

ITRAINONLINE MMTK

RADIO LINK CALCULATION HANDOUT

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Table of Contents

1. About this document.....	1
1.1 Copyright information.....	2
1.2 Degree of Difficulty.....	2
2. Introduction.....	2
3. What is a Link Budget?.....	2
4. The elements of a link budget.....	2
4.1 Transmitting side.....	3
4.1.1 Transmit power (Tx).....	3
4.1.2 Cable Loss.....	3
4.1.3 Loss in connectors.....	4
4.1.4 Amplifiers.....	4
4.1.5 Antenna Gain	4
4.2 Propagation Losses.....	5
4.2.1 Free Space Loss.....	5
4.2.2 Fresnel zones.....	6
4.3 Receiver side.....	7
4.3.1 Antenna Gain on receiver side.....	7
4.3.2 Amplifiers on receiver side.....	7
4.3.3 Receiver sensitivity.....	7
4.3.4 Margin and SNR.....	8
5. Terms and Concepts.....	8
6. Calculating with decibel (dB, dBm, dBi).....	9
6.1 Dimensionless Unit.....	9
6.2 Converting Watt to Decibel.....	9
7. Complete Link Budgets.....	10
7.1 Example 1: 50 kms Link.....	10
7.2 Example 2: 1 km Link.....	11
7.3 Other relevant calculations and approaches.....	11
7.3.1 Antenna tilt	12
7.3.2 Bearing Angle.....	12
7.3.3 Sources of latitude/longitude and elevation data.....	12
The bearing angle (towards north) and the distance from latitude/longitude can be calculated as:.....	12
8. Conclusions.....	13

1. About this document

These materials are part of the ItrainOnline Multimedia Training Kit (MMTK). The MMTK provides an integrated set of multimedia training materials and resources to support community media, community multimedia centres, telecentres, and other initiatives using information and communications technologies (ICTs) to empower communities and support development work.

1.1 Copyright information

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1.2 Degree of Difficulty

The degree of difficulty of this unit is “Basic” with some additional “Advanced” parts. All “Advanced” parts are marked with a red frame to inform about the higher level of difficulty of the content.

2. Introduction

No matter how good wireless equipment you have and how clear the Line of Sight is, you need to calculate your Link Budget. Overpowering a radio link will not necessary make things better for your implementation and your neighbours.

Having a good link budget is essential as it is the basic requirement of a functioning link. It can be compared with the foundation of a building. It does not matter how well the floors, walls and roofs are built if the foundation is weak, the whole building will collapse.

3. What is a Link Budget?

A wireless link budget for a point to point radio link is the accounting of all of the gains and losses from the radio transmitter (source of the radio signal), through cables, connectors and free air to the receiver. Estimating the value of the “power” in the different parts of the radio link is necessary to be able to make the best design and the most adequate choice of equipment.

4. The elements of a link budget

The elements can be broken down into 3 main parts:

1. Transmitting side with *effective transmit power*
2. Propagation part with *propagation losses*
3. Receiving side with *effective receiving sensibility*

A complete radio link budget is simply the sum of all contributions (in decibels) across the tree main parts of a transmission path. All positive values are gain and all negative values are losses.

Transmitter power [dBm] - **Cable TX loss** [dB] + Antenna TX gain [dBi] - **Free Space Path Loss** [dB] + Antenna RX gain [dBi]- **Cable RX loss** [dB] = Margin - **Receiver Sensitivity** [dBm]

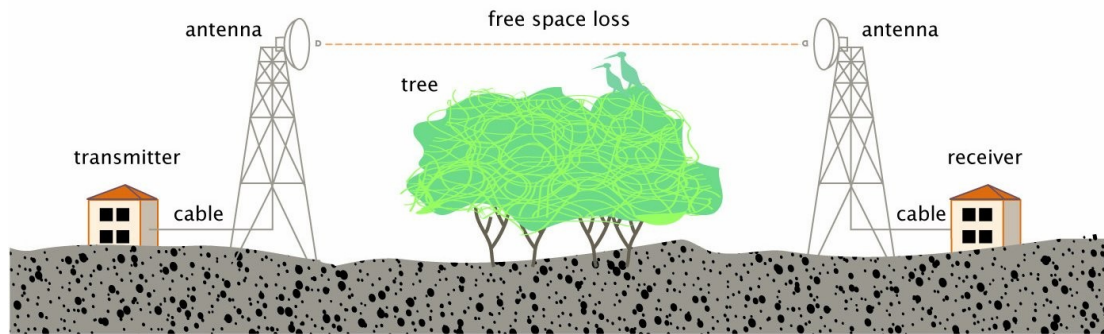


Image 1: The full transmission path from transmitter to the receiver.

