Power Budget

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The Abdus Salam International Centre for Theoretical Physics

UNESCO United Nations Educational, Scientific and Cultural Organization

Goals

- Examine the factors that influence the range of a wireless link, particularly the Fresnel zone clearance and the effect of the earth curvature.
- Provide the tools to determine the power budget.
- Use some simulation software that can leverage worldwide digital elevation maps.

Topology and link budget

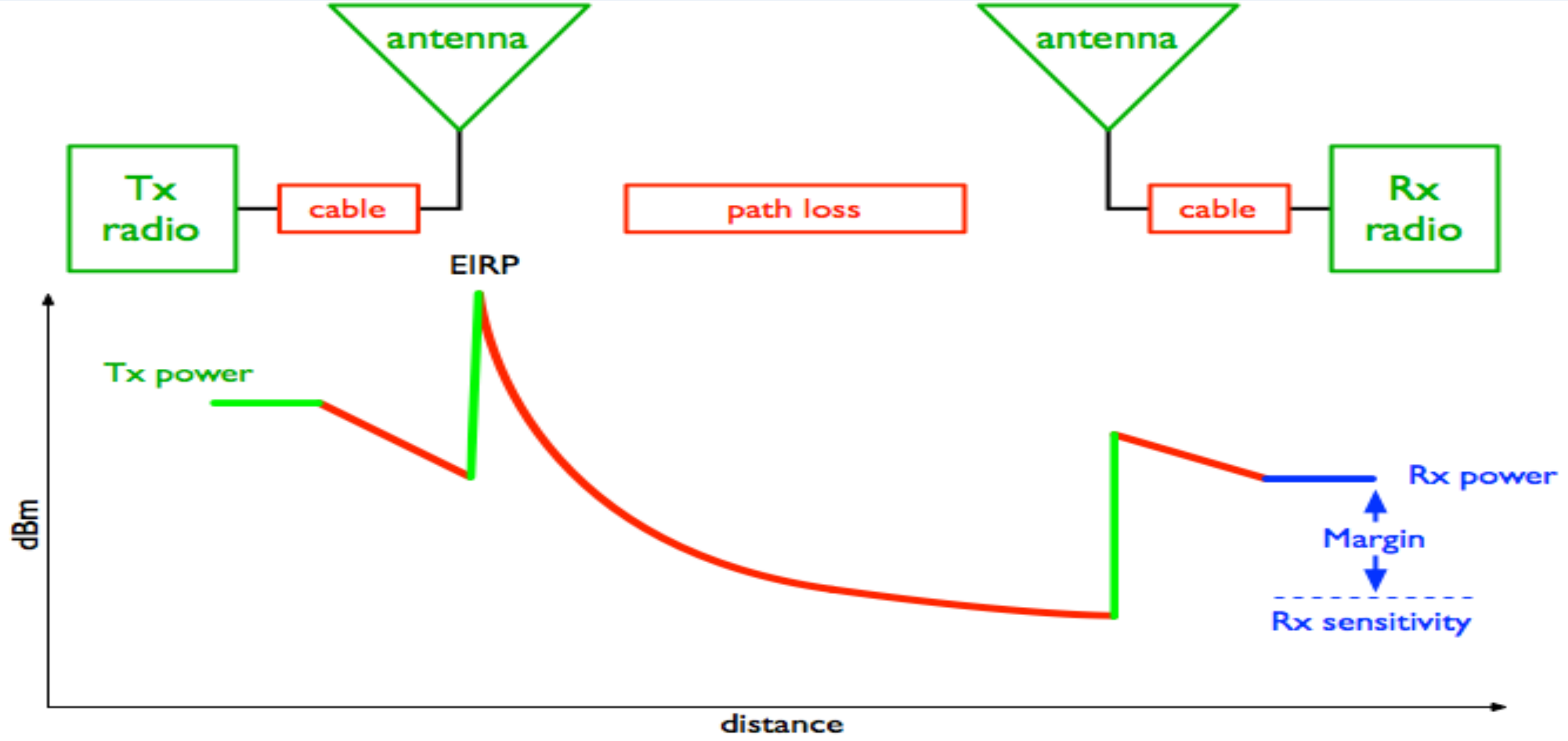
To extend the range of a wireless network we can:

- Increase the radio link power budget
- Use repeaters to relaunch the signal

Extending the range with repeaters

- If there is an obstacle in the trajectory or the distance is too great one can install an intermediate repeater to reach the destination.
- This implies extra costs, latency, and power consumption.
- An extension of this idea is to use a mesh topology in which every node can act as a forwarder of other nodes' traffic. This is the preferred approach to extend the range in short range technologies.

Power in a wireless system



Quiz

Why does the receivable signal power in a wireless link decreases with distance even in free space where there is no absorption nor obstacles in the trajectory?

Receiver sensitivity

The sensitivity of the receiver in dBm at ambient temperature is given by:

$$-174 + 10 \log_{10} (BW) + NF + S/N$$

Where BW is the bandwidth in Hz,

NF is the noise figure (extra noise introduced by the receiver circuitry)

S/N is the ratio between the power of the signal required to decode the signal and the power of the noise at the receiver.

Receiver sensitivity

The wider the receiver bandwidth the greater the amount of noise entering it and the lower the sensitivity.
The higher the transmission speed the more power is needed to obtain the same S/N ratio, since the energy received in a time interval is the product of the power and the duration.

Receiver sensitivity

The receiver sensitivity can be increased by reducing the bandwidth or by using a much higher transmission bandwidth and then lowering it at the receiver using spread spectrum techniques.
Sigfox uses the first approach and LoRa the second one.
Receiver sensitivity is stated by the vendor.

Quiz

Why does the receiver sensitivity decrease with temperature?

Why does the receiver sensitivity decrease when the transmission rate increases?

List three disadvantage associated with using repeaters in a wireless link.

Link budget

Link budget is a way of quantifying the link performance.

- The received power in an wireless link is determined by the following factors: transmitter power, loss of the cable between transmitter and antenna, transmitting antenna gain, *transmission path loss*, receiving antenna gain, and loss of the cable between the antenna and the receiver.
- If that power is greater than the ***sensitivity*** of the receiving radio, then the link is feasible.

