# Lecture 05
# BLE Connections

CS397/497 – Wireless Protocols for IoT

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Materials in collaboration
with Pat Pannuto (UCSD)

# Today’s Goals

- Explore how connections work
  - What does the link layer look like?
  - How do higher layers interact to share data?
- Investigate network questions about connections
- Overview of additions in BLE 5.0

# Useful documentation

- [5.2 specification] [4.2 specification] (link to PDF download)

- https://www.novelbits.io/deep-dive-ble-packets-events/

- Thinking about BLE connection data transfer rates
  1. https://punchthrough.com/maximizing-ble-throughput-on-ios-and-android/
  2. https://punchthrough.com/maximizing-ble-throughput-part-2-use-larger-att-mtu-2/
  3. https://punchthrough.com/maximizing-ble-throughput-part-3-data-length-extension-dle-2/

# Outline

- **Connection PHY and Link Layer**
- Connection Investigations
- GATT
- BLE 5

# Overview of connections

- Connections are for bi-directional communication with higher throughput than advertisements

- Simple view
  - A peripheral is either advertising or in a connection
  - A central is scanning and in one or more connections
  - (Remember: actually false, devices can have many roles simultaneously)

- While in a connection both devices act like servers
  - Either device can read/write fields available on the other device

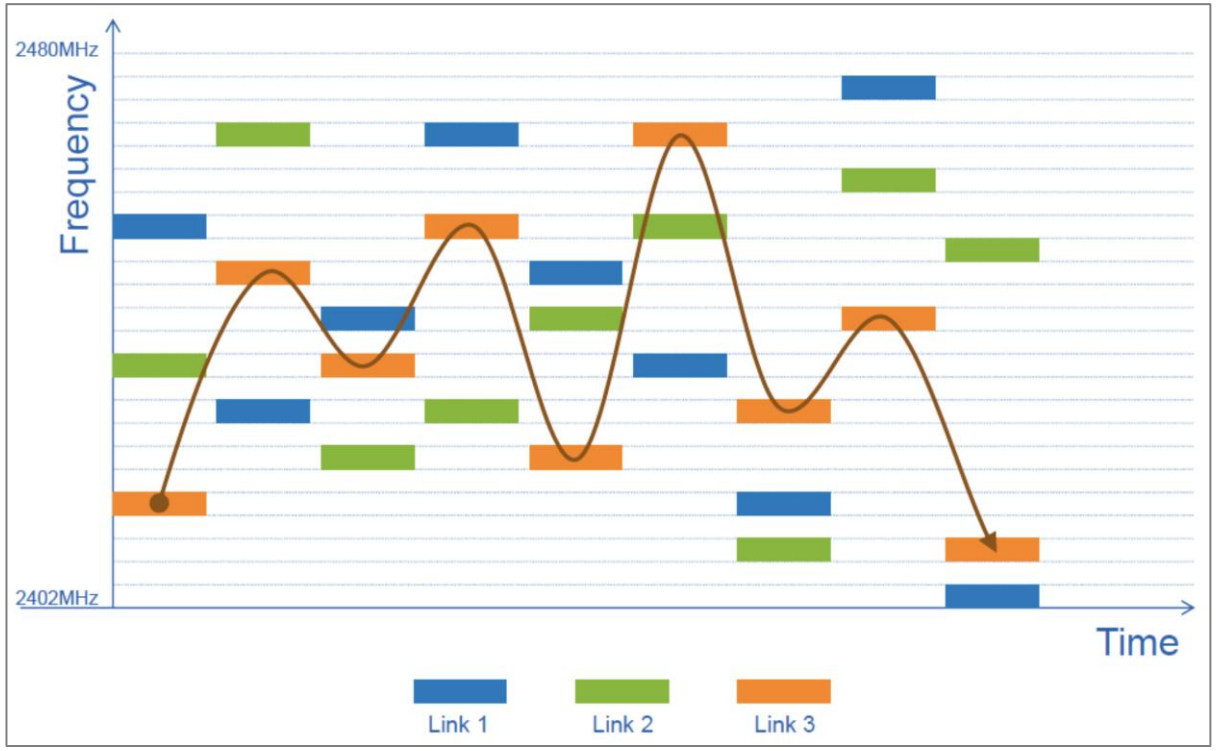
# Once a connection is established, BLE has more PHY options

- LE 1M (default)
  - 1 Msym/s (BLE encodes 1 bit / symbol, so this is also 1 Mbit/s)
- LE 2M
  - 2 Msym/s
- LE Coded
  - 1 Msym/s + FEC
    - S = 2, ~2x range, ½ effective data rate – 500 Kbit/s **goodput**
    - S = 8, ~4x range, 125 Kbits/s **goodput**

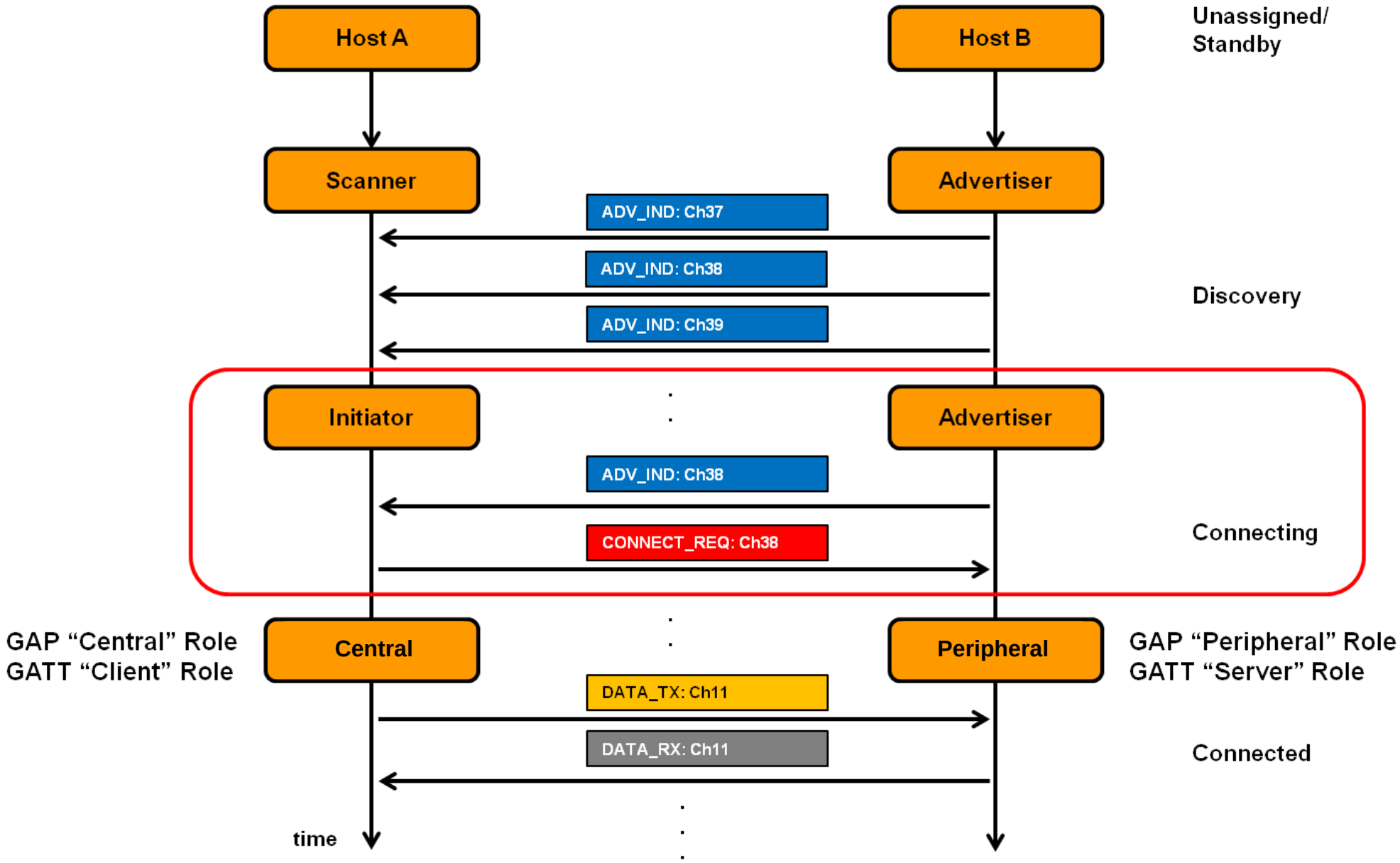
# Frequency Hopping Spread Spectrum (FHSS)

- Recall: Each BLE channel is 2 MHz wide, 40 channels,
  - 3 are used for advertising, remaining 37 are for connections
  - Frequency hopping: $f_{n+1} = (f_n + \text{hop}) \bmod 37$

- Which exact channels are used and in what order might vary
  - "Adaptive Frequency Hopping" avoids bad channels