The following section presents each element of a radio link budget.

4.1 Transmitting side

4.1.1 Transmit power (Tx)

The transmit power is the power output of the radio card. The upper limit depends on regulatory limits and therefore on country/region and point in time.

The transmit power of your card can normally be found in the vendor's technical specification. Keep in mind that while the technical specifications will give you lab values, real life values may vary with factors like temperature and voltage.

Typical transmission power in IEEE 802.11b equipment ranges from 15 - 20 dBm (30-100 mW).

Example from a IEEE 802.11a/b card data sheet:

<i>Protocol</i>	<i>Peak power [dBm]</i>	<i>Peak power [mW]</i>
IEEE 802.11b	18	65
IEEE 802.11a	20	100

Table 1: Example of (peak) transmit power from a typical IEEE 802.11a/b wireless card

4.1.2 Cable Loss

Losses in the radio signal will take place in the cables that connect the transmitter and the receiver to the antennas. The losses depend on the type of cable and frequency of operation and are normally measured in dB/m or dB/foot.

In general, no matter how good a cable is, it will always cause a loss. Because of that, remember to always keep the antenna cable as short as possible. Typical loss in cables is 0,1 dB/m - 1 dB/m.

To give you an idea of how large the power loss in a cable can be, consider that you are using a RG58/BNC cable, which has a loss of 1dB/m, to connect a transmitter to an antenna. Using 3 meters of RG58 cable is enough to lose 50% of the power (3dB).

Cable losses are very much dependent on frequency. So when calculating the loss of your cable, make sure you use the right values for your frequency range. Check the distributor's data sheets and if possible, verify the losses taking your own measurements.

As a rule of the thumb, you can count with double amount of cable loss [dB] for 5,4 GHz compared with 2,4 GHz.

<i>Cable type</i>	<i>Loss [db/100m]</i>
RG 58	ca 80-100
RG 213	ca 50
LMR-200	50
LMR-400	22
Aircom plus	22
LMR-600	14
1/2" Flexline	12
7/8" Flexline	6,6
C2FCP	21
Heliax 1/2 "	12
Heliax 7/8"	7

Table 2: Typical values of cable loss for 2.4 Ghz.

See unit "Antennas and Cables" for more information.

4.1.3 Loss in connectors

Allow at least 0.25 dB (loss) for each connector in your cabling. This value applies for properly made connectors while badly soldered DIY connectors will imply higher loss. Check data sheets for losses at your frequency range and for your connector type.

If long cables are used, the accounting of the connector losses are normally included in the "cable loss" part of the equation. But to be on the safe side, always assume an average of 0.3 to 0.5 dB loss per connector as a rule of the thumb.

Additionally, lightning arrestors that typically are used between antennas and the radio gear behind them, should be budgeted for 1 dB loss.

4.1.4 Amplifiers

Optionally, amplifiers can be used to compensate for cable loss or for other reasons as signal boosting. In general, the use of amplifiers should be seen as a last option. Intelligently optimized antennas and high sensitivity in the receiver are better than brute force amplification.

High quality amplifiers are expensive. Cheap amplifiers may change frequency characteristics (broadening) and add extra noise to the signal. Also, you must consider the legal limits of the region when adding amplifiers.

Purely technically speaking, there is hardly no limit to how much power you can add by amplifiers, but again, bear in mind that amplifiers will boost noise to your signal as well.

4.1.5 Antenna Gain

A typical antenna gain ranges from 2 dBi (simple integrated antenna) to 5 dBi (standard omni directional) up to 25-30 dBi (parabolic).

Keep in mind that there are many ways in which the nominal gain of an antenna might be reduced. Losses can take place due to a number of different reasons, mainly related to incorrect installation (tilt losses, polarization losses). That means that you can only expect to get the full gain out of the antenna if it is optimally installed.

See unit "Antennas and Cables" for further details.