Link budget

- The transmitter power is limited by the regulations of each country, and depends on the type of service.
- In the 2.4 GHz unlicensed band the maximum allowed EIRP is 20 dBm in Europe while it is 30 dBm in US.
- The allowed transmit power can be higher in licensed bands, broadcasters can transmit at thousand of watts.
- When using a high gain transmitter antenna the conducted power of the transmitter might have to be reduced to comply with the allowed EIRP.

Link budget: path loss

The path loss depends on:

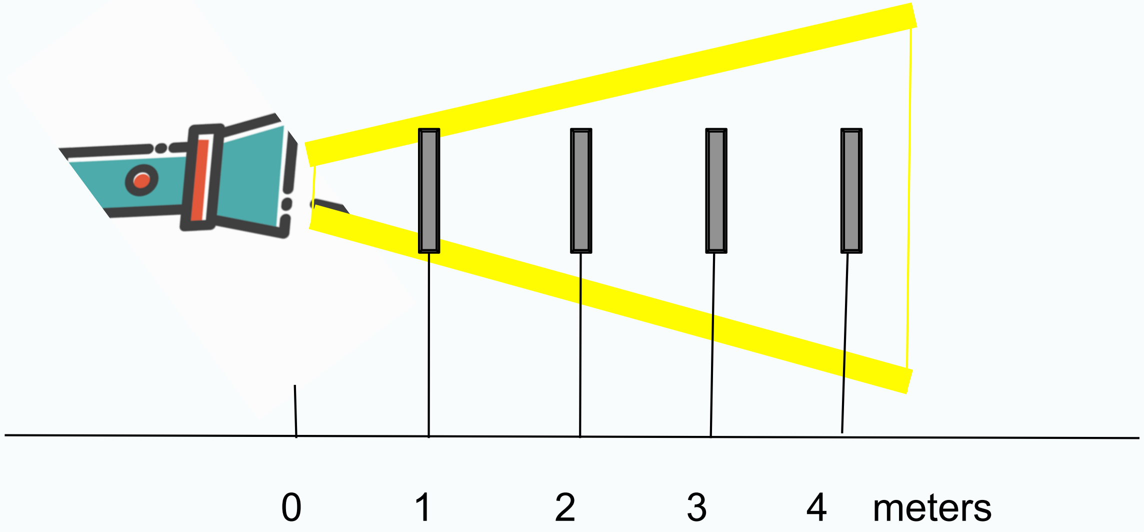
- Frequency of operation
- Distance between transmitter and receiver
- Intervening terrain and obstacles
- RF power absorption by the atmosphere, influenced by the weather
- Fading due to multipath

Free space loss: FSL

- Signal power density is diminished by the geometric spreading of the wavefront, commonly known as ***Free Space Loss***.
  - The power of the signal is spread over a wave front, the area of which increases as the distance from the transmitter increases. Therefore, the power density diminishes.

Free Space Loss (FSL)

As the wave propagate from the source it spreads over an ever increasing area, so an antenna of a given size would be able to capture a fraction of the wavefront that decreases with the square of the distance.



A screen at 1 m distance would capture all the light from the torch.
At 2 m would capture 1/4
At 3 m would capture 1/9
At 4 m would capture 1/16

Free space loss: FSL

The Free Space Loss is $(4\pi d/\lambda)^2$

and in decibels is given by:

$$L_{fs} = 32.45 + 20\log(d) + 20\log(f)$$

..where ***d*** is in kilometers and **f** is in MHz.

Free space loss at 2.4 GHz

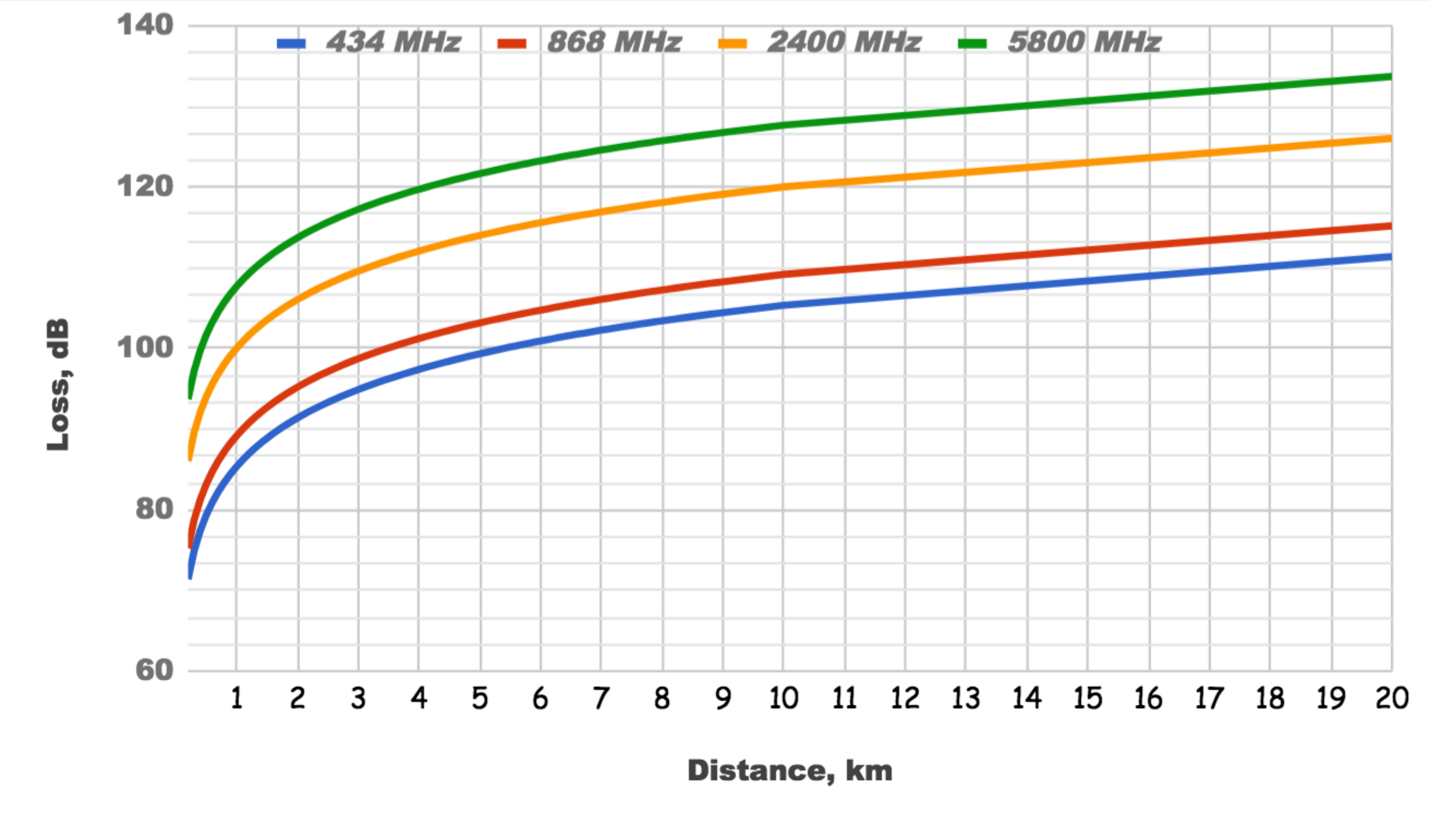
The Free Space Loss in decibels at 2.4 GHz is:

$$L_{fs} = 100 + 20\log(d)$$

..where L_{fs} is expressed in dB and ***d*** is in kilometers.

This formula is easy to remember, and by using the properties of the decibels one can very simply extend the results to any distance and even to other frequencies by mental calculation, starting from the fact that the loss at 1 km is 100 dB.

Free space loss at different frequencies



Example link budget calculation

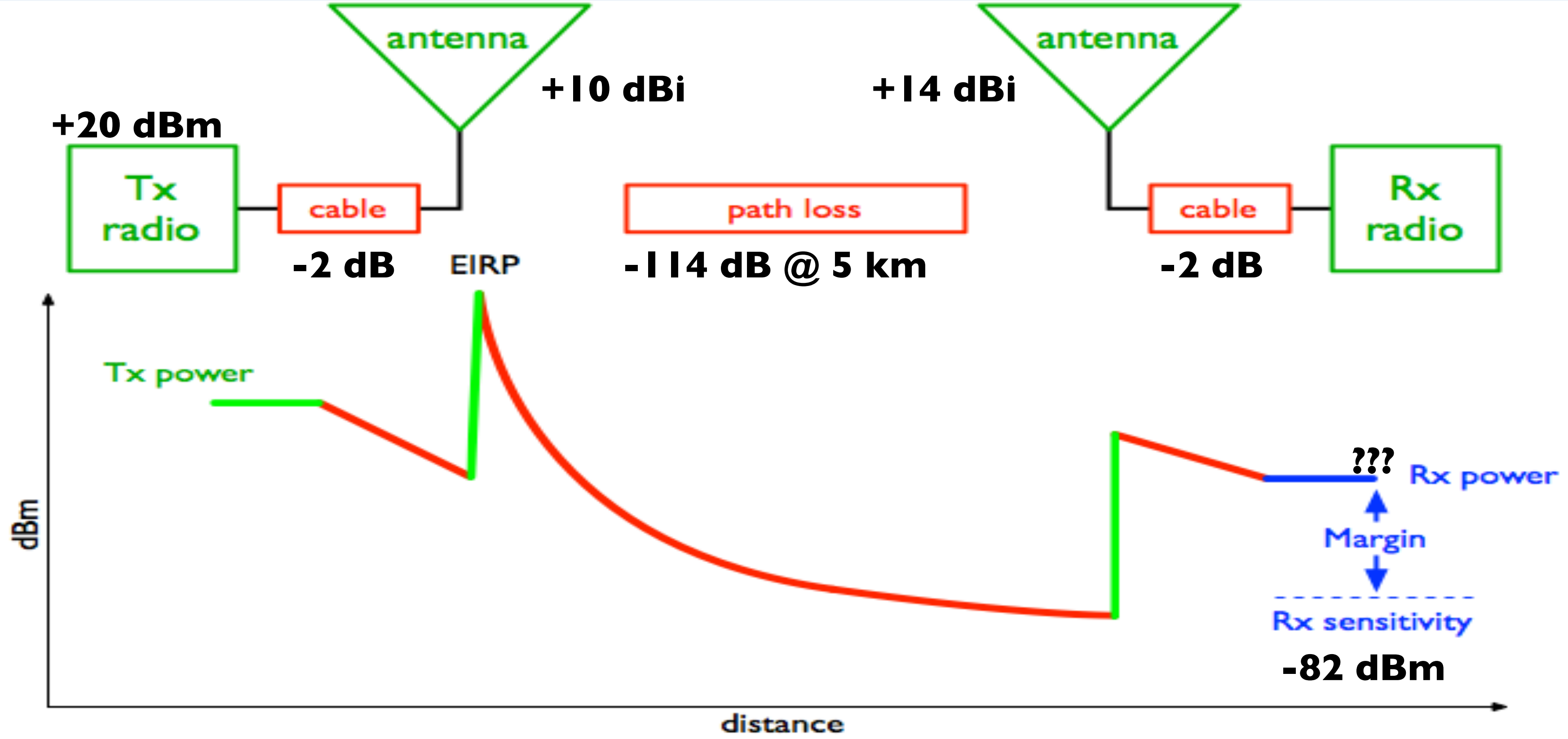
Let’s estimate the feasibility of a **5 km** link, with one access point (AP) and one client radio.

The access point is connected to an antenna with **10 dBi** gain, with a transmitting power of **20 dBm** and a receive sensitivity of **-89 dBm**.

The client is connected to an antenna with **14 dBi** gain, with a transmitting power of **15 dBm** and a receive sensitivity of **-82 dBm**.

The cables in both systems are short, with a loss of **2dB** at each side at the frequency of operation of 2.4 GHz.

