Bluetooth

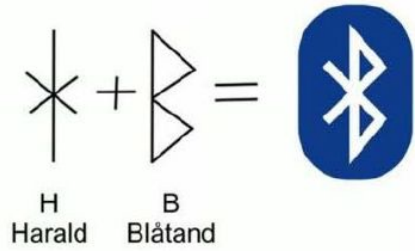
Communication Protocols

Bluetooth

- A wireless technology used for exchanging data between devices
- One of the most popular short-range wireless communication standard
- Uses UHF radio waves in the ISM radio bands, from 2.400 GHz to 2.4835 GHz
- Used for building personal area networks (PANs)
- Originally developed as a wireless alternative to RS-232 data cables
- Initial development was done at Ericsson Mobile in Lund, in 1989
- The IEEE standardized Bluetooth as IEEE 802.15.1 in 2002
  - But no longer maintains the standard
- The Bluetooth SIG (Special Interest Group) maintains the development of Bluetooth
  - A global community of over 34,000 companies such as Ericsson, IBM, Intel, Nokia, and etc.

Bluetooth

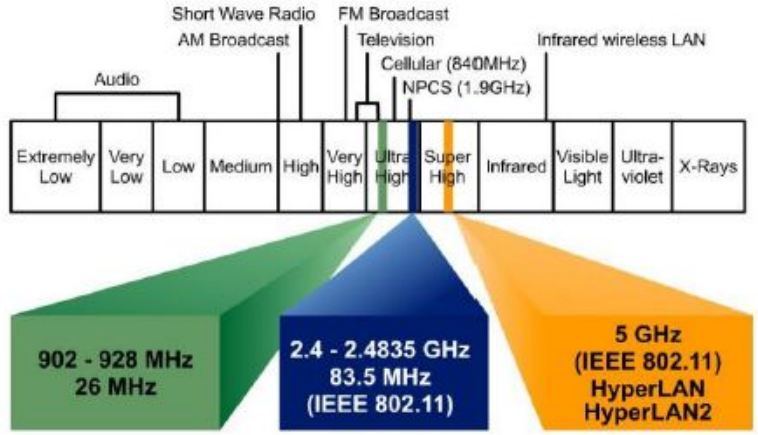
- Named after the danish king Harald Blåtand (Bluetooth)
  - He was good at communication and was a king that united Denmark
  - The idea behind the technology was to unite communication
- There are different versions of Bluetooth



Bluetooth 1.x (1998-2003)	Bluetooth 2.x (2004 - 2007)	Bluetooth 3.0 + HS (2009)	Bluetooth 4.x (2010 - 2014)	Bluetooth 5.x (2016 - …)
- Base Rate: 1 Mbps - Max Range: 10 m - Latest version: v1.2	- Enhanced Data Rate - Up to 3 Mbps - Max range: 10 m - **S**ecure **S**imple **P**airing - Latest version: 2.1 + EDR	- High Speed mode - Bluetooth v3.0: 3 Mbps - Max range: 10 m - HS Max rate: 24 Mbps - Transmission over WiFi (802.11) connection. - Bluetooth is only used to establish and manage a connection	- Bluetooth v4.2: 1 Mbps - Up to 24 Mbps - Up to 50 m - BLE introduced - Improved privacy to prevent tracking - Almost a new technology - Categories: classic, high-speed, and low-energy - Latest version: v4.2	- 2x speed, 4x range - Up to 48 Mbps - Up to 200 m - Select bands with less interference - Forward Error Correction - Needs new hardware

Classic Bluetooth

- Uses ISM (Industrial, Science and Medical) radio bands
- Frequency ranges: 2400MHz – 2483.5MHz
  - Power Constrained
  - License free and free to use
  - Coexistence: WLAN(802.11), Zigbee(802.15.4), …
  - Bluetooth divides the bandwidth into 79 channels
    - Each channel has a bandwidth of 1 MHz
    - Guard bands 2 MHz at the bottom end and 3.5 MHz at the top
    - Bluetooth divides data into packets, and transmits each packet on one of 79 channels

