Università Politecnica delle Marche
Facoltà di Ingegneria
Corso di Laurea in Ingegneria Elettronica

BLUETOOTH

1

1

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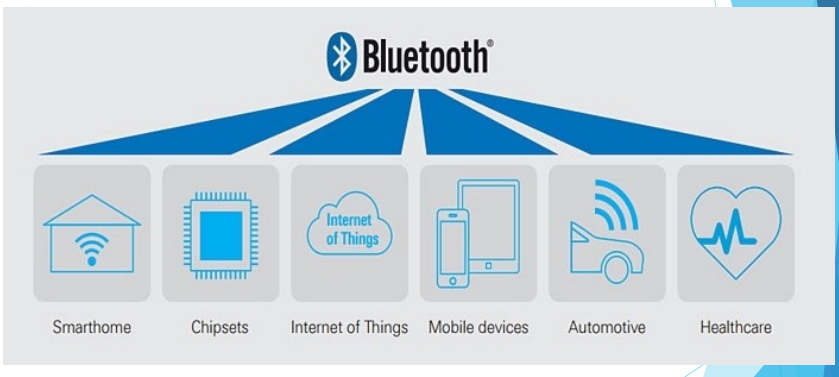

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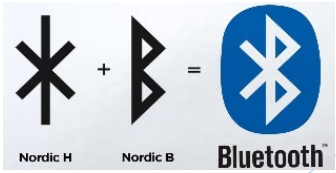
Bluetooth is a short range, low cost, low power radio communication system.

- The idea was born in 1994 from Ericson Mobile.
- The transformation into standard takes place by the Bluetooth Special Interest Group (SIG), founded in 1998 by Ericsson, IBM, Nokia Intel and Toshiba (today it includes more than 35000 companies).
- The name Bluetooth (Dente blue) derives from Harold Bluetooth (Harald Blåtand, in Scandinavian), a Viking king who lived between 910 and 940, who proposed to unify all the peoples of his kingdom under the same language, currency and religion.



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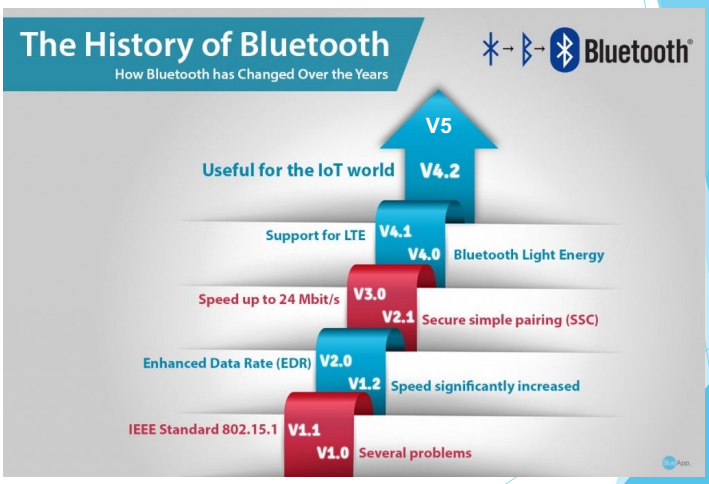
Evolution of Bluetooth



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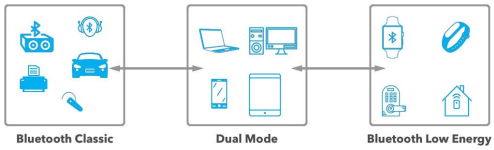
Two Types of devices

- ***Bluetooth Classic (BR/EDR)*** : used in wireless speakers, car infotainment systems, and headsets.
- ***Bluetooth Low Energy*** : is more prominent in applications where power consumption is crucial (such as battery-powered devices) and where small amounts of data are transferred infrequently (such as in sensor applications).

Taken individually, these two types of Bluetooth devices are incompatible with each other. However, there are **Dual Mode Bluetooth** devices that implement both types.



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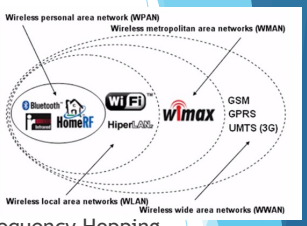
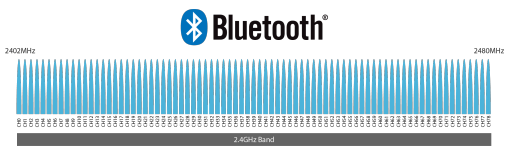
General features



- **Wireless link via radio** (WPAN)
- It operates between **2400 ÷ 2483.5 MHz**, in the universally recognized **ISM** (Industrial Scientific and Medical) open access range.
- To reduce interference and fading, there is a subdivision of the band into **40 or 79 channels** depending on the version and the devices adopt the Frequency Hopping technique.
- Transmission powers from **few mW** to a **hundredths mW**
- Range from a **few cm** (beacon) to **hundreds of meters** (v.5 - WLAN)
- Transfer rates between **125kbps and 24 Mbps.**



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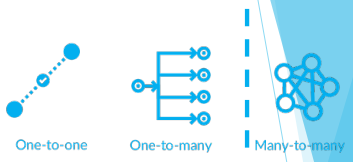
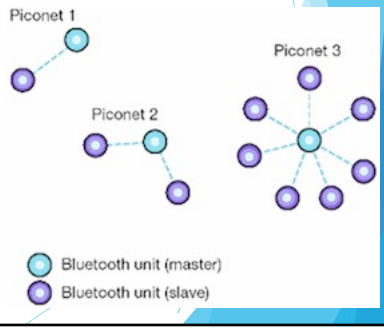
6

Piconet

- Basic Unit of a Bluetooth network
- Two or more units sharing the same channel form a network called Piconet.
- In every piconet there will always be 1 **Master** + [1..7] **Slave**
- Only one device at a time can communicate with the master.
- Two slaves cannot communicate with each other but must pass by the master as an intermediary.
- The master takes care of channel management, communications, clock synchronization and frequency hopping.





