Study of the physical layer of Bluetooth Low Energy (BLE) protocol

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1. What are the frequency ranges used by BLE (in Europe)?

Bluetooth Low Energy uses the Industrial, Scientific, and Medical (ISM) 2.4 GHz short-range radio band. It operates at frequencies from 2400 to 2500 MHz, including guard bands of 2 MHz at the low end and 3.5 MHz wide at the high end. Most of the time however, BLE operates on the 2.45 GHz frequency band.

Bluetooth Low Energy Frequency Bands (ISM)

Frequency Low (MHz)	Center Frequency (MHz)	Frequency High (MHz)	Bandwidth (MHz)	Qty of Channels	Geographical Area	Application
2400	2450	2500	100	40	Global	Bluetooth 802.15.1

Figure 1: Frequency bands for BLE defined globally.

2. What is the modulation used by BLE? What is the binary data rate? What is the bandwidth?

Modulation:
In version 1, **Bluetooth** used the Gaussian frequency-shift keying format, GFSK. However, with the need of higher data rates, two forms of phase-shift keying were introduced for its second version, to provide the Enhanced Data Rate, EDR capability.

The BLE radio uses **Gaussian frequency-shift keying** (GFSK). In this type of modulation, the pulses of data pass through a gaussian filter before being used to alter the carrier frequency. This way, instead of abruptly changing the frequency, the transition between frequencies becomes smoother. Gaussian modulation also provides a better spectrum efficiency.

In GFSK, the frequency of the carrier is shifted to carry the modulation. A binary one is represented by a positive frequency deviation and a binary zero is represented by a negative frequency deviation. The modulated signal is then filtered using a filter with a Gaussian response curve to ensure the sidebands do not extend too far either side of the main carrier. By doing this the Bluetooth modulation achieves a bandwidth of 1 MHz with stringent filter requirements to prevent interference on other channels. For correct operation, the level of BT is set to 0.5 and the modulation index must be between 0.28 and 0.35.

If, as introduced above, the higher data rates provided by Bluetooth 2 EDR (Enhanced Data Rate) are due to **phase shift keying** (PSK), for **Bluetooth 3**, higher data rates are not reached by changing the format of the Bluetooth modulation, but by working cooperatively with an IEEE 802.11g physical layer. This way, data rates of up to around 25 Mbps can be achieved.

Binary data rate:
For the BLE, the bit rate (number of bits that can be transmitted or processed in a period of time) is **1 Mbit/s (with an option of 2 Mbit/s in Bluetooth 5)**.

Bandwidth:
Bluetooth Low Energy technology operates in the same spectrum range (the 2.400–2.4835 GHz ISM band) as classic Bluetooth technology. The difference is that they use a different set of channels, instead of the classic Bluetooth 79 channels with 1-MHz bandwith, Bluetooth Low Energy has 40 channels with 2-MHz bandwith.

3. Define the packet structure. What is the actual throughput of BLE (precise all the hypotheses for this evaluation)? What is the time on air?

Packet format:
In the link layer of the BLE architecture, the format of the packet is defined as shown in Figure 2 below.

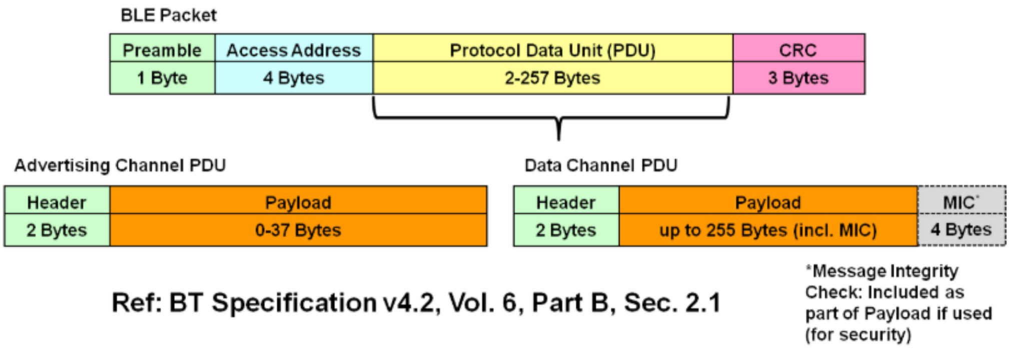

Figure 2: BLE packet structure

The packet is composed by the fields:

- Preamble: used by receiver for synchronization (time, frequency) and to perform AGC (Automatic Gain Control).
- Access Address: for advertising packets, it is configured with a default hex value “”0x8E89BED6” and used to identify the radio communication on the physical link. For data packets, it consists of 32 bits randomly generated by the BLE device in initiation.
- Protocol Data Unit: it is composed by either "advertising channel PDU" (broadcast, connect to followers) or "data channel PDU" (exchange data).
- CRC: it is used for error detection. Its value is calculated over the PDU.