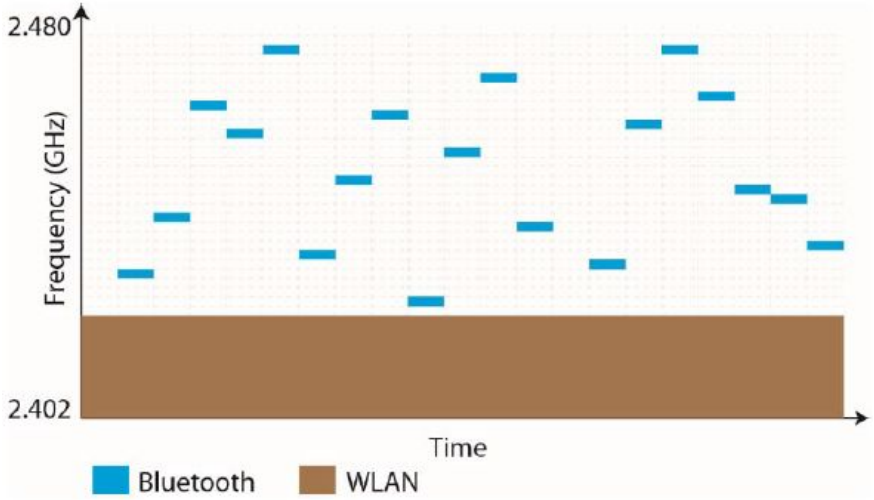


- Uses Frequency Hopping technology
  - A technology that spreads the signal over rapidly changing carrier frequencies
  - Data is sent on multiple radio spectrums

Classic Bluetooth

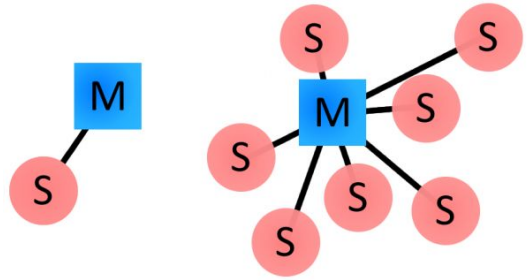
- Frequency Hopping / Adaptive Frequency Hopping and Time slots
  - Bluetooth changes the frequency of the data signal 1600 per second
  - Adaptive FH can detect the used spectrum bandwidth and avoid interference
  - Uses TDMA and each slot length is 625 µs
- The transmit power, and range of a Bluetooth module is defined by its power class
- A module can operate in one or more power classes

	Max. Output Power	Max. Range
Class 1	100 mw	100 m
Class 2	2.5 mw	10 m
Class 3	1 mw	1 m



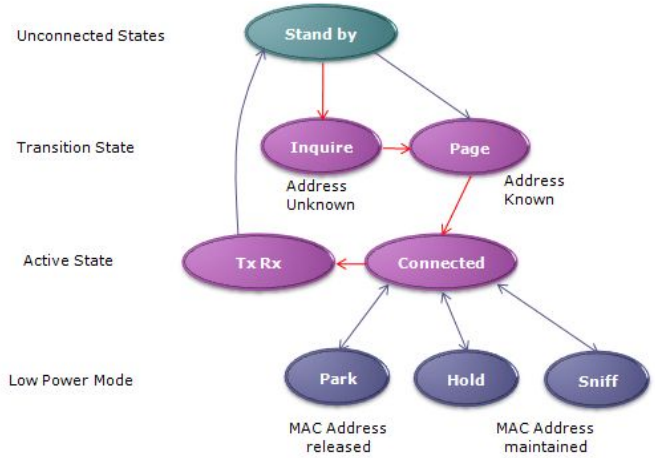
Classic Bluetooth

- Is a packet-based protocol
  - Every packet is an independent transaction
- Master/slave architecture in classic Bluetooth
  - Any slave in the network can only be connected to a single master
  - The slaves can not communicate to each other
- A master can communicate with up to seven slaves in a network
  - Slaves get synchronized to the master clock
  - The master's transmission begins in even slots and the slave's in odd slots
- Every Bluetooth device has a unique 48-bit address (BD_ADDR)
  - Follows same pattern as LAN MAC addresses
- Bluetooth devices can also have user-friendly names (up to 248 bytes long)



