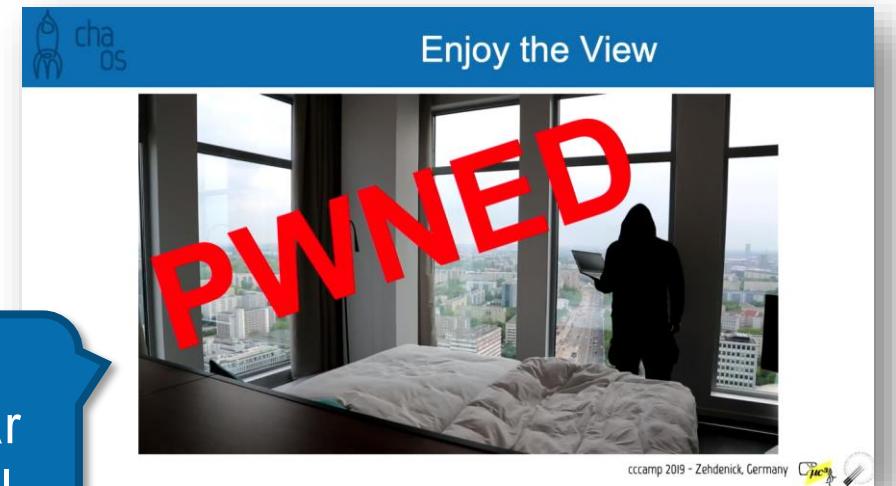
No pairing, code transmitted in clear in custom protocol

~~12~~ 14 of 16 locks vulnerable

- Rose & Ramsey at DefCon 24 (2016)
- 12 of 16 tested locks had simple BLE vulnerabilities
- Only two of the padlocks remained unbroken
- One of those we opened with a magnet, like its predecessor, ...

14/16 other analyzed locks had BLE vulns.

No pairing, hardcoded AES Key



Implementation Bugs

- There are several implementation bugs
- Example: BlueFrag vulnerability (CVE-2020-022) discovered by Jan Ruge
- RCE on all Android phones (version 8-9) when Bluetooth is just enabled

The screenshot shows a presentation slide with the following content:

hidden service Digital verteiltes Online-Chaos

ERNW providing security.

SEMO SECURE MOBILE NETWORKING

CVE-2020-0022 Disclosure

- Disclosed on Nov 3, 2019
- Patch on Feb 3, 2020 (Full 90 Days!)
 - Some devices only receive quarterly updates
 - Too many devices receive no patch at all
 - Automotive ?

source

CVE	References	Type	Severity	Updated AOSP versions
CVE-2020-0022	A-143894715	DoS	Moderate	10
		RCE	Critical	8.0, 8.1, 9

https://media.ccc.de/v/DiVOC-7-no_poc_no_fix_a_sad_story_about_bluetooth_security

Bluetooth Low Energy 5

Bluetooth Low Energy 5

- Version 5 released in 2016, Version 5.1 and 5.2 released in 2019
- Features: better speed, better range, improved coexistence
- In 2019: No BLE 5 products available in markets
 - Researcher has to build own BLE 5 devices in order to hack it

Core Specification Change History



9 CHANGES FROM v4.2 TO v5.0

9.1 NEW FEATURES

Several new features are introduced in version 5.0. The major areas of improvement are:

- Slot Availability Mask (SAM)
- 2 Msym/s PHY for LE
- LE Long Range
- High Duty Cycle Non-Connectable Advertising
- LE Advertising Extensions
- LE Channel Selection Algorithm #2

Interesting
DEF CON 27 Talk



The slide features a blue speech bubble in the top right corner containing the text "Interesting DEF CON 27 Talk". Below the bubble is a photograph of a speaker at a podium with a laptop, set against a backdrop of a city skyline at night. The slide has a white header area with the title "Defeating Bluetooth Low Energy 5 PRNG" and subtitle "for fun and jamming". At the bottom, it includes the author's name "Damien \"virtualabs\" Cauquil | DEF CON 27" and the source "digital.security". The DEF CON 27 logo and date "AUGUST 9-11, 2019" are visible along the bottom edge.

