실시간 통신과 IoT

(CC533)

경기대학교 컴퓨터과학과

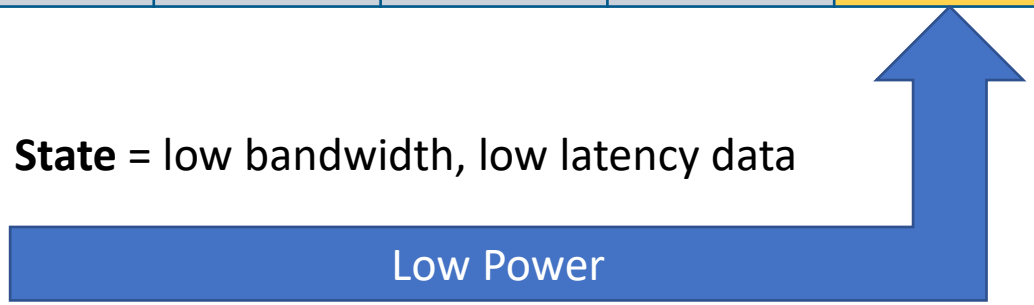
(Department of Computer Science)

Bluetooth 4.x: Low Energy

What is Bluetooth Low Energy?

Short Range Wireless Application Areas

	Voice	Data	Audio	Video	State
Bluetooth ACL/HS	X	Y	Y	X	X
Bluetooth SCO/eSCO	Y	X	X	X	X
Bluetooth low energy	X	X	X	X	Y
Wi-Fi	(VoIP)	Y	Y	Y	X
Wi-Fi Direct	Y	Y	Y	X	X
ZigBee	X	X	X	X	Y
ANT	X	X	X	X	Y



What is Bluetooth Low Energy?

- **Bluetooth Classic**
  - How much energy does traditional Bluetooth use?
    - Traditional Bluetooth is connection oriented
      - When a device is connected, a link is maintained, even if there is no data flowing.
    - Sniff modes (sleep)
      - Reducing power consumption to give months of battery life
    - Peak transmit current: 25mA
    - Not low enough power for coin cells
    - Range: < 100m (10m typical)
    - Reasonably fast data rate: 2.1 Mbps

What is Bluetooth Low Energy?

- **Bluetooth low energy is a NEW, open, short range radio technology**
  - Different to Bluetooth classic (BR/EDR)
  - Optimized for ultra low power
  - Enable coin cell battery use cases
    - < 20 mA peak current
    - < 5 uA average current

What is Bluetooth Low Energy?

- **In Short**
  - Wireless technology standard, designed from ground up
  - Simple and easy to use model
  - Small bursts of data
  - Impressive battery life
  - Low cost
  - Works on free 2.4 GHz band
  - Ideal for sensors / IoT
  - New advertising mechanism
    - For ease of discovery and connection
  - Connection-less MAC

Basic Concepts of Bluetooth Low Energy

- **Everything is optimized for lowest power consumption**
  - Short packets reduce TX peak current
  - Short packets reduce RX time
  - Less RF channels to improve discovery and connection time
  - Simple state machine
  - Single protocol

Basic Concepts of Bluetooth Low Energy

- **Everything has STATE**
  - Devices expose their state
  - There are servers
- **Clients can use the state exposed on servers**
  - Read it - get current temperature
  - Write it - increase set point temperature for room
- **Servers can tell clients when state updates**
  - Notify it - temperature up to set point

Basic Concepts of Bluetooth Low Energy

- **Client Server Architecture**
  - Proven architecture for web-infrastructure
- **Gateways: interconnect of internet & low energy**
  - Weighing scales send reports to doctor
  - Home security web site shows all windows closed
  - Assisted living for your parents allows low-cost monitoring
  - Sports data immediately uploaded via cellular phone

Bluetooth Low Energy Factsheet

Range:	~ 150 meters open field
Output Power:	~ 10 mW (10dBm)
Max Current:	~ 15 mA
Latency:	3 ms
Topology:	Star
Connections:	> 2 billion
Modulation:	GFSK @ 2.4 GHz
Robustness:	Adaptive Frequency Hopping, 24 bit CRC
Security:	128bit AES CCM
Sleep current:	~ 1µA
Modes:	Broadcast, Connection, Event Data Models, Reads, Writes

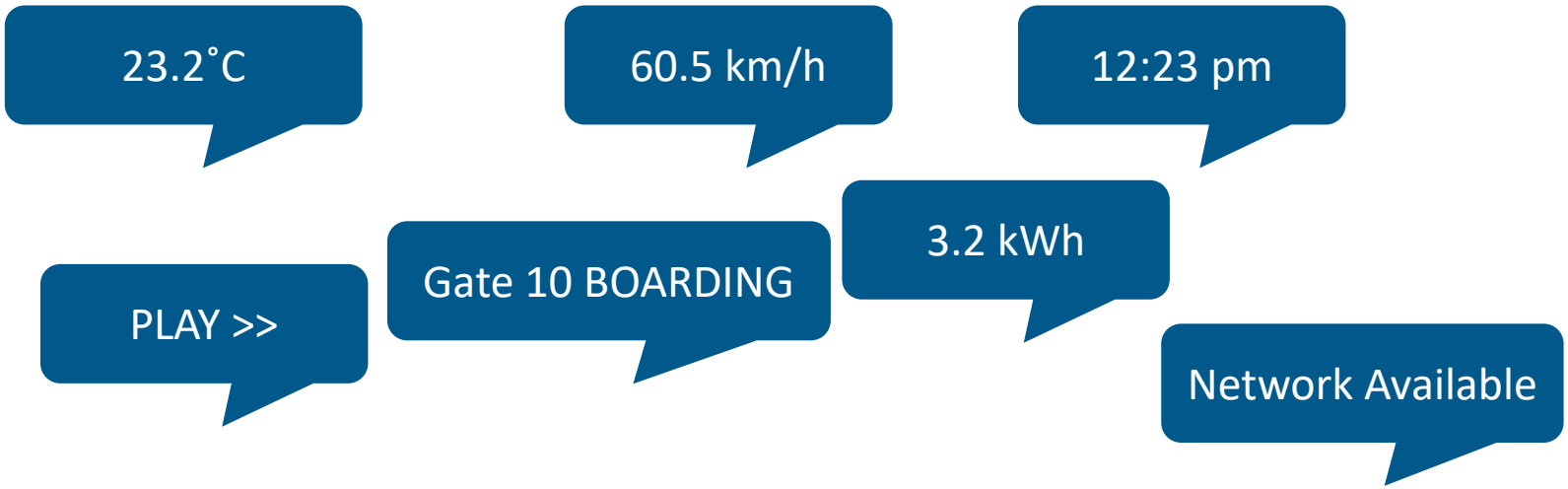
Bluetooth Low Energy Factsheet

Data Throughput

- For Bluetooth low energy, data throughput is not a meaningful parameter. It does not support streaming.
- It has a data rate of 1 Mbps, but is not optimized for file transfer.
- It is designed for sending small chunks of data (exposing state)

Designed for Exposing State

Exposing State



- It’s good at small, discrete data transfers.
- State information triggered by local events.
- Not streaming
- Data can be read at any time by a client.
- Interface model is very simple (GATT)

Bluetooth Low Energy Roles

Master
Client
Can read/write data to Slave/Server

Central

Peripheral

Slave
Server
Has read/write data

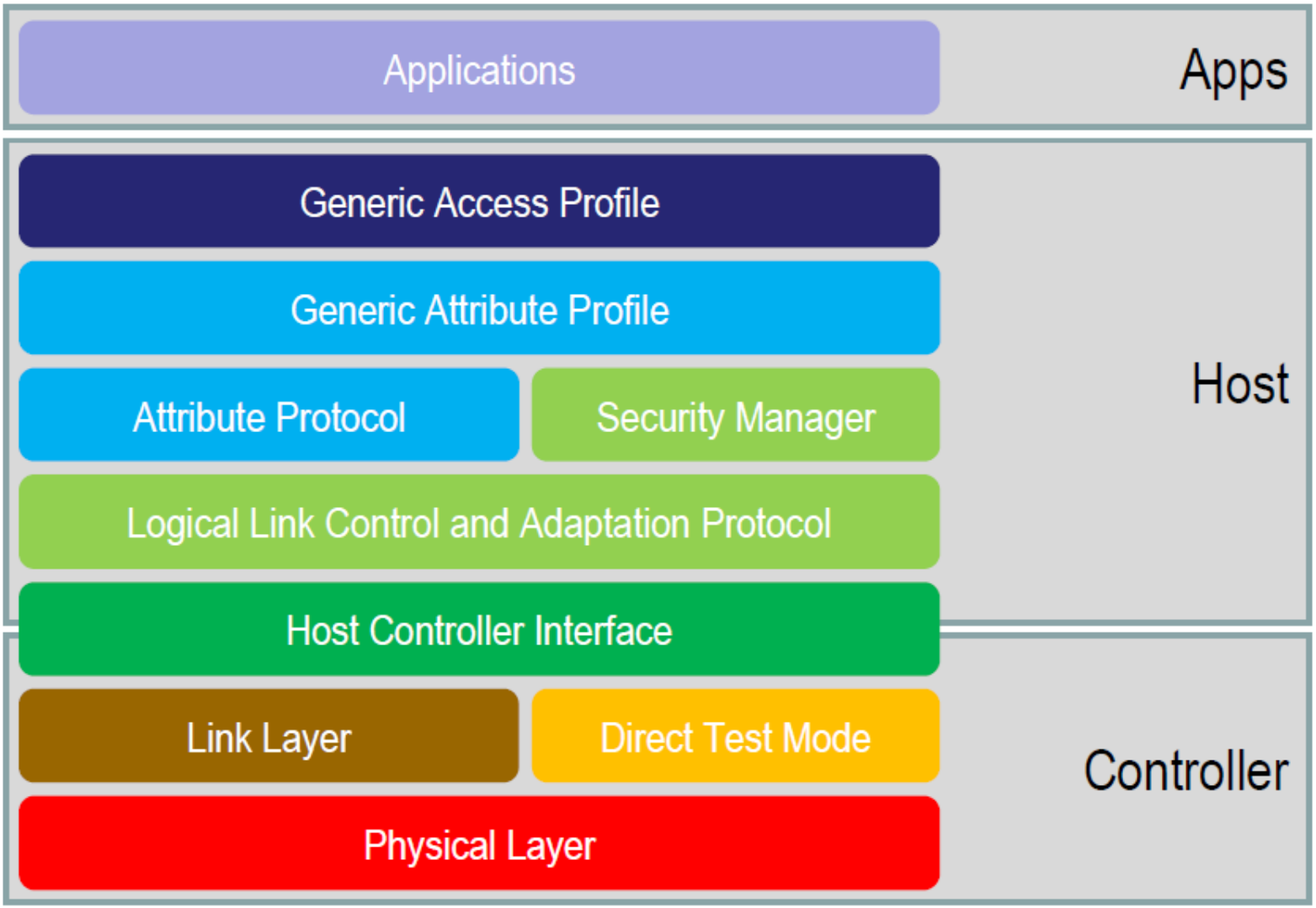
Can receive broadcast data

Observer

Broadcaster

Has read-only broadcast data

Bluetooth Low Energy Architecture



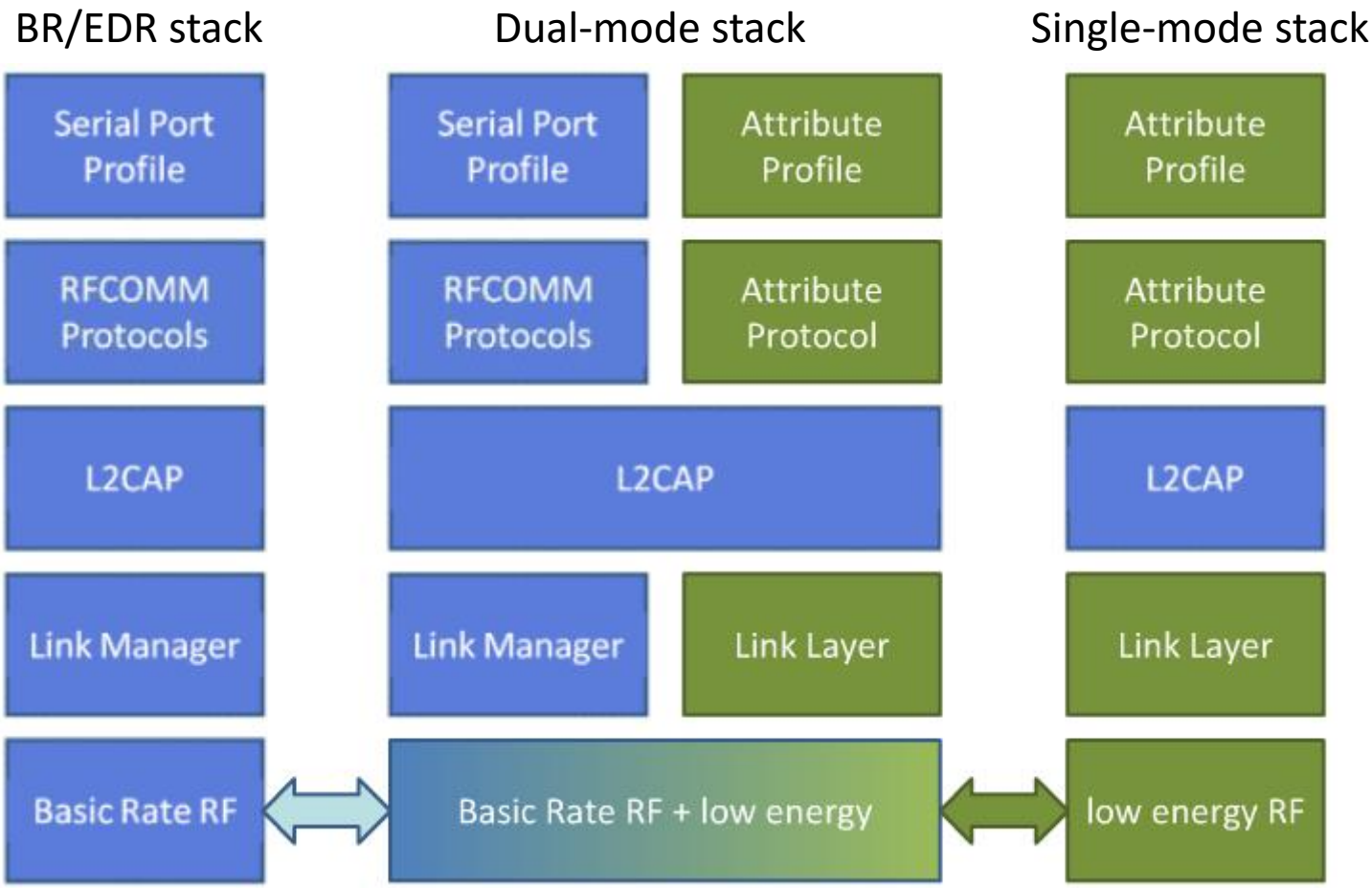
Device Modes

- **Dual Mode**
  - Bluetooth BR/EDR and LE
  - Used anywhere that BR/EDR is used today

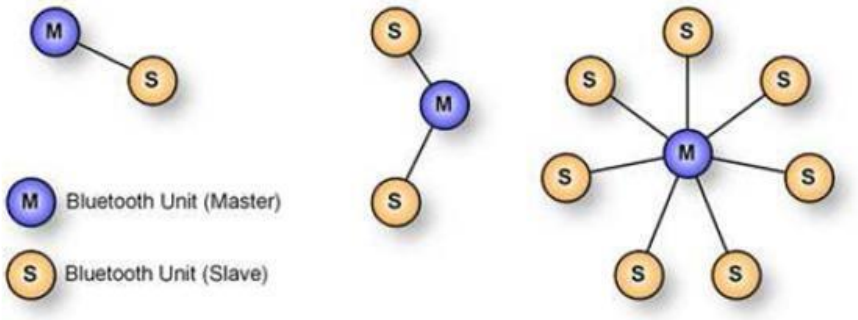
- **Single Mode**
  - Implements only Bluetooth low energy
  - Will be used in new devices / applications