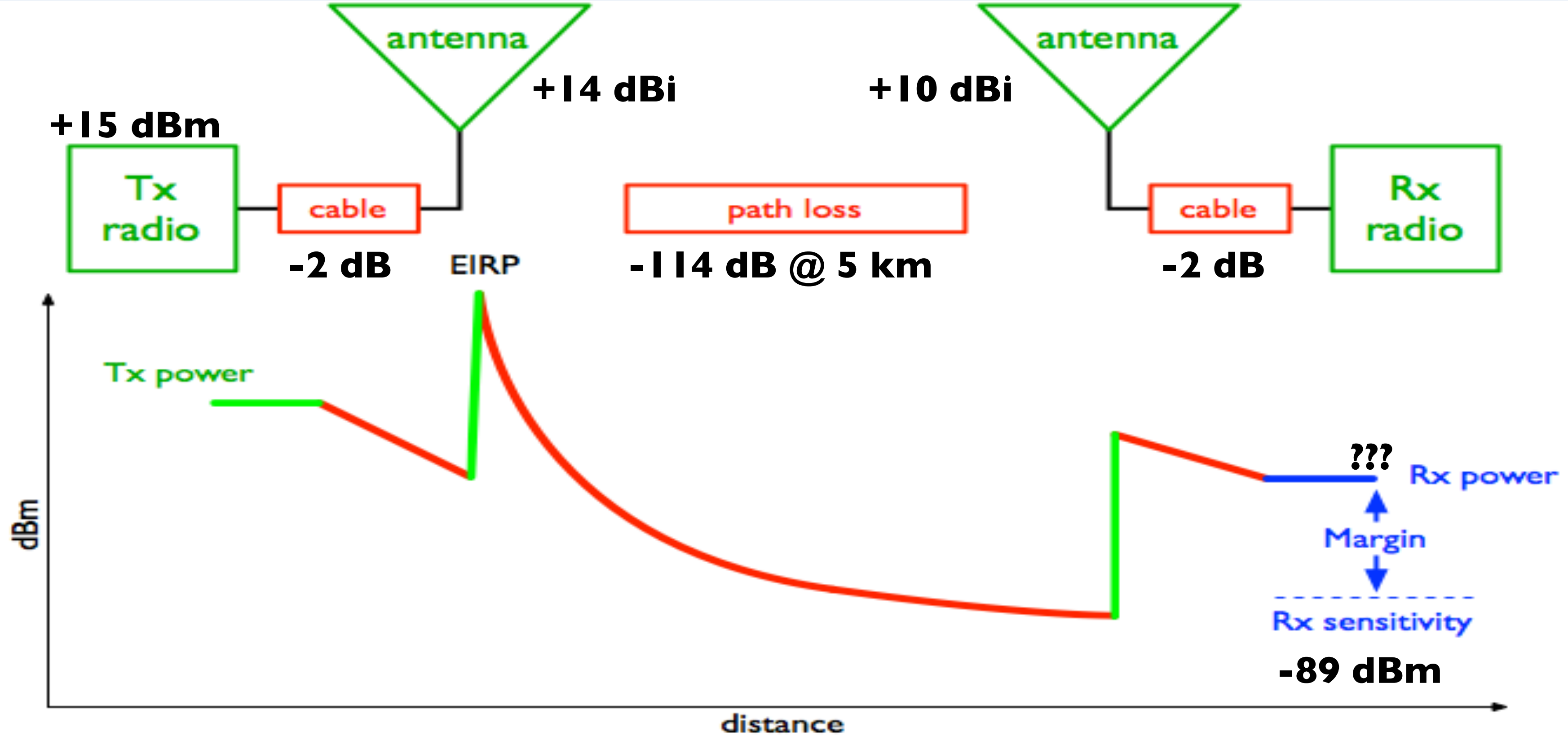
AP to Client link



Link budget: AP to Client link

20 dBm	(TX Power AP)
- 2 dB	(AP Cable Losses)
+ 10 dBi	(AP Antenna Gain)
-114 dB	(free space loss @5 km)
+ 14 dBi	(Client Antenna Gain)
- 2 dB	(Client Cable Losses)
-74 dBm	(expected received signal level)
-(-82 dBm)	(sensitivity of Client)
8 dB	(link margin)

Opposite direction: Client to AP



Link budget: Client to AP link

15 dBm	(Client TX Power)
- 2 dB	(Client Cable Losses)
+ 14 dBi	(Client Antenna Gain)
-114 dB	(free space loss @5 km)
+ 10 dBi	(AP Antenna Gain)
- 2 dB	(AP Cable Losses)
- 79 dBm	(expected received signal level)
-(-89 dBm)	(sensitivity of AP)
10 dB	(link margin)

Path Loss

Free space loss is the expected loss one would have for instance: between two space crafts

On earth, there are other factor that can cause additional losses, also called attenuation:

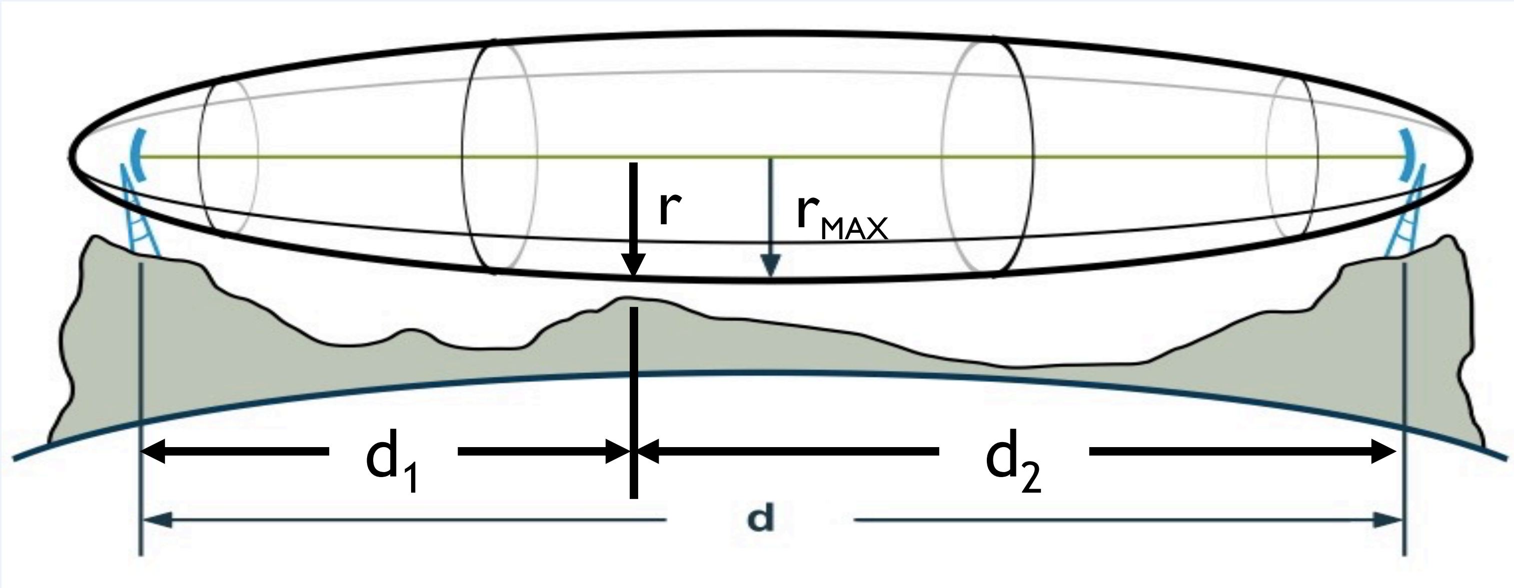
- Obstacles in the trajectory
- Absorption by atmospheric gases
- Rain and snow attenuation
- Multipath attenuation