Classic Bluetooth

- Connection Process: A multi-step process involving three progressive states
  - **Inquiry** - devices discover each other
  - **Paging** (Connecting) - process of forming a connection
  - **Connected** - After completing the paging process
    - **Active** Mode - The normal mode
      - The device actively transmitting or receiving data
    - **Sniff** Mode - A power-saving mode
      - The device sleeps and only listens to transmissions at a set interval (e.g. every 100ms)
    - **Hold** Mode - A temporary power-saving mode
      - The device sleeps for a defined period and then returns back to active mode
      - The master can command a slave device to hold
    - **Park** Mode - The deepest sleep mode
      - A master can command a slave to park
      - The slave will become inactive until the master command it to wake back up



Classic Bluetooth

- Bonding and Pairing
  - Bonds are created through a one-time process called pairing
  - Pairing is a form of information registration for connected devices
    - They share their addresses, names, and profiles, and usually store them in memory
    - They also share a common secret key, which allows them to bond in the future
  - Pairing usually requires an authentication process; e.g. entering a PIN code
  - Bonded devices automatically establish a connection whenever they're close enough
- Bluetooth Profiles
  - Additional protocols, built upon the basic Bluetooth standard
  - More clearly define what kind of data and application a Bluetooth module is transmitting
  - For two Bluetooth devices to be compatible, they must support the same profiles
  - E.g. Serial Port Profile (like RS-232 and UART), Human Interface Device (like keyboards), FTP ...

Classic Bluetooth - Summery

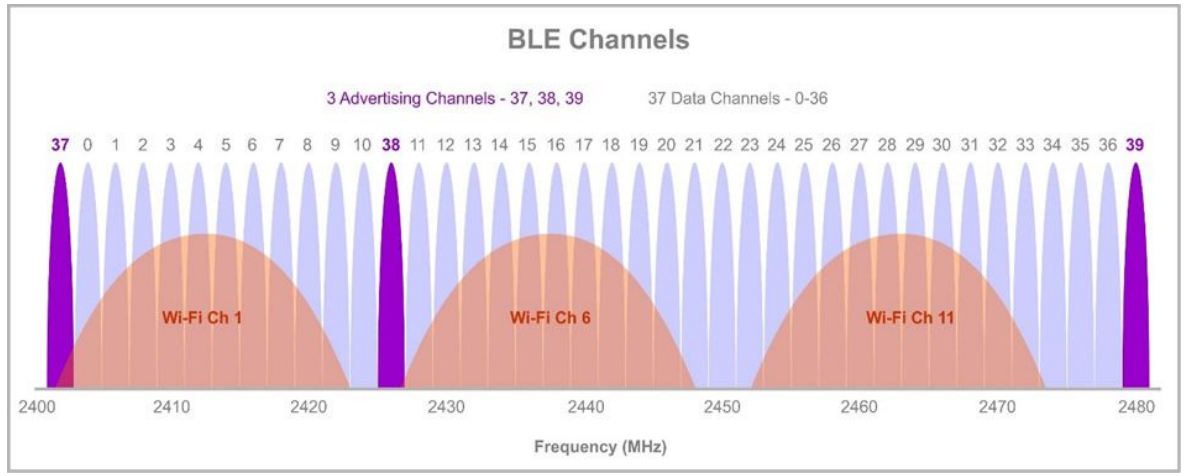
- Reliable - transmissions are based on connected link
- Relatively high speed, especially with EDR
  - Suitable for applications which require high data rate and stability
  - Music / File / Voice
- High Power Consumption
  - To perform high speed transmission
  - To maintain the Link
- Supports Asynchronous Connection-Less (ACL) transmission
  - Used for general data packets which are transmitted at irregular intervals
- Synchronous Connection-Oriented (SCO) transmission
  - Used for voice data. Each device transmits encoded voice data in the reserved timeslot.