# Connection timeline (in picture form)



# Connection timeline

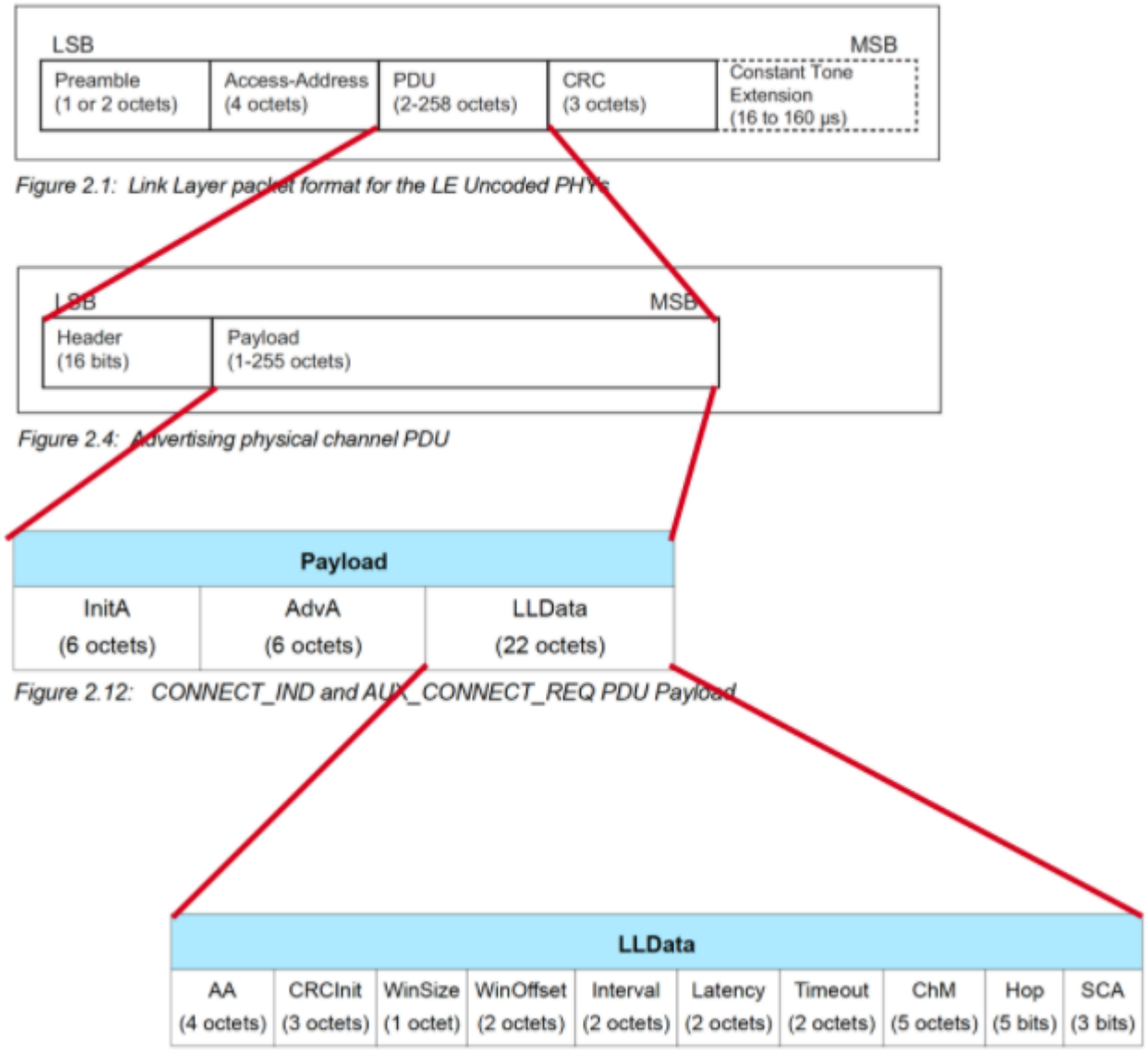
- Initiating a connection
  - Peripheral is sending broadcast advertisements
  - Central is scanning and receives an advertisement
  - Central sends connection request

- During a connection
  - Central sends a packet each “connection interval”
  - Peripheral immediately responds with a packet
  - Multiple packets may be exchanged this way until done
  - Repeat at next connection interval

- Ending a connection
  - Either device sends termination packet
  - Timeout occurs on either device

# Connection request packet

- Scanner waits until it sees an advertisement from a device it wants to connect to
  - Requesting a connection (in higher layers) just starts this search process
- Sends connection request payload in response to advertisement



# Request parameters

| LLData | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| AA (4 octets) | CRCInit (3 octets) | WinSize (1 octet) | WinOffset (2 octets) | Interval (2 octets) | Latency (2 octets) | Timeout (2 octets) | ChM (5 octets) | Hop (5 bits) | SCA (3 bits) |

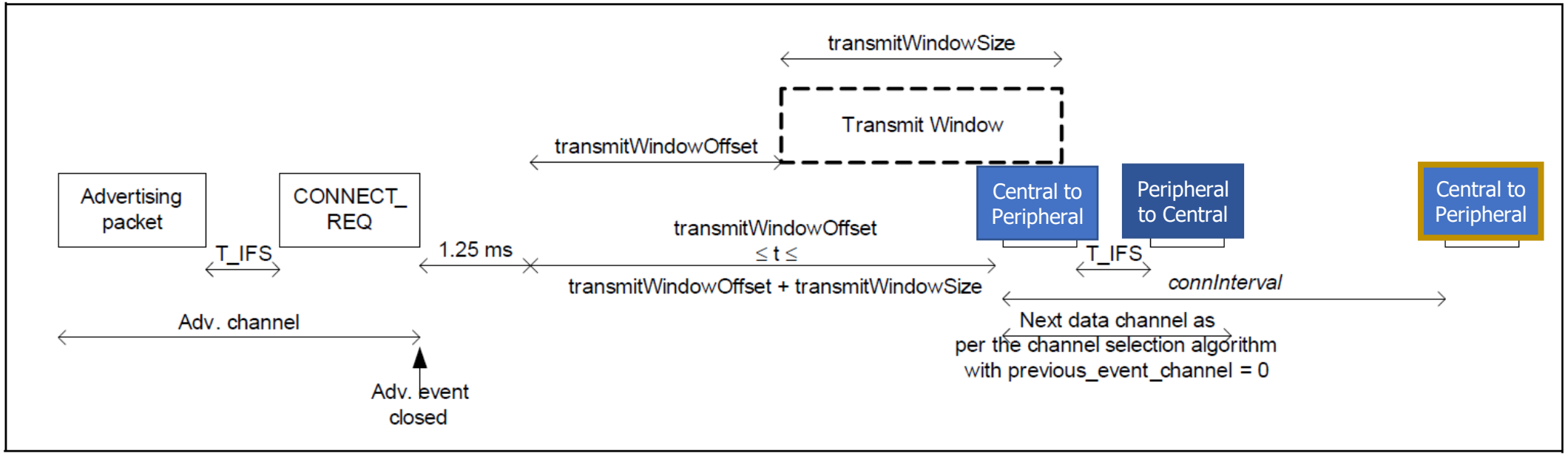
- Specifies parameters of the connection
  - Peripheral must either agree or totally reject the connection
  - Peripheral can later propose a change to the connection parameters

- Interval is how frequently connection events occur (7.5ms – 4s)
- Timeout is how long since hearing from a device before the connection breaks

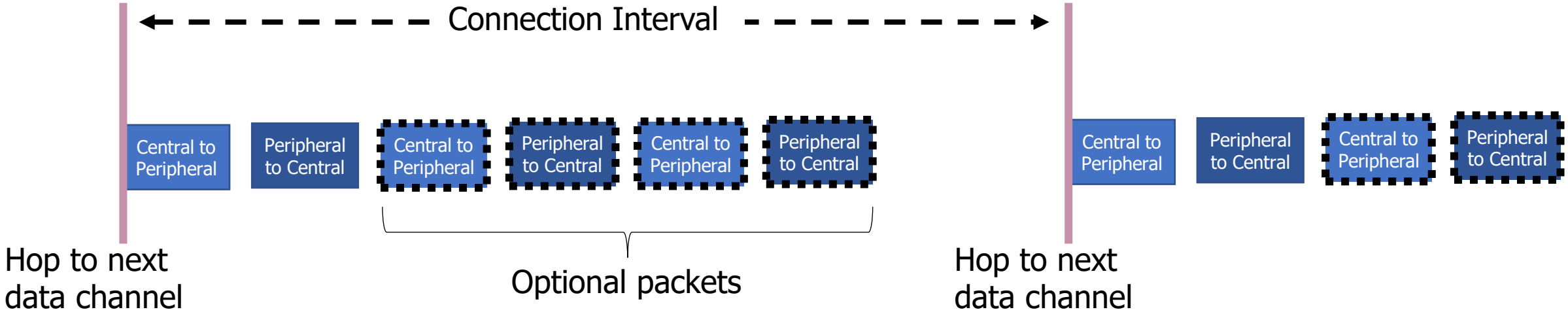
- Channel Map and Hop have to do with FHSS pattern

# The Central schedules the first connection event

- WinSize and WinOffset specify start of the first connection event
  - Places an "anchor" point that defines the TDMA schedule for this device
  - Interval specifies duration between connection events starting at "anchor"
  - Allows Central to place this connection, avoiding others it has
    - Before first response from peripheral, timeouts are faster



# Steady-state connection timing




- Some data can be exchanged at each interval
  - Might just be acknowledgements
  - Additional packets can be sent if there is a lot to transmit
  - Each interval is on the next channel in the hopping sequence

- Peripheral can skip a number of intervals to save energy
  - Defined by the Latency connection request parameter

# Connection packet layering

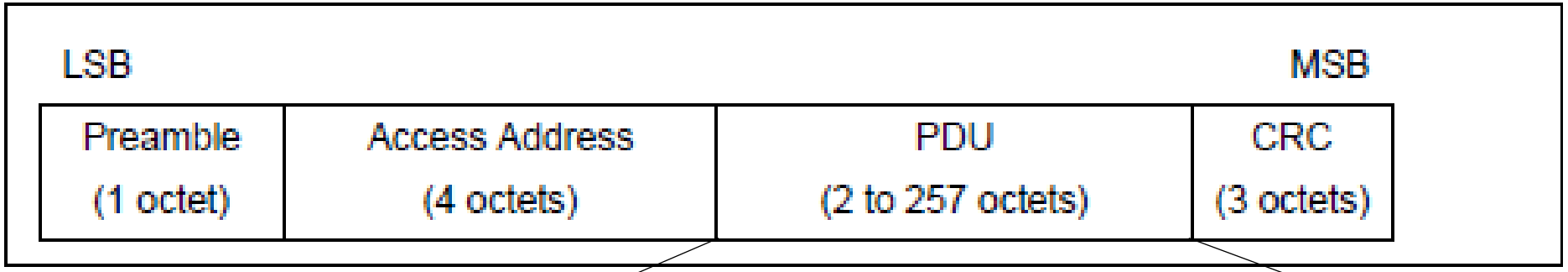



*Figure 2.1: Link Layer packet format*

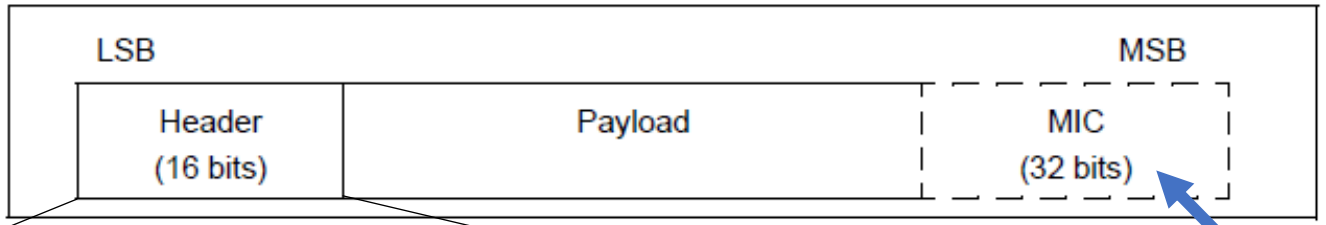



*Figure 2.12: Data Channel PDU*

Optional authentication

LLID – link layer ID
- Empty data / Fragment
- Data
- Control

MD – more data (continues connection event)