4.2 Propagation Losses

The propagation losses are related to all attenuation of the signal that takes place when the signal has left the transmitting antenna until it reaches the receiving antenna.

4.2.1 Free Space Loss

The majority of the power of a radio signal will be lost in the air. Even in perfect vacuum, a radio wave loses some of its energy since (according to the Huygens Principle) some energy is always radiated in directions other than our link axis. Note that this has nothing to do with air, fog, rain or any other influence that will further add losses.

The Free Space Loss (FSL) measures the power loss in free space without any kind of obstacles. The radio signal weakens in free space due to expansion into a spherical surface.

FSL is proportional to the square of the distance and also proportional to the square of the radio frequency. In decibel, that results in the following equation:

$$FSL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + K$$

d = distance

f = frequency

K = constant that depends on the units used for d and f

If d is measured in meters, f in Hz and the link uses isotropic antennas, the formula is:

$$FSL(dB) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5$$

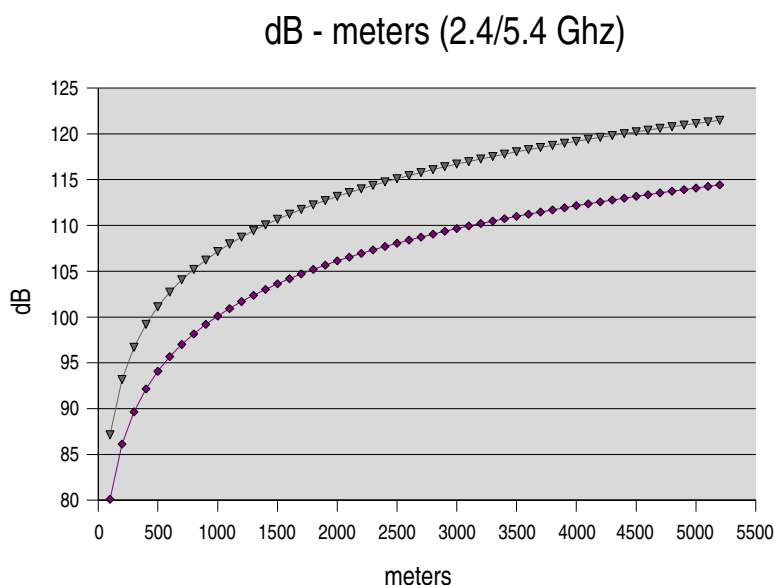


Image 2: dB Linear approximation after 1.5 Kms

The graphic shows the loss in dB for 2.4 GHz [1] and 5.4 GHz [1]. You can see that after the 1.5 kms, the loss can be seen as “linear” in dB.

As a rule of the thumb in a 2.4 GHz wireless network, 100 dB are lost in the first kilometer and the signal is reduced by 6 dB every time that the distance doubles. That implies that a 2 km link has a loss of 106 dB and a 4 km link has a loss of 112 dB etc.

Distance [km]	915 Mhz	2,4 Ghz	5,8GHz
1	92 dB	100 dB	108 dB
10	112 dB	120 dB	128 dB
100	132 dB	140 dB	148 dB

Table 3: Free Space Loss (FSL) in dB for a set of distances and frequencies.

These values are theoretical values and can very well differ from your measurements. The term “free space” is never quite so “free”, and the losses can many times be larger due to terrain influences and climatic conditions.

See unit “Basic Radio Physics” for further information.

4.2.2 Fresnel zones

Taking our starting point in the Huygens principle, we can calculate the zones, the space around an axis that relevantly contributes to the transfer of power from source to destination.

Based on this, we can then find out what the minimum distance of an obstacle (e.g. a building or a hill) from our axis should be.