Bluetooth Low Energy - Key Features

- A Wireless Personal Area Network technology
- Low power protocol (1 year on coin cell battery)
  - For applications with low power requirements; e.g. IoT, mobile phones, tablets and etc.
- Maintain connection for long time (3 ms vs. 0.625 ms)
- Stateless protocol (every request is an independent transaction)
- Shorter connecting time (6 ms vs. 100 ms)
- Max. Range: less than 100 m
- Max. data rate: 1 Mbps
- Small size and low cost
- Flexibel topology

Bluetooth Low Energy - Bands and Channels

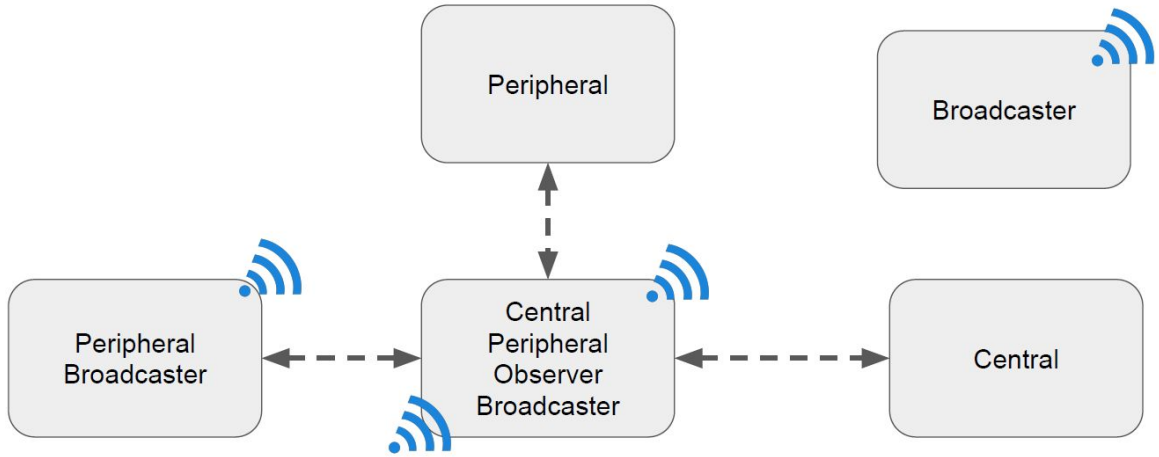
- Uses ISM radio bands (2.400–2.4835 GHz)
  - Divided in 40 RF Channels with 2 MHz spacing
  - 3 Advertising Channels
    - Device discovery
    - Connection establishment
    - Broadcasts
    - Selected to minimize interference
  - 37 Data Channels



- Uses Adaptive Frequency Hopping
  - To detect used band to avoid interference
  - Regular Hopping Sequence with given intervals