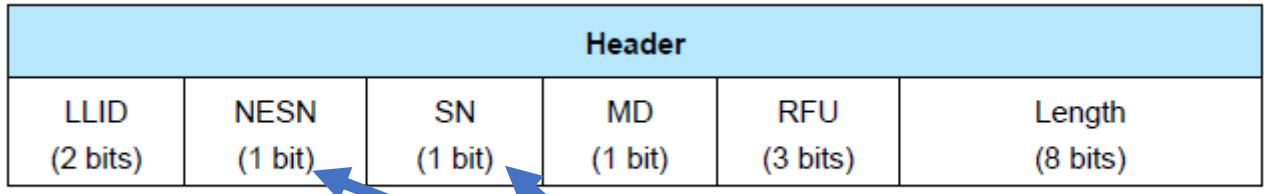
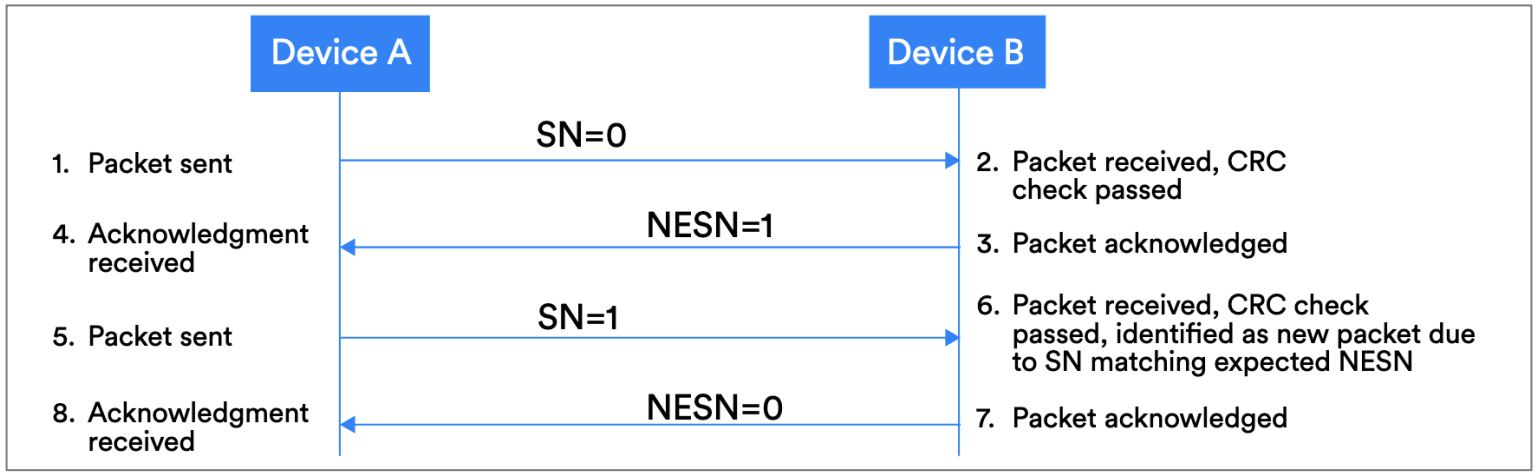
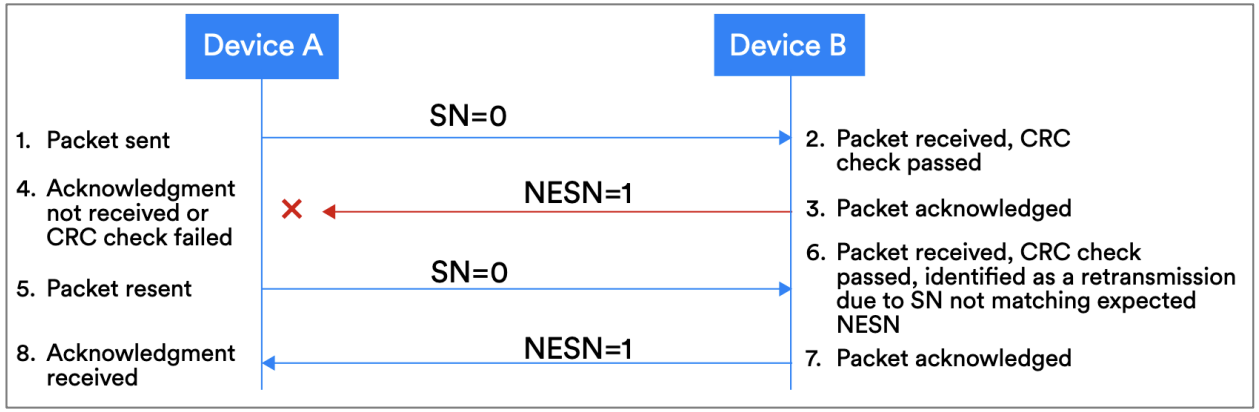


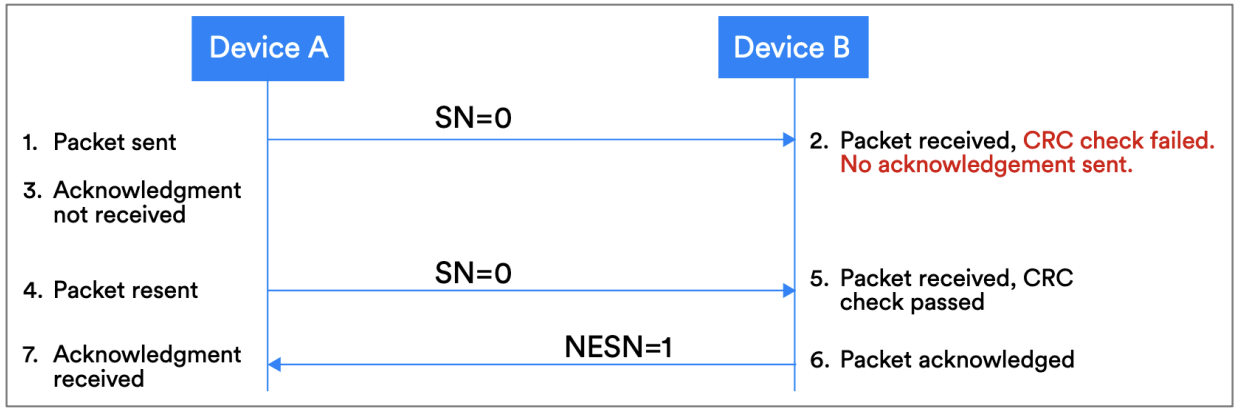

*Figure 2.13: Data channel PDU header*

[Next Expected] Sequence Number – acknowledgements

# Acknowledgement protocol




See §4.2.3 of Reliability Doc for more

# Control payloads

Examples:

- Request update to connection parameters like interval (by peripheral)
- Begin encrypting communication
- Terminate a connection

| Opcode | Control PDU Name |
|---|---|
| 0x00 | LL_CONNECTION_UPDATE_REQ |
| 0x01 | LL_CHANNEL_MAP_REQ |
| 0x02 | LL_TERMINATE_IND |
| 0x03 | LL_ENC_REQ |
| 0x04 | LL_ENC_RSP |
| 0x05 | LL_START_ENC_REQ |
| 0x06 | LL_START_ENC_RSP |
| 0x07 | LL_UNKNOWN_RSP |
| 0x08 | LL_FEATURE_REQ |
| 0x09 | LL_FEATURE_RSP |
| 0x0A | LL_PAUSE_ENC_REQ |
| 0x0B | LL_PAUSE_ENC_RSP |
| 0x0C | LL_VERSION_IND |
| 0x0D | LL_REJECT_IND |
| 0x0E | LL_SLAVE_FEATURE_REQ |
| 0x0F | LL_CONNECTION_PARAM_REQ |
| 0x10 | LL_CONNECTION_PARAM_RSP |
| 0x11 | LL_REJECT_IND_EXT |
| 0x12 | LL_PING_REQ |
| 0x13 | LL_PING_RSP |
| 0x14 | LL_LENGTH_REQ |
| 0x15 | LL_LENGTH_RSP |