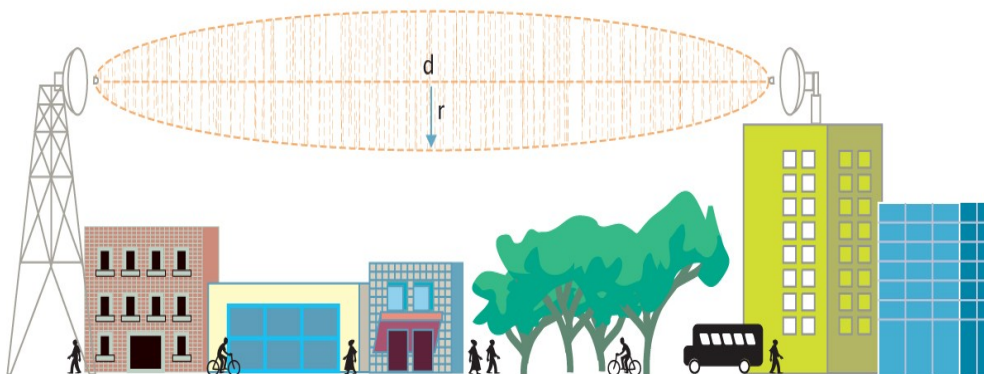


Image 3: Fresnel zones

Most wireless professionals work with an approach that demands that the first Fresnel zone be unobstructed, although one might be more demanding. Others demand a radius containing 60% of the total power unobstructed.

The formula below calculates the first Fresnel zone.

$$r = 17,32 * \sqrt{((d1 * d2) / (d * f))}$$

d1= distance to obstacle from transmitter

d2 = distance to obstacle from receiver

d = distance [km]
 f= frequency [Ghz]
 r= radius [m]

If the obstacle is situated in the middle (d1=d2), the formula can be simplified as:

$$r = 17,32 * \sqrt{(d/4f)}$$

The radio containing 60% of the total power can be calculated as:

$$r (60 \text{ percent}) = 10,4 * (d/4f)$$

Distance[km]	915 Mhz	2,4 Ghz	5,8 GHz	Height [m] (rel. earth*)
1	9	6	4	0,02
10	29	18	11	2
100	90	56	36	200

Table 4: Radius [m] for the first Fresnel zone

The "relative earth height" describes the "hill" that the earth curvature creates between two points.

4.3 Receiver side

The calculations are almost identical to the ones at the transmitter side.

4.3.1 Antenna Gain on receiver side

See Antenna Gain on transmitter side.

4.3.2 Amplifiers on receiver side

The calculation and the principles are the same as on the transmitting side. Again, amplification is not a recommended method unless all other options have been considered and it is really needed, e.g. for cable loss compensation.

4.3.3 Receiver sensitivity

The sensitivity of a receiver is a parameter that deserve special attention as it indicates the *minimum value of power* that is needed to successfully decode/extract "logical bits" and achieve a certain bit rate.

The lower the sensitivity is, the better radio receiver. A typical value is -82 dBm for a 11 Mbps link and -94 dBm for a 1 Mbps link.

A 10 dB difference here (which easily can be found between different cards) is just as important as a 10 dB gain that might be won by the use of amplifiers or bigger antennas.

Card	11 Mbps	5,5 Mbps	2 Mbps	1 Mbps
Orinoco cards PCMCIA Silver/Gold	-82 dBm	-87 dBm	-91 dBm	-94 dBm
Senao 802.11b card	-89	-91	-93	-95

Table 5: Typical values of receive sensitivity of wireless network cards.

4.3.4 Margin and SNR

Although the signal received in the receiver is bigger than the sensitivity, it is also needed a certain *margin* between noise and signal to achieve a certain data bit rate.

The relationship between noise and signal is measured by the signal to noise ratio or SNR. A typical requirement of SNR is 16 dB for a 11 Mbps connection and 4 dB for the lower speed of 1 Mbps.

In situations where there is very little noise, the radio link is first limited by the sensitivity of the receiver. In urban areas where there are many radio links operating, it is common to see high levels of noise (as big as -92 dBm). In those scenarios, the radio link is limited by the need of a high received signal to satisfy the Signal to Noise (SNR) condition.

$$\text{Signal to Noise Ratio [dB]} = 10 * \text{Log}_{10} (\text{Signal Power [W]} / \text{Noise Power [W]})$$

In normal conditions without any other source in the 2.4 Ghz band and without industrial noise, the noise level is around -100 dBm.

5. Terms and Concepts

There are a number of terms and concepts you will meet when dealing with radio link calculations.

Link Budget / Power Budget / System Gain

All of these concepts basically mean the same thing: a calculation of signal/power throughout the system.

System operating margin

This values tells you the difference between the signal value and the sensibility.