Device Modes

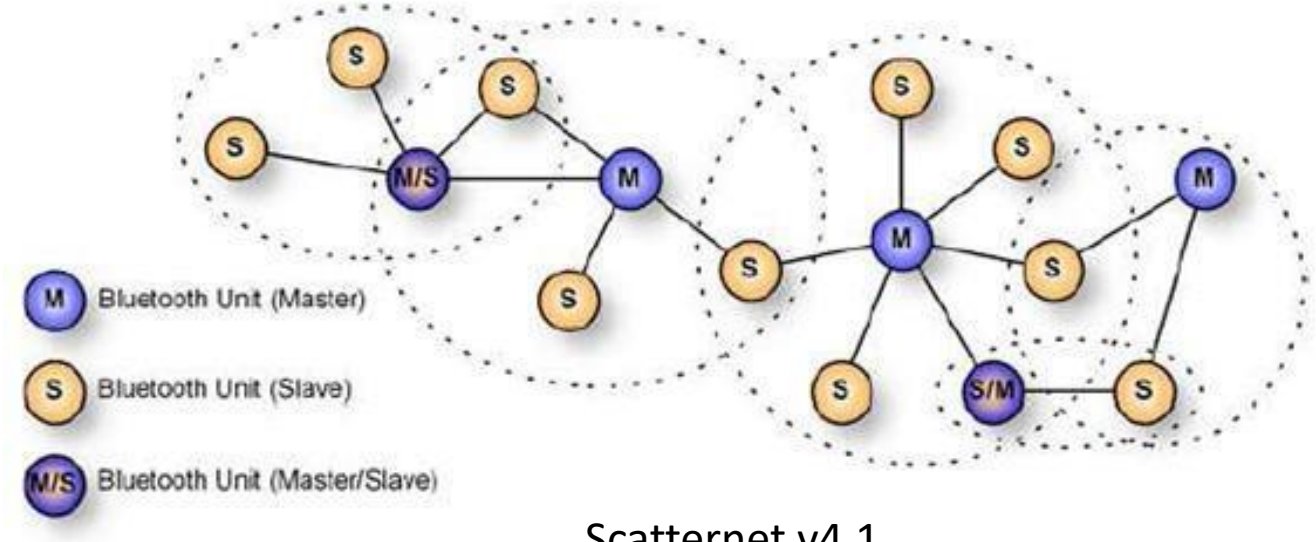
- **Dual Mode + Single Modes**



Topology



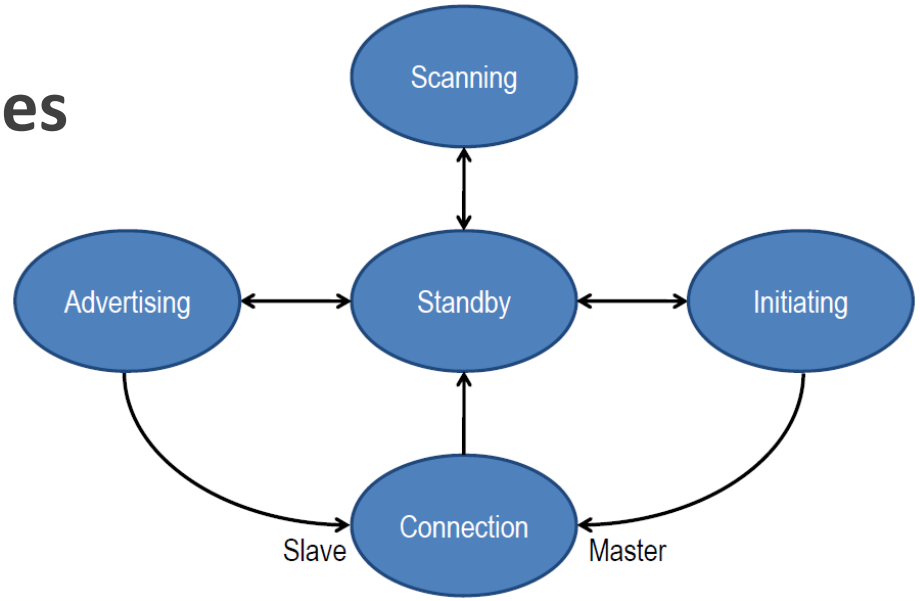
Piconet v4.0



Scatternet v4.1

Architectural Overview

- **Operation States and Roles**
  - Master / Slave only
    - No scatternet
    - No role switches



State		State Description
Standby		Does not transmit or receive packets
Advertising		Broadcasts advertisements in advertising channels
Scanning		Looks for advertisers
Initiating		Initiates connection to advertiser
Connection	Master	Communicates with device in the Slave role, defines timings of transmissions
	Slave	Communicates with single device in Master role

Architectural Overview

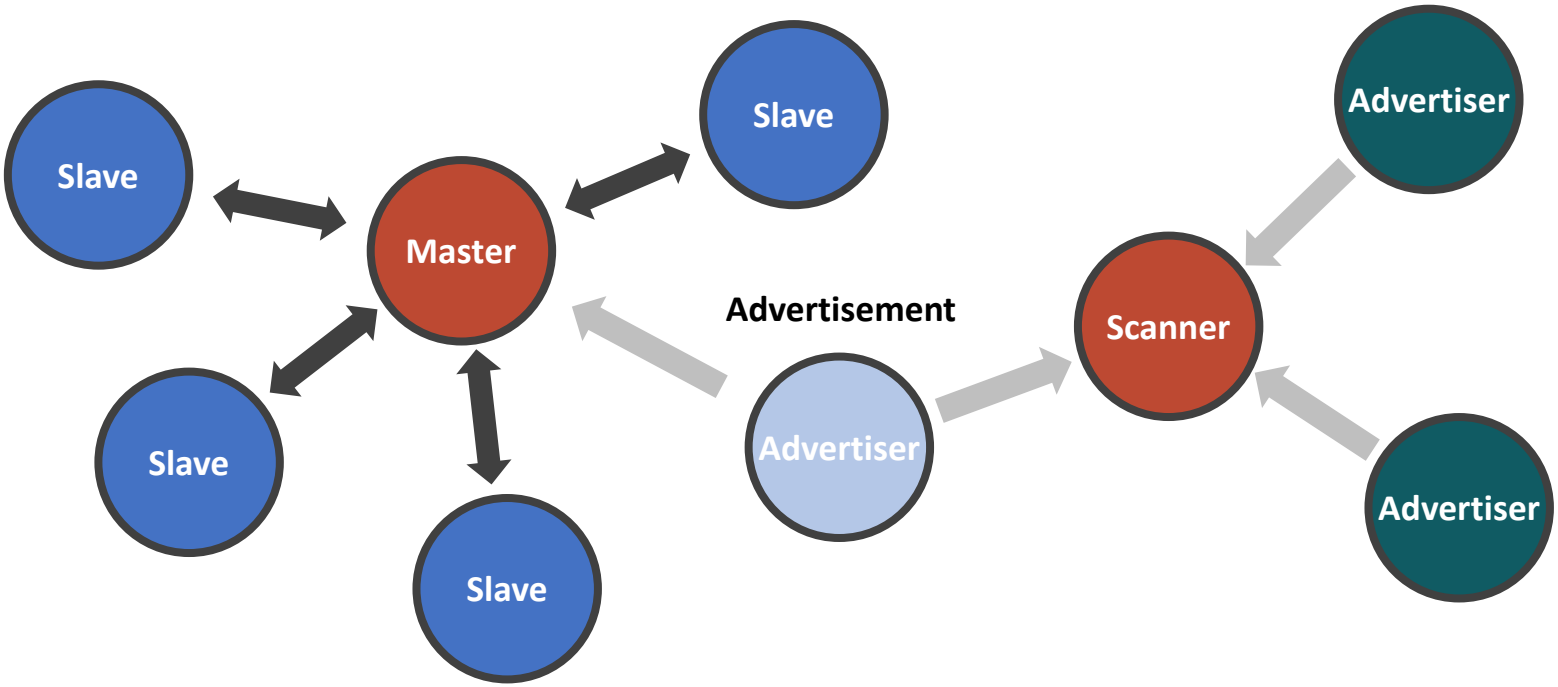
- BLE devices may have more than one instance of the Link Layer state machine at any one time
  - However, a BLE device cannot be master and slave at the same time

Multiple State Machine States and Roles		Advertising	Scanning	Initiating	Connection	
					Master	Slave
Advertising		No	Yes	Yes*	Yes*	Yes*
Scanning		Yes	No	Yes	Yes	Yes
Initiating		Yes*	Yes	No	Yes	No
Connection	Master	Yes*	Yes	Yes	Yes	No
	Slave	Yes*	Yes	No	No	No

* Only advertising packets that will not result in Link Layer entering a Slave Role

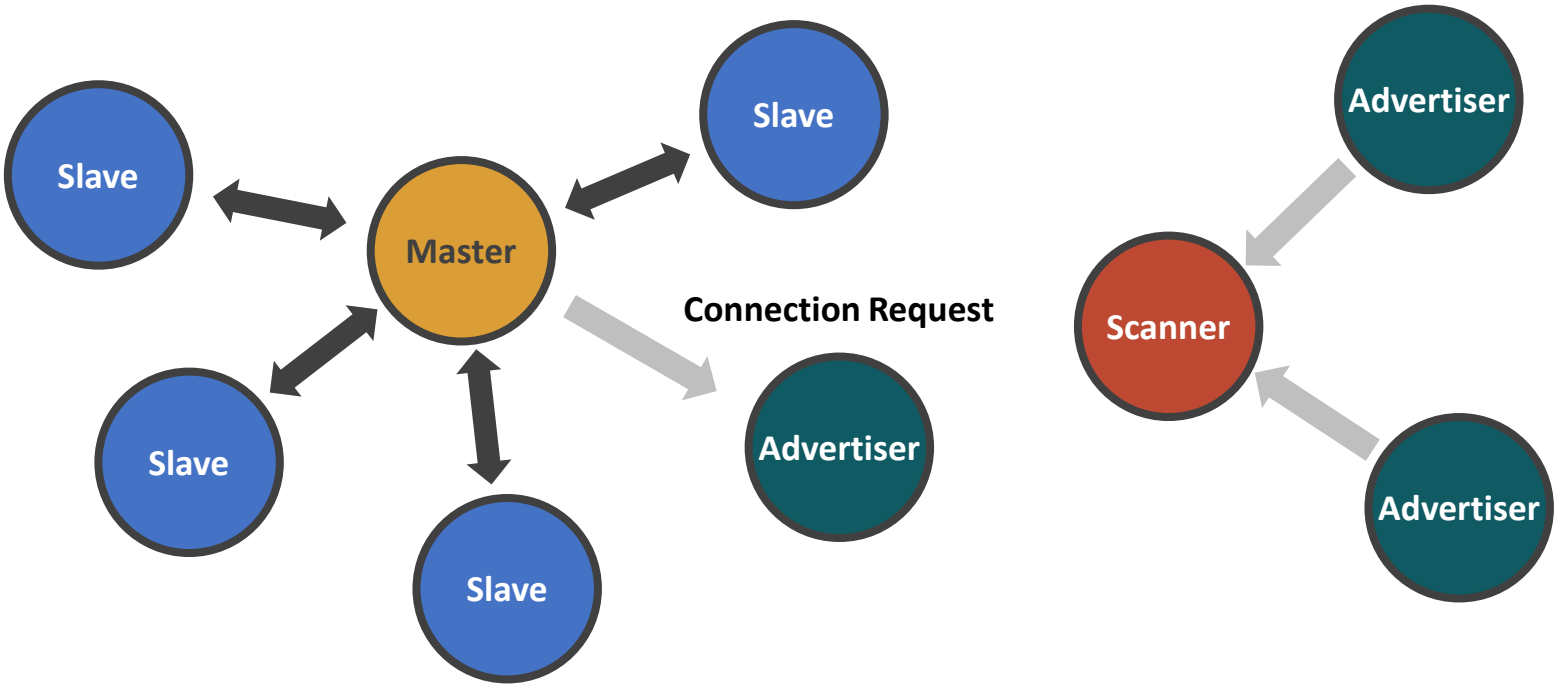
Architectural Overview

- **Topology Example**
  - Star topology
    - Master can have multiple link layer connections
    - Slave can have only one link layer connection



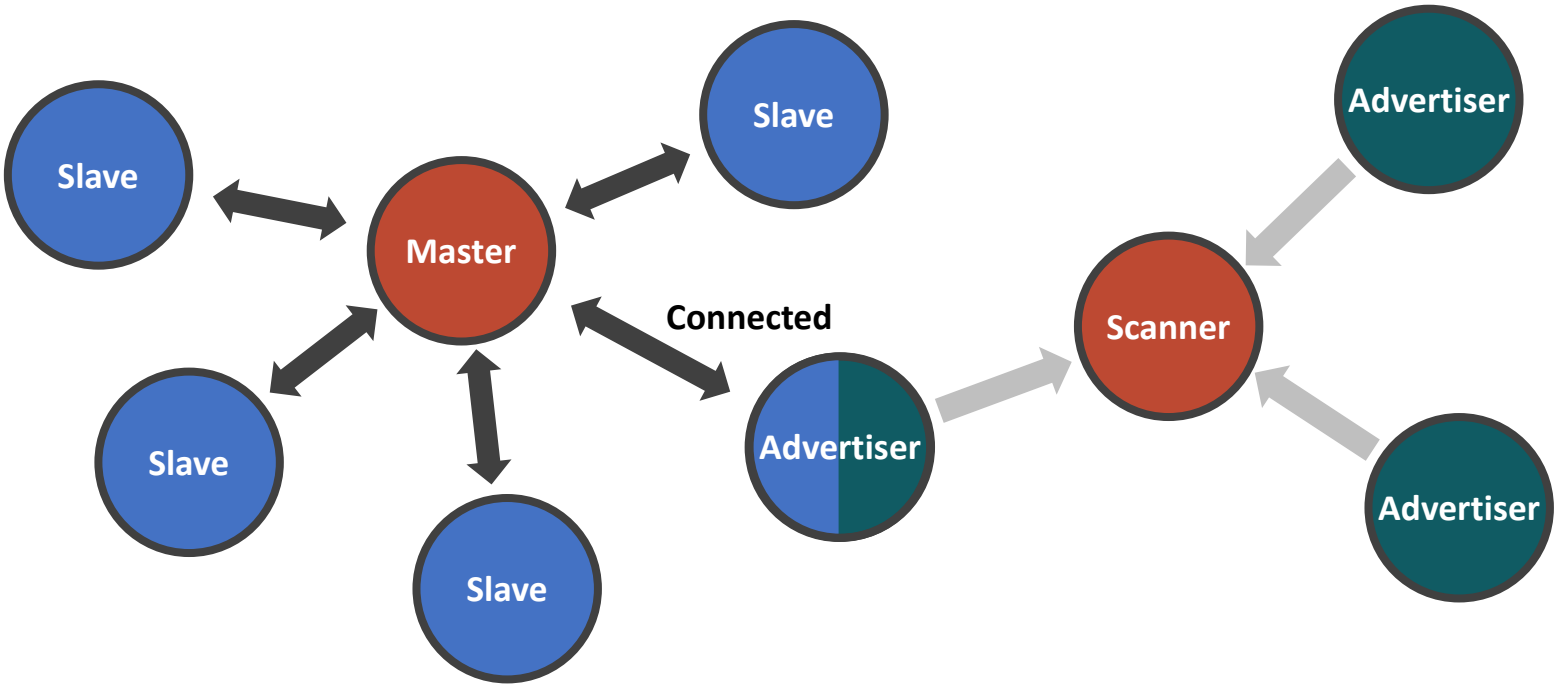
Architectural Overview

- Initiation of connection requests
  - Master can simultaneously be scanner and master
  - Master can simultaneously be initiator and master



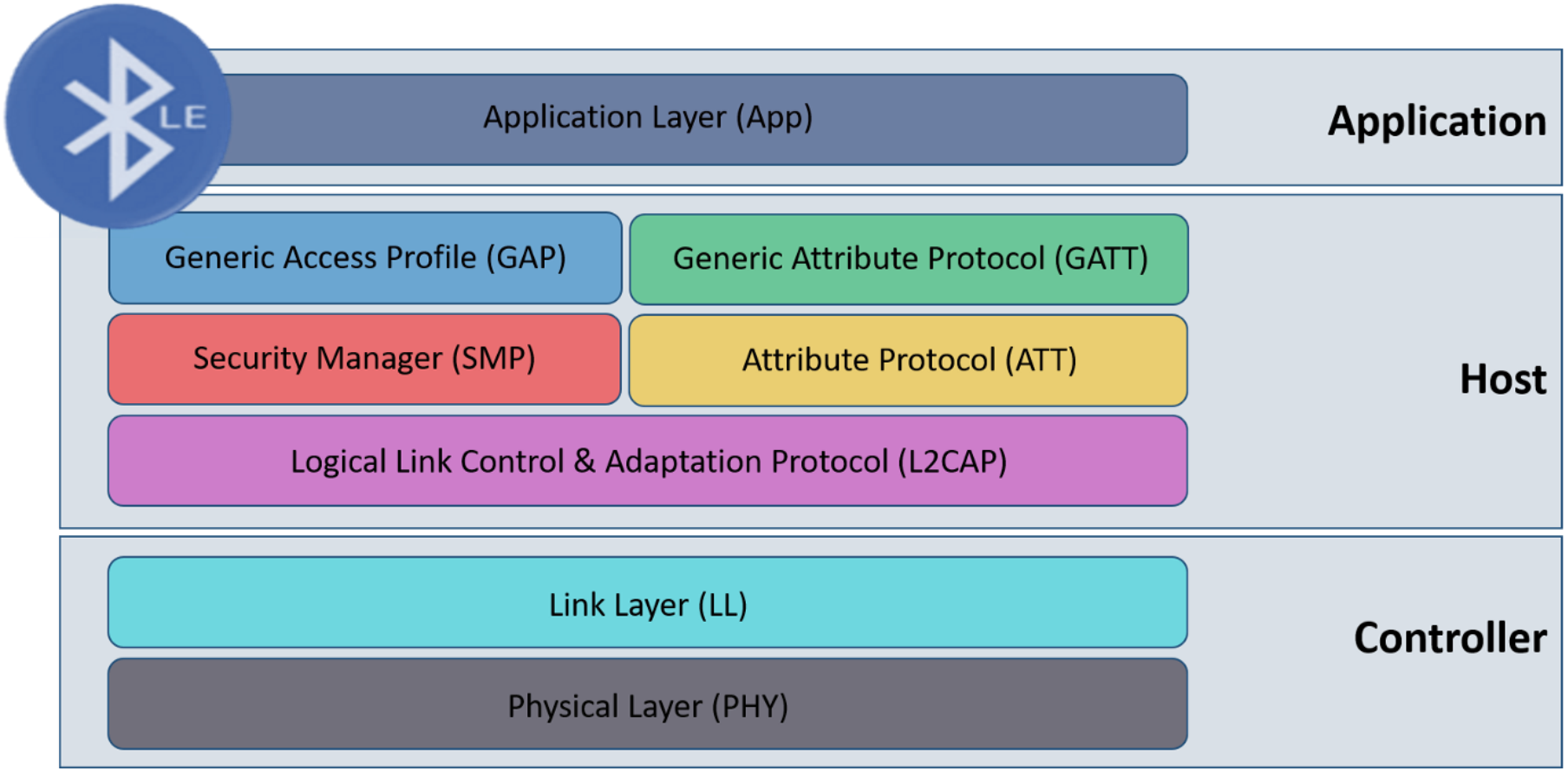
Architectural Overview

- Master and Slave can both act as Advertiser
  - Only advertising events that will not result in connection as Slave are allowed