# Data payloads

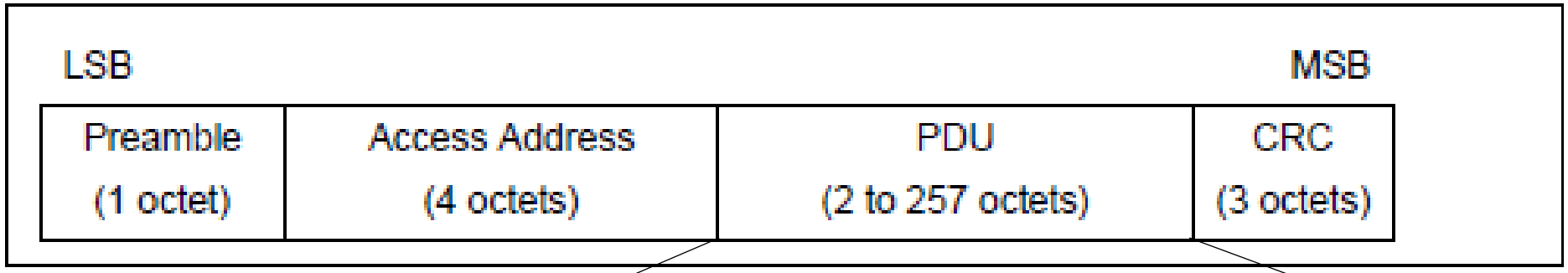



*Figure 2.1: Link Layer packet format*

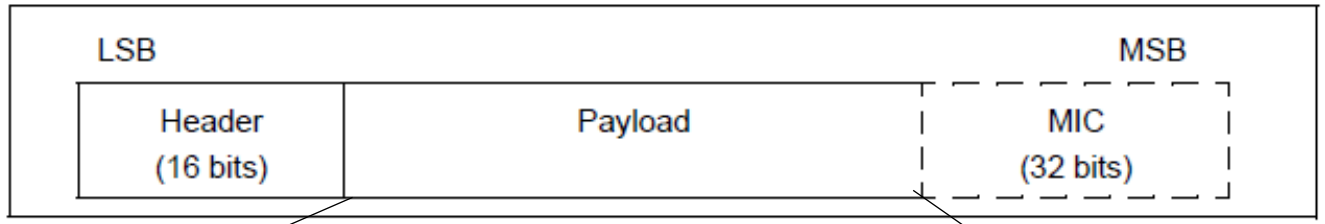



*Figure 2.12: Data Channel PDU*

SDU – Service Data Unit

- Logical packet that may be split into several physical packets

Channel ID

- Destination for data
- ATTributes or Security
- Can also make custom endpoints

| Length (16 bits) | Channel ID (16 bits) | L2CAP SDU Length* (16 bits) | Information Payload (0 to 249 octets) |
|---|---|---|---|

# Next steps in a connection

- Control packets
  - Version
    - Bluetooth version, Company ID of Software Stack
  - Features
    - Various connection features supported by the device
    - Encryption, Ping, Channel selection algorithms, Various 5.0 features
  - Etc.
    - Extended packet length, Various 5.0 features (change PHY)
    - Various “procedures” for setting up changes in the connection

- Data packets
  - Attribute discovery
  - Attribute reading

# Very briefly: security in connections

Either side can request secure connection [central -> Pairing; peripheral -> Security Req]


Pairing Request Command Format


Pairing Response Command Format


Peripheral Security Request Command Format

| Association Models | Conditions for Use |
|---|---|
| Just Works | This model is used when there is no Out of Band (OOB) data available and neither device has input capabilities. |
| Passkey Entry | This model is used when there is no OOB data available, at least one device has the I/O capability to enter a passkey, and the other device has the capability to display a passkey. |
| Numeric Comparison | This model is used if both devices support Secure Connections, can display a yes or no message and have some input capability. |
| Out of Band | If OOB data is available on either device, this model will be chosen. |

"Bonding" saves pairing info between connections

- Excellent TI resource here for more details: https://dev.ti.com/tirex/explore/node?node=AOPOY.GDApakIOYjiwoY6A__pTTHBmu__LATEST

# Very briefly: security in addresses

- All devices have a unique, hardware "Identity Address", but may not share it
  - **Public Address** - Use the Identity Address. (The BDA never changes.)
  - **Random Static Address** - Generate a random address per power cycle. The address cannot be regenerated at any other time. Can be used as an Identity Address.
  - **Resolvable Private Address (RPA)** - Generate a random address with a given time interval. Generated using Identity Resolving Key (IRK) which can also be used by trusted peers (bonded devices) to resolve the Random Address to the Identity Address.
  - **Non-resolvable Private Address** - Generate a random address with a given time interval. Generated randomly. Cannot be resolved to an Identity Address.

# Ending connections

- Termination control packet

- Timeout parameter from connection parameters
  - Human-based devices may just wander away from each other
  - Or be shut off, or reprogrammed, etc.

# Break + Check your understanding

- What makes connections more reliable than advertisements?

- How does a Peripheral send data to a Central in a connection?

- Why is a “termination” control packet useful?

# Break + Check your understanding

- What makes connections more reliable than advertisements?
  - Each packet sent is acknowledged or resent
  - TDMA schedule and FHSS means less likely to collide

- How does a Peripheral send data to a Central in a connection?
  - Wait until next connection interval
  - Respond to packet from Central with a data payload

- Why is a “termination” control packet useful?
  - Timeout could delay for a while
  - Enables re-connection if desired

# Outline

- Connection PHY and Link Layer
- **Connection Investigations**
- GATT

- BLE 5

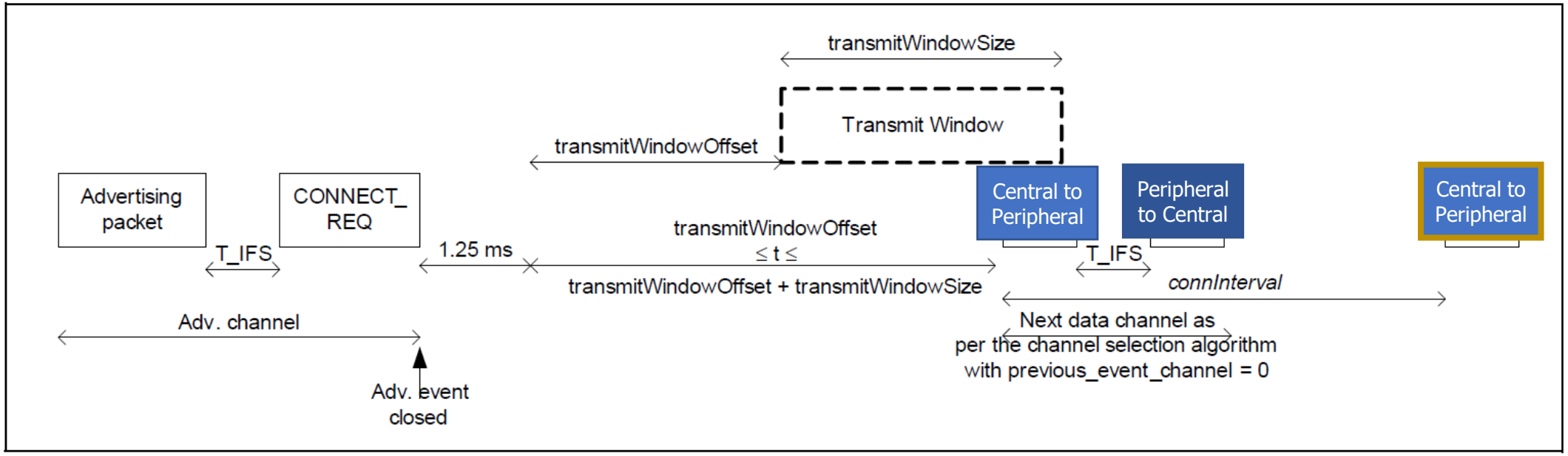
# Questions about how a connection “network” works

- How does TDMA MAC for connections work?
  - Implies a schedule
  - Implies synchronization
- How many devices can be in a network?
- How much throughput can a device have?

# How is the TDMA schedule created/managed?

- Only the central needs to know the schedule
  - It controls interactions with the peripheral(s) it is connected to

- Anchor point and connection interval determines the schedule for a specific device



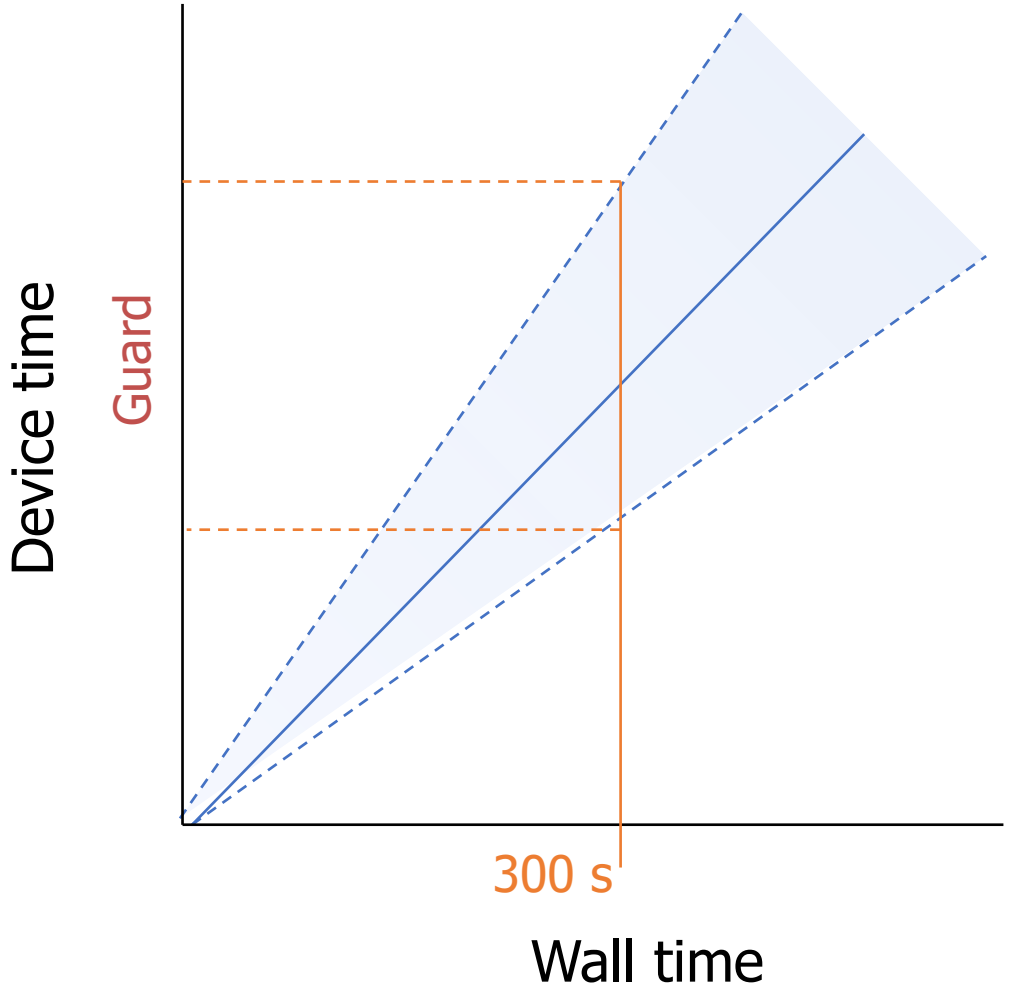
# How is synchronization managed?

