Link Budget Calculation

Training materials for wireless trainers

The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

Wednesday, March 5, 14

This 60 minute talk is about estimating wireless link performance by using link budget calculations. It also introduces the Radio Mobile link design tool.

Version 1.5 by Rob, @2009-11-23
Version 1.7 by Carlo, @2010-01-13 (in Pune)
Version 1.8 by Rob, @2010-02-28
Version 1.9 by Rob, @2010-03-02
Version 1.10 by Rob, @2010-03-12
Version 1.12 by Carlo, @2011-03-22
Version 1.13 by Carlo, @2011-03-23 - corrected a mistake of 1dB in the Lfs in slides 11 to 14
version 1.15 by Ermanno, some changes in formulas and corrections in slides

Goals

- To be able to calculate how far we can go with the equipment we have
- To understand why we need high masts for long links
- To learn about software that helps to automate the process of planning radio links

Free space loss

- Signal power is diminished by 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.

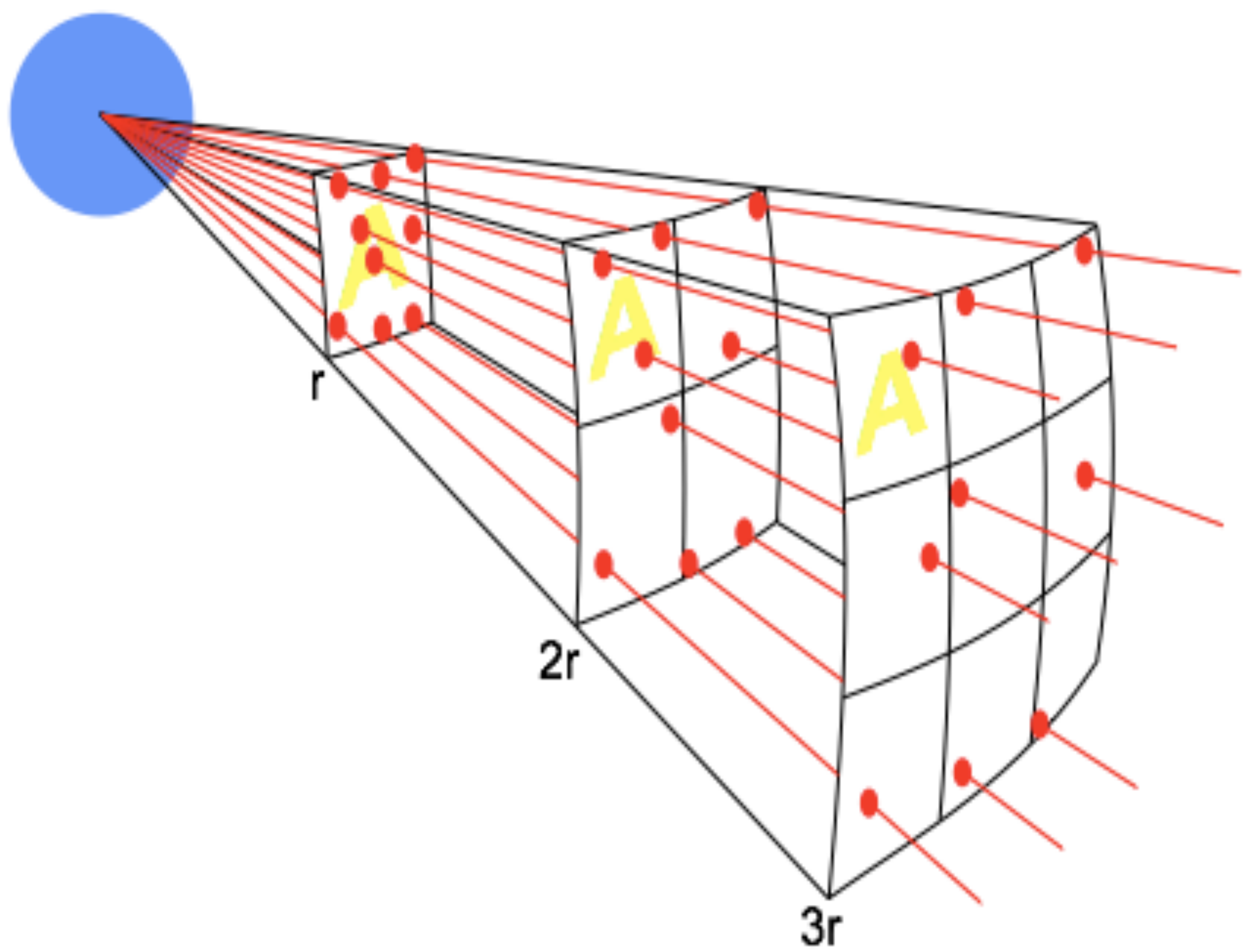


Figure from *http://en.wikipedia.org/wiki/Inverse_square*

A light bulb analogy will help understand this. If we watch the quantity of light shed over a piece of paper, we will notice that this diminishes as we take it further away from a light bulb. This is a purely geometric phenomenon, it happens even in a vacuum where there is nothing that can absorb the em radiation. That is why it is called free space loss. An even better term would be "geometric spread loss"

Free Space Loss (@2.4 GHz)

- Using decibels to express the loss and using 2.4 GHz as the signal frequency, the equation for the Free Space Loss is:

$$L_{fs} = 100 + 20*\log_{10}(d)$$

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

The log in this formula is in base 10.
It is quite easy to use this simple formula, because the result is: 100dB (for 1 km), plus 20 dB for every time you multiply the distance by 10... (10 km -> 120dB, 100 km-> 140dB, etc...).
Then if you remember that log(2)=~0.3, you simply add 20*0.3 = 6dB every time you double the distance, e.g.
1km -> 100dB
2km -> 106dB
4km -> 112dB
8km -> 118dB
10km -> 120dB
20km -> 126dB
40km -> 132dB
80km -> 138dB
100km -> 140dB
and so on...