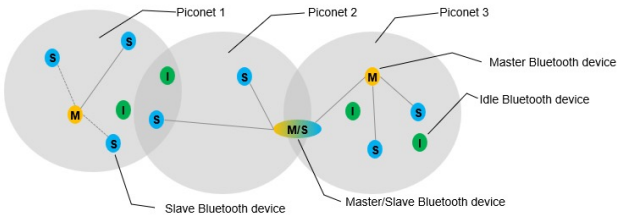
7

Scatternet

- The interconnection between two or more Piconet is called **Scatternet**
- «**Bridge Node**» – It is a node in a piconet, whether a master or a slave, that acts as a slave in another piconet. A bridge connects the individual piconets to form the scatternet.

✅ It allows multiple devices to share the same physical area and efficiently use the available bandwidth.

❌ As the number of piconets increases, the probability of collision between the transmissions of the different piconets increases.

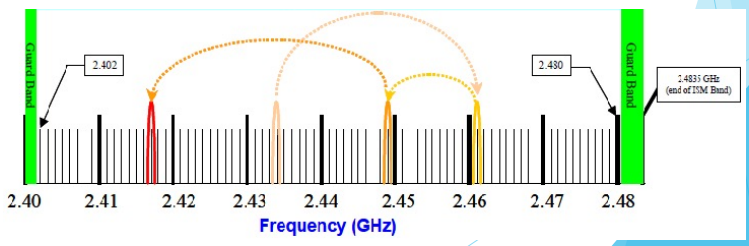


8

Transmission technique

Bluetooth technology uses FHSS - Frequency Hopping Spread Spectrum

- Jump from one physical channel to another based on a pseudorandom sequence (based on the Bluetooth address of the Master)
- The sequence is unique for all piconet devices.
- 1600 hops/s , each channel is occupied for 0.625 ms (Slot)
- Ensure resistance to interference and multipath effects;
- Increases the security of communication, only the units concerned know the correct jump sequence



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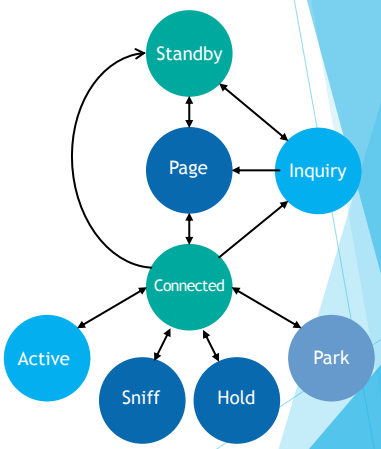
10

Modalità di funzionamento

- **Standby** by default all Bluetooth devices are in this state. Periodically performs a scan cycle to check for communications from other devices.
- **Inquiry** procedure for identifying the BT devices in the vicinity. The device creates a list with the addresses of the devices found.
- **Page** initial phase of the connection procedure. The Master sends paging type messages that contain the access code (DAC) of the slave.



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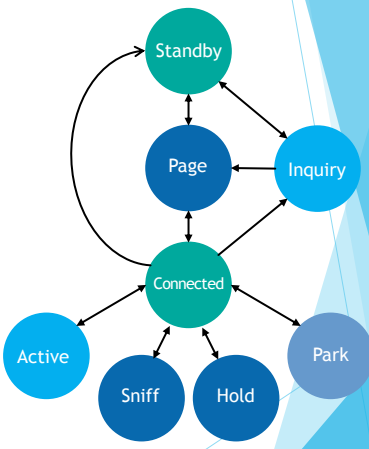
12

Modalità di funzionamento (2)

In connection, the devices can operate in:

- **Active mode**: standard mode where the device transmits and receives.
- **Sniff mode**: power saving mode and only listen.
- **Hold mode**: temporary power saving, return to Active mode when time runs out
- **Park mode**: sleep mode ordered by the master.



13

13

Bluetooth®

LOW ENERGY (4.0) / SMART

15

15

A **new radio, new protocol stack, new profile architecture**. Released in 2010.

Features:

- Mostly **new PHY**; some parts derived from the Basic Rate (BR) radio New advertising mechanism, for ease of discovery & connection
- **New Generic Attribute Profile (GATT)** to simplify devices and the software that uses them.
- Asynchronous **Client / Server architecture**
- Designed to be **lowest cost** and **easy to implement**
- AFH – Adaptive Frequency Hopping, it makes the connection more reliable and robust
- **Retransmission** in case of error and CRC (Cyclic Redundancy Checks)
- Security, achieved by pairing, connecting, protection MITM (Man in the Middle) AES-128 encryption

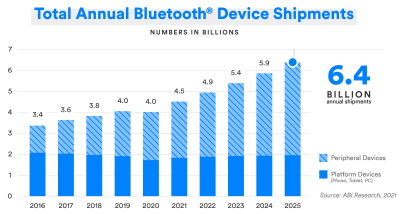
16

16

Advantages of BLE

- **Lower power consumption.** It's optimized, and less power consumed, by turning the radio off as much as possible, in addition to sending small amounts of data at low transfer speeds.
- **No cost to access the official specification documents.** Free download from Bluetooth SIG website. (https://www.bluetooth.com/specifications/specs/core-specification/)
- **Lower cost of modules and chipsets** when compared to other similar technologies.