- Central sends first packet at each connection interval
  - So peripheral must be synchronized to central
  - Resynchronization can occur on each received packet

- Specification describes how a peripheral must widen its listening window based on "Source Clock Accuracy"

$$windowWidening = \left(\frac{centralSCA + peripheralSCA}{1000000}\right) * timeSinceLastAnchor$$

# Clock drift is an energy burden due to large guard bands and energy cost of precise timekeeping




1200 µs
@ 2ppm

Static Power:
100 nW+

**CC2520 Radio + AM18xx RTC:**

300s * 2ppm * 2 = 1.2 ms guard
1.2 ms * 60 mW = 36 µJ (RF loss)
300s * 150nW = 45 µJ (RTC loss)
≈ 100 µJ loss / packet @ 300 s

**(CC2520 is a 15.4 radio, but same idea applies)**

Max connection interval in BLE is 4 seconds

# How many devices can be connected?

- We can schedule with granularity of *at least* 1.25 ms (offset steps)
  - That's at least 800 devices per second
- Intervals go up to 4 seconds, so multiply by four
  - That's 3200 devices per max interval
- Plus central can skip intervals on occasion without dropping the connection
  - And really the offset defines a window. More granularity is available
- Answer: thousands of devices
  - Although each is sending minimum-sized packets each interval

# How many devices can be connected in the real world?

- The limit is much much lower on real devices
  - Example: Android sets a limit at around 4-15
  - nRF52 s140 softdevice allows up to 20

- Connection management is often done in firmware
  - Softdevice for nRF, firmware on the radio chip in smartphones

- Limited by memory and complexity

# How much throughput can a device have?

- **1 Mbps?**

# How much throughput can a device have?

- **1 Mbps?** Not even close. Packet overhead plus timing delays

- Step 1: decrease connection interval as much as possible
  - More connection events per second mean more data
  - Range: 7.5 ms to 4.0 s
  - Somewhat device-specific configuration
    - Android allows 7.5 ms
    - iOS allows 15 ms

# How much throughput can a device have?

- Step 2, increase packet size

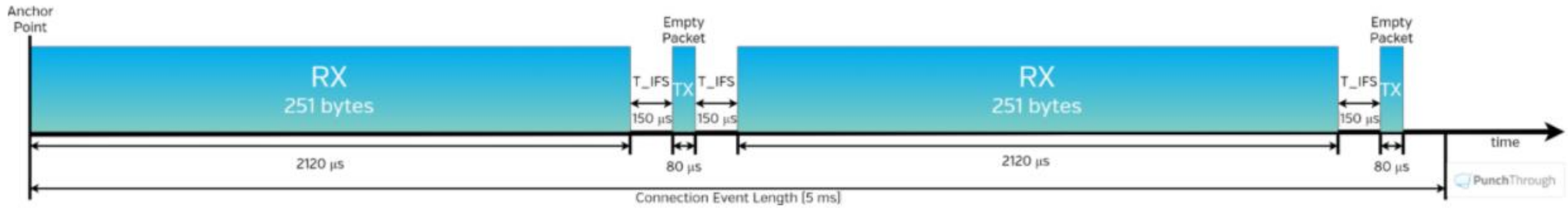



Figure 5 – A single connection event (from the slave's perspective) in a DLE-enabled connection in which the master is transmitting as much data as possible within the effective Connection Event Length

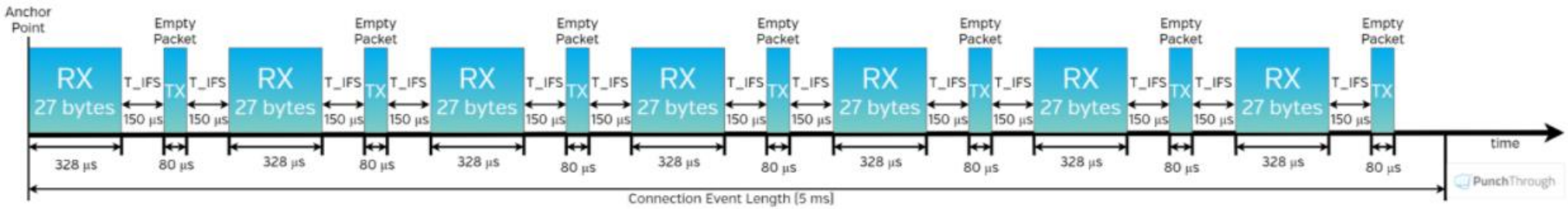



Figure 6 – A single connection event (from the slave's perspective) in a connection without DLE, in which the master is transmitting as much data as possible within the effective Connection Event Length

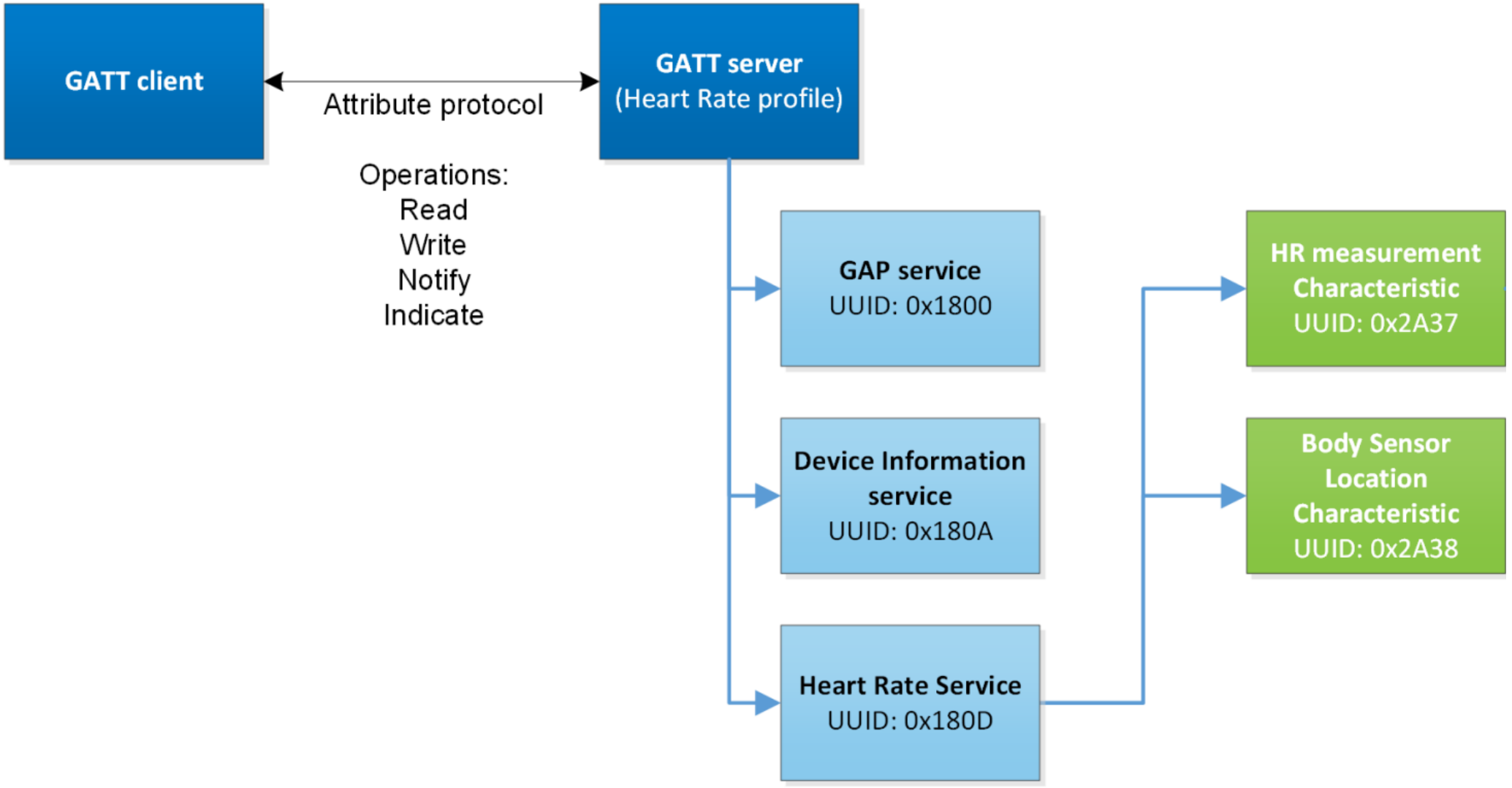
# How much throughput can a device have?

- 488 bytes per connection event
  - Maximum sized packets, discounting headers and timing delays
- Connection event every 7.5 ms
- Result: 520 kbps (65 kB per second)
  - iOS result 260 kbps
  - Original BLE 4.1 result on Android: 128 kbps
  - Lower in practice due to lost packets