Application throughput of BLE: 0.27-1.37 Mbit/s

For Bluetooth 4.0, the BLE Radio is capable of transmitting 1 symbol per microsecond and one bit of data can be encoded in each symbol. This gives a raw radio bitrate of 1 Megabit per second (Mbps). This is not the throughput which will be observed for several reasons:

- There is a mandatory 150µs delay that must be between each packet sent. This is known as the Inter Frame Space (T_IFS);
- The BLE Link Layer protocol is reliable meaning every packet of data sent from one side must be acknowledged (ACK'd) by the other. The size of an ACK packet is 80bits and thus takes 80µs to transmit;
- The BLE protocol has overhead for every data payload which is sent so some time is spent sending headers, etc for data payloads.

Time on air:

For BLE, the time on air is really short, considering a data rate of 1Mbit/s a 265-Bytes long data frame (the longest), we calculate $ToA = \frac{256 \times 8}{1 \times 10^6} = 2ms$

4. What are the features used by BLE to reduce the effect of interferences?

BLE **frequency hopping** leads to a reduction interferences' impacts. Indeed, along with many other proprietary radios, BLE uses the license-free 2.4GHz Industrial Scientific Medical (ISM) band. Considering the large number of technologies sharing the same radio band, interferences appear, implying a reduction of wireless performances, by increasing latency and decreasing throughput, due to the need for error correction and retransmission. In demanding applications, interferences can be reduced through frequency planning and special antenna design. As both classic Bluetooth technology and BLE technology utilize Adaptive Frequency Hoping (AFH), which minimizes interference with other radio technologies, we can see Bluetooth transmissions as robust and reliable.

5. What is the maximum transmitted power? What should be the theoretical sensitivity of a BLE receiver? What is the typical sensitivity of a BLE receiver? Compute the typical link budget of a BLE wireless network.

Maximum transmitted power: 10 mW (100 mW in Bluetooth 5).

Receiver sensitivity:

The receiver sensitivity is defined in BLE as the signal level at the receiver for which a Bit Error Rate (BER) of 10-3 is achieved. The BLE specification mandates a sensitivity better than or equal to **−70 dBm**. The coverage range is typically over various tens of meters.

Link budget:

For calculating the link budget, instead of using the minimum value required, we decided to consider an actual Bluetooth Low Energy module, and here a Microchip Bluetooth® 4.2 Low Energy Module, the RN4870/71, whose datasheet can be found here [http://www.farnell.com/datasheets/2151205.pdf], with depicted below an overview of its general specification:

TABLE 2-1: GENERAL SPECIFICATIONS

Specification	Description
Standard Compliance	Bluetooth 4.2
Frequency Band	2.402 to 2.480 GHz
Modulation Method	GFSK
Maximum Data Rate (Transparent UART)	10 kBps (iOS®9)
Antenna	Ceramic
Interface	UART, AIO, PIO
Operating Range	1.9V to 3.6V
Sensitivity	-90 dBm
RF TX Power	0 dBm
Operating Temperature Range	-20°C to +70°C
Storage Temperature Range	-65°C to +150°C
Operating Relative Humidity Range	10% to 90%
Storage Relative Humidity Range	10% to 90%
Moisture Sensitivity Level	2

Figure 3: General specifications of the RN4870/71

As most of BLE modules, its sensitivity values $-90dBm$. Now, for our link budget calculation, we assume there is no loss in emission nor reception:

Emitter	Electrical power (dBm)	0
	Gain emitter antenna (dB)	0
	Losses emitter (dB)	0
	EIRP (dBm)	0
Receptor	Bandwith (MHz)	2
	Throughput (kBps)	270 - 1370
	Thermal noise floor @ 300K	0
	Noise figure (dB)	0
	SNR @ BER < 1% (dB)	0
	Sensitivity receiver (dBm)	-90
	Losses receiver (dB)	0
	Gain receiver antenna (dB)	0
	Minimal input power (dBm)	0
Path loss (dB)		90

6. If a free space environment is considered, what is the radio range of BLE?

In a space free of obstacles, BLE can reach a range of up to 100m. In Figure 3 we can see a comparison between other Bluetooth.