- Its **existence in most smartphones in the market** (compared to competitors such as ZigBee, Z-Wave, and Thread)



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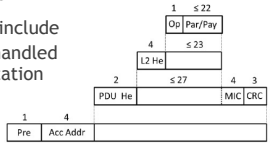
17

Limitations of BLE

- **Data Throughput** is limited by the physical radio data rate. This rate depends on the Bluetooth version used (v4.2 and earlier --> 1Mbps; v5 and later --> 125Kbps, 250Kbps, 1Mbps and 2Mbps). At the application layer and for the end-user, the data rate is much lower than the radio data rate due to the following factors:
  - **Gaps in between packets:** The Bluetooth specification defines a gap of 150 microseconds between packets being transmitted as a requirement to comply to the specification. This gap is time lost with no data exchange between two devices

  - **Packet overhead**: All packets include header information and data handled at levels lower than the application level



Par/Pay:	Parameters and Payload
Op:	ATT Opcode
PDU He:	PDU Header
L2 He:	L2CAP Header
Acc Addr:	Access Address
Pre:	Preamble
MIC:	Message Integrity Check
CRC:	Cyclic Redundancy Check

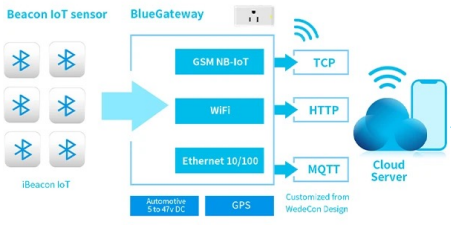
  - **Slave data packets requirement:** The requirement to send back data packets from the slave, even when no data needs to be sent back and empty packets are sent.
  - **Retransmission of data packets** in the case of packet loss or interference from devices in the surrounding environment

18

18

Limitations of BLE

- **Range,** BLE was designed for short range application. There are a few factors that limit the range of BLE:
  - It operates in the 2.4 GHz ISM spectrum which is greatly affected by **obstacles** (metal objects, walls, and water (especially human bodies)).
  - **Performance and design** of the **antenna** of the BLE device.
  - Physical enclosure of the device which affects the antenna performance
  - **Device orientation**, which effectively relates to the **positioning of the antenna** (e.g. in smartphones).
- **Gateway requirement for Internet connectivity**



19

Application for BLE

Although the limitations and benefits of BLE mentioned before, there are a number of use cases where BLE makes the most sense:

- Low-Bandwidth data
- Device Configuration
- Using a smarthphone as an interface
- Personal and wereable devices
- Broadcast-only devices

These are all great use cases that could benefit from utilizing BLE. On the other hand, use cases that are not (generally) suitable for BLE include:

- Video streaming
- High-quality audio streaming (BLE 4.x)
- Large data transfer for prolonged periods of time

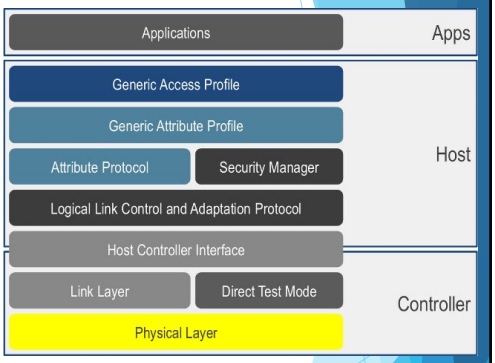
20

20

Architecture BLE

Three main block: **Apps**, **Host**, and **Controller**

The **Application** layer is use-case dependent and refers to the implementation on top of the Generic Access Profile (GAP) and Generic Attribute Profile (GATT), which refer to how the developer application handles data received from and sent to other devices and the logic behind it.



L'Host Controller Interface : standardize communication between controller and host. It can be internal or external to the chipset.

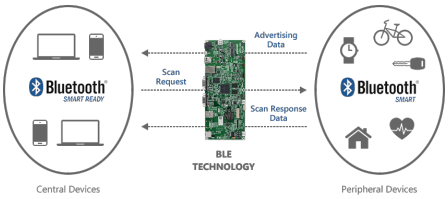
Direct Test Mode : is only needed for performing RF test used during manufacturing and for certification tests.

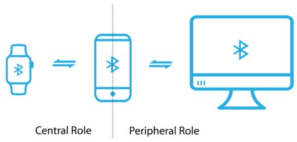
21

21

BLE Peripherals and Centrals

- **BLE Peripheral**, is a device that announces its presence by sending out advertising packets and accepts a connection from another BLE device
- **BLE Central**, is a device that discovers and listens to other BLE devices that are advertising. It is also capable of establishing a connection to BLE peripherals



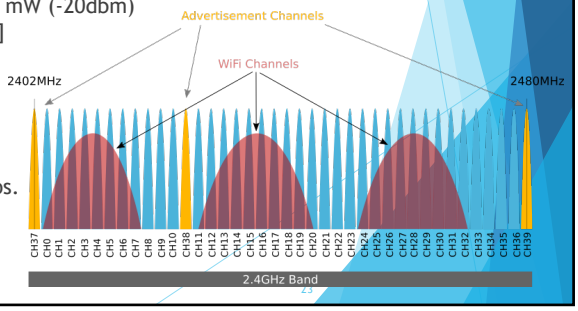


In some use cases, a BLE device might act in multiple roles at the same time.

22

Physical Layer (PHY)

- It refers to the **radio hardware** used for **communication** and for **modulating/ demodulating** the data.
- 3 fixed Channels called **Primary Advertising Channels** (discovery, advertising, non-connection mode).
- 37 Data Channels for **Secondary Advertisements and data** transfer bi-directional (in-connection mode).
- fn = 2402 + 2*n MHz (n=0..39) (with FHSS radio hops technique)
- Trasmit power level : min 0.01 mW (-20dbm) ÷ max 10mW (10dbm) [<= v4.2]
- AFH = **Adaptive-FHSS** (Frequency Hopping Spread Spectrum)
- Data rate is fixed at **1 Mbps**. The data Throughput =<100kbps.