# Outline

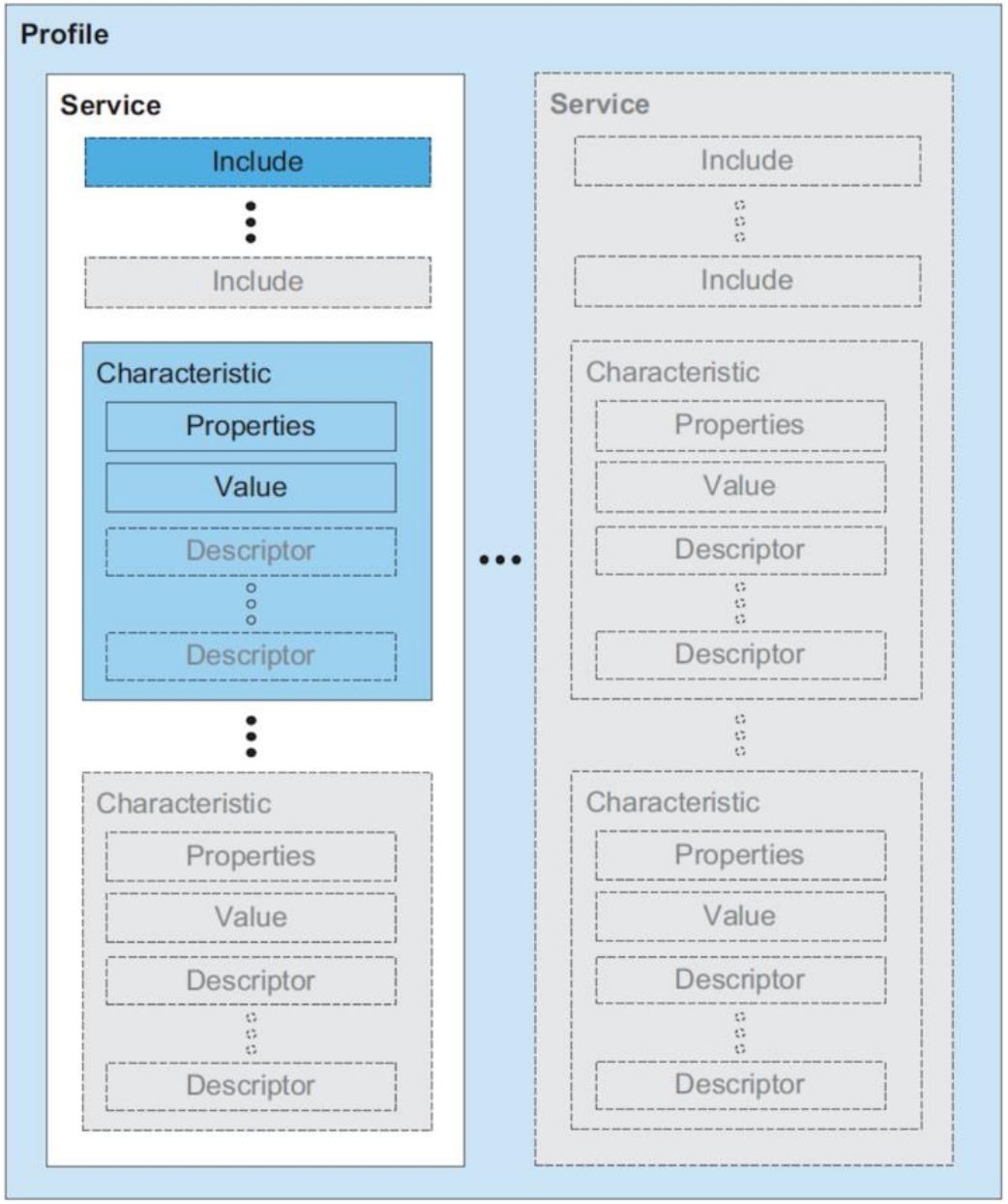
- Connection PHY and Link Layer
- Connection Investigations
- **GATT**
- BLE 5

# Overview of Generic Attribute Profile (GATT)

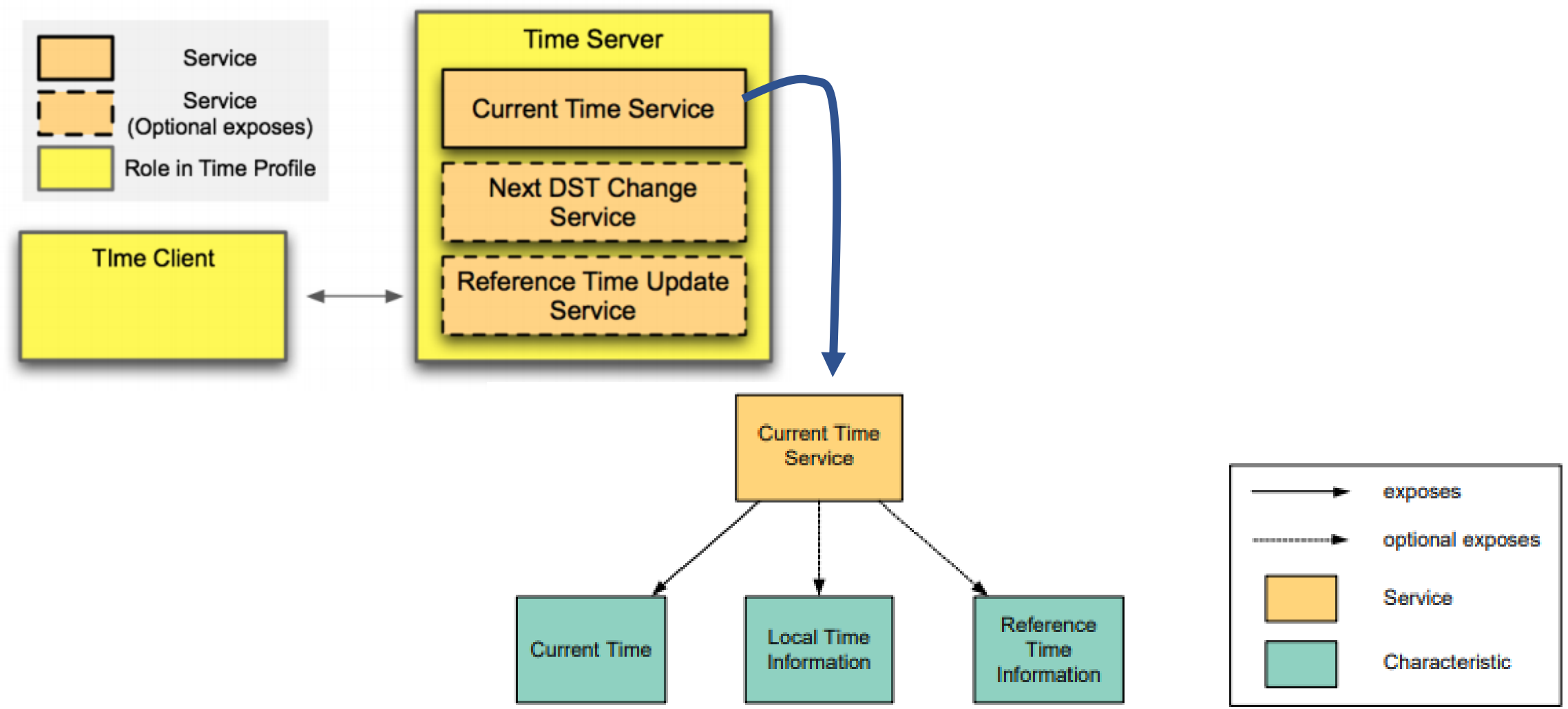


# Attribute server keywords

- Characteristic
  - A field with properties and a value
  - Descriptor: metadata about the characteristic
- Service
  - Collection of characteristics
- Profile
  - Collection of services



# Example: Time Profile



# Current time characteristic

| Field | Data Type | Size (in octets) | Description |
|---|---|---|---|
| Exact Time 256 | struct | 9 | Refer to the Exact Time 256 characteristic in Section 3.64 |
| Adjust Reason | uint8 | 1 | See Section 3.58.2.1 |

| Bit | Bit Name |
|---|---|
| 0 | Manual Time Update |
| 1 | External Reference Time Update |
| 2 | Change of Time Zone |
| 3 | Change of DST |
| 4–7 | Reserved for Future Use |

| Field | Data Type | Size (in octets) | Description |
|---|---|---|---|
| Day Date Time | struct | 8 | Refer to the Day Date Time characteristic in Section 3.54. |
| Fractions256 | uint8 | 1 | The number of 1/256 fractions of a second. Valid range 0–255. |

| Field | Data Type | Size (in octets) | Description |
|---|---|---|---|
| Date Time | struct | 7 | Refer to the Date Time characteristic in Section 3.53 |
| Day of Week | struct | 1 | Refer to the Day of Week characteristic in Section 3.55 |

| Field | Data Type | Size (in octets) | Description |
|---|---|---|---|
| Year | uint16 | 2 | Year as defined by the Gregorian calendar. Valid range 1582 to 9999. A value of 0 means that the year is not known. All other values are reserved for future use (RFU). |
| Month | uint8 | 1 | Month of the year as defined by the Gregorian calendar. Valid range 1 (January) |

The Bluetooth SIG are pedantic people

# Documentation of GATT standards

- https://www.bluetooth.com/specifications/gatt/
  - Various profiles and services that have been standardized

- GATT Specification Supplement
  - Various characteristic definitions that have been standardized

- Both incredibly specific and woefully inexhaustive

# UUIDs and handles

- Universally Unique Identifiers
  - 128-bit, mostly random with a few bits for versioning
  - Example: 00000000-0000-1000-8000-00805F9B34FB
    - This is the default BLE UUID for *known* services
    - You can generate your own UUID for custom services

- Handles
  - Too long to pass around all the time, so pick 16 bits that mean that UUID
    - Must be unique among services/characteristics on that device
  - Taken from UUID: 0000**xxxx**-0000-1000-8000-00805F9B34FB
  - Handle often sequentially incremented for each new characteristic within a service

*Resource: Useful post on identifying handles in the wild*

# Discovery

- When a connection first occurs, each device can query the other for a list of services
  - And can further query for a list of characteristics in that service
  - Gets a list of handles/UUIDs

- Standardized UUIDs can be interpreted immediately
  - Custom services/characteristics need documentation from the manufacturer

# Interacting with characteristics

- Depends on their permissions
  - Readable, Writable, Notify-able, etc.