EIRP (Effective Isotropic Radiated Power)

The Effective Isotropically-Radiated Power (EIRP) or the *Maximum Radiated Power* is regulated by the national radio regulatory authority. It specifies the *maximum power that is legally permitted to be send out to the free air* in a specific country/area. The legal limit in Europe is normally 100 mW. In some very concrete scenarios (point-to-point links) and in some countries outside of Europe, the maximum allowed radiated power is 1 - 4 W.

EIRP is a measure of the effective output of a system and is expressed as equivalent to an isotropically radiating system. In simple words, this parameter tells you how *strong* you are allowed to send your signal in the free air.

The Radiated Power is the result of subtracting power losses in the cable and connectors to the Transmitter Power and adding the relative “gain” of the antenna.

Radiated Power (dBm) =

Transmitter Power (dBm) – Losses from cable and connectors (dB) + Antenna Gain (dBi).

6. Calculating with decibel (dB, dBm, dBi)

6.1 Dimensionless Unit

As mentioned earlier, a link budget is the accounting of all of the gains and losses from the radio transmitter (source of the radio signal), through cables, connectors and free air to the receiver.

Transmitter power [dBm] - Cable TX loss [dB] + Antenna TX gain [dBi] - Free Space Path Loss [dB] + Antenna RX gain [dBi] - Cable RX loss [dB] = Margin - Receiver Sensitivity [dBm]

One aspect that might be surprising is that the equation is adding dBm, dB and dBi units like they were of the same dimension. How is it possible to simply add and subtract dBm, dB and dBi?

The answer lies in the fact that the decibel (dB) is a measure of the “ratio” between two quantities and it is a dimensionless unit like percent (%). Hence, different “kinds” of decibel units can be added and subtracted and the results will remain dimensionless.

6.2 Converting Watt to Decibel

To be familiar with conversion between power (W) and decibel comes very handy when dealing with link calculations.

In link calculations, three different types of decibel occurs.

dB (decibel)

Used for measuring losses in cables and connectors. Decibel is the relative unit compared to 1 W.

$$\text{dB} = 10 \cdot \log(P(W)/1W)$$

dBm (decibel milli)

Transmitted power is normally expressed in (dBm). A dBm is a decibel relative unit compared to 1 milliwatt (0.001 W). The conversion between power (W) and dBm is calculated as following:

$$\text{dBm} = 10 \cdot \log(P/0.001) = 10 \cdot \log(P(W)/1mW)$$

dBi (decibel isotropic)

Used for expressing the antenna gain.

dBi = dB relative to an ideal isotropic antenna

When using dB as a way to calculate the power the following “guidelines” are useful to remember:

1. Duplicating the power is equal to adding 3 dB
2. Reducing the power by half is equal to subtracting 3 dB

Let us say that we have a transmitting power of 100 mW (20 dBm).

If we duplicate the power of the transmitter to 200 mW, we add 3 dB to 20 dBm which gives us 23 dBm.

In that way, 400 mW gives us 26 dBm and 800 mW gives us 29dBm.

Following the same reasoning implies that 50 mW is 17 dBm (20 dBm - 3 dB).

7. Complete Link Budgets

Calculating link budgets is all about making sure that the margin in the receiver side is higher than a certain threshold. Furthermore, the EIRP must be within regulations.

The margin of a link budget can be summarized as follows:

Margin = Transmitter power [dBm] - **Cable TX loss** [dB] + Antenna TX gain [dBi] - **Free Space Path Loss** [dB] + Antenna RX gain [dBi]- **Cable RX loss** [dB] - **Receiver Sensitivity** [dBm]

The following section will provide two realistic examples of link budgets, one for a 50 km link and another for a 1 km link.

7.1 Example 1: 50 kms Link

Distance: 50 kms (31,1 miles)

Frequency: 2,4 GHz

Element	Value
Transmit output	+ 15 dBm
Cable and connectors	- 3 dB
Antenna TX	+ 24 dBi
FSL	-134 dB
Antenna RX	+ 24 dBi
Cable and connectors	- 3 dB
Receive Sensibility	- 85 dBm
Total: (margin)	+ 8 dB

The margin of this link is 8 dB and the transmitting power is 36 dB (> 3 W). This link might not be legal.