23

Link Layer

The **Link Layer** is the layer that interfaces with the **Physical Layer (radio)** and provides the higher-level layers an abstraction and a way to interact with the radio

- State machines and state transitions in Bluetooth Low Energy;
- Formats of data and advertising packets;
- CRC (error checking)
- Connections, packet timing, retransmissions;
- Encryption

The three main states in which a BLE device operates in are:

- **Advertising**
- **Scanning**
- **Connected**

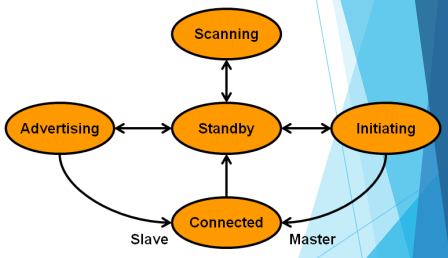
When a device advertises, it allows other devices that are scanning to find the device and possibly **connect** to it. If the advertising device allows **connections** and a scanning device finds it and decides to connect to it, they each enter into the **connected** state.

24

Link Layer (2)

The Link Layer manages the different states:

- **Standby:** the radio doesn't transmit or receive any data.
- **Advertising:** device send out advertising packets for other device to discover and read
- **Scanning:** device scan for device that are advertising
- **Initiating:** a scanning device decides to establish a connection with a device
- **Conneted**: device has an established link with another device and regulary exchanged data with this other device.



25

Link Layer Packet

BLE Packet

Preamble	Access Address	Protocol Data Unit (PDU)	CRC
1 Byte	4 Bytes	2-257 Bytes	3 Bytes

Advertising Channel PDU

Header	Payload
2 Bytes	0-37 Bytes

Data Channel PDU

Header	Payload	MIC*
2 Bytes	up to 255 Bytes (incl. MIC)	4 Bytes

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

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

- **Preamble**: used in the receiver to perform frequency synchronization, automatic gain control training, and symbol timing estimation. The preamble is a fixed sequence of alternating 0 and 1 bit
- **Access Address**: 4 bytes length, configured with the default hex value 0x8E89BED6 and used to identify the radio communication on the physical link.
- **Protocol Data Unit (PDU)**: It can be of two types based on the type of channel used. It contains the data coming from the higher levels that must be transmitted.
- **Cyclic Redundancy Check** : is an error-detecting code used to verify data integrity.

26

26

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L2CAP

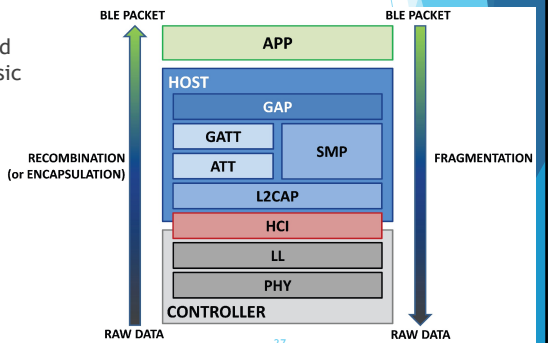
The **Logical Link Control and Adaptation Protocol** layer acts as a protocol-multiplexer:

- Handles **fragmentation** and **recombination**.
- Takes multiple protocols from the upper layers and places them in standard BLE packets that are passed down to the lower layers beneath it.

L2CAP used in BLE is an optimized and simplified protocol based on the classic L2CAP Bluetooth Classic

For BLE, the L2CAP layer handles two main protocols:

- **Attribute Protocol** (ATT)
- **Security Manager Protocol** (SMP)



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27

Security in BLE

The BLE offers **three basic security services**:

- **Authentication and authorization**, i.e. establishing trust relationships between devices;
- **Data encryption and protection**, i.e. protecting the integrity and confidentiality of data;
- **Privacy and Confidentiality**: prevent device monitoring.

These services are implemented through **5 security functions** :

- **Pairing**: is the process for creating shared secret keys;
- **Bonding**: storage of the keys created during the coupling so that they can later be used, as needed;
- **Device authentication:** verification of stored keys;
- **Encryption:** confidentiality of data;
- **Integrity of messages**: protection against data alteration.

28

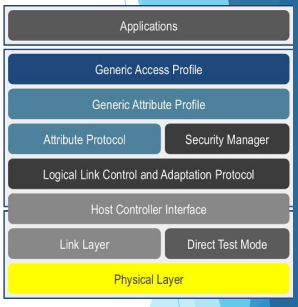
28

Security Manager (SM)

Ensure the trust, integrity, privacy and encryption of data

The Security Manager is responsible for :

- Pairing;
- Distribution of keys;
- Short-term hash and key generation.



Together with the Link Layer that deals with data encryption and decryption, the security features of BLE provide protection against major threats:

- Man-in-the-Middle
- Passive wiretapping
- Privacy

29

29

Advertising

A BLE device always starts in the **advertising state** (Exept Observer roles). It is **essential to communicate** to surrounding devices (within range coverage or range) their **presence** (advertisement), to **establish a connection** or optionally **provide data** on services.

- Advertisement **always start with Advertisement Pakets sent** on the 3 Primary Advertising Channel (37, 38, 39).
- The packets are sent at a fixed interval defined as the **advertising interval.**
- Peripheral (es Smartphone) can initiate a connection if the advertiser allow it.
- Peripheral can also request a Scan Request, and if the Advertiser supports it will respond with a Scan Response. useful for exchanging additional data.

31

31

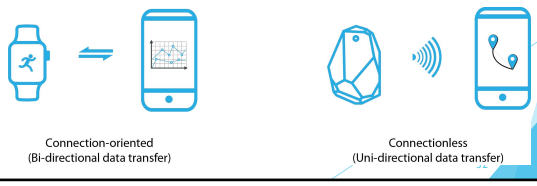
Connectionless or Connection Oriented Advertising

- **Connectionless Advertising**: devices stay in the advertising state and do not accept connection. Primary advertisement data is limited to 31 bytes

Advertising state:

- Multiple centrals can discover the advertising without need for a connection
- The lack of security and the inability for the advertiser to receive data from the central (data transfer is unidirectional)

- **Connection-oriented Advertising**: transition to connected state if the control panel initiates a connection. Secondary advertising data is used, which supports up to 254 bytes of data.