- Notify
  - Automatically get a message sent whenever the characteristic value updates
  - Note: have to enable this on both sides, it’s not the default behavior

- Long characteristics are automatically fragmented across multiple packets and/or connection events
  - L2CAP is in charge of this

# Break + Example Services

| Allocated UUID | Allocated for |
|---|---|
| 0x1803 | Link Loss |
| 0x1804 | Tx Power |
| 0x1805 | Current Time |
| 0x1806 | Reference Time Update |
| 0x1807 | Next DST Change |
| 0x1808 | Glucose |
| 0x1809 | Health Thermometer |
| 0x180A | Device Information |
| 0x180D | Heart Rate |
| 0x180E | Phone Alert Status |
| 0x180F | Battery |
| 0x1810 | Blood Pressure |
| 0x1811 | Alert Notification |
| 0x1812 | Human Interface Device |
| 0x1813 | Scan Parameters |
| 0x1814 | Running Speed and Cadence |
| 0x1815 | Automation IO |
| 0x1816 | Cycling Speed and Cadence |
| 0x1818 | Cycling Power |
| 0x1819 | Location and Navigation |
| 0x181A | Environmental Sensing |
| 0x181B | Body Composition |
| 0x181C | User Data |
| 0x181D | Weight Scale |
| 0x181E | Bond Management |
| 0x181F | Continuous Glucose Monitoring |
| 0x1820 | Internet Protocol Support |
| 0x1821 | Indoor Positioning |
| 0x1822 | Pulse Oximeter |
| 0x1823 | HTTP Proxy |
| 0x1824 | Transport Discovery |
| 0x1825 | Object Transfer |
| 0x1826 | Fitness Machine |

https://btprodspecificationrefs.blob.core.windows.net/assigned-values/16-bit%20UUID%20Numbers%20Document.pdf

# Outline

- Connection PHY and Link Layer
- Connection Investigations
- GATT

- **BLE 5**

# Changes in BLE 5

- Major changes
  - Multiple physical layers (optional implementation 😠)
  - Advertising extensions
  - Localization extensions (will discuss later with localization)

- Minor changes
  - Various quality of life improvements
  - Examples:
    - Advertise on channels in any order
    - Better data channel hopping algorithm

# Revised physical layers

- 2 Mbps PHY
  - Transmit data faster
  - Transmit more data in the same time

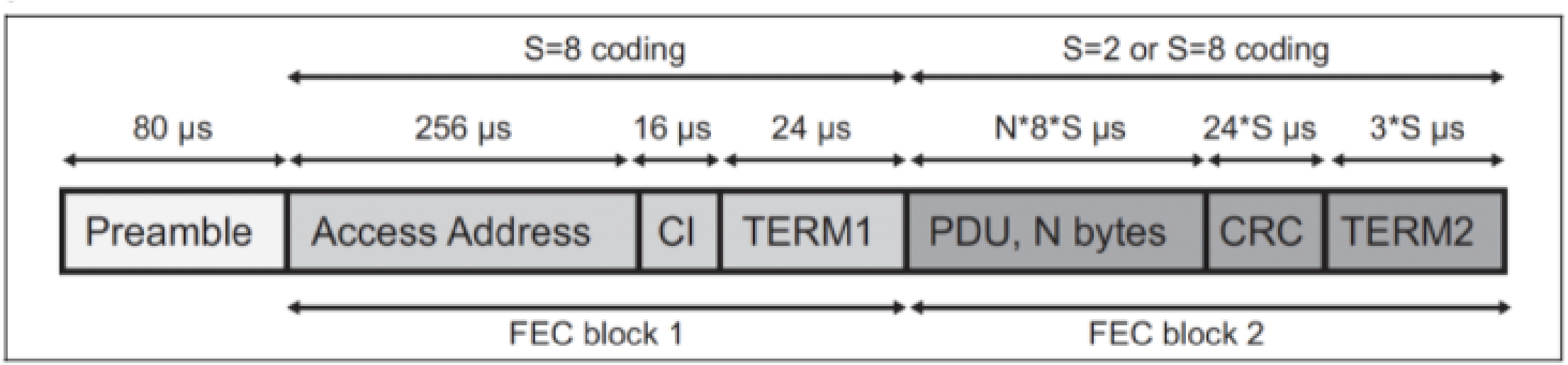
- Coded PHY
  - Forward Error Correction in the data stream
    - 1 bit -> 2 symbols or 8 symbols
  - Makes bits more reliable -> longer distance
  - 500 kbps and 125 kbps modes

- Connections can switch to these PHYs after creation
- Advertisements can use these with extensions only

# Coded PHY mixes physical and link layers

- Different PHY settings at different times
  - Make beginning headers extra-reliable
  - Data might be slightly less reliable as a trade for faster speed

## Packet sent with coded PHY



# Revised processing path

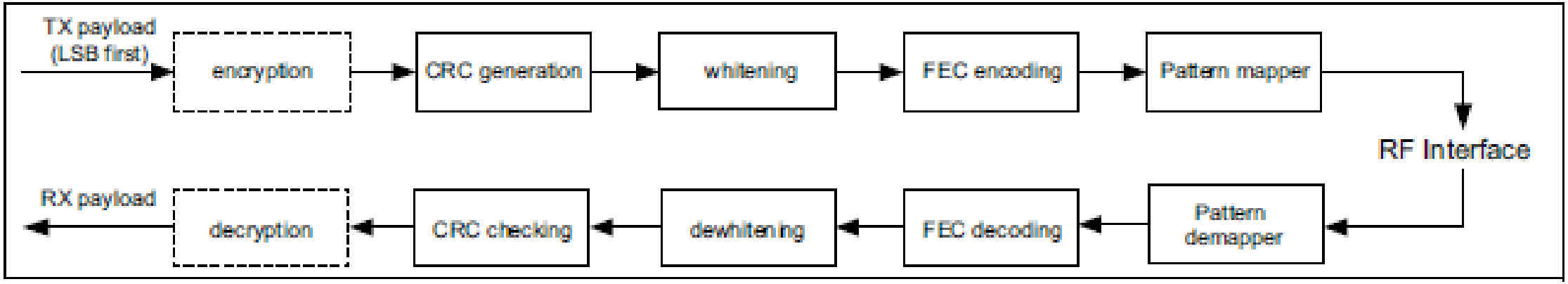
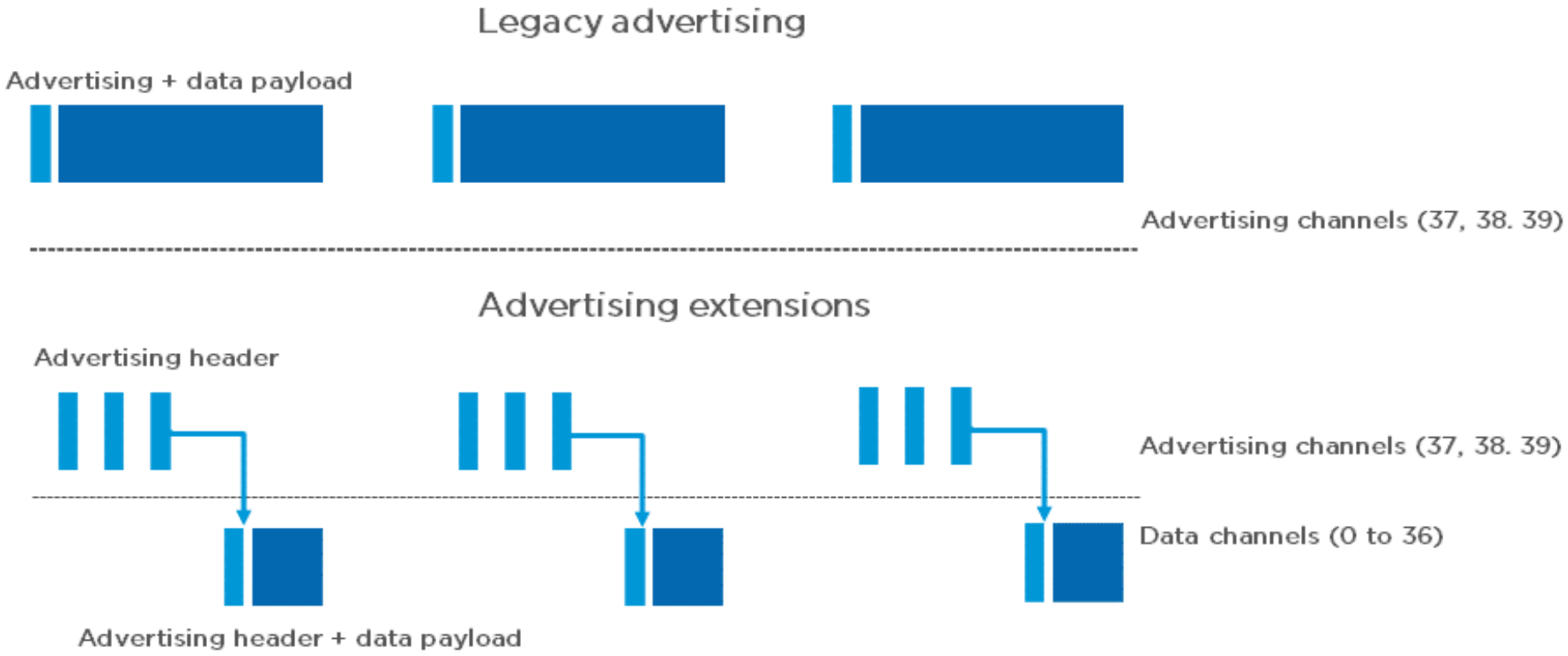