Physical Layers

- Two new physical layers
 - 2M LE Uncoded PHY: Better throughput up to 2 Mbps
 - LE Coded PHY: 4 times the range (125 kbps, up to 400m) or 2 times the range (500 kbps, up to 200m)
- Not supported by BtleJack at the moment, another chip would be needed

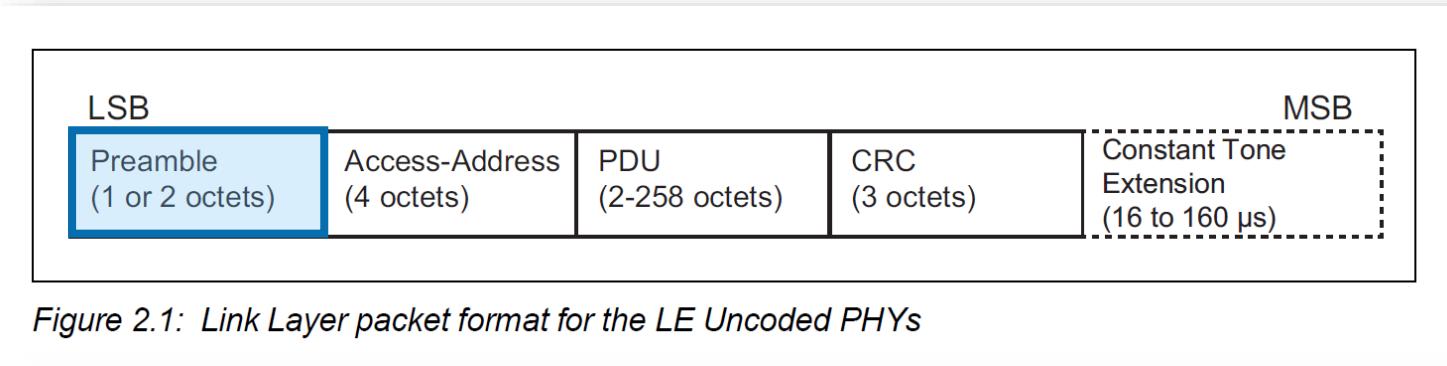


Figure 2.1: Link Layer packet format for the LE Uncoded PHYs

2 Octet Preamble:
2M LE Uncoded PHY

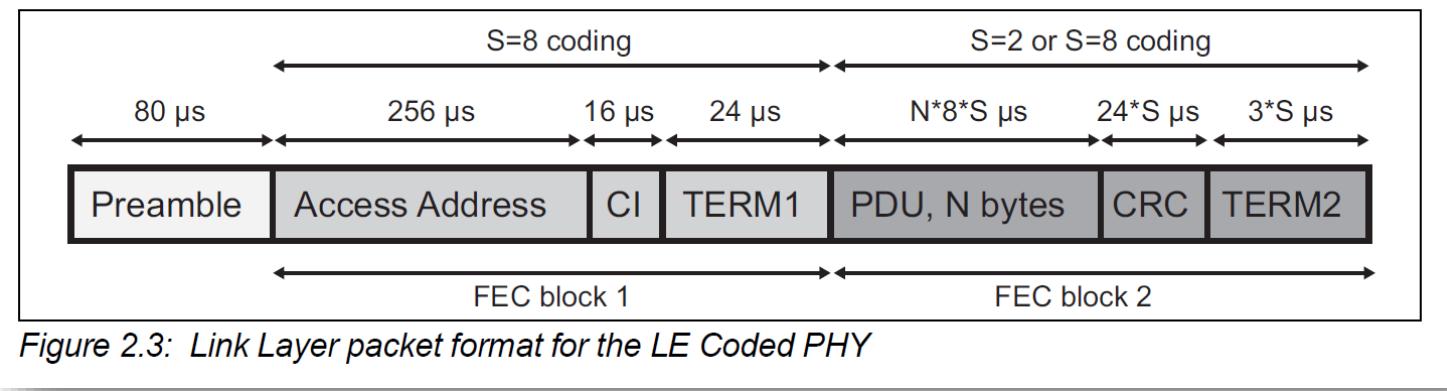


Figure 2.3: Link Layer packet format for the LE Coded PHY

LE Coded PHY

Channel Selection Algorithm

- New Hopping Scheme / Channel Selection Algorithm (CSA #2)
 - More random by using a Pseudorandom Number Generator (PRNG)
 - Devices specify in the advertisement packages if they support this (ChSel bit)
 - 65536-hop instead of 37-hop sequence

Matthew Green
@matthew_d_green

Every single page of the Bluetooth spec should be illegal.

[Tweet übersetzen](#)

BLUETOOTH CORE SPECIFICATION Version 5.1 | Vol 6, Part B page 2789

Link Layer Specification

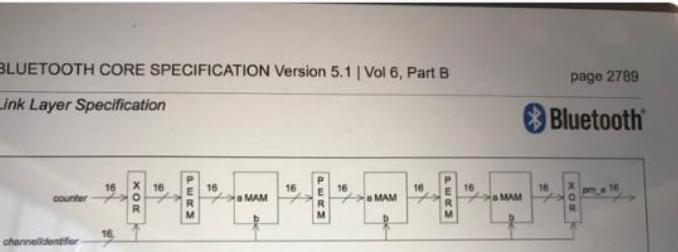


Figure 4.36: Event pseudo-random number generation

unmappedChannel is then calculated as pm_e modulo 37. A block diagram of the overall process is shown in Figure 4.37.