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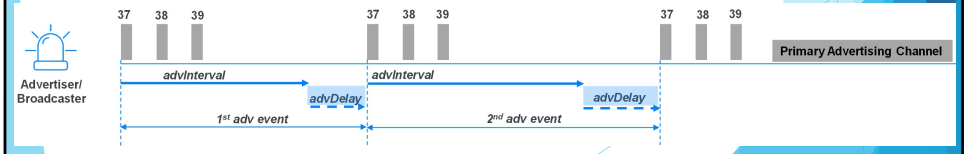
32

Advertising Parameters

PARAMETRO	VALORE	DESCRIZIONE
Advertisement Interval	20÷10.240 ms	Definisce l'intervallo tra gli eventi di advertisement
Advertisement channels	37, 38 e 39	Canali RF fisici utilizzati per trasmettere i pacchetti advertisement
Discoverability	Not discoverable, Generic Discoverable, Limited Discoverable, Broadcast	Definisce come il dispositivo che effettua l'advertisement è visibile agli altri.
Connectability mode	Not Connectable, Directed Connectable, Undirected Connectable	Definisce se l'advertiser può essere connesso o meno.
Payload	0÷31 Byte	Dati includibili in ogni pacchetto



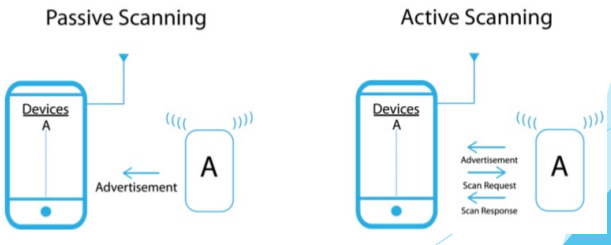
33

Scanning

Scanning is the operation with which a device that is in scanner mode (device search) is waiting for an advertisement event in order to find, find and connect or simply to receive the data-broadcast from the advertiser devices.

Two scanning modes are supported in Bleutooth Low Energy:

- **Passive Scanning:** devide that passively listens to advertising packets.
- **Active Scanning:** the listening device, once it receives the advertisement, sends a Scan Request to get more data from the advertiser.



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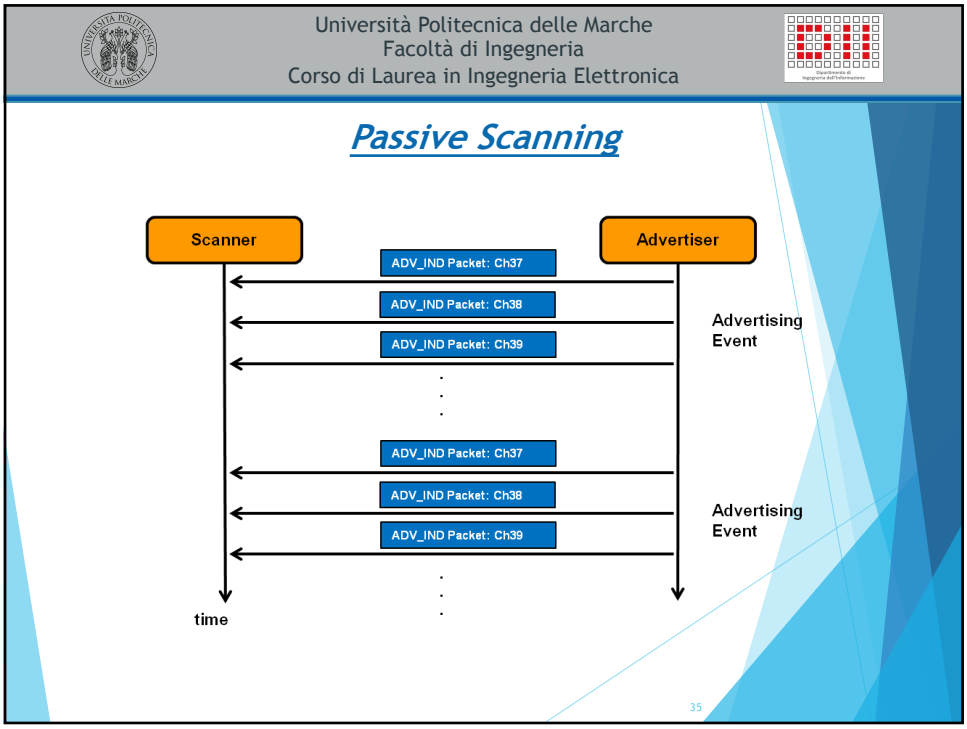
Università Politecnica delle Marche
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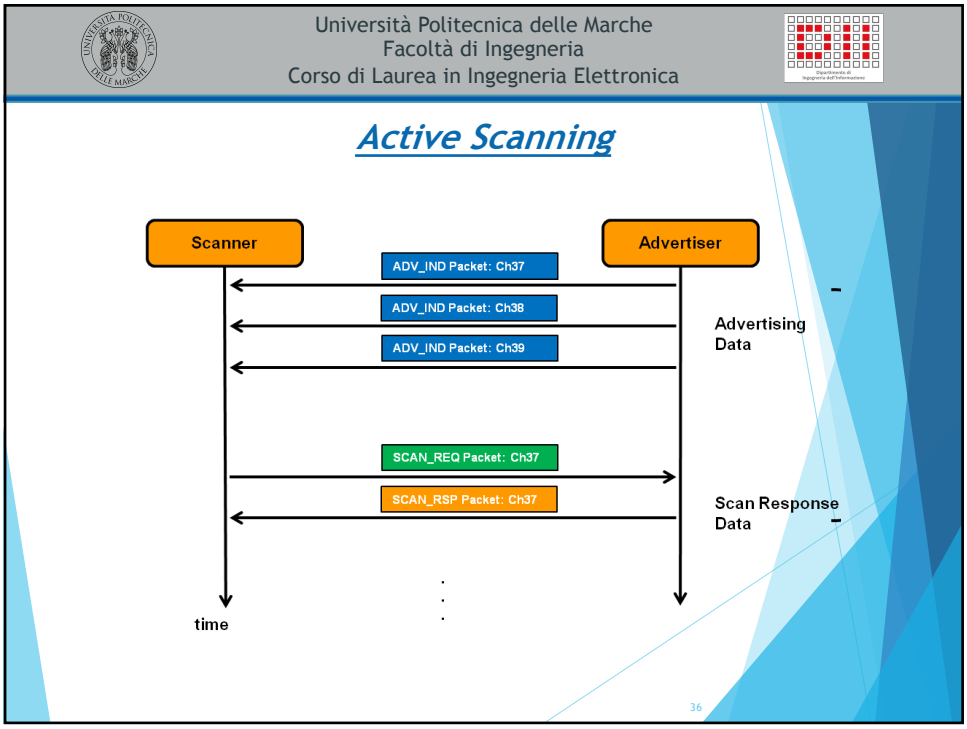
Passive Scanning
Scanner
Advertiser
ADV_IND Packet: Ch37
ADV_IND Packet: Ch38
ADV_IND Packet: Ch39
Advertising Event
ADV_IND Packet: Ch37
ADV_IND Packet: Ch38
ADV_IND Packet: Ch39
Advertising Event
time
35