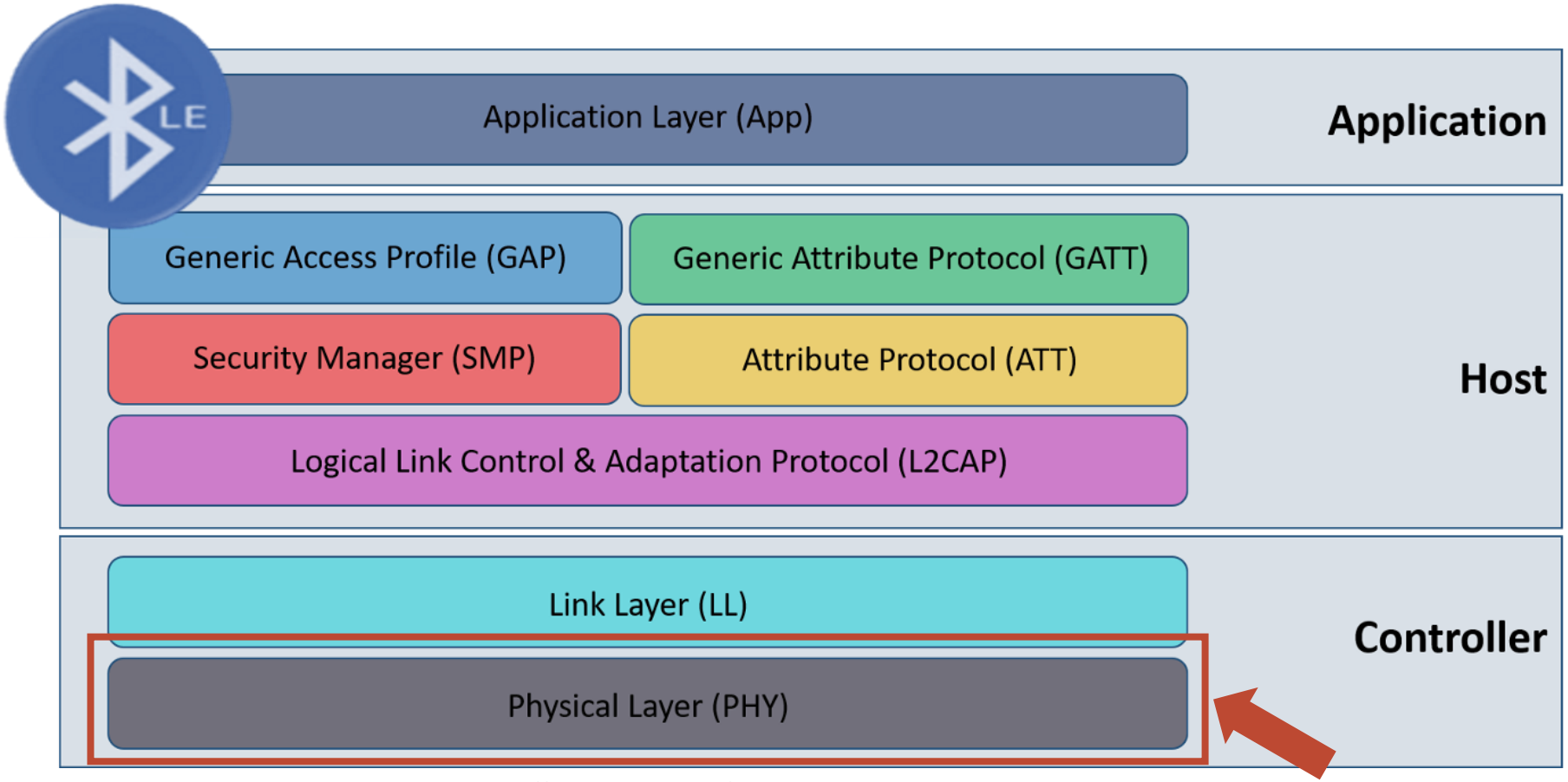
Stack Architecture

Stack Architecture



https://pcng.medium.com/ble-protocol-stack-controller-2d2d5371deec

Physical Layer



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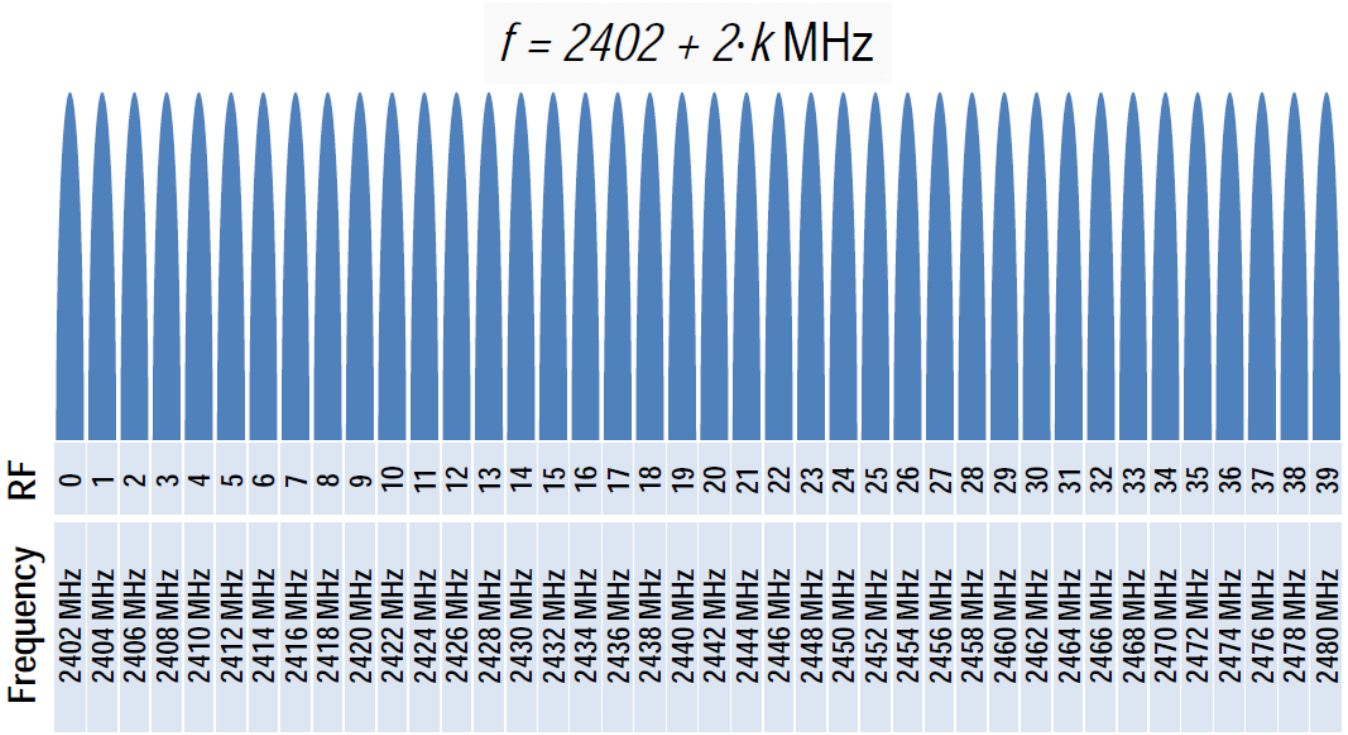
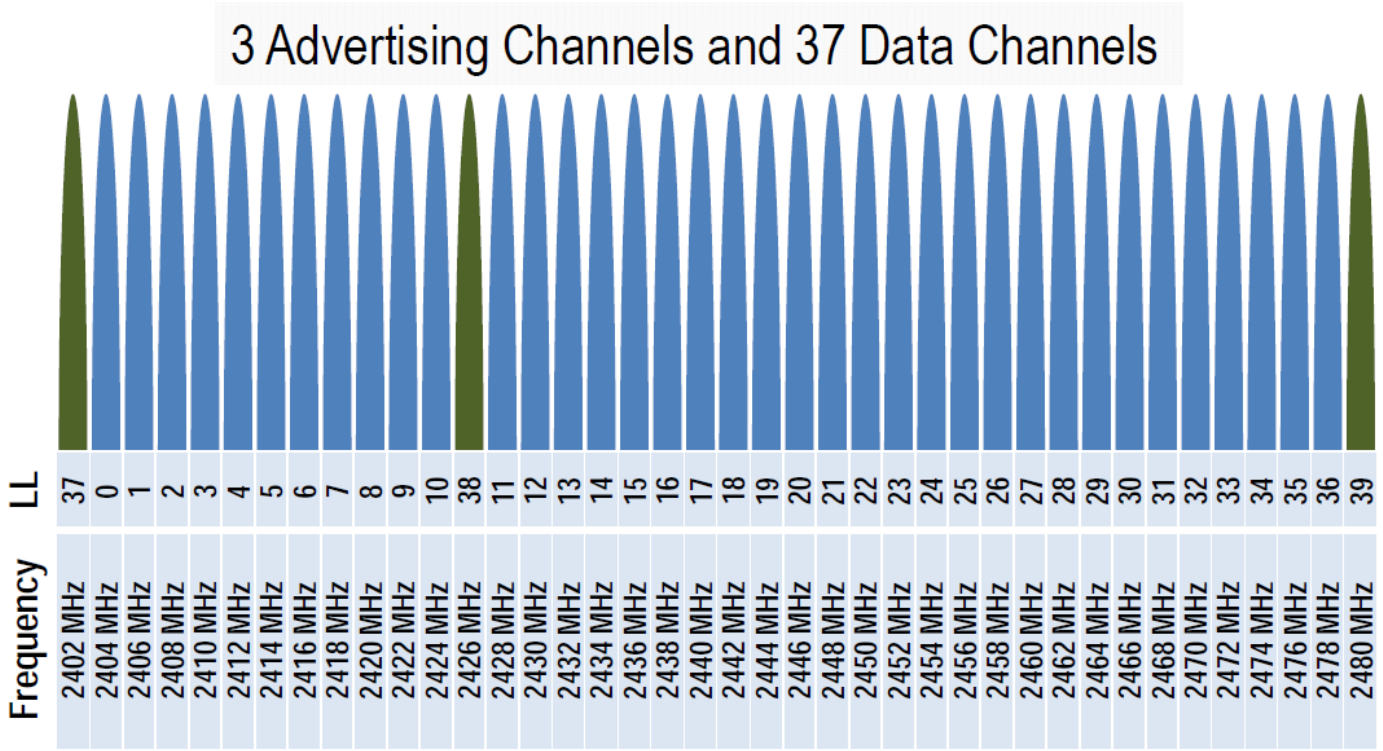
Physical Layer

- **Frequency and Channels**
  - 2.4 GHz ISM band
  - 1 Mbps GFSK
  - 40 Channels on 2 MHz spacing



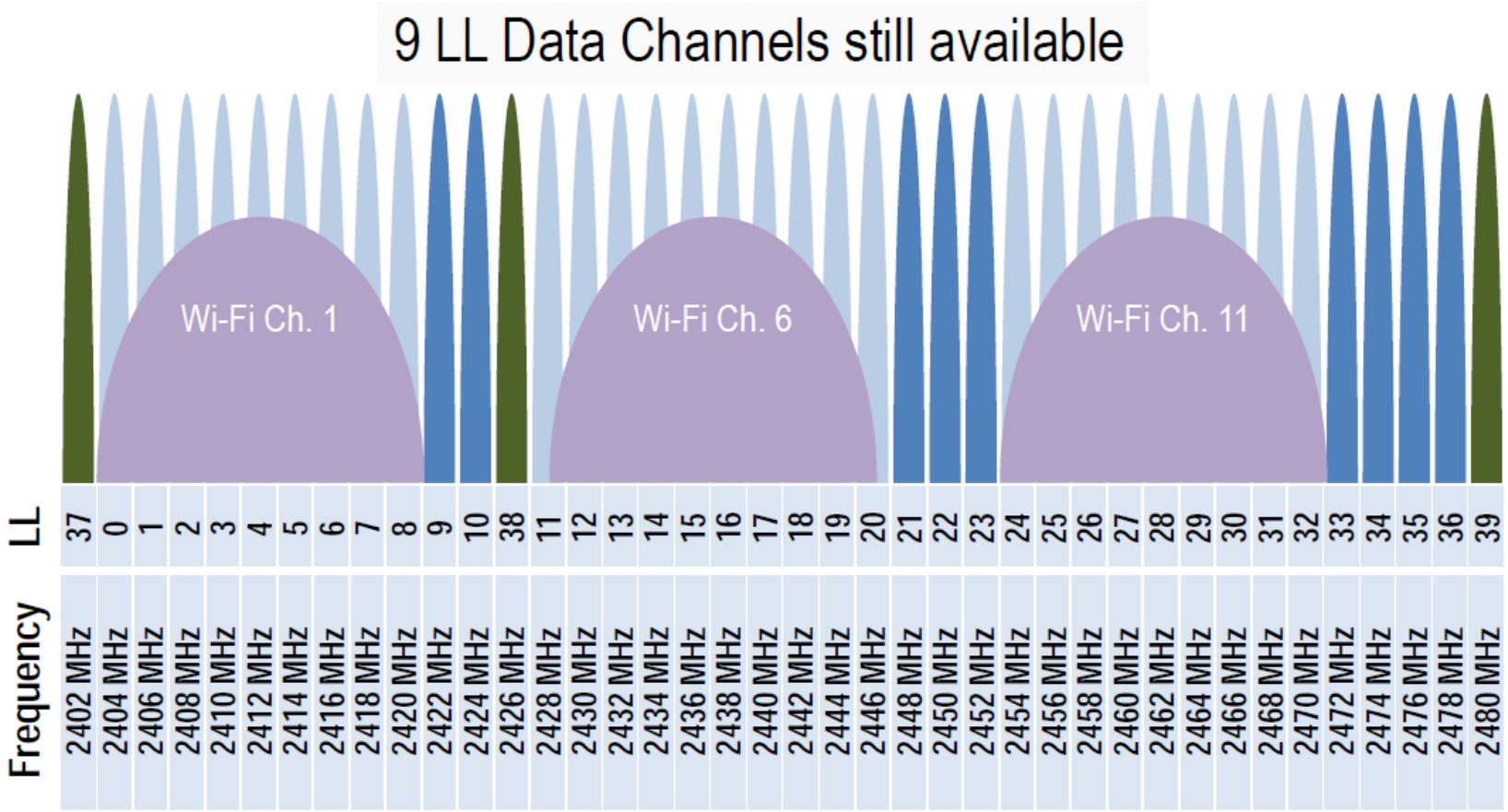
Physical Layer

- **Channel Arrangement**
  - 3 advertising channels (37, 38, 39)
  - 37 data channels (0-36)
  - cf) Bluetooth classic: 79 channels