The path loss is therefore the sum of the FSL plus all the above

Fresnel Zone

The First Fresnel Zone is an ellipsoid-shaped volume around the Line-of-Sight (LOS) path between transmitter and receiver.
The Fresnel Zone clearance is important to the integrity of the RF link because it defines a volume around the LOS that must be clear of any obstacle for the the maximum power to reach the receiving antenna.
Objects in the Fresnel Zone as trees, hilltops and buildings can considerably attenuate the received signal, even when there is an unobstructed line between the TX and RX.

Line of Sight and Fresnel Zones



$r = \text{sqrt}(\lambda * d_1 * d_2 / d)$

$r_{MAX} = 1/2 * \text{sqrt}(\lambda * d)$

where all the dimensions are in meters

Optical and Radio LOS

- Optical signals also spread over a Fresnel zone, but since the wavelength is so small, we don't notice it.

- Therefore, clearance of optical LOS does not guarantee the clearance of RADIO LOS.

Earth Curvature

- For links above 10 km the curvature of the earth must be accounted for since it will intercept the line of sight and might completely block the signal.
- On the other hand the radio wave bends because of the changing of the refraction index with height, so that the radio horizon is about 4/3 of the optical horizon in normal propagation conditions.
- So it is more convenient to represent the radio beam with a straight line drawn on a graph in which the radius of the earth has been multiplied by k=4/3

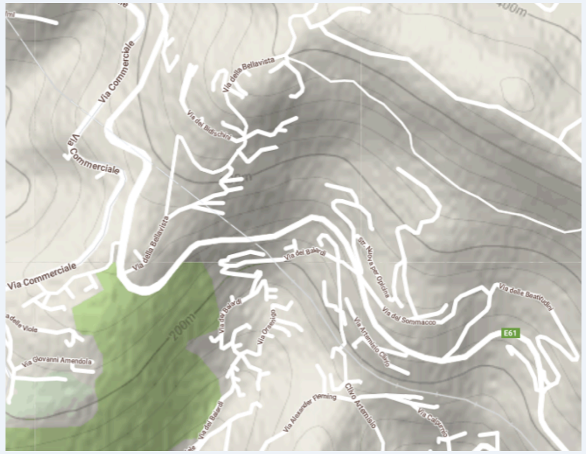
Clearance of the Fresnel zone and earth curvature

This table shows the minimum height above flat ground required to clear 60% of the first Fresnel zone for various link distances at 2.4 GHz. Notice that earth curvature plays a small role at short distances, but becomes more important as the distance increases.

Distance (km)	1st zone (m)	60% (m)	Earth curvature (m)	Required height (m)
1	5.5	3.3	0.0	3.9
5	12.4	7.44	0.4	7.84
10	17.5	10.5	1.5	12
15	21.4	12.84	3.3	16.13
20	24.7	15.82	5.9	21.72
25	27.7	16.62	9.2	25.82
30	30.3	18.18	13.3	32.5

Clearance of the Fresnel zone and earth curvature

Since to verify the clearance we need data about the elevation profile between transmitter and receiver, a number of simulation tools relying on digital elevation maps (DEM) have been developed to facilitate the task. Some also take into account other details to provide an estimate of the feasibility of a given link.



Path loss simulation tool

- There are many commercial software tools to simulate links, and a few are available for free.
- Radio Mobile is a free and powerful simulation tool for the Windows operating system. There is also an on-line version at: http://www.ve2dbe.com/rmonline.html
- BotRf is very simple to use android app based on Telegram

BotRf: a telegram application for wireless links

To install the tool, first install the telegram application from the *play store* in your device.

You need to have a cell phone to receive an sms with the code that will grant you access. It does not need to be a smart phone.

With that code, you can run telegram in any web browser capable device, laptop, tablet or desktop, besides an android phone.

Once telegram is running choose BotRf as a contact, and you are set.

BotRf: a telegram application for wireless links

To plan a point to point link you need:

- Coordinates and height above the terrain of the two antennas
- Frequency of operation in megahertz
- Transmission power and receiver sensitivity at the operating rate
- Transmitting and receiving antenna gains in the chosen direction
- Losses of the cables between the device and the antenna, if any

BotRf: a telegram application for wireless links

BotRf will fetch the required digital elevation maps to:

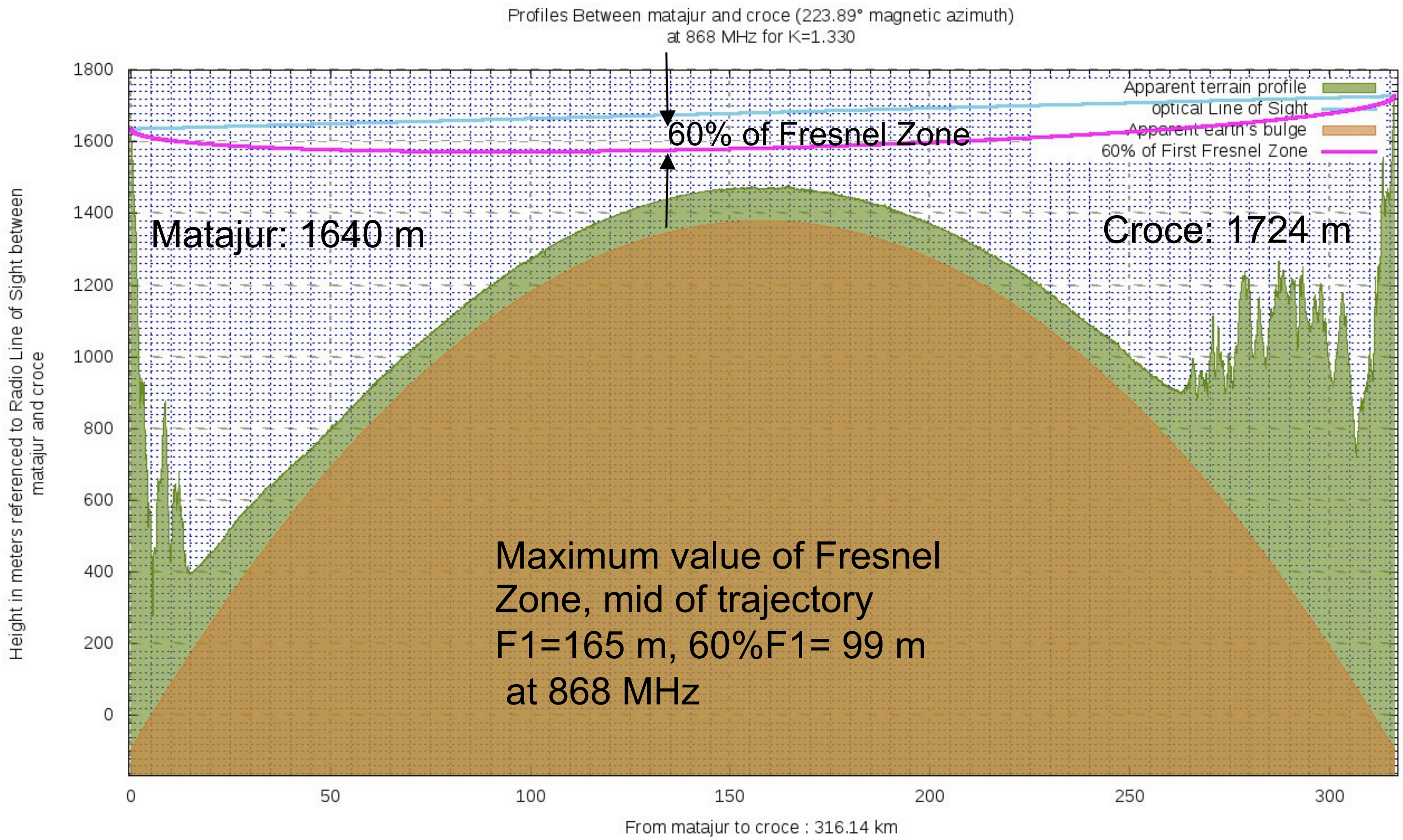
- Draw the first Fresnel zone ellipsoid and optical line of sight
- Draw the apparent earth curvature for the specified refraction index
- Calculate the distance and the angles between both antennas
- Calculate the free space loss on the path and the estimated attenuation introduced by obstacles, if present
- Show a profile of the terrain between the antennas

BotRf: a telegram application for wireless links

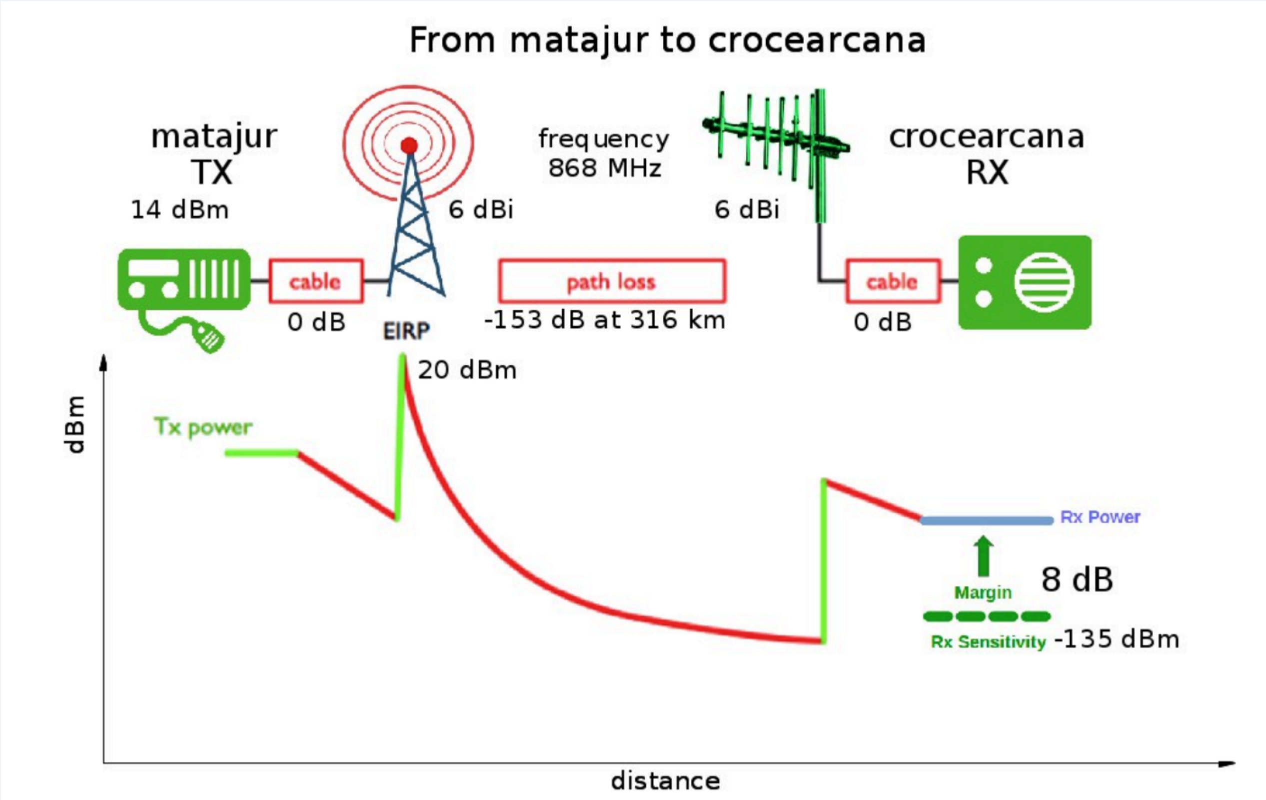
BotRf will also:

- Draw a graph of power versus distance along the link
- Calculate the estimated received power and the link margin
- Draw a map of the the area surrounding the two end points
- Present a view from one end point to the other, identifying relevant landmarks
- Additionally, BotRf will do many magnitude and units conversions to facilitate the planning of the link