35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Active Scanning
Scanner
Advertiser
ADV_IND Packet: Ch37
ADV_IND Packet: Ch38
ADV_IND Packet: Ch39
Advertising Data
SCAN_REQ Packet: Ch37
SCAN_RSP Packet: Ch37
Scan Response Data
time
36

36

Scanning parameters

PARAMETRO	VALORE	DESCRIZIONE
Scan Interval	2,5÷10.240 ms	Intervallo tra l'inizio di un evento di scansione e l'inizio di uno consecutivo
Scan Window	2,5 ÷ 10.240 ms	Durata della scansione.
Scan Type	Limited, Generic, Observation	Tipi di advertiser riportati dallo scanner.
Scan Mode	Active, Passive	Definisce la modalità di scansione.
Connectability Mode	Not Connectable, Directed Connectable, Undirected Connectable	Specifica se l'advertiser può essere o meno connesso.

37

37

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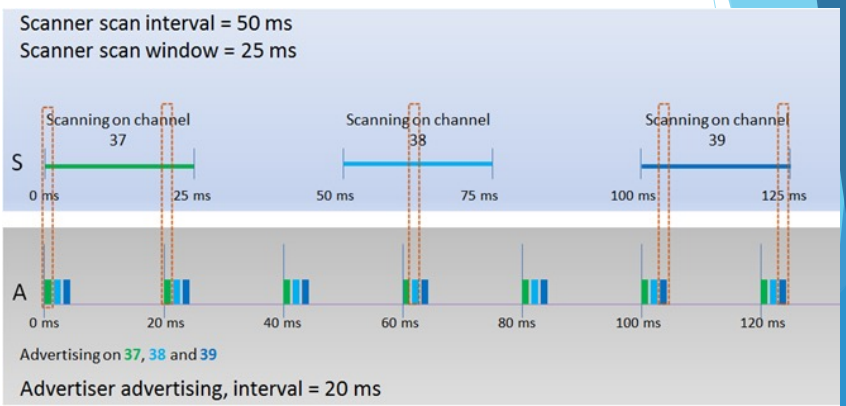
Advertising & Scanning



38

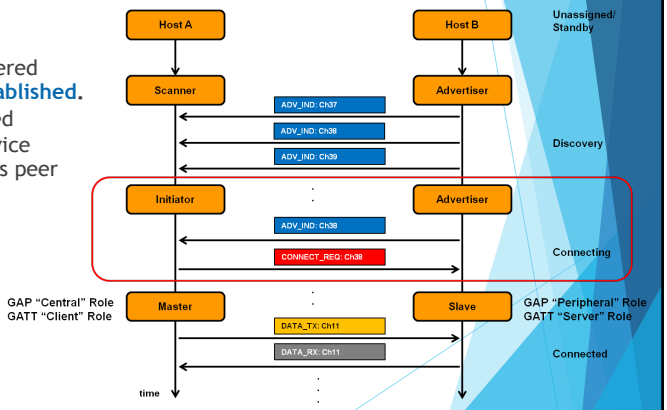
38

Connections

The **connection** is the phase that allows the application data to be transmitted in a reliable, robust (CRC, Acknowledgment, retransmission), confidential (encryption, decryption) manner.

The connection is considered **created**, but not yet **established**. A connection is considered **established** once the device receives a packet from its peer device.

The device that initiated the connection is called **master**, and the device that was advertising is now called the **slave.**



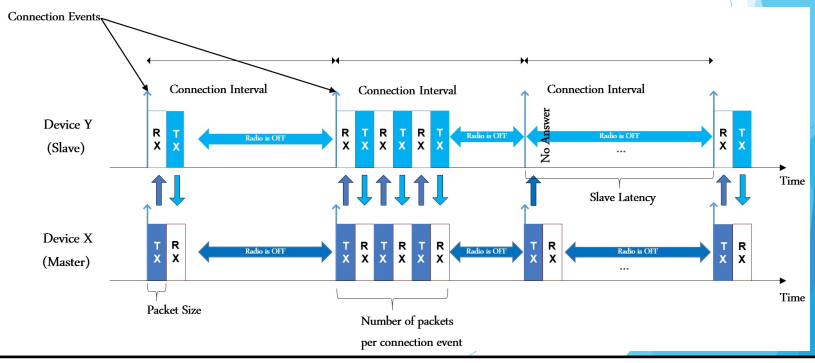
The master is responsible for managing the connection, controlling the connection parameters, and the timing of the different events within a connection.

41

41

Connection Parameters

- **Connection interval** : 7.5ms ÷ 4 seconds; it is set by the central in the connection request packet.
- **Connection supervision timeout** : the maximum time between two received valid data packets before a connection is considered lost.
- **Slave Latency** : number of consecutive connection events and not listen the central that a slave can skip without risking a disconnetion.