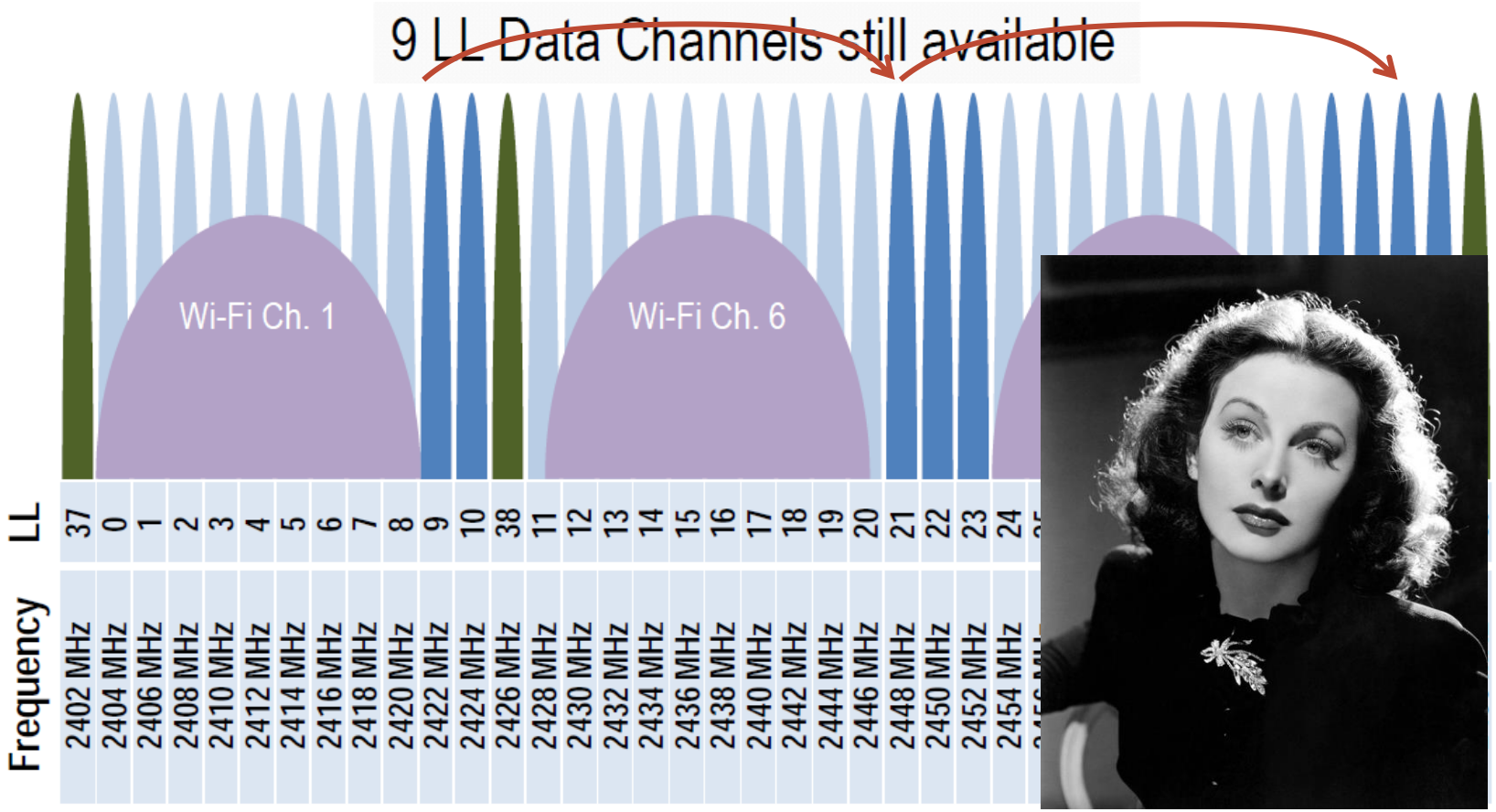
Physical Layer

- **Advertising channels avoid 802.11**



Physical Layer

- **Spectrum/Adaptive Frequency Hopping**



Hedy Lamarr

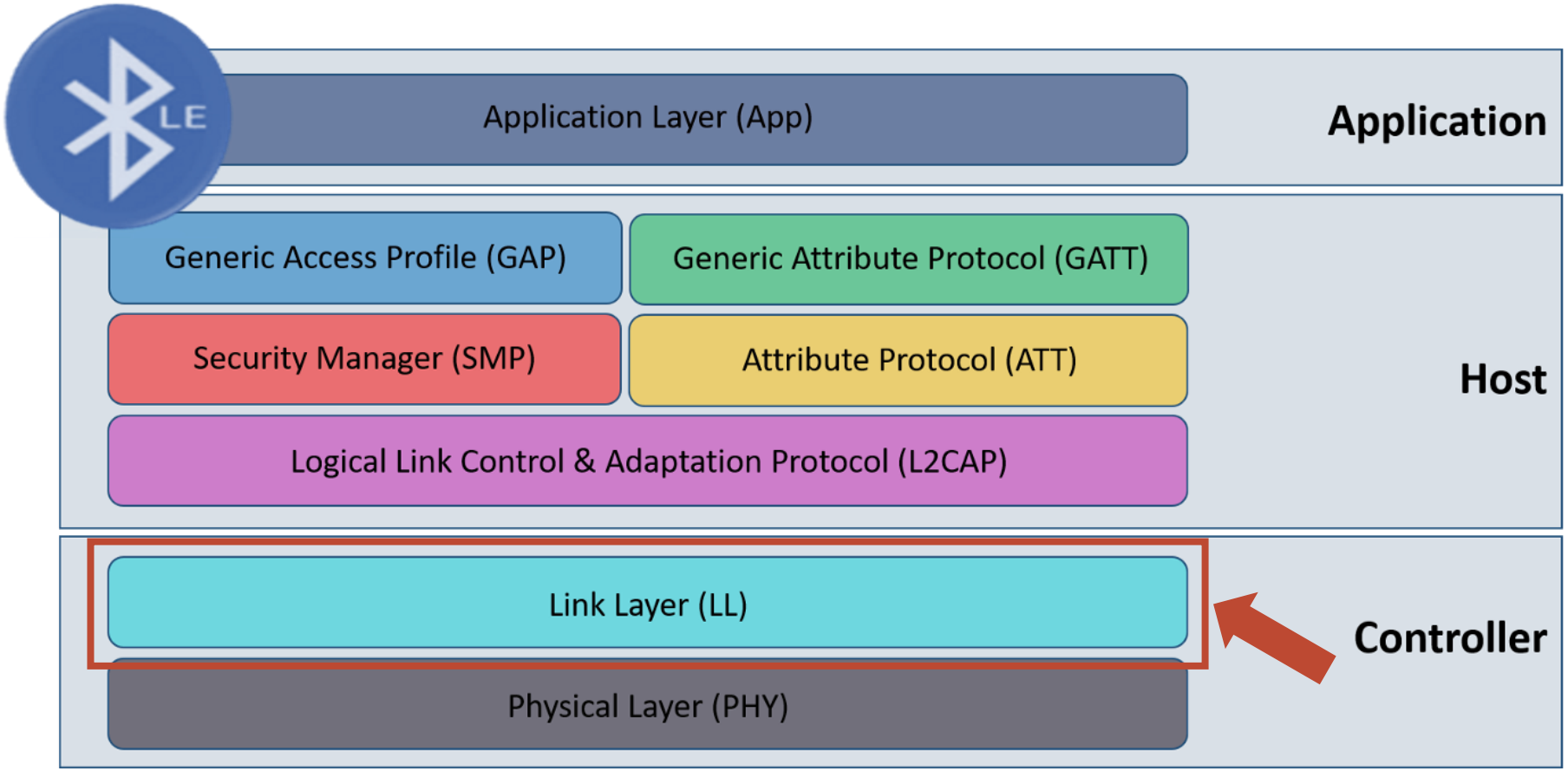
Physical Layer

- **Transmitter and Receiver Characteristics**
  - Transmit output power
    - -20 dBm (0.01 mW) to +10 dBm (10 mW)
    - No concept of Class 1 / 2 / 3
  - Receive sensitivity
    - -70 dBm (-90 dBm is expected performance)

Physical Layer

- **FHSS (Frequency Hopping Spread Spectrum)**
  - BLE splits the spectrum up into 37 1MHz wide channels
  - FHSS occurs while in a connection
  - Frequency hops follow a hop-length that is pseudo-random per connection
    - Communicated in the "Connection Request"
    - Provides instant adaptive frequency hopping capability
    - Can be updated using a channel update message

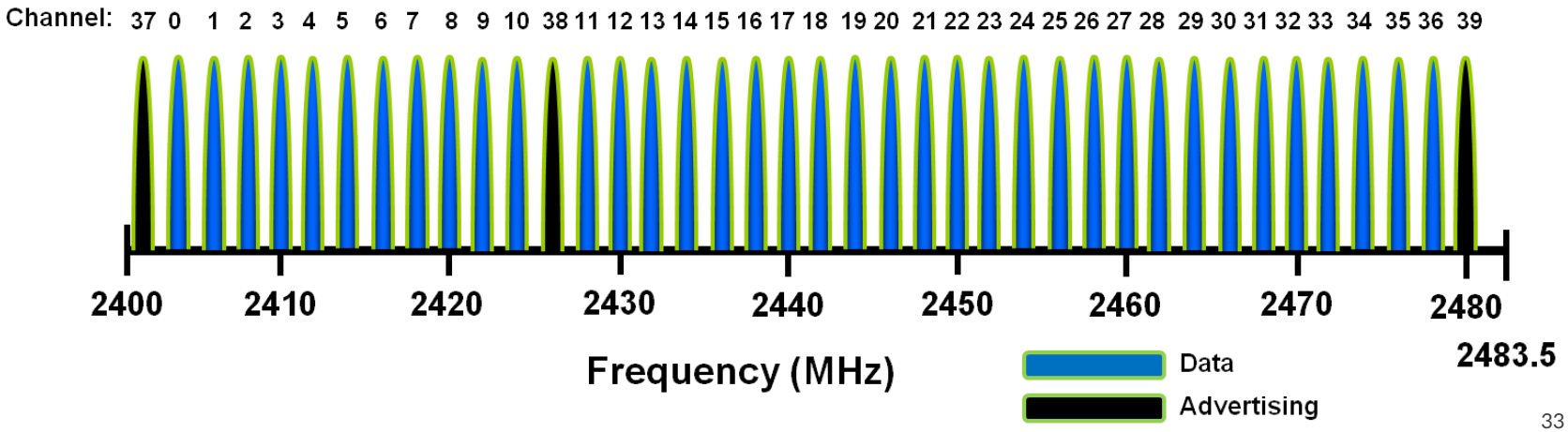
Link Layer



https://pcng.medium.com/ble-protocol-stack-controller-2d2d5371deec

Link Layer

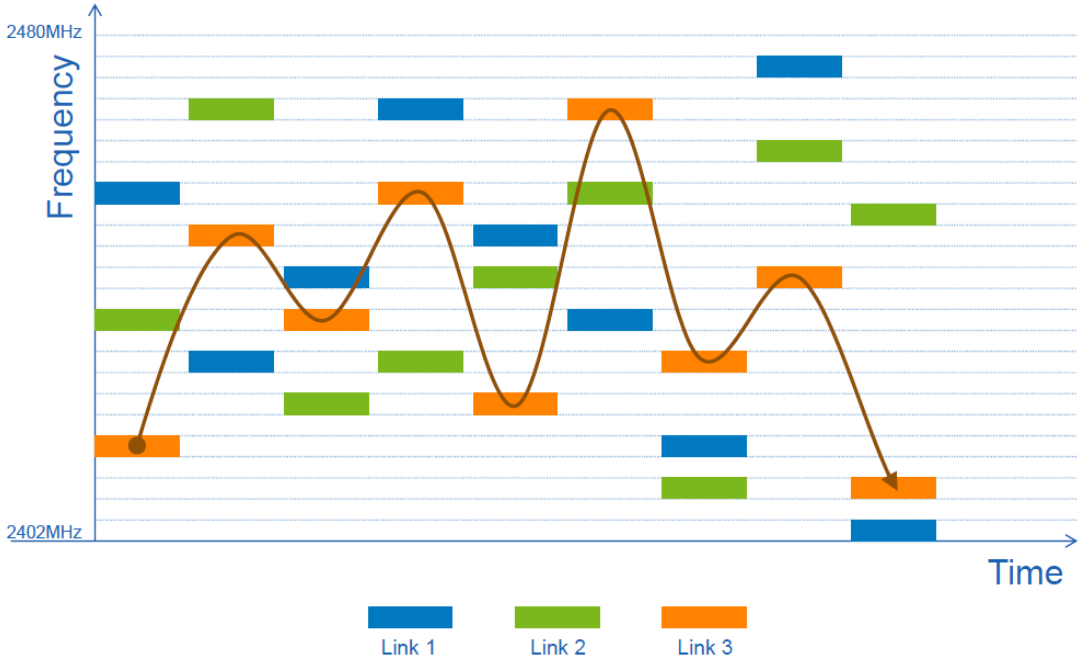
- **Channels**
  - 2 types
    - Advertising channel
      - Device discovery
      - Connection establishment
      - Broadcast transmissions
    - Data channel
      - Bidirectional communication between connected devices
      - Adaptive frequency hopping used for subsequent connection events



(Adaptive) Frequency Hopping

- When in a data connection, a frequency hopping algorithm is used to cycle through the 37 data channels

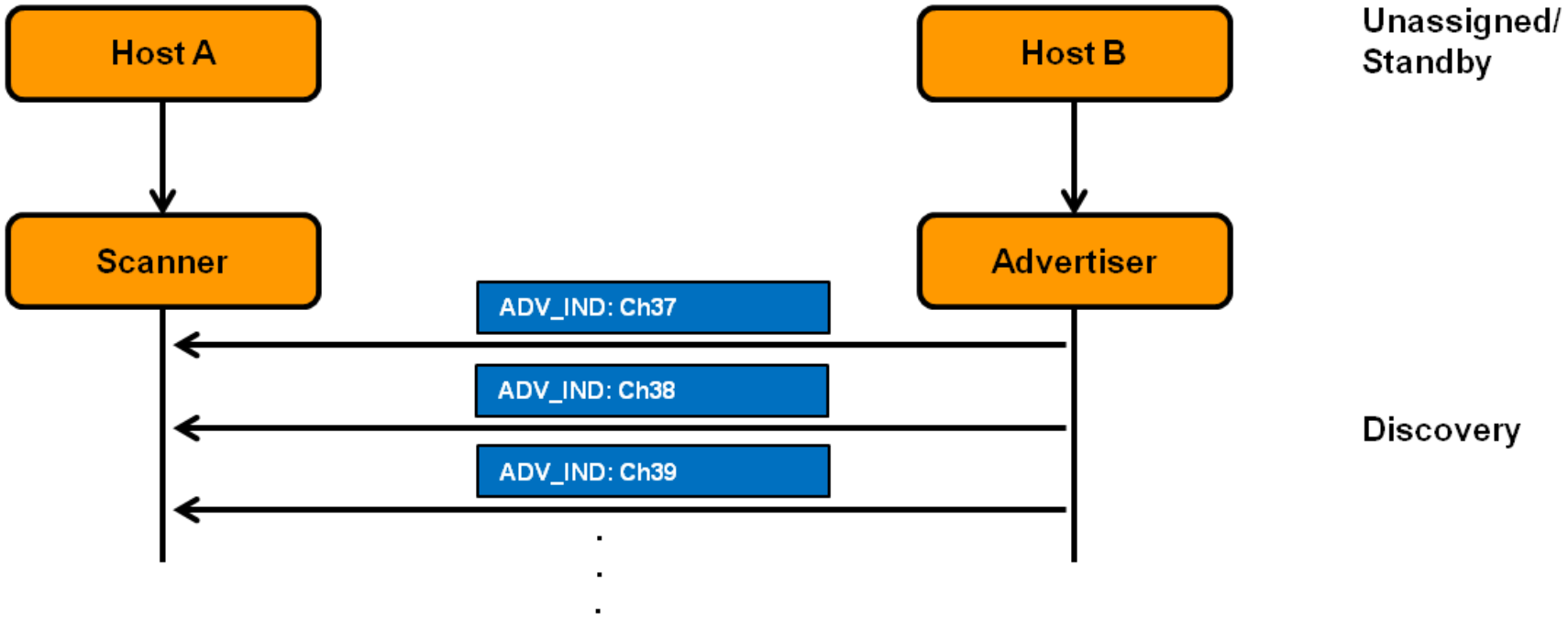
$$f_{n+1} = (f_n + hop) mod\ 37$$



This mechanism is used by the link layer to remap a given packet from a known bad channel to a known good channel so that interference from other devices (i.e., Wi-Fi®) is reduced.

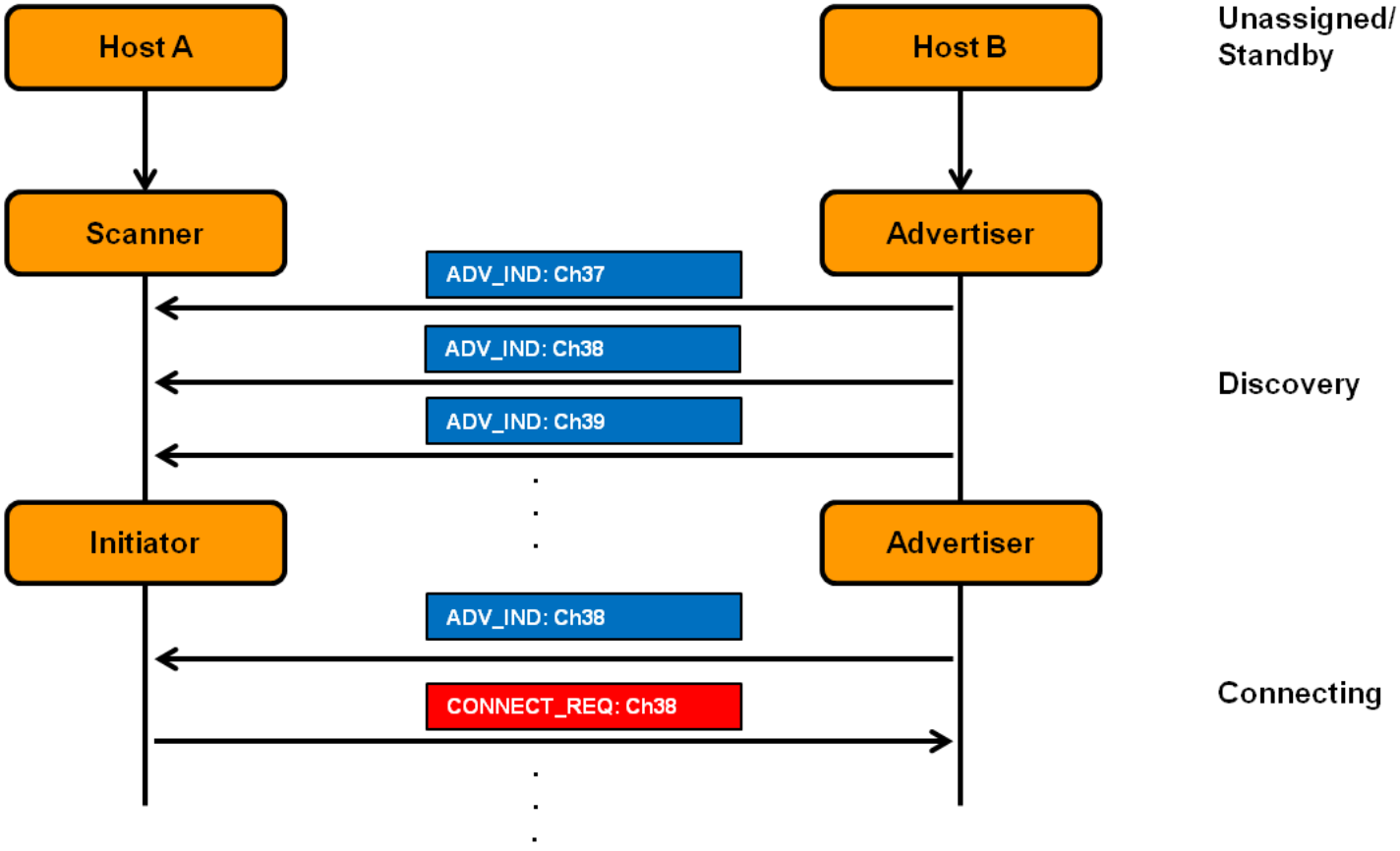
- **Roles and States**
  - Role pairs
    - Advertiser / Scanner (Initiator)
    - Slave / Master
    - Broadcaster / Observer

- **Unicast (Peer-Peer) Connection**
  - Host A: wishing to be connected → Scanner
  - Host B: wishing to be discovered → Advertiser
    - Sends advertising packets (basic information about the host)