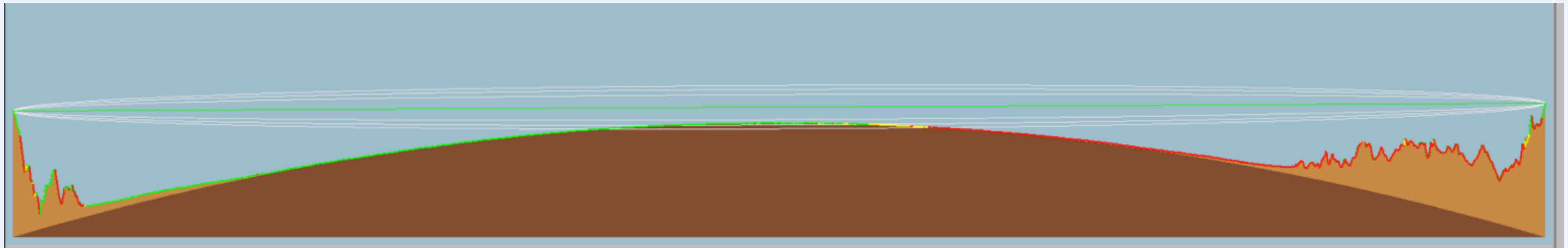
Example of BotRf simulation



Example of BotRf simulation



Radio Mobile simulation



Croce Matajur			
Matajur (1)			(2) croce
Latitude	46.212100°	Latitude	44.129500°
Longitude	13.529400°	Longitude	10.783600°
Ground elevation	1623.8m	Ground elevation	1724.0m
Antenna height	4.0m	Antenna height	2.0m
Azimuth	223.89 TN | 220.64 MG°	Azimuth	41.94 TN | 39.37 MG°
Tilt	-1.40°	Tilt	-1.44°
Radio system			**Propagation**
TX power	13.98dBm	Free space loss	141.50dB
TX line loss	0.00dB	Obstuction loss	-1.04dB
TX antenna gain	11.00dBi	Forest loss	0.00dB
RX antenna gain	11.00dBi	Urban loss	0.00dB
RX line loss	0.00dB	Statistical loss	5.52dB
RX sensitivity	-127.00dBm	Total path loss	145.98dB

Performance	
Distance	**316.123km**
Precision	158.1m
Frequency	902.000MHz
Equivalent Isotropically Radiated Power	0.315W
System gain	162.98dB
Required reliability	70.000%
Received Signal	-110.00dBm
Received Signal	0.71μV
Fade Margin	**17.00dB**

http://www.ve2dbe.com/rmonline.html

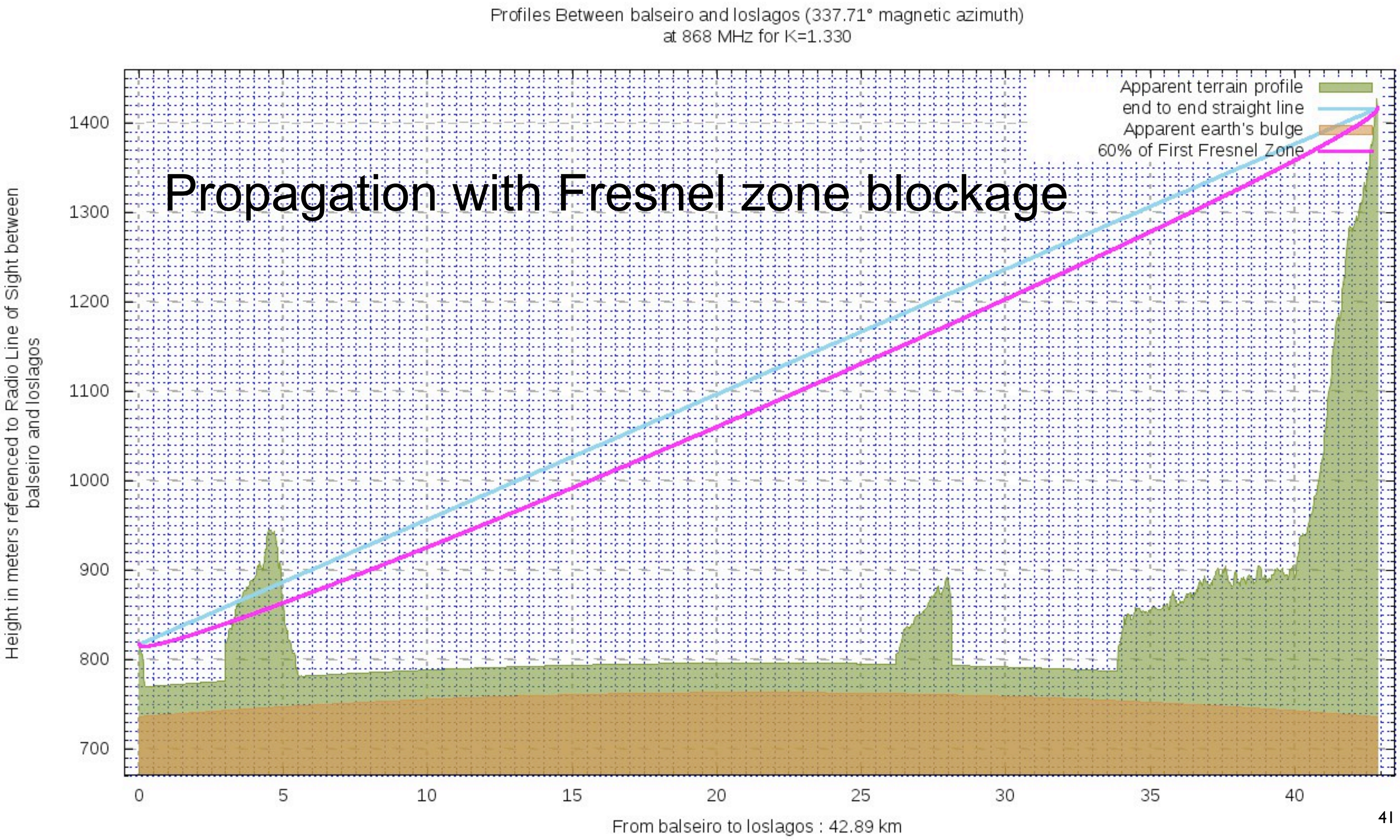
Link assessment with Google Earth

- Google earth can be used to determine LOS over short distance links.
- But it does not consider the curvature of the earth nor the bending of the radio waves because of the variation of the refractive index, so it is not a good simulation tool for radio links.