	BLUETOOTH V2.1	BLUETOOTH 4.0 (LE)	BLUETOOTH 5 (LE)
Range	Up to 100 m	Up to 100 m	Up to 400 m
Max range (free field)	Around 100 m (class 2 outdoors)	Around 100 m (outdoors)	Around 1,000m (outdoors)

Figure 4: Comparison between Bluetooth ranges

Now, let's consider our BLE 4.2 module (question 5), considering the hypothesizes we made there. With the free space propagation given by the Friis formula given by (1) we can estimate the radio range with the equation (2).

$$L_p(dB) = 32.4 + 20\,.\log\big(d(km)\big) + 20.\log(\mathrm{f(MHz)}) \tag{1}$$

$$\Leftrightarrow 20\,.\log\big(d(km)\big) = L_p(dB) - 32.4 - 20.\log(\mathrm{f(MHz)}) \tag{2}$$

Where:

- $d(km)$ is the range we are looking for
- L_p is the maximum loss due to propagation (maximum path loss)
- f is the signal frequency in MHz

Our Bluetooth 4.2 Low Energy module has a RX Sensitivity of $-90dBm$ and a TX Power $0dBm$, and with the other hypothesis explained above, we can calculate the maximum propagation loss, which here is simply:

$$L_p(dB) = transmission\ power - receiver\ sensitivity \tag{3}$$

$$L_p(dB) = 0 - (-90) = 90dB \tag{4}$$

So we have a maximum propagation loss in free space of $90dB$.

By applying the results found in (4), the Friis formula given by (2), and the value of the frequency of 2.4 GHz we're able to find the maximum radio range as follows:

$$20\,.\log\big(d(km)\big) = L_p(dB) - 32.4 - 20.\log(\mathrm{f(MHz)})$$

$$\Leftrightarrow 20\,.\log\big(d(km)\big) = 90 - 32.4 - 20.\log(2.4 \times 10^3)$$

$$\Leftrightarrow \log\big(d(km)\big) = 2.88 - \log\ (2.4 \times 10^3)$$

$$\Leftrightarrow d(km) = \ 2.88 - \log\ (2.4 \times 10^3)$$

$$d = 0.316km = 316m$$

So the distance of maximum propagation in free space is $d = 316m$ for BLE.

7. For an indoor application, evaluate the radio range of BLE. The model IEEE P802.11 will be used for this purpose.

So by using the model for different indoor test environments, validated on the ISM band at 2400 MHz (shown in FIgure 5), we consider the model D (of a typical office environment) to make our calculations.

Model	Environment	Delay (ns)	d_{BP} (m)	Shadowing σ (dB) for LOS / NLOS
B	Residential	15	5	3 / 4
C	Small office	30	5	3 / 5
D	Typical office	50	10	3 / 5
E	Large office	100	20	3 / 6
F	Large open space	150	30	3 / 6

Figure 5: Models for different indoor environments, with d_{BP} the breakdown distance.

From the Friis formula given by (1):

$$L_0(d_{BP}) = 32.4 + 20\log\big(d_{BP}(km)\big) + 20\log\big(f(MHz)\big)$$
$$L_0(dB) = 32.4 + 20\,.\log(0.01) + 20.\log(24\text{x}10^3)$$

$$\Leftrightarrow L_0 = 60dB$$

So 60 dB is the free space path loss at a distance of 10m.

From the equation given by (5) we can estimate the radio range of BLE, as follows:

$$\begin{aligned} L(dB) &= L_0(d_{BP}), && \text{if } \mathrm{d} \leq \mathrm{d_{BP}} \\ L(dB) &= L_0(d_{BP}) + 35.\log\left(\frac{d}{d_{BP}}\right), && \text{if } \mathrm{d} > \mathrm{d_{BP}} \end{aligned} \tag{5}$$

Where:

- L is the path loss
- d_{BP} is the breakdown distance
- d is the distance between emitter and receiver (in m)
- $L_0(x)$ the free space path loss at distance x

Rewriting the equation (5), we have:

$$L(dB) - L_0(d_{BP}) = 35.\log\left(\frac{d}{d_{BP}}\right)$$

$$\Leftrightarrow \frac{L(dB) - L_0(d_{BP})}{35} = \log\left(\frac{d}{d_{BP}}\right)$$

$$\Leftrightarrow \frac{100-60}{35} = \log\left(\frac{d}{10}\right)$$

$$d = 138m$$

So the maximum radio range for BLE this indoor application is of 138m.