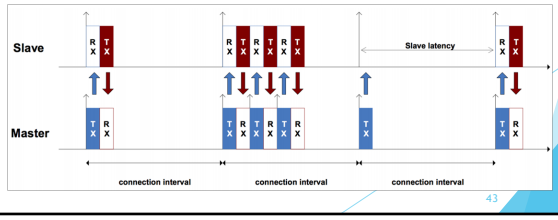
42

Connection Event

During **Connection event**, the master and slave alternate sending data packets to each other until neither side has more data left to send.

Aspect of connection that are very important to know:

- A connection event occurs **periodically and continuously** until the connection is closed or lost.
- A connection event **contains at least one packet** sent by the master.
- The slave always sends a packet back if it receives a packet from the master
- If the master does not receive a packet back from the slave, the master will close the connection Event — *it resumes sending packets at the next connection Event*.
- The connection Event can be **closed by either side**.



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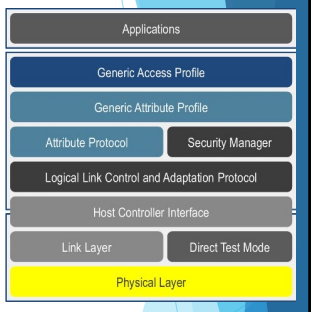
GAP

The **Generic Access Profile (GAP)** provides the framework that defines how BLE devices interact with each other, and includes the following aspects:

- **States** and **Roles** of BLE devices.
- **Advertisements** (advertising, scanning, advertising parameters, advertising data, scanning parameters).
- **Connection establishment** (initiating, accepting, connection parameters)
- Security.



The implementation of this framework is **mandatory per the official specification**, and it is what allows two or more BLE devices to interoperate, communicate, and be able to exchange data with each other

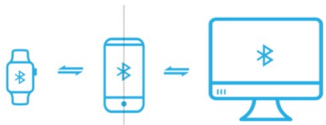
GAP: Roles of devices

The roles determine the mode of operation of the radio part:

Only Transmit (TX) - **Only Receive (RX)** - **Both (RX/TX)**

Roles can be:

- **Broadcaster** (Only TX) : sends advertisement events and broadcast data (eg Beacon))
- **Observer** (Only RX) : it only discovers advertising devices (es. Sniffer)
- **Peripheral** (RX e TX): it announces its presence by sending out advertising packets and accepts a connection from another BLE device. It is always slave.
- **Central** (RX e TX): device that discovers and listens to other BLE device that are advertising. It's also capable to establishing a connection. It's always Master.



Each Bluetooth LE device can take on more than one role, but only one at a time.

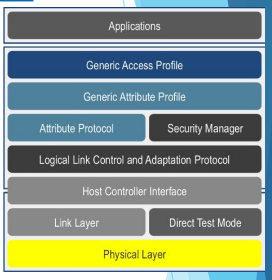
GAP

The GAP also defines the **modalities** for **discovery, connection** and **linking**.

The terminology is the same for Bluetooth and BR / EDR, although the underlying technology may differ. The possible ways are:

- **Connectability** - can make a connection (status can be Non-connectable or Connectable);
- **Discoverability:** can be found (corresponds to the advertisement); the status can be None, Limited or General;
- **Bonding**: if connectable, it can pair with the connected device for a long-term connection; the status can be Nonbondable or Bondable.

Attribute Protocol (ATT)



ATT defines how data is represented in a BLE server database and the methods by which that data can be read or written. There are two roles within the ATT:

- **Server**: exposes the data it controls or contains, and possibly some other aspects of server behavior.
  It accept incoming command, and sends responses, notification, and indications.

  es. thermometer (temperature, units, battery level, interval)

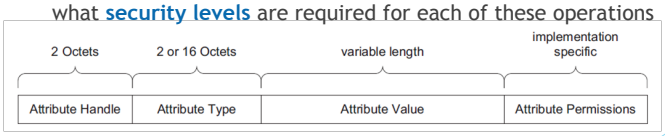
- **Client**: device that interfaces with the server with the purpose of reading the server's exposed data and/or controlling the server's behavior.
  It sends commands and request and accepts incoming notifications and indications.

  Es. smarphone (read data of thermometer)

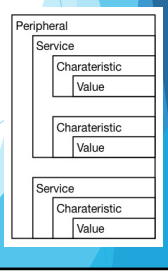
The data that the server exposes is structured as **attributes**. An attribute is the generic term for any type of data exposed by the server and defines the structure of this data.

Attribute

- **Attribute Handle**: 16-bit value that server assigns to each of its attributes. It uniquely identifies an attribute during the life of connection between two devices. 0x0001-0xFFFF.
- **Attribute Type** (Universally Unique Identifier or UUID):
  - **Globally unique 16-bit UUID**, defined in the characteristics specification (Bluetooth SIG-Adopted Attribute) and unique;
    es. 0000**0000**-0000-1000-8000-00805F9B34FB
  - **Manufacturer-specific 128-bit UUIDs**.
- **Attribute Permissions**: Permissions determine whether an attribute can be **read** or **written** to, whether it can be **notified** or **indicated**, and what **security levels** are required for each of these operations



HANDLE	UUID	VALORE	DESCRIZIONE
0x0001	0x1804	0x0000	Potenza TX in dBm
T0x0002	0x2a00	0x426c7565676967612054656368e6f6c6f6769657	Device name, UTF-8



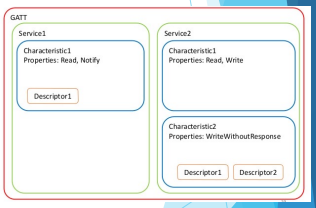
GATT

Generic Attribute Profile (GATT) is built on top of the Attribute Protocol (ATT) and establishes common **operations** and a **framework** for the **data transported and stored** by the Attribute Protocol.