7.2 Example 2: 1 km Link

- Distance: 1 km (0,622 miles)
- Frequency: 2,4 Ghz
- Low quality cabling
- Low antenna gain

Element	Value
Transmit output	+ 18 dBm
Cable and connectors	- 5 dB
Antenna TX	+ 5 dBi
FSL	-100 dB
Antenna RX	+ 8 dBi
Cable and connectors	- 5 dB
Receive Sensibility	- 92 dBm
Total: (margin)	+ 13 dB

The margin of this link is 13 dB and the transmitting power is 15 dB (< 50 W). This link is legal.

7.3 Other relevant calculations and approaches

In addition to the elements considered so far, we have to take into account correction factors due to terrain and building structures, climatic factors, and many others. All of these are very empirical by nature.

You will find them under terms like *rain fade*, *urban fade*, *terrain fade*, with a lot of different approaches to calculating them properly. However, there are limits to these theories as the factors that can NOT be easily calculated or predicted, are normally the ones that decide whether a link works or not.

In a long distance link, factors like rain, fog and even a changing in vegetation conditions can easily contribute to 15 dB in losses.

7.3.1 Antenna tilt

Antenna tilt to compensate for earth curvature and tower height differences:

$$\text{Angle} = \text{Tan}^{-1} \left(\frac{(h_1 - h_2)}{(D * 5280)} \right)$$

where D is the distance [m]

7.3.2 Bearing Angle

The bearing angle (towards north) and the distance from latitude/longitude can be calculated as:

distance =

$$r * \arccos[\sin(\text{lat}1/57.2958) * \sin(\text{lat}2/57.2958) + \cos(\text{lat}1/57.2958) * \cos(\text{lat}2/57.2958) * \cos(\text{lon}2/57.2958 - \text{lon}1/57.2958)]$$

lat, lon in metric degrees

$$r = 6378.7 \text{ [km]}$$

$$r = 3963.0 \text{ [miles]}$$

7.3.3 Sources of latitude/longitude and elevation data

When planning a link, a first step often is to get reliable latitude/longitude and elevation data. Some starting points for this can be:

1. GPS data that you measure yourself.
2. The SRTM (Shuttle Radar Topology Mission) project maintains a database of free elevation data for the whole planet, although in variable accuracy.
3. Aviation sites and airport locators often list precise lat/lon data.
4. Ham (amateur) radio sites often locate their stations quite precisely.
5. Islamic sites often give the coordinates of mosques and bearing towards Mecca (and thereby to any other place).
6. Online city lists sometimes list coordinates
7. The *confluence.org* project is a fascinating projects that collects data and images for each full digit pair of latitude / longitude. On top of its aesthetic qualities, this can be a good first input for getting started researching an area.
8. Don't forget local knowledge and methods. Fireworks can sometimes be a good way to find out about distance.

RadioMobile Software

Radio Mobile is the name of software coming from the Ham radio scene. It allows for integrated network planning, line of sight and coverage calculations based on terrain data. The program currently runs under Windows only and is used by many wireless networkers as a planning/support tool.

It can use elevation data from various sources in HGT, DTED, GLOBE, SRTM30, GTOPO, ... formats.

A popular source is the NASA's SRTM (Shuttle Radio Topology Mission) repository of free elevation data, covering the whole planet at variable resolution. Radi Mobile can integrate maps and backgrounds as well as GIS data.

URL: <http://www.cplus.org/rmw/english1.html>

Online calculators & spreadsheets

Online calculators and spreadsheets for offline use are a valuable tool supporting your work with link budgets. Always make sure though that you can work offline, and if need be, with pen and paper, as well as online.

We provide a spreadsheet calculator with this unit which should serve as an example. It is easy to adjust and create your own calculator fitting your needs.

8. Conclusions

To understand the link elements and, their contribution to the overall budget, in terms of gains or losses, is crucial to implement reliable wireless internetworking.

The five main issues you should remember from this unit can be summarized as:

1. Having a good link budget is the basic requirement of a well functioning link
2. A wireless link budget is the accounting of all of the gains and losses from the radio transmitter to the receiver
3. The largest loss of a link takes place in free space propagation due to attenuation of the signal
4. EIRP is a value that specifies the *maximum power that is legally permitted* to be send out to the free air
5. The *receiver sensitivity* is the parameter that indicates the *minimum value of power* that is needed to achieve a certain bit rate