Bluetooth Low Energy - GAP Roles

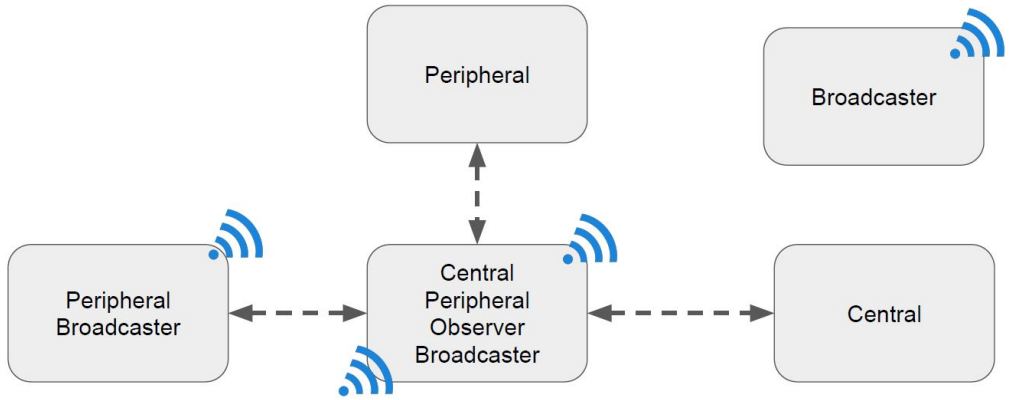
- All BLE devices use a GAP (Generic Access Profile) to
  - Define device roles, network topology, discovery process, device management, security and connection process between BLE devices.
- The GAP defines four roles:
  - **Broadcaster** (Transmitter only)
    - Can only advertise
      - Sends only advertising packets
    - Can be discovered by observers
    - Cannot be connected



  - **Observer** (Receiver only)
    - Scans for broadcasters and reports the information to an application.
    - Can only send scan requests, but cannot be connected.

Bluetooth Low Energy - GAP Roles

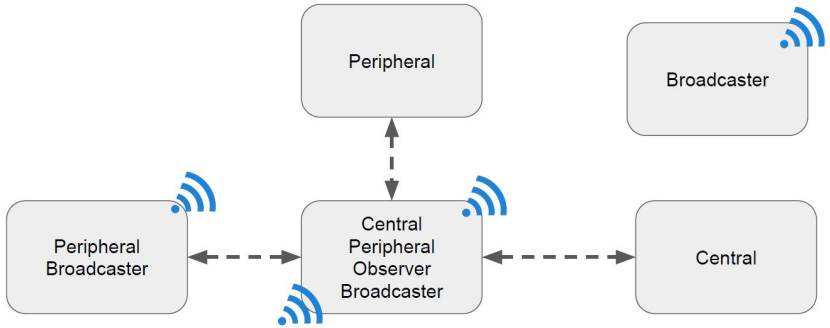
- The GAP defines four roles:
  - **Peripheral** - A device that
    - Advertises connectable advertising packets
    - Becomes a slave once it gets connected.
  - **Central** - A device that
    - Initiates connections to peripherals
    - Becomes master when connections are established
    - Supports multiple connections



- A BLE device may support multiple roles
- Each BLE device has a unique 48 bit address which can be
  - Private: Is static but can be changed after power cycle
  - Public: Follows the same pattern as MAC addresses; Obtained from IEEE

Bluetooth Low Energy - Advertising (Broadcasting)

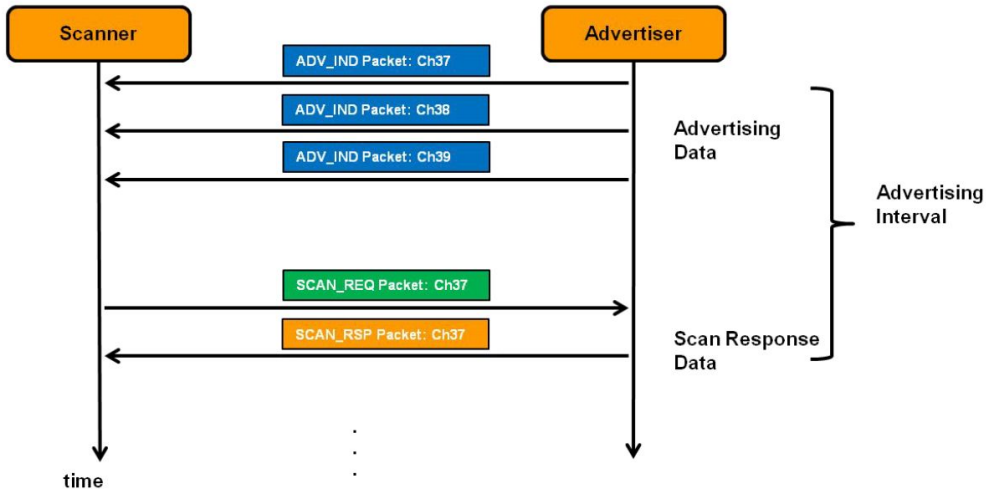
- Reporting data / advertisement
- There are three advertising channels
  - Transmit on all advertising channels each connection interval
- Configurable; channel / power / time interval
- A central node can request data via “Scan request”
  - Receives a “Scan response”
- Supports multiple Scan request - scan response
  - Request more data without initiating a new connection
- BLE devices are detected on broadcasting advertising packets
  - A scanner listens to the advertising channels intervally