Exercise

Install the Telegram application in your device of choice: smart phone, laptop (any operating system since it can be used as a web browser application). Once telegram is running choose BotRf as a contact. Using the s command, insert the name and coordinates of two sites, as well as the heights of the antennas above the ground.
The r command will then generate a complete report.

Propagation with Fresnel zone blockage



Transmitter site: balseiro
Site location: (-41.1136,-71.4142) (-41 6'48"/-71 24'51")
Elevation: 814 m above sea level
Antenna height: 3 m above ground / 817 m above sea level
Azimuth to loslagos: 337.71 degrees
Elevation angle to loslagos: +0.6567 degrees
Elevation angle to the first obstruction: +0.6760 degrees

Receiver site: loslagos
Site location: (-40.7566,-71.6073) (-40 45'23"/-71 36'26")
Elevation: 1414 m above sea level
Antenna height: 3 m above ground / 1417 m above sea level
Azimuth to balseiro: 157.84 degrees
Depression angle to balseiro: -0.9466 degrees
Elevation angle to the first obstruction: +0.9759 degrees

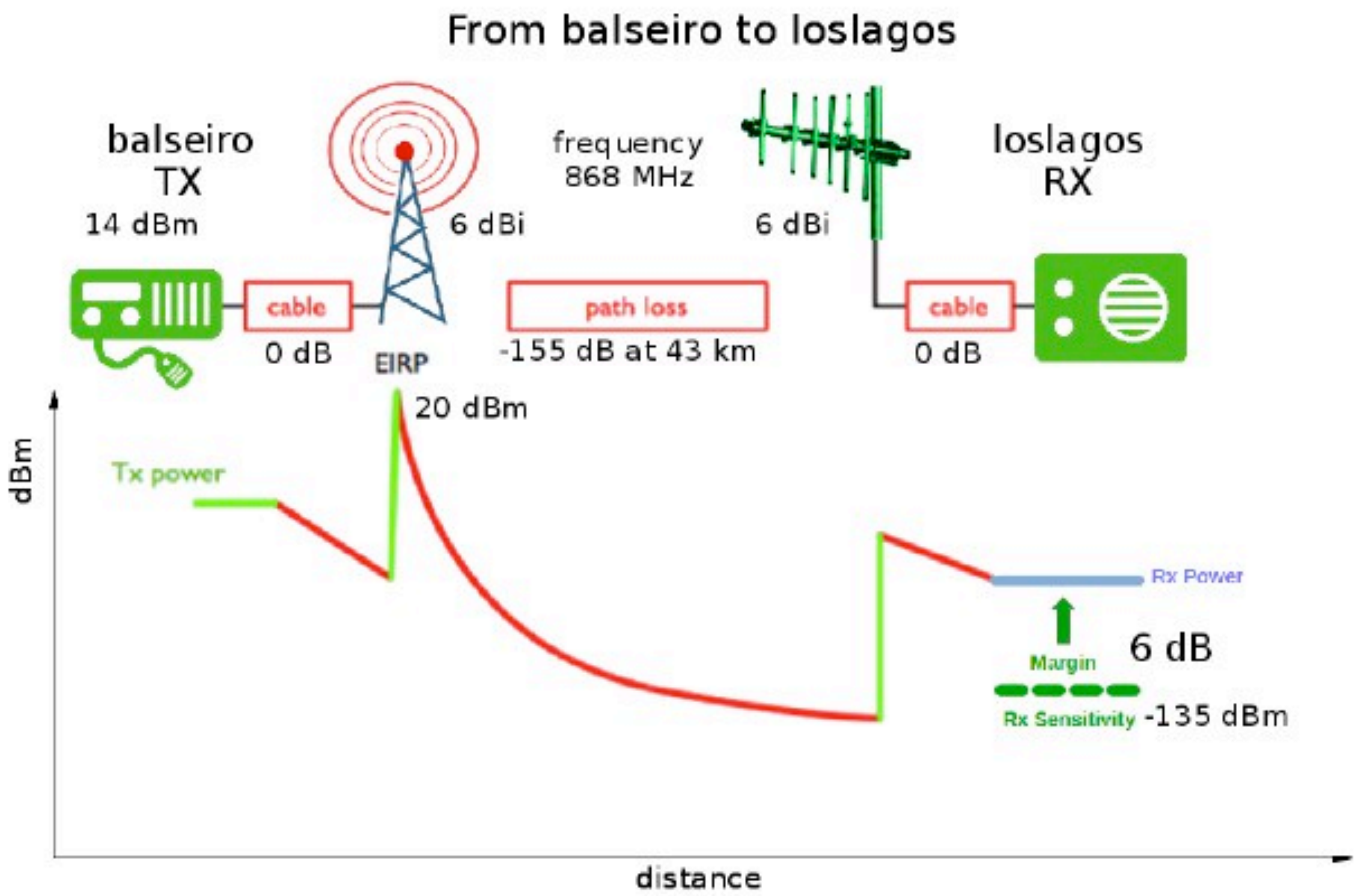
Diffraction dominated propagation

Free space path loss: 123.88 dB
Longley-Rice path loss: 155.10 dB
Attenuation due to terrain shielding: 31.22 dB
Mode of propagation:
Single Horizon, Diffraction Dominant
Longley-Rice model error code: 0
ErrorMessage[0]: "No error"

Diffraction dominated propagation

N. of obstructions detected: 12

Coordinates	distance (km),	height (m) above sea level:
(–40.7569,–71.6071),	42.9,	1427.0
(–41.0728,–71.4364),	4.9,	886.0
(–41.0731,–71.4362),	4.9,	899.0
(–41.0735,–71.4360),	4.8,	901.0
(–41.0738,–71.4358),	4.8,	914.0
(–41.0740,–71.4357),	4.8,	916.0
(–41.0743,–71.4356),	4.7,	928.0
(–41.0745,–71.4354),	4.7,	930.0
(–41.0748,–71.4353),	4.7,	933.0
(–41.0755,–71.4349),	4.6,	934.0
(–41.0757,–71.4348),	4.5,	935.0
(–41.0760,–71.4347),	4.5,	935.0



pow balseiro loslagos 14 0 6 6 0 -135

Conclusions

- We looked at the main factors that affect the range of a link.
- The free space loss is proportional to the square of the distance, **but** when obstacles are present the loss will be much higher.
- To clear the Fresnel zone and the curvature of the earth the antennas must have a certain height that is better calculated with simulation tools like BotRf that use digital elevation maps.