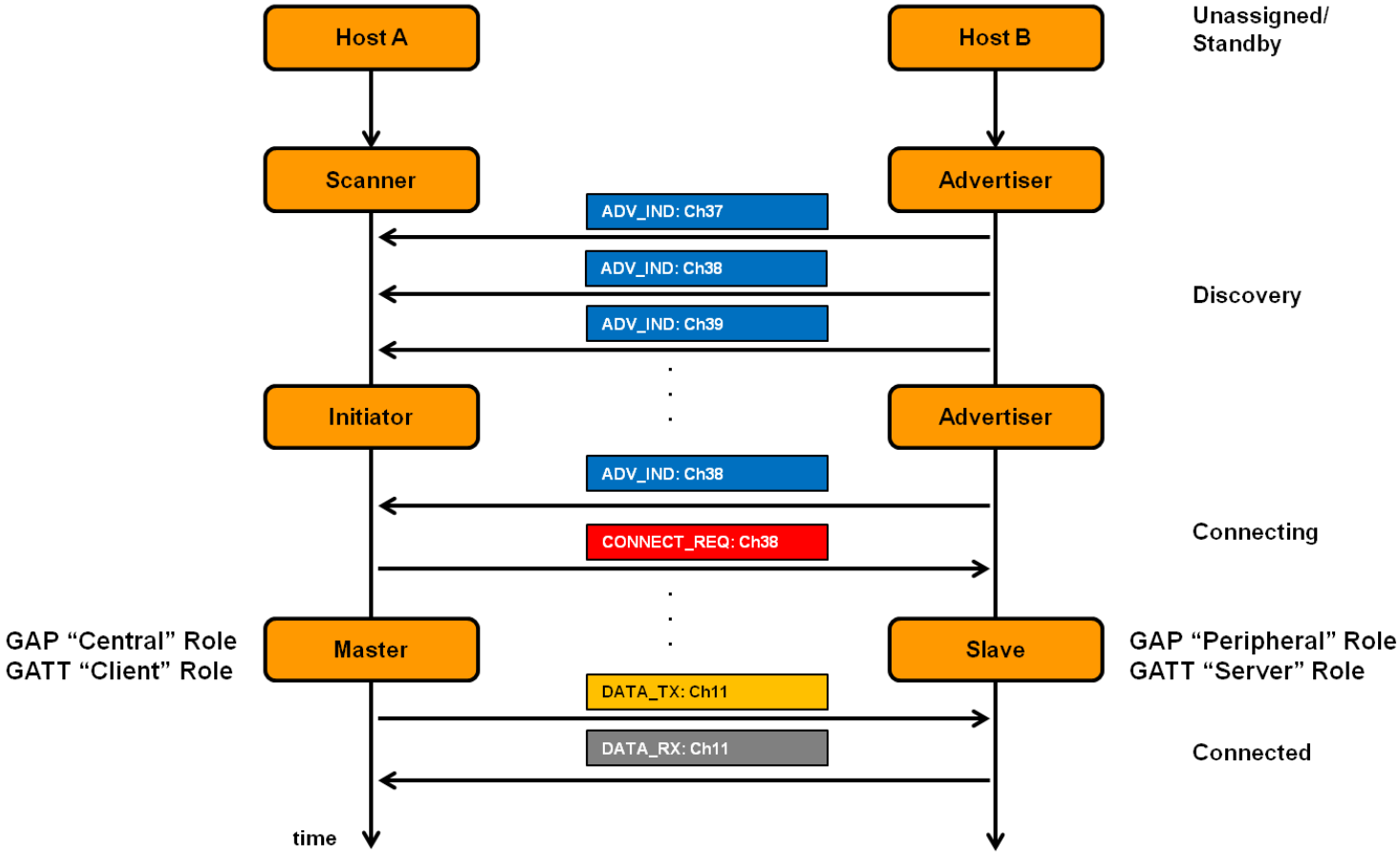
Link Layer

- Host A (Scanner) → Initiator
  - Initiates connection with a specific advertiser (connecting phase)



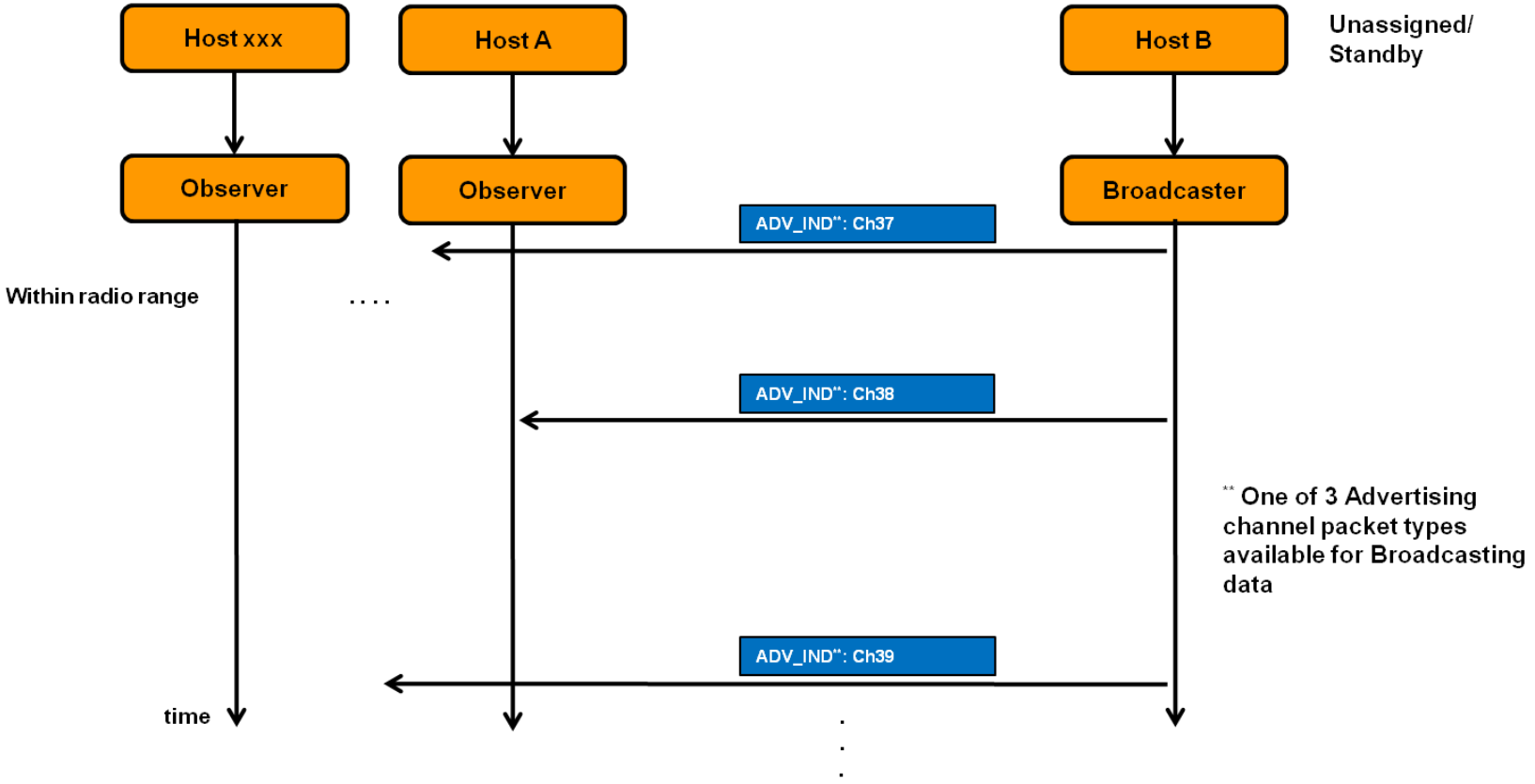
Link Layer

- Host A (Initiator) → Master
- Host B (Advertiser) → Slave
  - Accepts the connection request



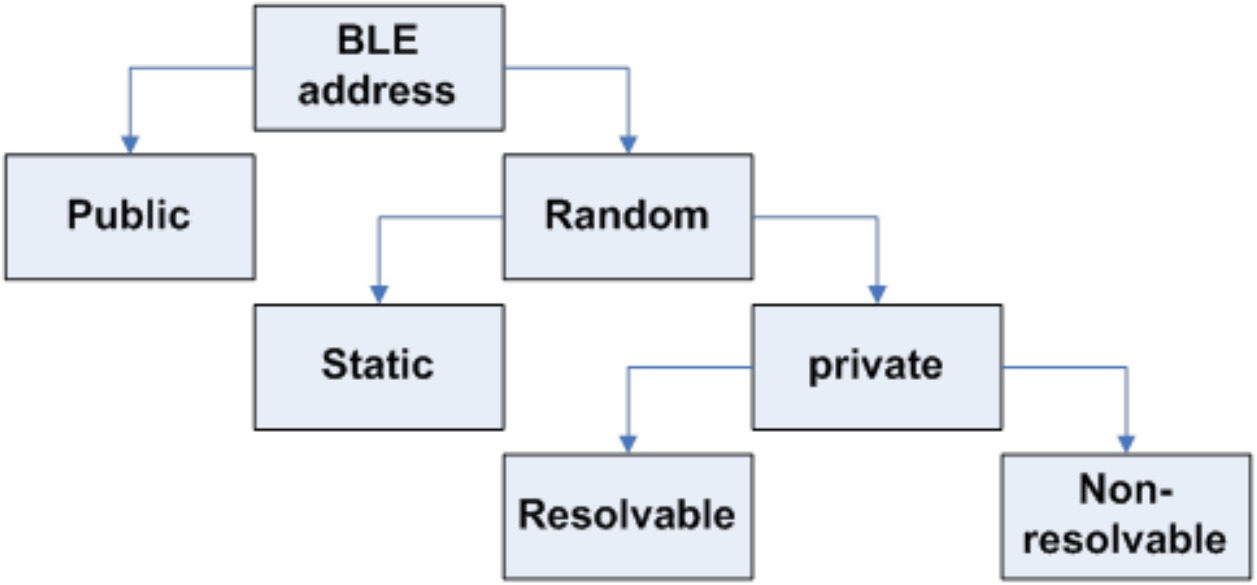
Link Layer

- **Broadcast Connection**
  - Broadcaster / Observer
  - Messages are one-way
  - Messages are one-to-many

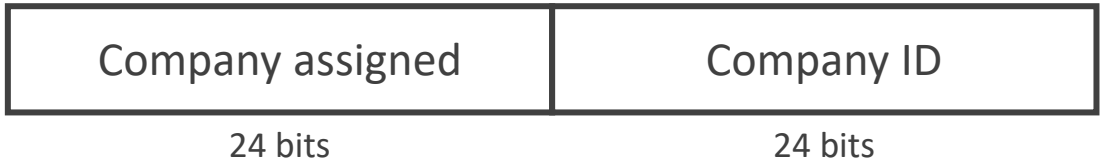


Device Address

- Media Access Control (MAC) address (similar to Ethernet of Wi-Fi): 48-bit (6-byte) number
  - Public device address
  - Random device address



- **Public Device Address**
  - Standard, IEEE-assigned 48-bit universal LAN MAC address
  - Two fields
    - Company ID (MSB)
      - Publicly assigned company ID by the IEEE
    - Company assigned (LSB)
      - Internally assigned device ID by the company



- **Random Device Address**
  - More popular than public addresses
    - Do not require registration with the IEEE
  - Programmed into the device or generated at runtime
  - Two subtypes
    - Random Static Address
    - Random Private Address

Link Layer

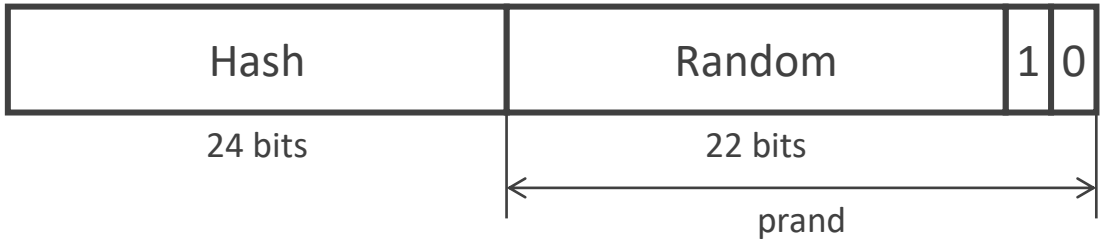
- Random Static Address
  - 48-bit randomly generated address
  - Can be assigned and fixed for the lifetime of the device
  - Can be changed at bootup (cannot be changed during runtime)
    - Existing connection using the old address will be lost
    - Must reconnect using the new address

Link Layer

- Random Private Address
  - Used when a device wants to remain private to hide the identity
  - Periodically changed → cannot be tracked
  - May or may not be resolvable
    - Resolvable Random Private Address
    - Non-resolvable Random Private Address

Link Layer

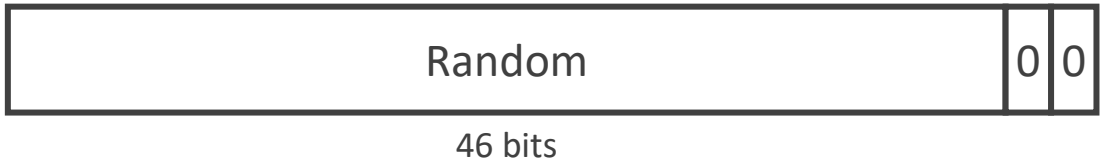
- Resolvable Random Private Address
  - Can be resolved through a pre-shared hash key
  - To prevent malicious third-parties from tracking the device
  - Generated using IRK (Identity Resolving Key) and a random number
  - Periodically changed (e.g. every 15 minutes)



    - Hash: generated using the prand and the IRL

Link Layer

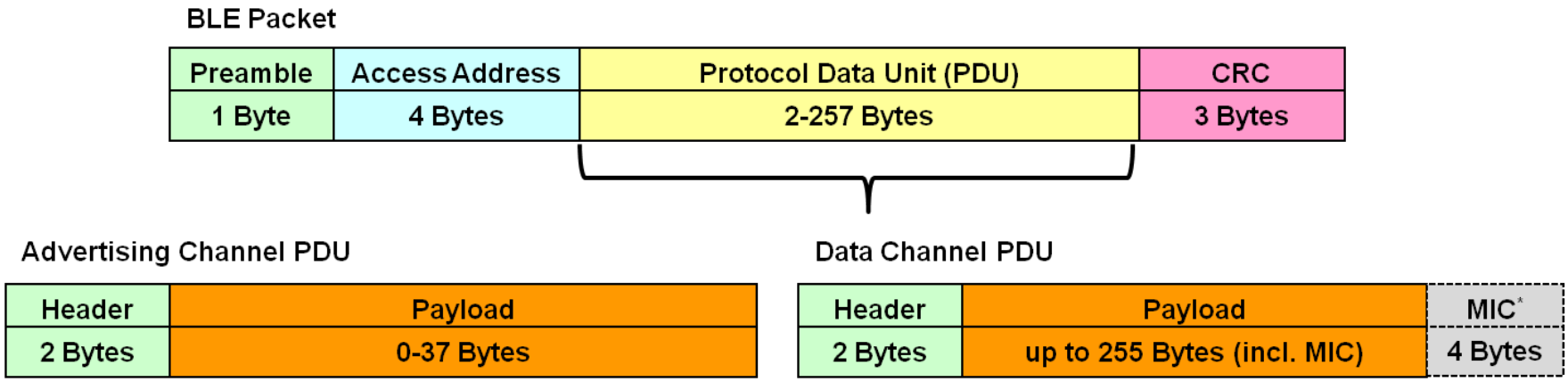
- Non-resolvable Random Private Address
  - Random and cannot be expected
  - Changed periodically
  - To prevent tracking by any other BLE devices
  - Not very common



Link Layer

Packet Types

- Only one packet format
  - Preamble (0x55, 0xAA)
    - Frequency synchronization, symbol timing estimation
  - Access Address
    - Advertising packets - always 0x8e89bed6
    - Data packets - different for each link layer connection

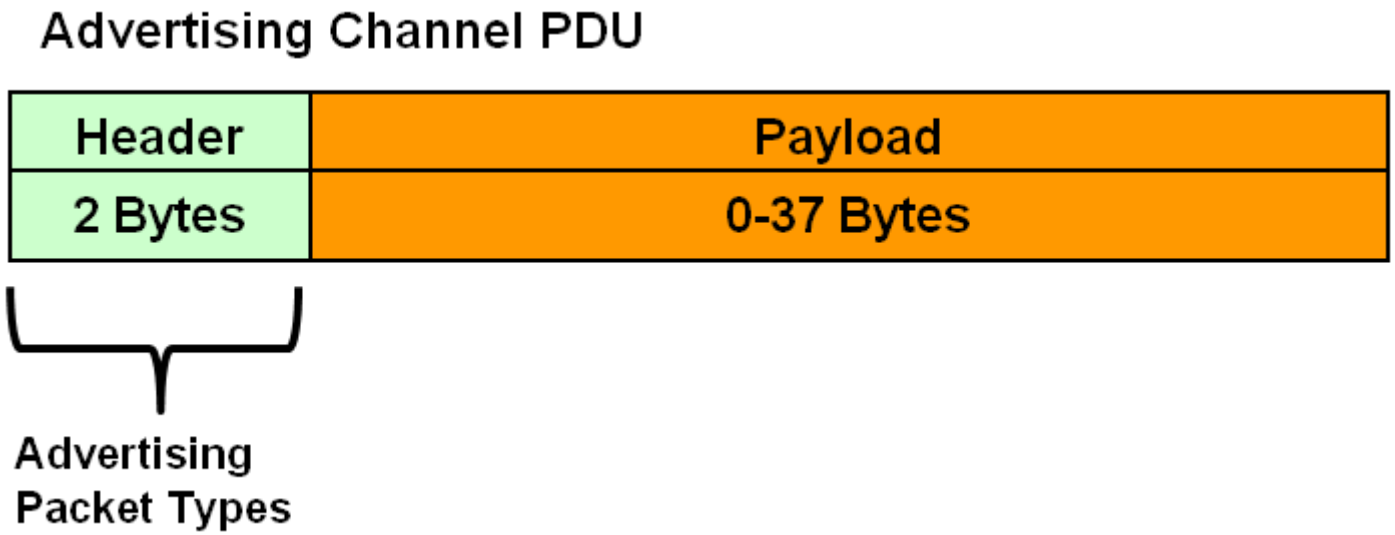


Ref: BT Specification v4.2, Vol. 6, Part B, Sec. 2.1

*Message Integrity Check: Included as part of Payload if used (for security)