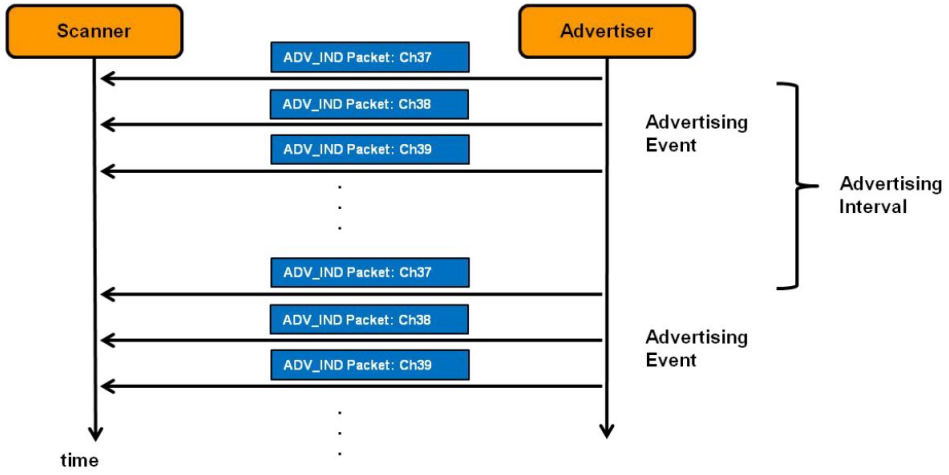
Bluetooth Low Energy - Scan and Discovery

- Passive Scan
- Active Scan
  - SCAN_REQ: “I want more information”
  - SCAN_RSP: “More information as you wish”

