# The Physical Layer

## Frequency Band

Bluetooth low energy (BLE) uses the 2.4GHz Industrial, Scientific, and Medical (ISM) band for transmitting information. This band is a license-free frequency band and is the same in all countries.

## Modulation

* BLE uses Gaussian frequency-shift keying- optimizes the transition from one symbol to the next by increasing the time that is used to slide the frequency from one value to another.
* It can transmit 1 million bits per second (Mbps), with one bit per symbol.
* It has a modulation index that can vary between 0.45 and 0.55 which means it is not classified as a minimum-shift keying, but does a lot of what MSK does.
* To send a zero, a negative frequency deviation is used. To send a one, a positive frequency deviation is used. The minimum frequency deviation is about 180kHz.

## Radio Channels



* BLE uses 40 channels to transmit information.
* The center frequency for each channel can be calculated with:

*f*c = 2402 + 2*k* *f*c: center frequency *k*: radio channel

## Transmit Power

* Specification limits BLE maximum transmit power to + 10dBm (10mW) and a minimum transmit power to -20dBm (10µW).

## Tolerance

* The more accurate the tolerance, the costlier the devices.
* The center frequency tolerance of BLE is ± 150kHz for the whole packet.
* The reason the center frequency might be off is that it is typically obtained by multiplying the frequency from a known frequency crystal. The crystal typically has a frequency of 16MHz; therefore, it must be multiplied by a factor of over 150 to get up to 2400MHz. Inaccuracies in the crystal would be multiplied, as well, and included in the transmission frequencies.
* If the crystal was actually outputting 16.0001 MHz, the center freq would be off by about 150kHz. The crystal would be said to have an error rate of 62 parts per million. Typically, low-cost, high-volume crystals with an error rate of approximately 50 ppm are readily available.
* The other issue is how much the radio drifts from its center frequency during the packet. This drift is caused by heat that builds up in a silicon chip during use. As heat builds, the internal frequencies used in the radio will drift slightly. A BLE radio cannot drift more than 50kHz during a packet. There is a maximum drift rate of 400Hz/µs.

## Receiver Sensitivity

* Receiver sensitivity: how sensitive the radio is to detecting wireless transmissions from another device (measured in dBm and is typically a very small number).
* The required rcvr sensitivity for BLE is -70dBm. It has to be able to pick up 0.0000001mW of electromagnetic energy to be able to work.
* In practice, the sensitivity threshold is set at the value where a signal can be decoded with an acceptable bit error rate (BER). For BLE, this has been chosen as 0.1 percent BER.
* Most controllers supporting BLE will have a rcvr sensitivity of about -90dBm, or 1pW.

## Range

* To calculate the range of a BLE radio, the *link budget* of the system needs to be determined. This is made up of a number of elements that use the power from the transmitter in a silicon chip before it is received by a peer silicon chip (antenna, circuit gains/losses, and path loss).
* Path loss is the main contributor to the link budget and is a measure of how much the radio signal has reduced in power between the antenna in the transmitter and the antenna in the receiver. Equation is an approximation, valid only for an isotropic antenna, and ignores any losses in the transmit/receive systems.

*path loss* = 40 + 25log(d) *d:* distance between the transmitter and the receiver

* When the transmit power is -20dBm and the receiver sensitivity is -70dBm, a path loss of 50dB results in a range of 2.5 meters. This is the distance possible when the minimum transmit power is used, with the minimum receiver sensitivity.
* When the transmit power is 0dBM and the receiver sensitivity is -80dBM, a path loss of 80dB results in a range of 40 meters. This is the distance possible when a moderate transmit power is used, with a moderate receiver sensitivity.
* When the transmit power is 10dBm and the receiver sensitivity is -90dBM, a path loss of 100dB results in a range of 250 meters. This is the distance possible when the maximum transmit power is used with the receiver sensitivity possible with modern chips.