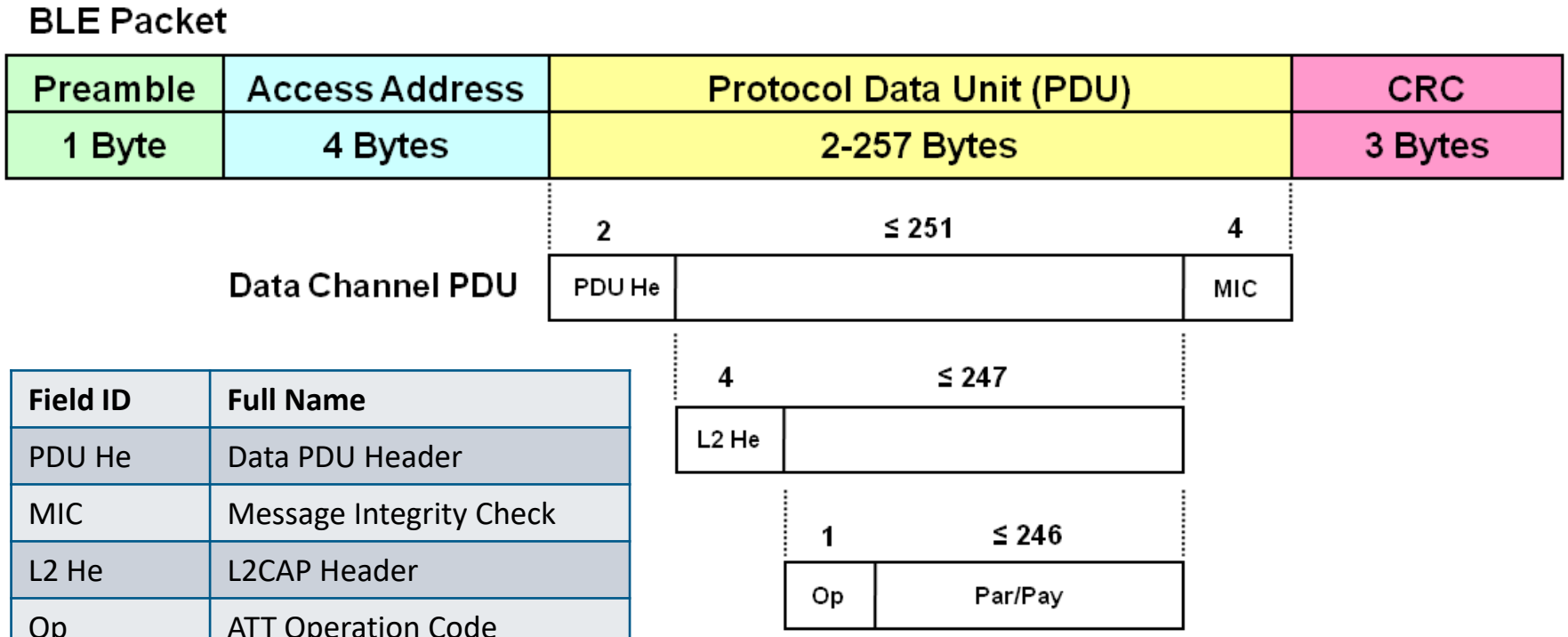
Link Layer

- Advertising Channel PDUs
  - Broadcast data for applications
  - Discover Slaves and connect to them



Link Layer

- Data Channel PDUs
  - In a connection, to exchanging data
  - Maximum data payload: 246 bytes

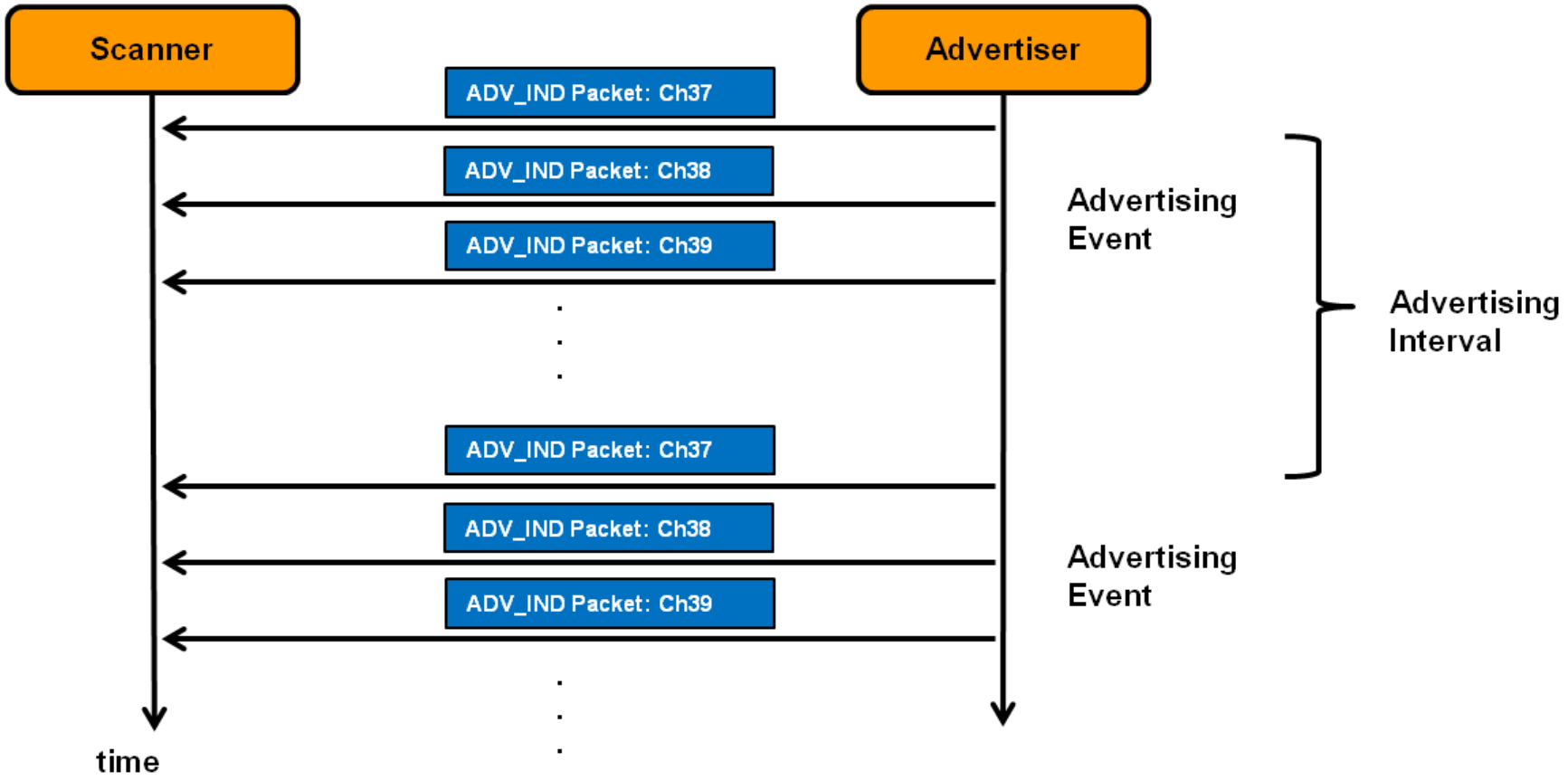


Field ID	Full Name
PDU He	Data PDU Header
MIC	Message Integrity Check
L2 He	L2CAP Header
Op	ATT Operation Code
Par/Pay	ATT Parameters & Payload

- **Discovery Process**
  - Devices use advertising channels to find each other
  - Advertising
    - 4 types
      - General, directed, nonconnectable, discoverable
    - Transmitting the same packet in each of the three advertising channels
  - Scanning
    - To complete the discovery process
    - Receiving advertising packets
    - 2 types
      - Passive and Active

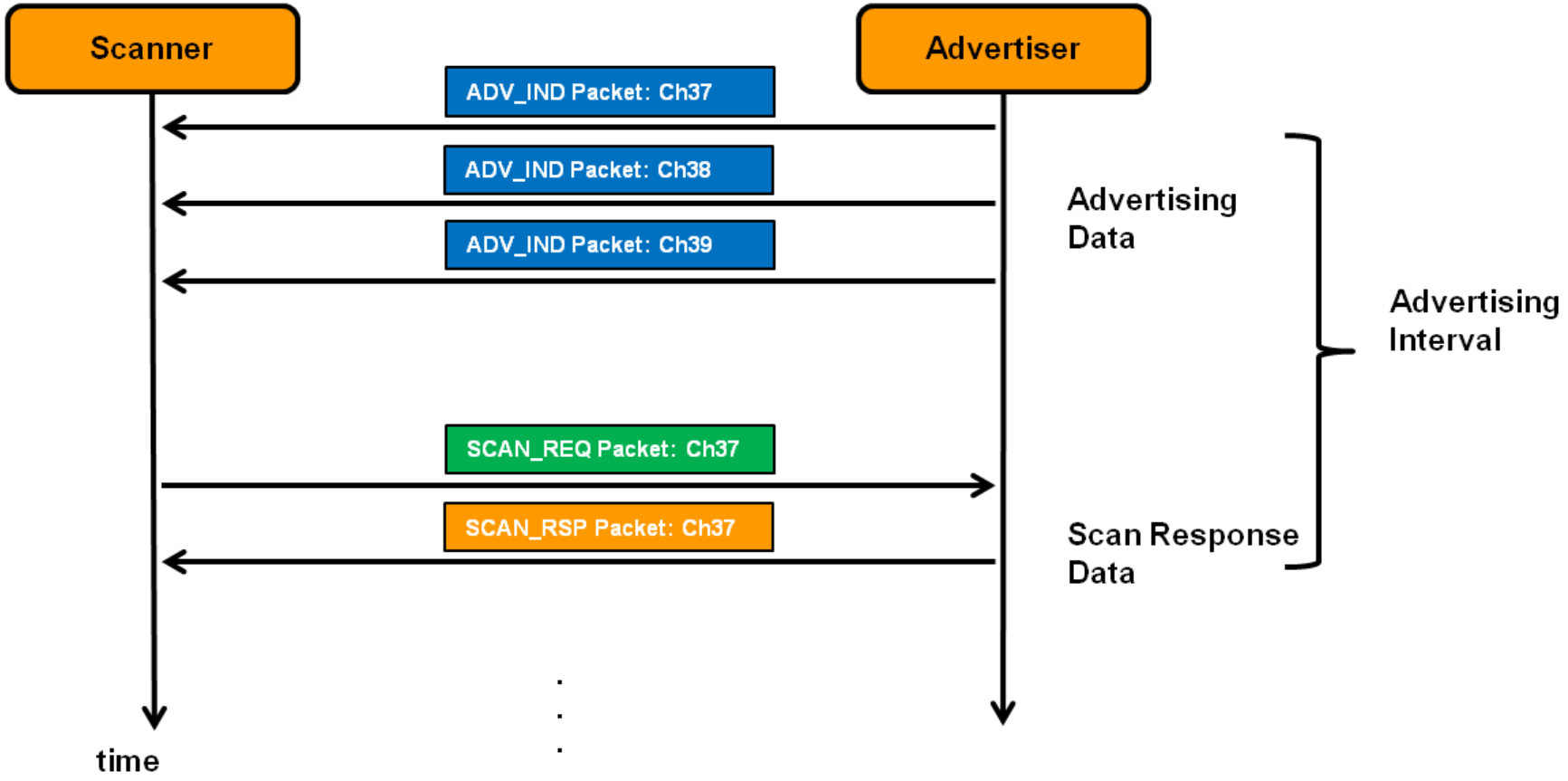
Link Layer

- Passive scanning
  - Listens for advertising packets
  - The Advertiser is never aware that packets were received



Link Layer

- Active Scanning
  - Scanner issues a SCAN_REQ to require more information
  - Advertiser responds with more information in a SCAN_RSP packet.



Connection Process

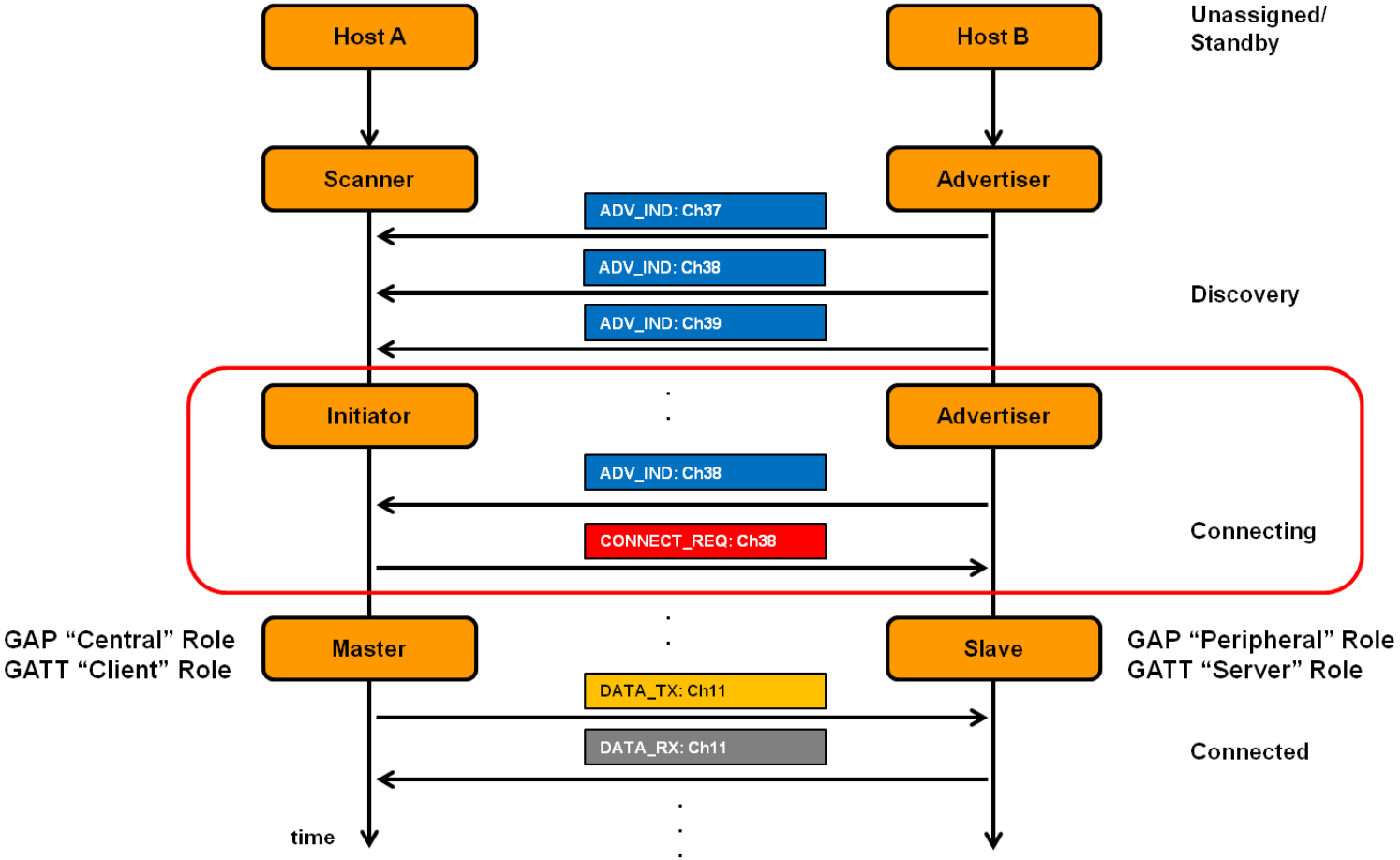
- Once a Scanner has acquired enough information to decide which Advertiser to connect to → becomes an Initiator
- Initiator starts connection process

- Initiating a connection
  - The scanner selects a suitable Advertiser to connect with
    - Based on device name, service UUID, RSSI, ...
    - Becomes Initiator

  - Initiator responds to the advertising packet with a CONNECT_REQ
    - Includes frequency hopping sequence, connection interval (time between two connection events), slave latency, supervision timeout

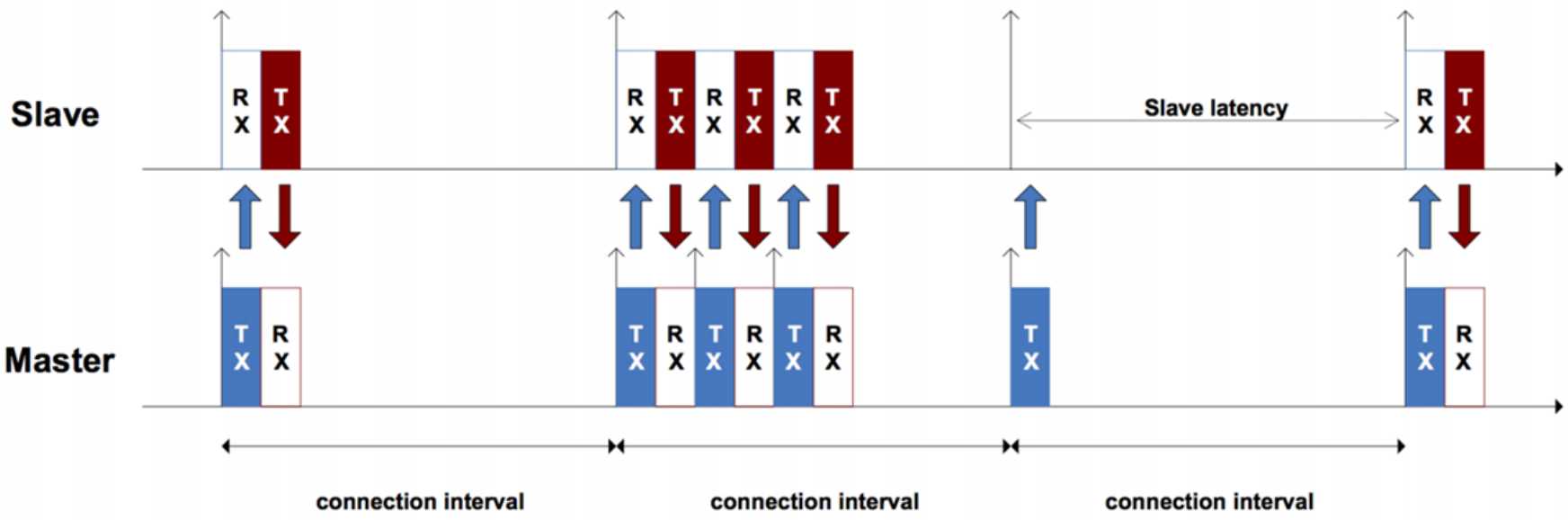
Link Layer

- Then, devices are connected and data packets can be exchanged
- Initiator → Master
- Advertiser → Slave