BLE Active scanning

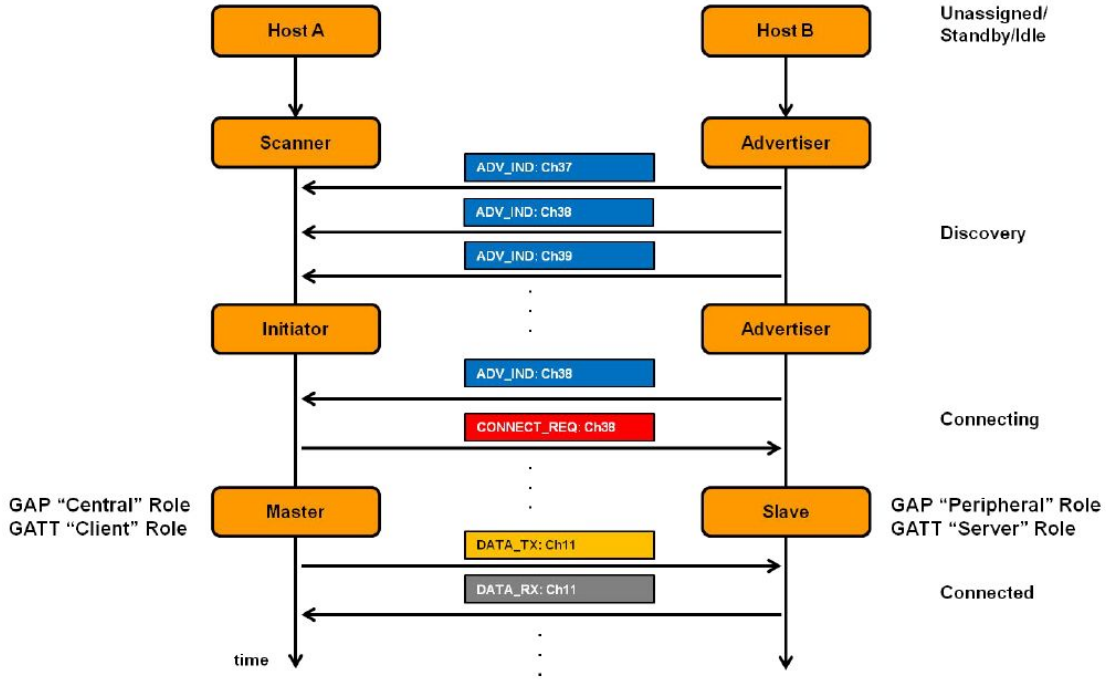


BLE Passive scanning



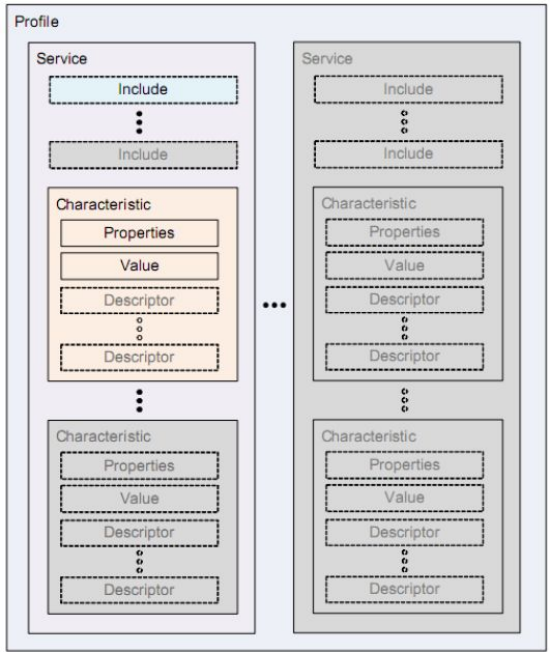
Bluetooth Low Energy

- Scan and Connect
  - CONNECT_REQ: “OK, let’s connect”
    - “Follow these parameters: … … …”
  - Connection Interval (7.5ms – 4s)
  - Connection Timeout (100ms – 32s)



Bluetooth Low Energy - Software Model

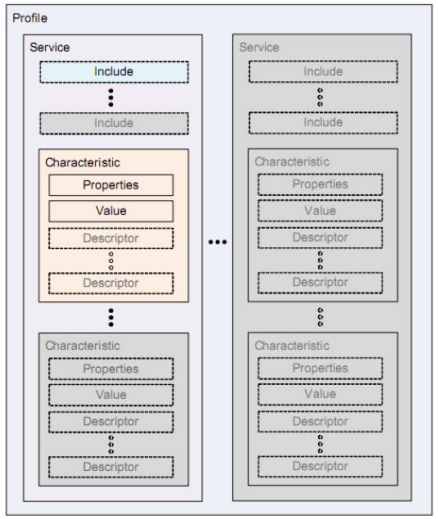
- BLE devices use Generic Attribute Profiles (GATT). A GATT
  - Describes an application
  - Is a collection of services; defined by Bluetooth SIG or the customer
- **Client**: A device that initiates GATT commands and requests, and accepts responses. For example, a computer or smartphone
- **Server**: A device that receives GATT commands and requests, and returns responses. For example, a temperature sensor
- **Characteristic**: A data value transferred between client and server
  - For example, the current temperature.