*Figure 3.2: Bit stream processing for the LE Coded PHYs*

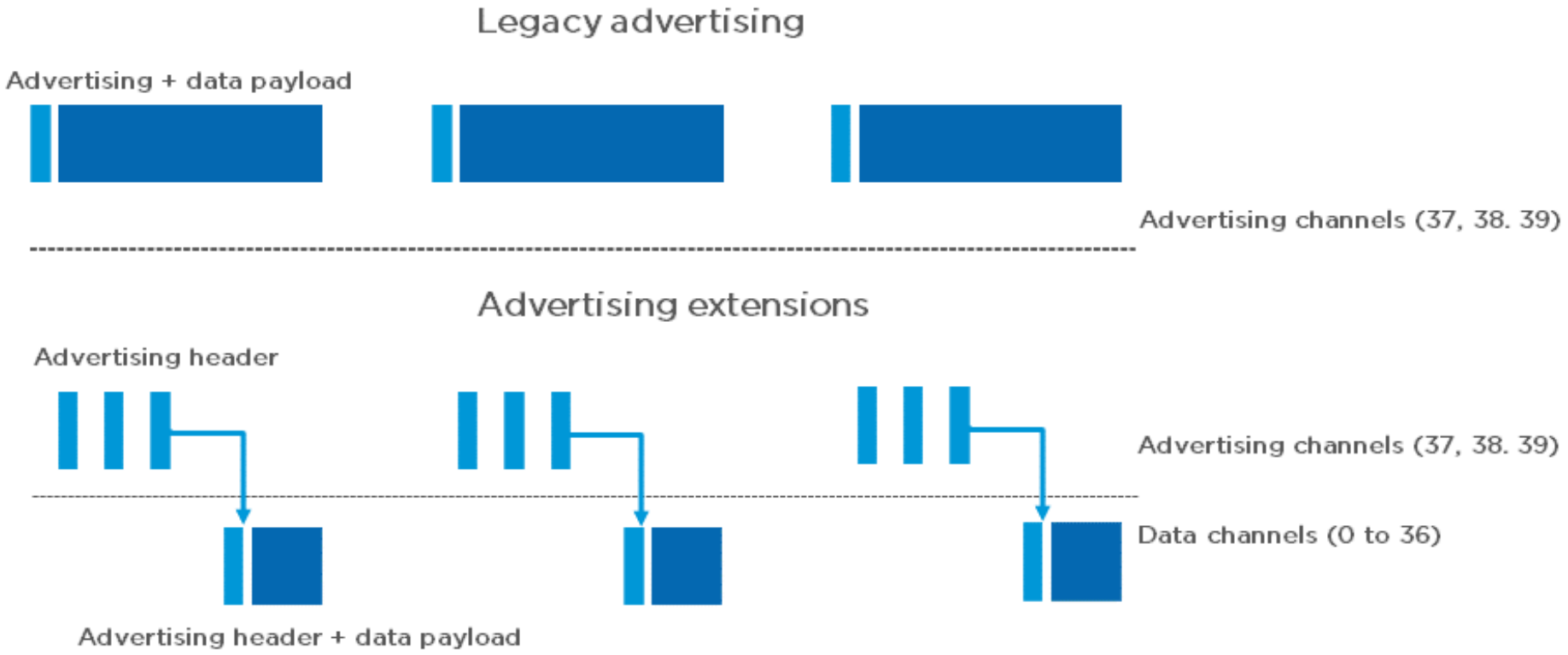
# Extended advertising

- Allow bigger payloads and/or different PHYs
  - Uses Data Channels to do so. **Why?**
  - Regular advertisements point to extended advertisements



# Extended advertising

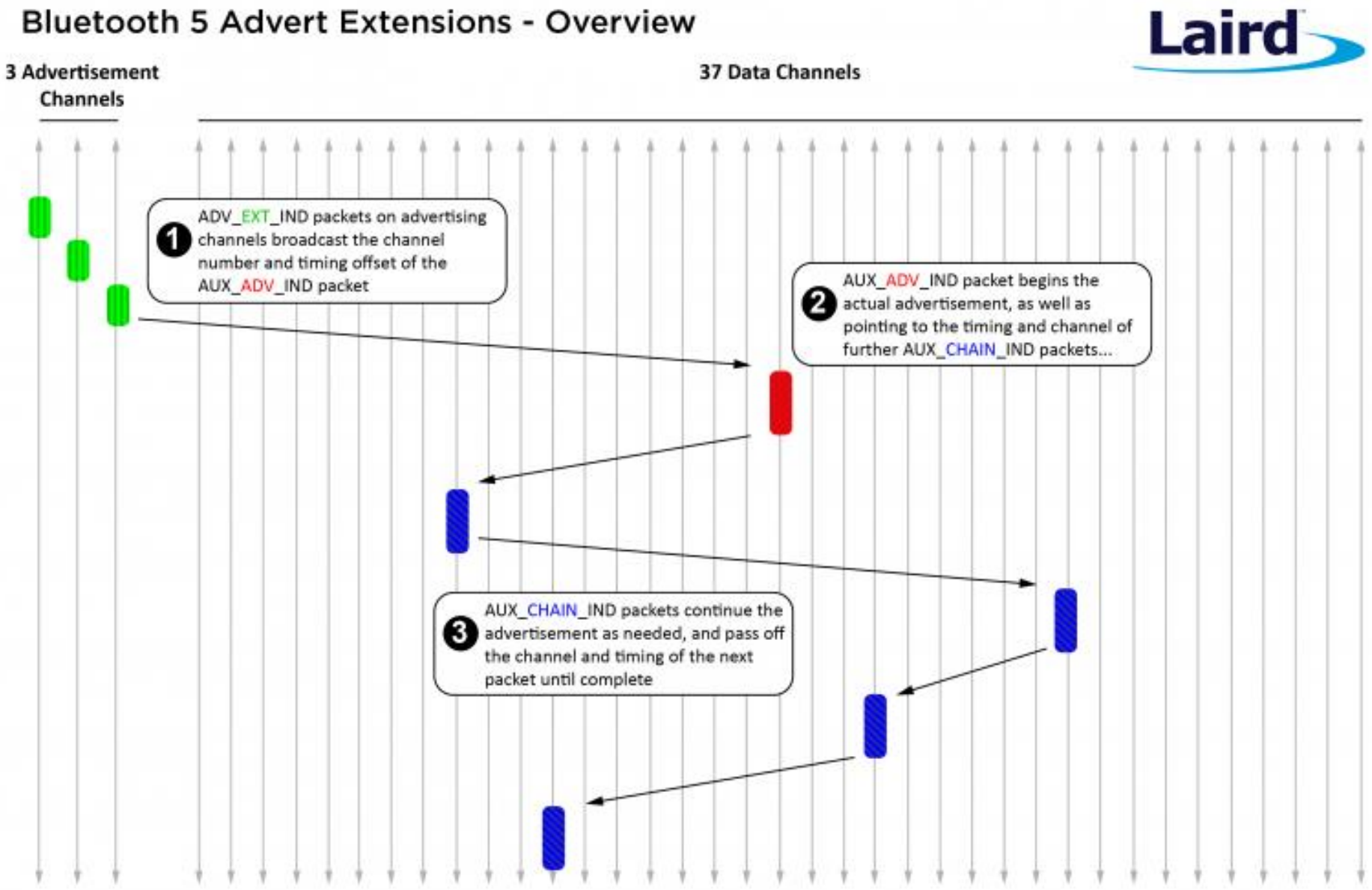
- Allow bigger payloads and/or different PHYs
  - Uses Data Channels to do so. **Why?** **Packet collisions!**
  - Regular advertisements point to extended advertisements



# Procedure for scanning extended advertisements

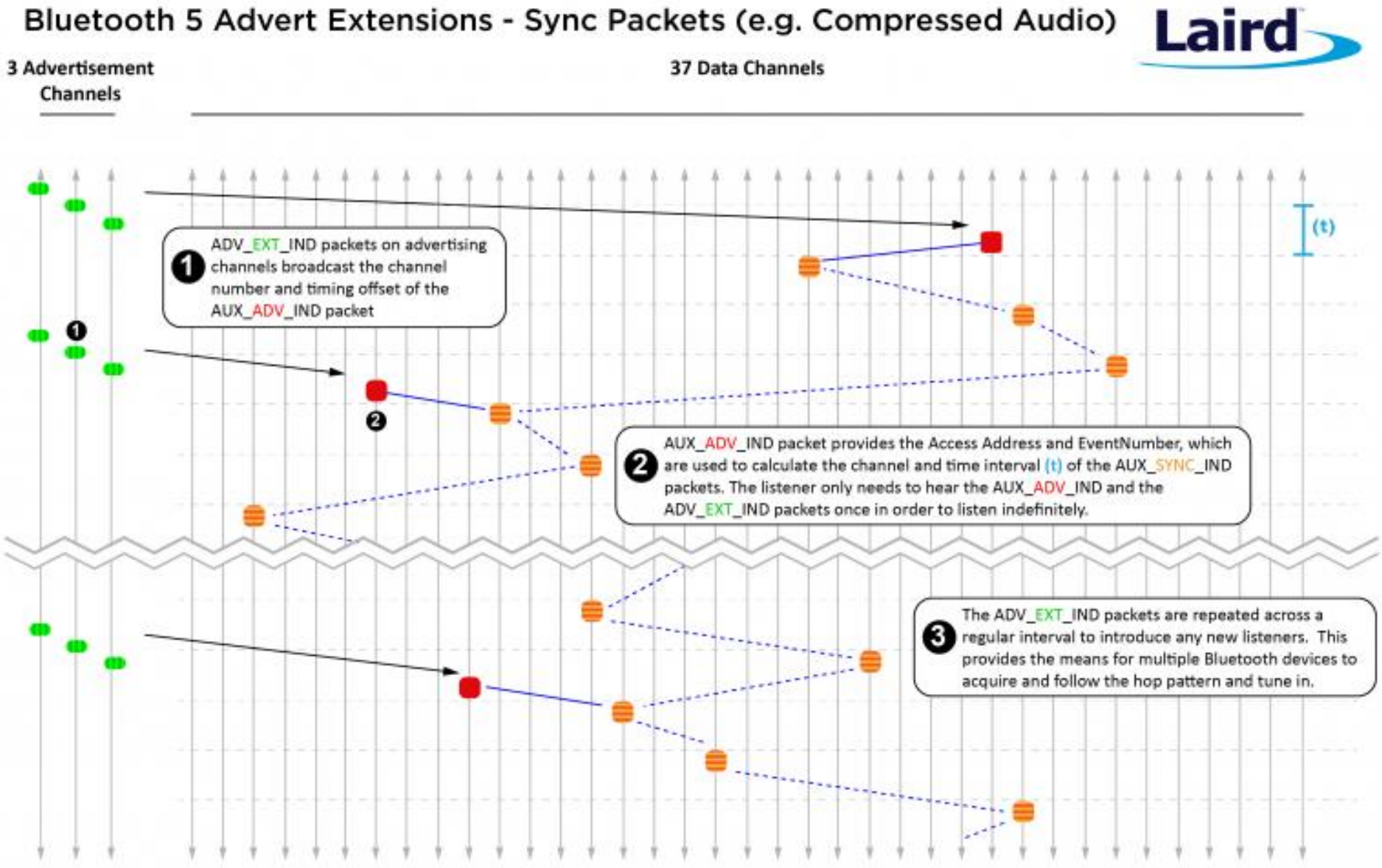
1. Scan on 3 primary channels for advertising packets.
2. If ADV_EXT_IND is scanned, record the secondary channel information (which channel and when etc.)
3. Scan the specific secondary channel at the given time.

# Extended advertisement train on data channels




Use case:
long advertisements that need to be fragmented

# Periodic advertising on data channels




Use case: publicly-available localized audio sources

- TV in a bar
- Commentary in a museum

Broadcast analogy of a connection

Downside:
how many of these can a gateway follow at a time?

# Outline

- Connection PHY and Link Layer
- Connection Investigations
- GATT

- BLE 5