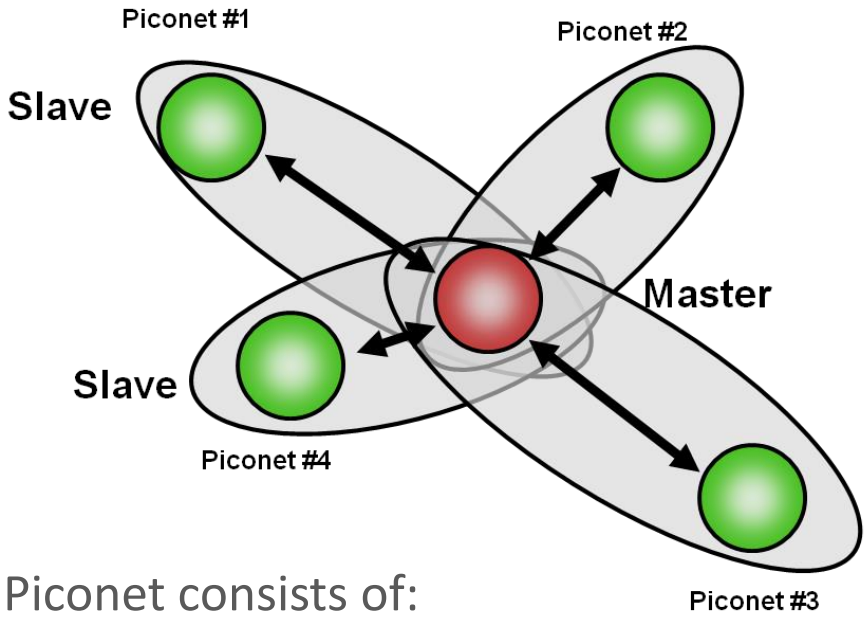
Link Layer

- Connection Events
  - Master and Slave exchange data packets at regular intervals (called "connection events")
  - 7.5 ms to 4 s (step size: 1.25 ms)
  - 0-byte data packets are exchanged if there is no other data to exchange



Link Layer

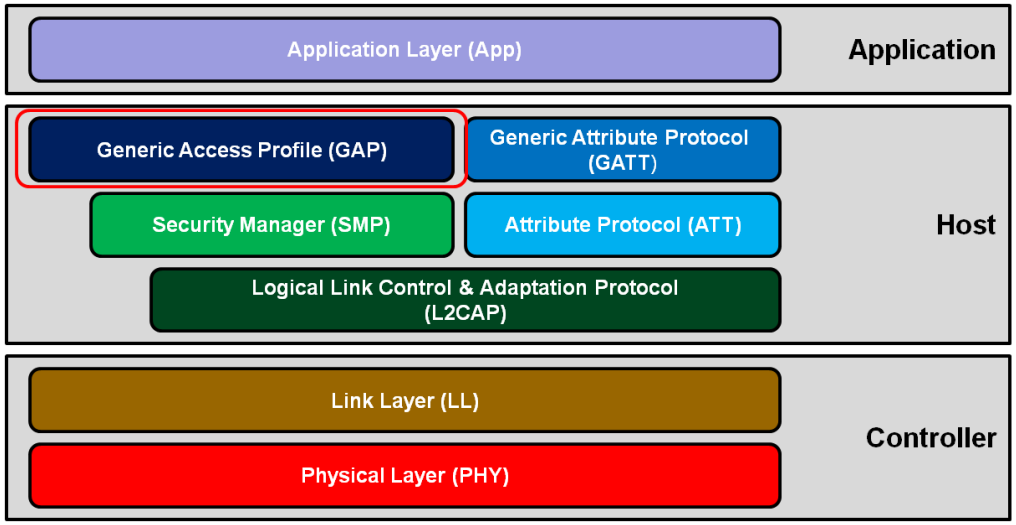
- Network topology
  - BLE Unicast connections maintain a Piconet network structure



  - The Piconet consists of:
    - A single Master, coordinating data transfer with one or more Slaves.
    - Number of slaves is hardware/OS-dependent
      (BM70 as Master supports 1 connection)
    - A Slave can only belong to one Piconet.

Host Layer

- **Generic Access Profile (GAP)**
  - Discover and connect with peers
  - Broadcast data
  - Establish secure connections
  - Defines
    - Roles
    - Operational modes and procedures
    - Security modes and procedures



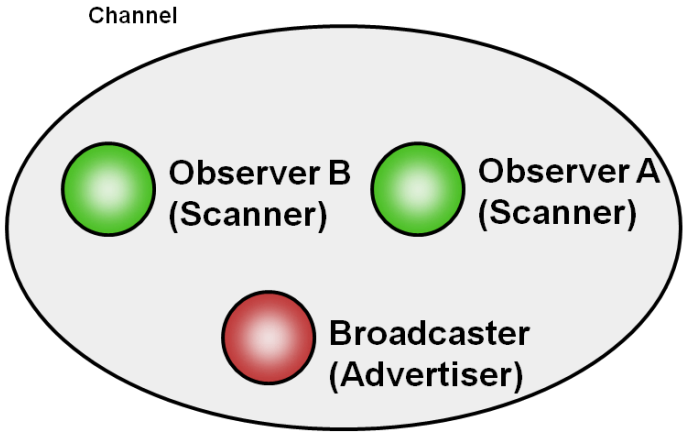
Host Layer

- GAP roles
  - Broadcaster / Observer, Peripheral / Central
  - Imposes restrictions and enforces behavior
    → Generally fixed in the design stage of the device

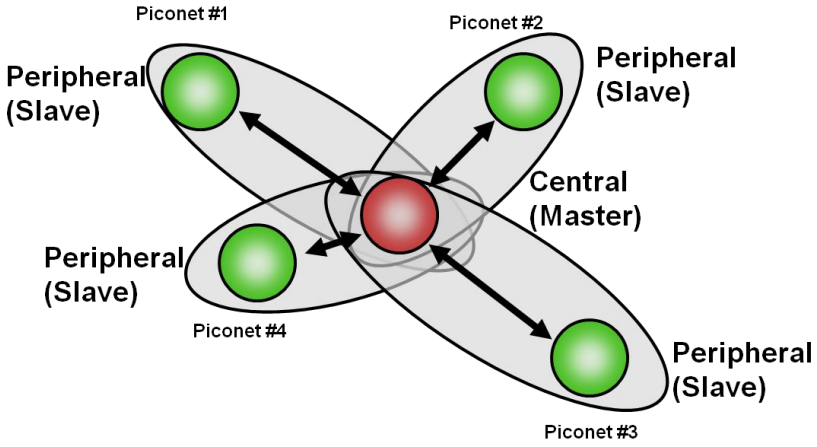
  - Broadcaster / Observer
    - Unidirectional, connection-less communications

    - Broadcaster
      - Periodically sends advertising packets with data
      - Uses the Advertiser role

    - Observer
      - Scans for broadcasters, listening for advertising data
      - Uses the Scanner role



Host Layer



- Peripheral / Central
  - Bidirectional, connection-oriented communications
  - Peripheral
    - Slave role
    - Advertises by using connectable advertising packets
    - Optimized to consume the least amount of processing power and memory
    - Enables a low-cost design
  - Central
    - Master role
    - Capable of establishing and managing a connection
    - May be connected to various devices simultaneously

Host Layer

- **GAP Modes & Procedures**
  - Discover and connect with peers
  - Broadcast data
  - Establish secure connections

Host Layer

- **GAP Modes**
  - Discovery modes
    - Non-Discoverable
    - Limited-Discoverable
    - General-Discoverable
  - Connection Modes
    - Non-Connectable
    - Directed-Connectable
    - Undirected-Connectable

Host Layer

- **GAP Procedures**
  - Discovery Procedures
    - Limited-Discovery
    - General-Discovery
  - Connection Procedures
    - General-Connection
    - Direct-Connection

Discovery Modes and Applicable Procedures

- How a peripheral advertises its presence
- What central devices can/should do with that information

Discovery Modes	Applicable Role	Applicable Peer Procedure
Non-discoverable	Peripheral	N/A
Limited-discoverable	Peripheral	Limited and General-discovery
General-discoverable	Peripheral	General-discovery

First-time connection

Host Layer

- General-discoverable mode
  - Discovery by peers for connection establishment
  - ADV_IND advertising packets at regular intervals
  - Initial factory default state for the peripheral.

  - Peripheral Configuration before entering this mode (state)
    - Advertising Packet Type (ADV_IND)
    - Advertising Interval
    - Advertising Packet Payload (Local Name, Service UUID)
    - (Optional) Scan Response Payload (TX Power, Battery Level, Custom Data)

Host Layer

- Limited-discoverable mode
  - To reconnect to a specific peer
  - ADV_DIRECT_IND advertising packets in short bursts
  - These packets contain the MAC address of the desired central device

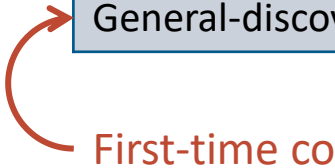
Host Layer

- General Discovery Procedure
  - Central device start scanning with no white-list filtering
    (i.e., analyzes all Advertising Packet Type flags received)
  - Required Central Configuration before beginning this procedure
    - Scan Interval, Scan Window
- Limited Discovery Procedure
  - Partially assisted by the BLE Link Layer
    - During scanning, if the Link Layer detects an ADV_DIRECT_IND packet with a matching MAC address, it will notify the application layer
  - Other BLE radios in the vicinity will ignore ADV_DIRECT_IND packets not addressed to them.

Connection Establishment Modes and Applicable Procedures

- How a central device selects which peripheral device to interact with

Discovery Modes	Applicable Role	Applicable Peer Procedure
Non-discoverable	Peripheral	N/A
Limited-discoverable	Peripheral	Limited and General-discovery
General-discoverable	Peripheral	General-discovery



First-time connection

Host Layer

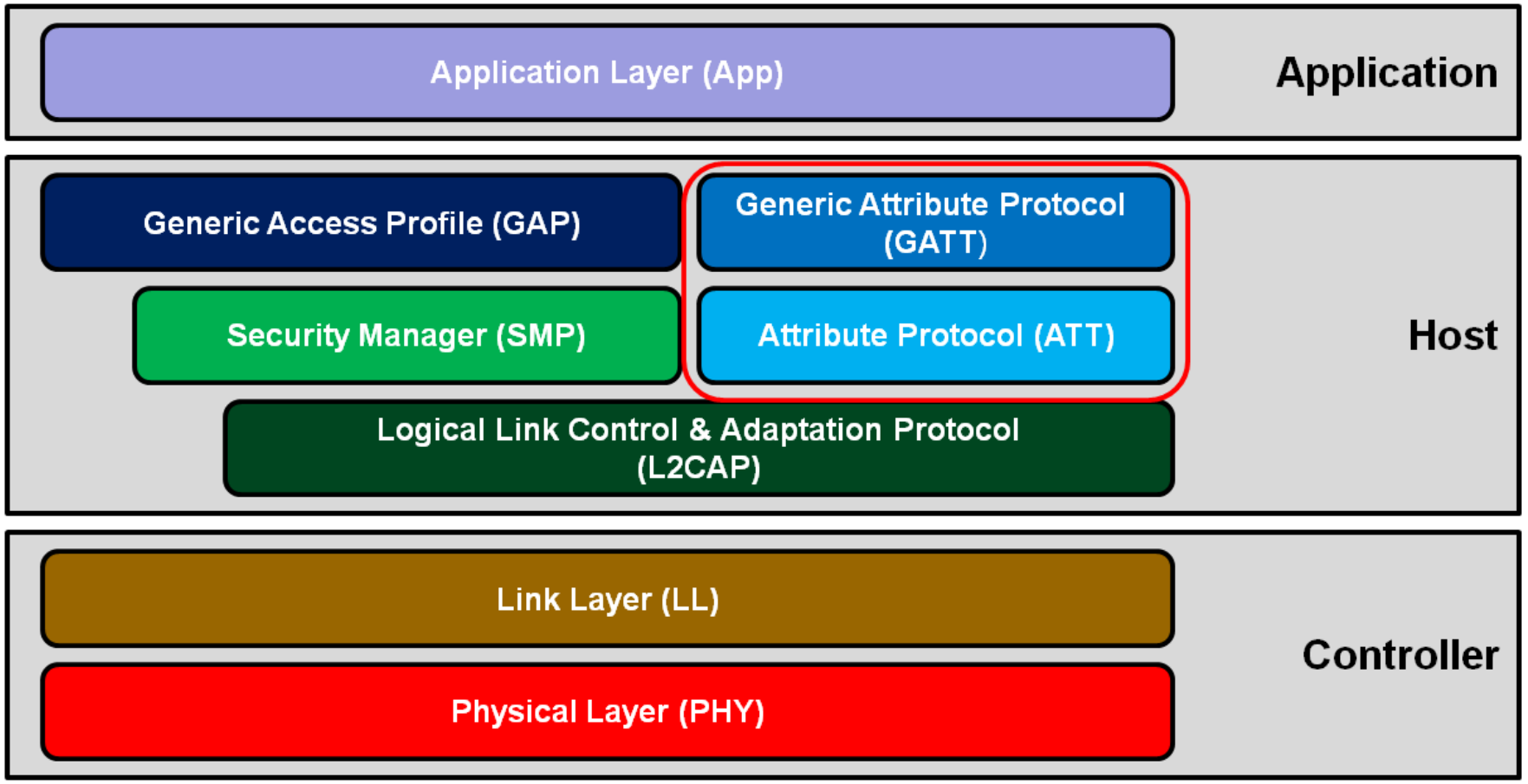
- Undirected-Connectable Mode
  - A peripheral is automatically in this "connection mode" when operating in General-Discoverable mode
  - Broadcasting ADV_IND packets
  - Looking for a connection with any peer ("Undirected")

- General Connection Establishment Procedure (two-step)
  1. Accept all ADV_IND packets, and filter on data in the packet's payload
     - Local Name, Service UUID, Custom Data, etc.
     - This step produces the MAC address of the desired peripheral to connect with.
  2. Stop scanning, and connect to that device using the Direct Connection Establishment procedure
     - Initiate a connection to a single device using its MAC address
       - Uses CONNECT_REQ Initiating PDU advertising packet

Host Layer

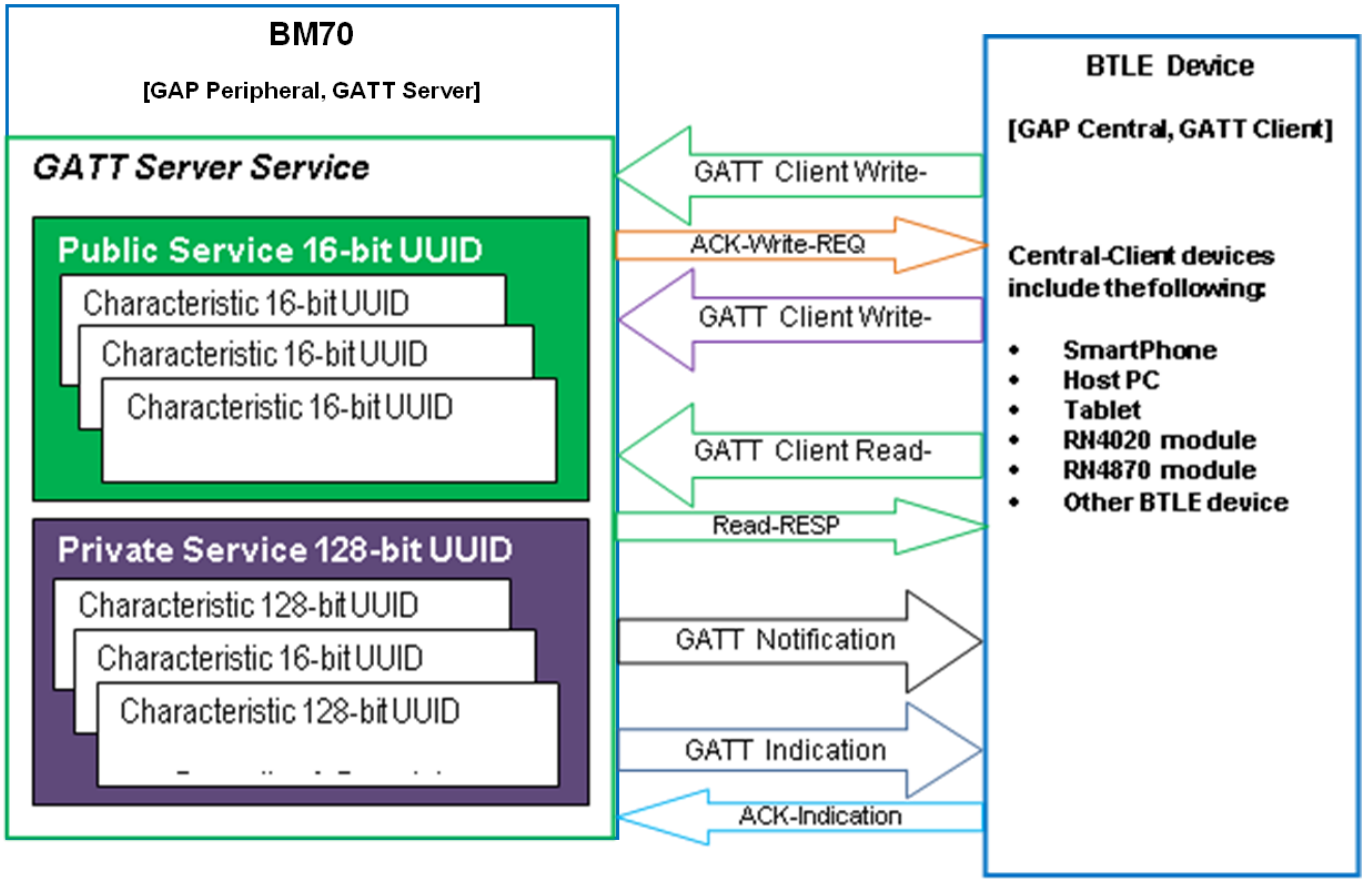
- **Generic Attribute Profile (GATT)**
  - How data will be organized and exchanged over a BLE connection
  - Certain use-case-specific profiles (GATT-Based Profiles) are standardized
    - Heart Rate Profile, Proximity Profile, etc.
  - Uses the Attribute Protocol (ATT) as a transport mechanism
  - Key aspects of GATT
    - Universally Unique Identifiers (UUIDs)
    - Roles
    - Attributes
    - Data Organization