GATT defines a strict hierarchical structure to organize attributes:

Profiles { Services {Characteristics {Declaration, value, descriptor, properties}}}

- Profile: define the use case of the device
- Services : define the functions of the device
- Characteristics : containers for user data



The GATT comes into play **only after you have established a connection**.

- defines the **procedures** needed to access the data exposed by a device.
- It assumes the same roles as ATT: **Server** and **Client**.
- Responds to requests for reading and writing
- Send notifications to subscribed clients

51

51

Schematic of the GATT

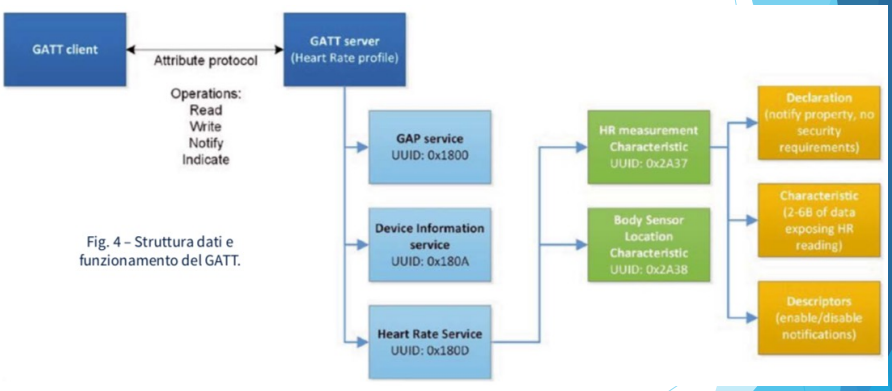


Fig. 4 – Struttura dati e funzionamento del GATT.

52

52

Services

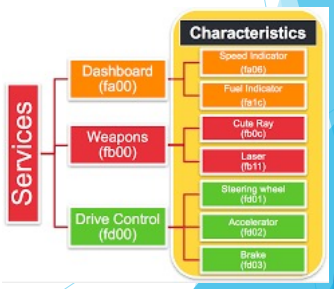
«A service is a collection of data and associated behaviors to accomplish a particular function or feature. [...] A service definition may contain […] mandatory characteristics and optional characteristics.» (Bluetooth SIG - Core specification)

Es. Battery service -> Battery level (characteristics)

that **help structure the data within a service** (service declarations, characteristics declarations, ecc.)

A Service is made up of:

- One or more **characteristics**
- One or more **include services**
- One or more **non characteristics**, help structure the data within a service (service declarations, characteristics declarations, ecc.)



Characteristics

A **Characteristic** is always part of a Service and it represents a piece of information/data that a Server wants to expose to a client.

Es. Battery Level Characteristics represents the remaining power level of battery.

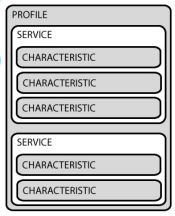
It encapsulates at least two attributes:

- Value attribute: it contains the user data in its value field.
- Characteristics declaration attribute: it contains metadata about the characteristics
  - Value UUID, value Handle, Properties (read, write, notify, indicate, broadcast)
- Descriptor, used to contain related information about the characteristic Value (presentation of value, unit, user descriptor, ecc)

Our Service	Handle	UUID Type of attribute	Attribute permission	Attribute value
Service Declaration	0x000X	**Service declaration** Standard UUID$_{Service}$ 0x2800	Read Only, No Authentication, No Authorization	Our custom service UUID 0x0000F005-1212-EFDE-1523-785FEF13D123
Characteristic Declaration	0x000X	**Characteristic declaration** Standard UUID$_{Characteristic}$ 0x2803	Read Only, No Authentication, No Authorization	Properties: Notify, Read, Write Value Handle (0x000X), Our custom characteristic UUID 0x0000BEEF-1212-EFDE-1523-785FEF13D123
Characteristic Value Declaration	0x000X	**Our Characteristic** UUID found in the Characteristic declaration value 0x0000BEEF-1212-EFDE-1523-785FEF13D123	Read Only, No Authentication, No Authorization (Configured by us)	Temperature value (of type int32_t, presented in array of 4 bytes. E.g. 0x00-00-00-65)
Descriptor Declaration	0x000X	**Client Characteristic Configuration Descriptor (CCCD)** Standard UUID$_{CCCD}$ 0x2902	Read and write, No Authentication, No Authorization	Notification enabled 0x00-XX

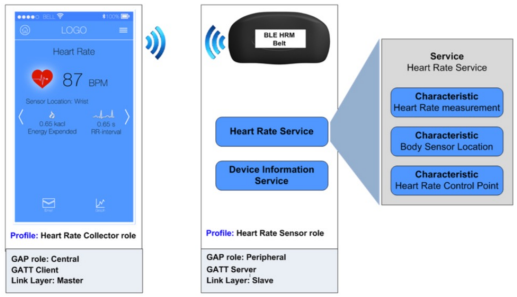
Profiles (1/2)

Bluetooth profiles specify the structure in which data is exchanged. Typically a profile consists of one or more services that are needed to accomplish a high-level use case



In a **Profile** specification, will be generally found the following:

- Definition of roles and the relationship between the GATT Server and Client.
- Required Services.
- Service requirements.
- How the required services and characteristics are used.
- Details of connection establishment requirements including advertising and connection parameters.
- Security considerations.



55

Profile (2/2)

Bluetooth SIG has decided to standardize a whole series of Profiles in order to ensure interoperability between devices and applications from different vendors.

- **Serial Port Profile (SPP)**
- **Human Interface Device (HID)** is the profile of mouse, keyboards, joysticks, PS3 controllers
- **Hand-Free Profile (HFP)** and **Headset Profile (HSP**) used in car integrated hands-free systems. Bi-directional.
- **Advance Audio Distribution Profile (A2DP)** used for audio transmission. Unidirectional. Quality superior to HSP and HFP.
- **A / V Remote Control Profile (AVRCP),** allows remote control of a Bluetooth device
- ….

56

56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GRAZIE
PER
L'ATTENZIONE
59

59