- **Service**: A collection of related characteristics, operate together to perform a particular function.
  - For example, the ***Health Thermometer*** service includes characteristics for a temperature measurement value, and a time interval between measurements.

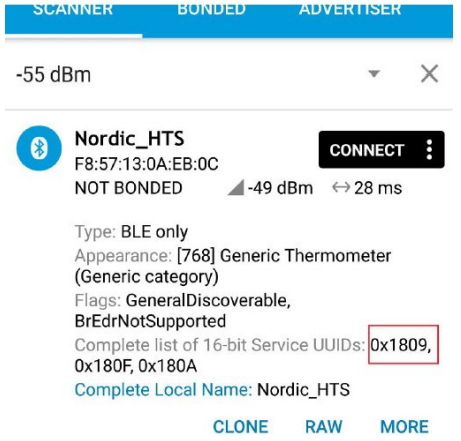
Bluetooth Low Energy - Software model

- **Descriptor**: A descriptor provides additional information about a characteristic
  - For example, a temperature value characteristic may have
    - An indication of its units (e.g. Celsius), and
    - The maximum and minimum values which the sensor can measure.
  - Optional – each characteristic can have any number of descriptors.
- Services may also include other services as sub-functions;
  - The main functions of the device are so-called primary services
  - The auxiliary functions they refer to are secondary services
- BLE Identifying applications
  - Services, characteristics, and descriptors are collectively referred to as attributes, and identified by 128 bits UUIDs (Universal Unique Identifier)



Bluetooth Low Energy - Software model

- BLE Identifying applications …
  - Broadcasted on advertising channels
  - A random or pseudo random UUID can be used for private use
  - The Bluetooth SIG have reserved a range of UUIDs (of the form xxxxxxxx-0000-1000-8000-00805F9B34FB) for standard attributes
    - For efficiency, these identifiers are represented as 16-bit or 32-bit values
  - Services defined by the Bluetooth SIG
  - E.g. UART over BLE (6E400001-B5A3-F393-E0A9-E50E24DCCA9E)
    - RX Characteristic (UUID: 6E400002-B5A3-F393-E0A9-E50E24DCCA9E)
    - TX Characteristic (UUID: 6E400003-B5A3-F393-E0A9-E50E24DCCA9E)
- Data exchange
  - Read / write the value of characteristics; may need authentication



Bluetooth Low Energy - Software model

- GATT operations: The GATT protocol provides a number of commands
  - Discover UUIDs for all primary services
  - Find a service with a given UUID
  - Find secondary services for a given primary service
  - Discover all characteristics for a given service
  - Find characteristics matching a given UUID
  - Read all descriptors for a particular characteristic
  - Read (data transfer from server to client) and Write (from client to server) the values of characteristics
  - GATT offers notifications and indications:
    - The client may request a **notification** for a particular characteristic from the server.
      - The server can then send the value to the client whenever it becomes available.
    - An **indication** is similar to a notification, except that it requires a response from the client, as confirmation that it has received the message

Bluetooth Low Energy - Security

- BLE Encryption
  - AES128 encryption to protect the content
- Keys
  - Temporary key: Used in pairing process
  - Short term key: Used to encrypt connection during initial pairing
  - Long term key: Replaces short term to encrypt connection
  - Identity resolving key: Used to hide identities
  - Connection signature key: Authentication key
- Higher level encryption
  - Application level encryption

Bluetooth

- Some useful links
  - Bluetooth
  - Bluetooth Core Specification v4.2
  - Bluetooth Basics
  - How Bluetooth Works
  - Bluetooth 5: a concrete step forward towards the IoT
  - ESP32 Bluetooth Classic with Arduino
  - Getting Started with ESP32 Bluetooth Low Energy
  - Bluetooth Low Energy App Development: The Basics
  - All About Bluetooth - For the Layman
  - What is Bluetooth 5? - Gary explains