Host Layer


Application Layer (App)
Application
Generic Access Profile (GAP)
Generic Attribute Protocol (GATT)
Security Manager (SMP)
Attribute Protocol (ATT)
Host
Logical Link Control & Adaptation Protocol (L2CAP)
Link Layer (LL)
Physical Layer (PHY)
Controller

Host Layer

- GATT Example
  - GATT Server having two services (one public, one private)
  - Client executing several GATT operations to read/write the data (characteristics) in those services



Host Layer

- **Universally Unique Identifier (UUID)**
  - Globally unique 128-bit (16-byte) number that is used to identify profiles, services, and data types in a Generic Attribute (GATT) profile
  - For efficiency, BLE adds support for shortened 16-bit UUIDs

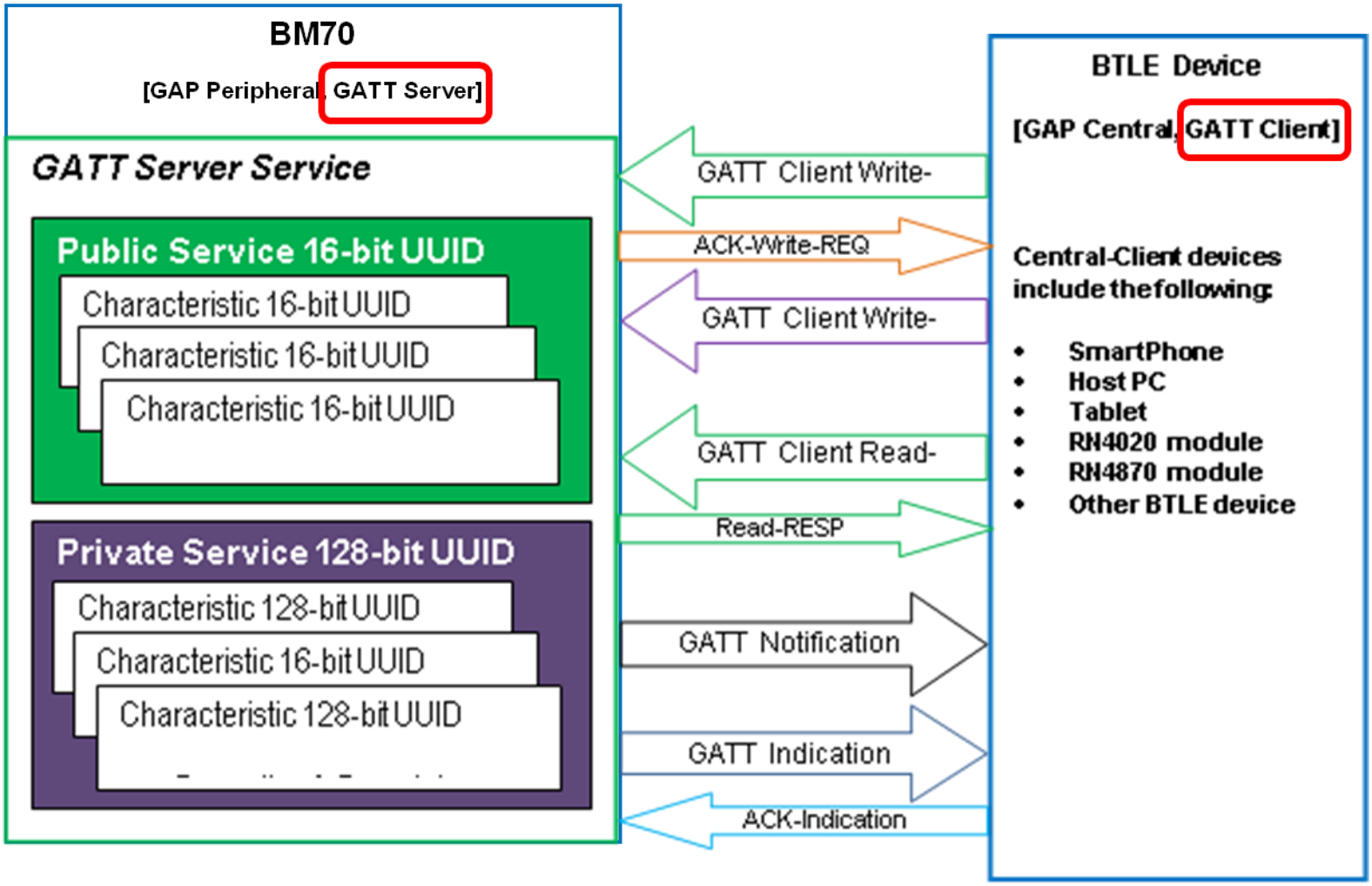
```
d60266c9-5a87-4435-8057-9371e0b9c874

70f6c5f6-c045-4fbe-9e58-8d6eb8815455

73b77305-3495-4062-ad00-c064edd8863c

4caf7b21-c365-44a1-9480-e0a8e0a75075

2c2bfccb-5e4a-4479-b181-28464b76d865
```

Host Layer

- **GATT Roles**
  - Server
    - Contains the resources (data) to be monitored
      - Organized as an Attribute Database
    - Receives requests from a client and sends responses back
    - Typically associated with the Link Layer Slave and GAP Peripheral device roles
  - Client
    - Inquires about the presence and nature of the attributes on a server
      - Performs Service Discovery
    - Sends requests to a server and receives responses
    - Typically associated with the Link Layer Master and GAP Central device roles

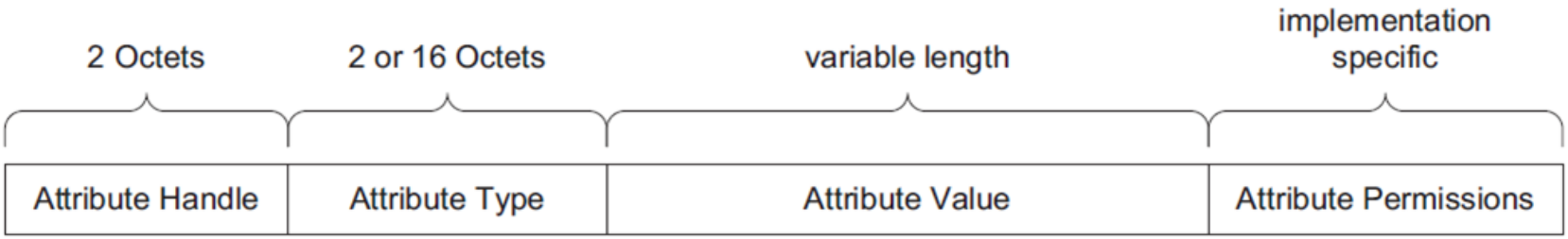
Host Layer

- Role Example



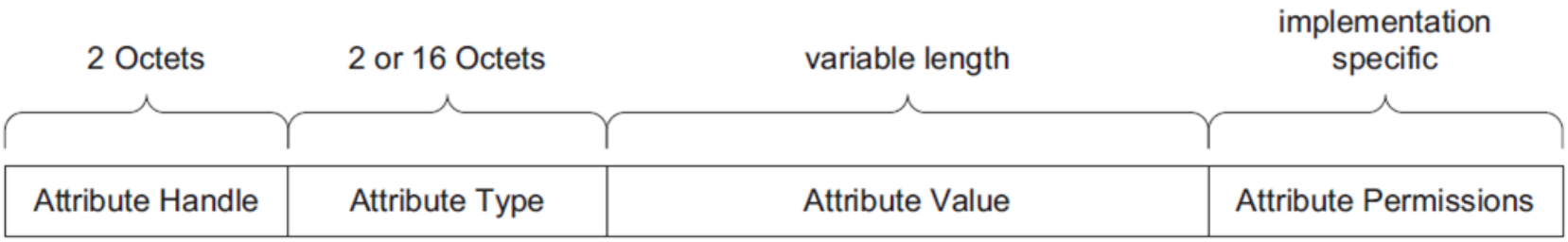
GATT Attributes

- A GATT Server contains data organized in the form of attributes



- Attribute Handle
  - Unique 16-bit identifier
    - Makes the attribute "addressable"
    - Does not change

Host Layer

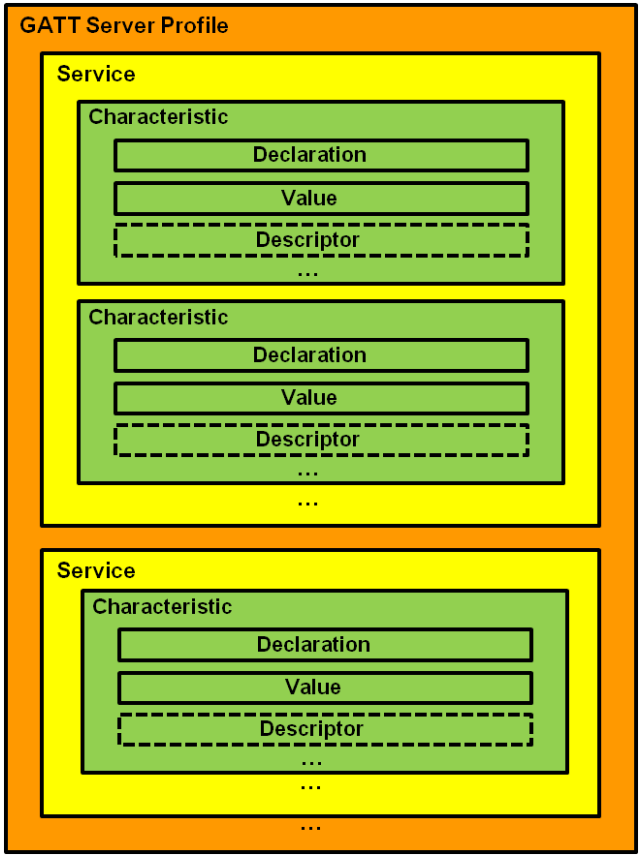


- Attribute Type (Universally Unique Identifier (UUID))
  - Determines the kind of data
  - 2-byte or 16-byte UUID
    - Service UUID, Characteristic UUID, Profile UUID, Vendor-Specified UUID, ...
- Attribute Value
  - Actual data content, which is accessible by a Client
- Attribute Permissions
  - ATT access operations allowed on the Attribute Value
    - Read Operations, Write Operations, No Operations
  - Security requirements
    - Encryption (level required), Authorization required (Yes/No)

Host Layer

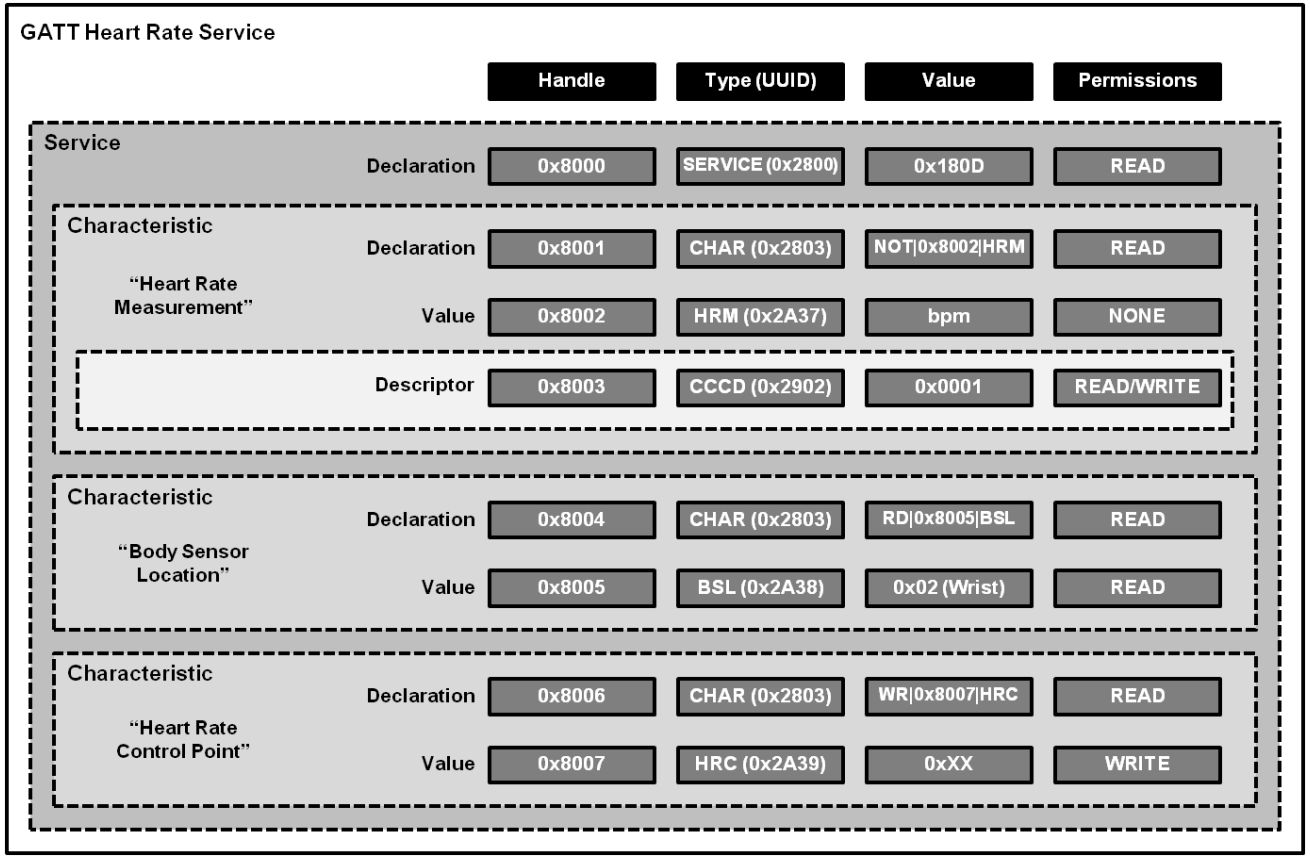
Attribute and Data Hierarchy

- GATT establishes a hierarchy to organize attributes
  - GATT Server Profile → Services → Characteristics → Attributes



GATT Profile Example

- GATT Heart Rate Service
  - 8 attributes, 3 characteristics



How Low Can the Energy Get?

- **From the previous slide, calculate energy per transaction**
  - Assume an upper bound of 3ms per minimal transaction
  - Estimated TX power is 15mW (mostly TX power amp for 65nm chips)
  - For 1.5v battery, this is 10mA. 0.015W * 0.003 sec = 45 micro Joule
- **How long could a sensor last on a battery?**
  - An example battery: Lenmar WC357, 1.55v, 180mAh, $2-5
  - 180mAh/10mA = 18Hr = 64,800 seconds = 21.6M transactions
  - Suppose this sensor sends a report every minute = 1440/day
  - For just the BT LE transactions, this is 15,000 days, or > 40 years
  - This far exceeds the life of the battery and/or the product
- **This means that battery will cost more than the electronics**
  - This sensor could run on scavenged power, e.g. ambient light

Competitive Perspective

Technology	Classic *Bluetooth* technology (BR/EDR)[1]	*Bluetooth* low energy technology[2]	ZigBee
Radio Frequency	2.4 GHz	2.4 GHz	2.4 GHz
Distance / Range	10 to 100 meters[3]	10 to 100 meters[3]	10 to 200 meters[4]
Over the air Data Rate	1-3Mbps	1Mbps	250kbps at 2.4 GHz.
Application Throughput	0.7-2.1 Mbps	0.2 Mbps	<0.1 Mbps
Nodes/Active Slaves	7 / 16777184[5]	Unlimited[6]	65535[7]
Security	64b/128b and applications layer user defined	128b AES and application layer user defined	128b AES and application layer user defined
Robustness	Adaptive fast frequency hopping, FEC, fast ACK	Adaptive fast frequency hopping	DSSS, Uses only 16 ch. in ISM band, optional mesh topology has long recovery time
Latency (from a non connected state)			
Total time to send data (det.battery life)[8]	100ms	<3ms	<10ms
Government Regulation	Worldwide	Worldwide	Worldwide
Certification Body	Bluetooth SIG	Bluetooth SIG	ZigBee Alliance
Voice capable	Yes	No	No
Network topology	Scatternet	Star-bus	Star or Mesh
Power Consumption	1 as the reference	0.01 to 0.5(depending on use-case)	2 (router) / 0.1 (end point)
Peak current consumption (max 15 mA to run on coin cell battery)	<30 mA	<15 mA	<15 mA
Service discovery	Yes	Yes	No
Profile concept	Yes	Yes	Yes
Primary Use Cases	Mobile phones, gaming, headsets, stereo audio streaming, automotive, PCs, consumer electronics, etc.	Mobile phones, gaming, PCs, watches, sports & fitness, healthcare, automotive, consumer electronics, automation, industrial, etc.	Fixed location industrial, building & home automation, AMI/SmartEnergy

ZigBee and Bluetooth Low Energy

- **Business comparison:**
  - ZigBee is older. It has gone through some iterations
  - ZigBee has market mindshare, but not a lot of shipments yet.
  - Market barriers: connectivity – ZigBee is not in PCs or mobile phones yet.
- **Technical comparison:**
  - Zigbee is low power; Bluetooth LE is even lower. Detailed analysis depends on specific applications and design detail, no to mention chip geometry.
  - ZigBee stack is light; the Bluetooth LE/GATT stack is even simpler
- **Going forward:**
  - ZigBee has a lead on developing applications and presence
  - Bluetooth low energy has improved technology, and a commanding presence in several existing markets: mobile phones, automobiles, consumer electronics, PC industry
  - Replacing “classic Bluetooth ” with “dual mode” devices will bootstrap this market quickly

What are the USE CASES planned for BT 4.0?

- Proximity
- Time
- Emergency
- Network availability
- Personal User Interface
- Simple remote control
- Browse over Bluetooth
- Temperature Sensor
- Humidity Sensor
- HVAC
- Generic I/O (automation)
- Battery status
- Heart rate monitor
- Physical activity monitor
- Blood glucose monitor
- Cycling sensors
- Pulse Oximeter
- Body thermometer

Use Cases

- **Physical Security**

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EMTEK ASSA ABLOY

Bluetooth

INTERIOR TRIM

Use Cases

- **Home Automation**

Use Cases

- Geo-fencing / Positioning