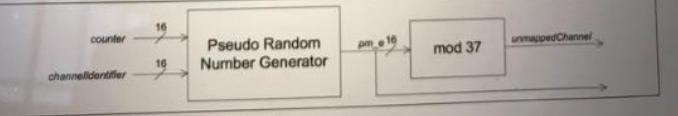


Figure 4.37: Unmapped channel selection process

9:37 nachm. · 12. Feb. 2019 · [Twitter for iPhone](#)

Matthew Green
@matthew_d_green

This one too. Ugh.

BLUETOOTH CORE SPECIFICATION Version 5.1 | Vol 6, Part B page 2788

Link Layer Specification

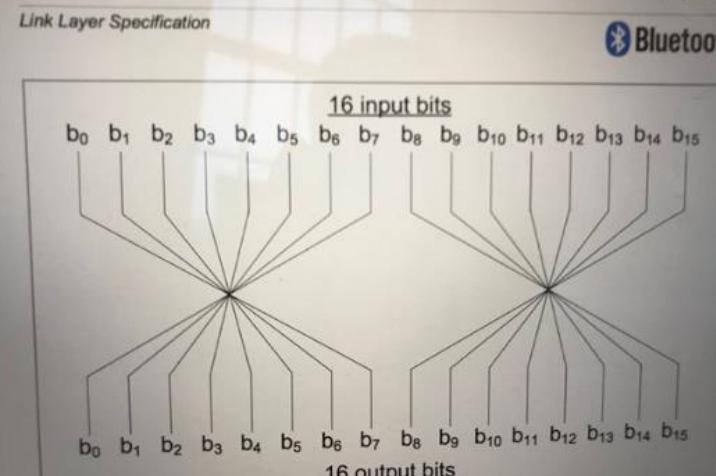


Figure 4.34: Permutation operation

9:50 nachm. · 12. Feb. 2019 · [Twitter for iPhone](#)

Easy, right?

Channel Selection Algorithm

- Channel = PRNG(Channel Identifier, Counter) mod 37
- Channel Identifier (16 bit)
 - Can be calculated from the Access Address (split in 2 and XOR)
- Counter (16 bit)
 - Periodically incremented by 1
- The counter can be guessed by measuring time difference between consecutive channels and some math™
- Knowing both, it's possible to follow the connection
- Used to improve coexistence, not security!
- Implemented in BtleJack version 2.0

BLE 5 Attacks

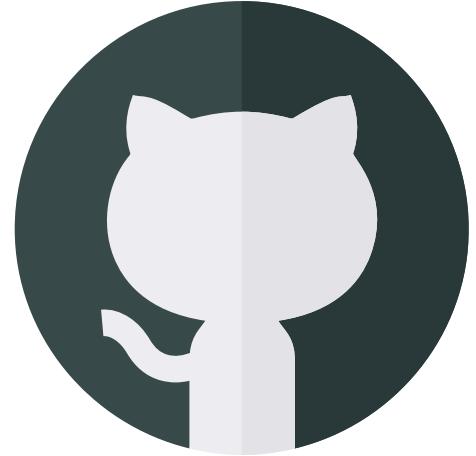
- No sniffing devices for the new physical layers at the moment
- Sniffing new connections is possible
- Sniffing existing connections is possible
- Jamming existing connections is possible
- Hijacking existing connections is theoretically possible
 - Not implemented in BtleJack at the moment because the attack is time-sensitive

References

Resources @ <https://github.com/CompassSecurity>



The screenshot shows a GitHub repository page for 'Bluetooth_Low_Energy_BLE_Beertalk'. The page includes a search bar, navigation links for Pull requests, Issues, Marketplace, and Explore, and a main content area with a 'Code' tab selected. It displays 6 commits, 1 branch, and a single commit from 'mindfuckup' adding a logo. The repository has no description, website, or topics provided. A large watermark reading 'git.io/BLE' is overlaid on the page. At the bottom, there is a blue call-to-action button with white text that says 'Check out the GitHub repository!'. On the left side of the page, there is a snippet of a presentation slide titled 'Bluetooth Low Energy BLE Beertalk' with the subtitle 'Protocol, Security & Attacks'.



- Slides (full version!)
- Links to demo videos
- Links to this Beer-Talk video
- Links to software / hardware
- Example PCAPs
- Links to further resources