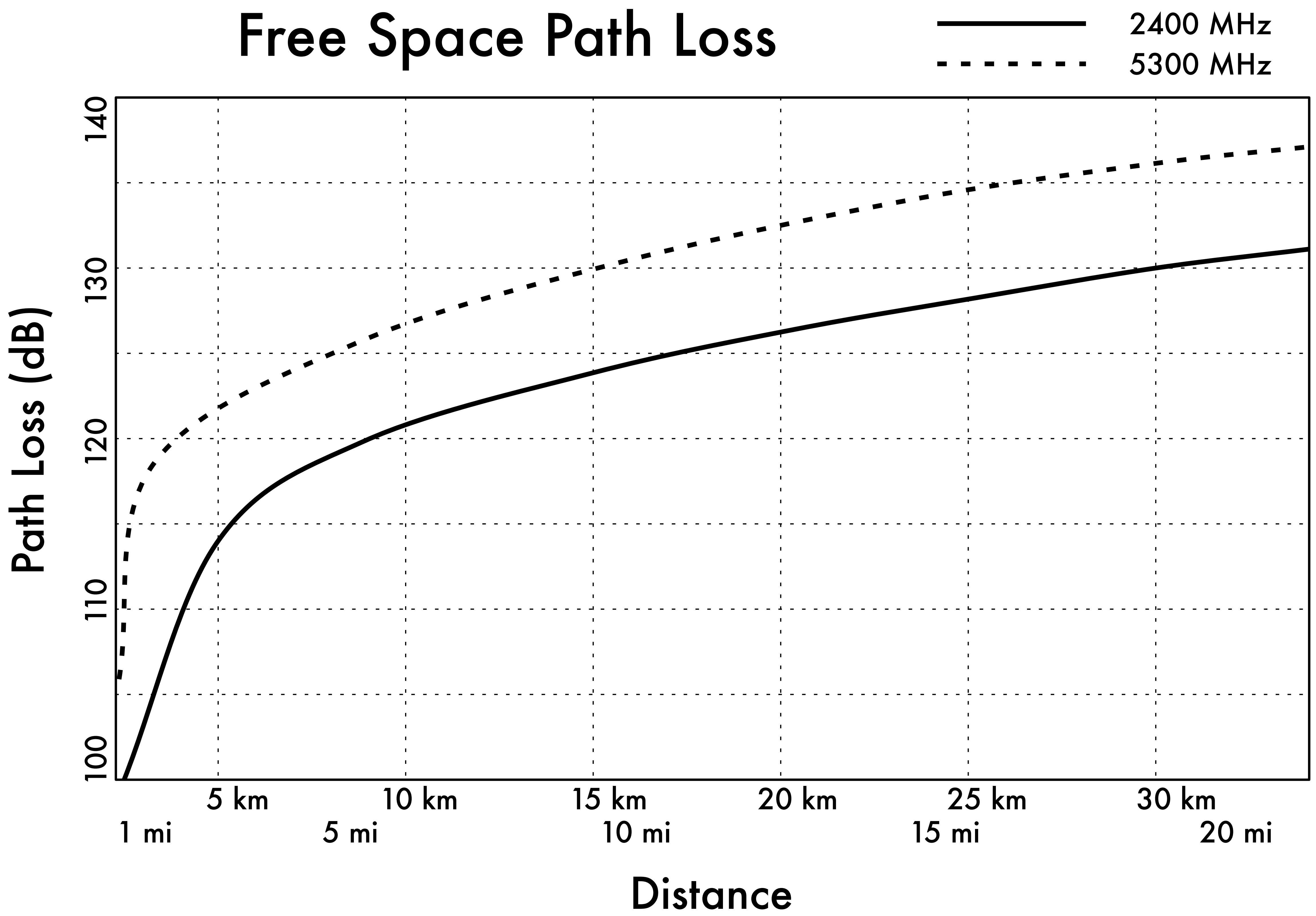
Free Space Loss (any frequency)

- Using decibels to express the loss and at a generic frequency f, the equation for the Free Space Loss is:

$$L_{fs} = 92,45 + 20*\log(d) + 20*\log(f)$$

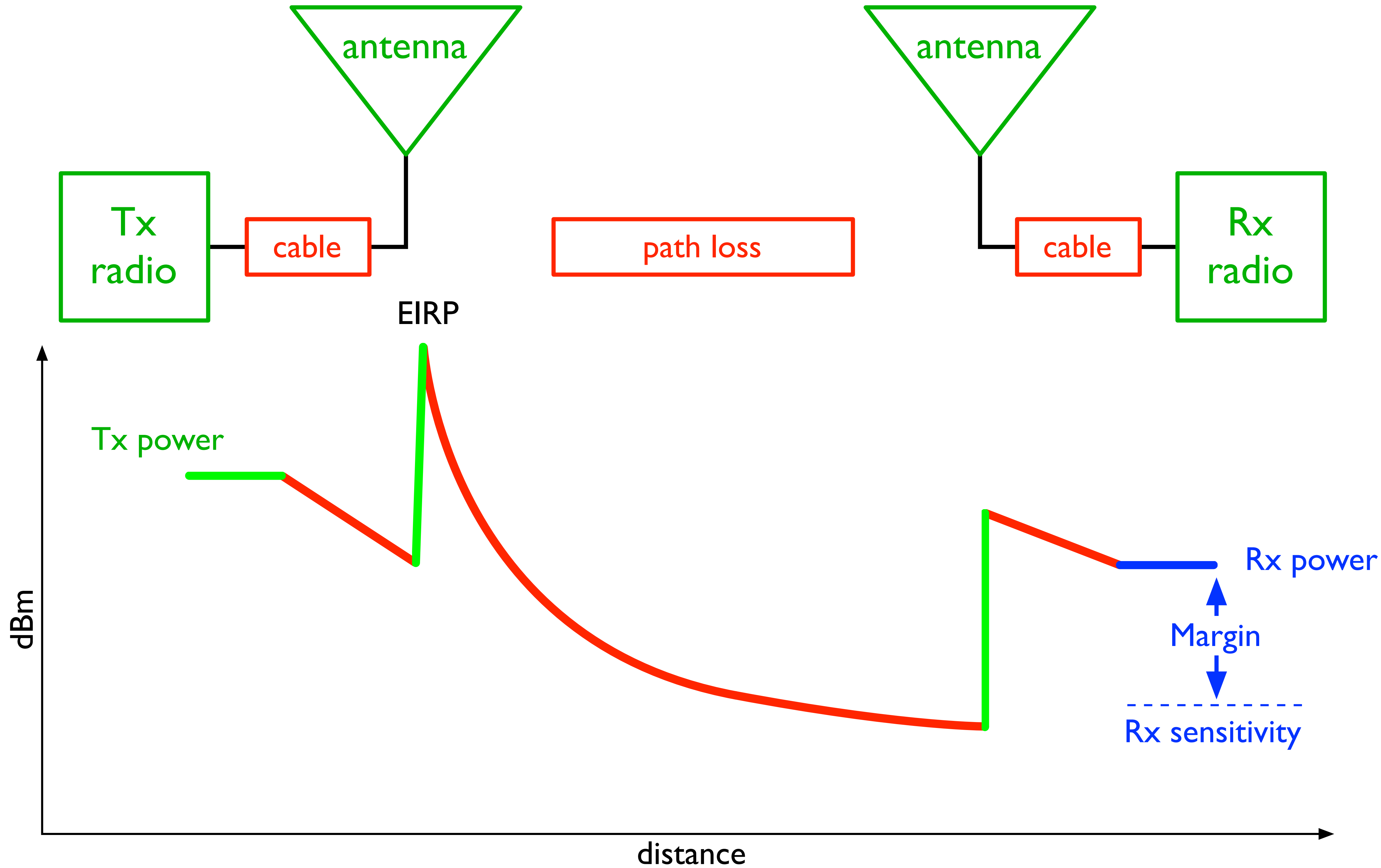
- ...where ***L_{fs}*** is expressed in dB, ***d*** is in kilometers and **f** is in GHz.

The formula in the previous slide is a particular case of this one, obtained making f=2.4 Ghz in this formula.



This graph show the free space path loss for distances up to 40 km, for both 2.4 and 5.3 GHz.
Hint: if the frequency used is in the range of 5 GHz (instead of 2.4GHz) you have to add 6 dB to the loss to obtain the right result.

Power in a wireless system



This graph shows the relative amount of gains and losses as well as the absolute power at each point in a wireless link.

The transmitter provides some amount of power. A small amount is lost in attenuation between the transmitter and the antenna. The antenna then focuses the power, providing a gain. At this point, the power is at the maximum possible value for the link. This power is called EIRP (Equivalent Isotropic Radiated Power). Most regulators impose a limit on the maximum allowable value of EIRP in a given country.

Then there are free space and environmental losses (which together form the path loss), which increase with the distance between the link endpoints. The receiving antenna provides some additional gain. Then there is a small amount of loss between the receiving antenna and the receiving radio.

If the received amount of power at the far end is greater than the receive sensitivity of the radio, by a certain margin M, then the link is possible. The value of M will determine the reliability of the link, a good starting point is to have at least 10 dB margin. For critical links, it is better to strive for a 20 dB margin.

Link budget

- The performance of any communication link depends on the quality of the equipment being used.
- ***Link budget*** is a way of quantifying the link performance.
- The received power in an wireless link is determined by three factors: ***transmit power***, ***transmitting antenna gain***, and ***receiving antenna gain***.
- If that power, minus the ***free space loss*** of the link path, is greater than the ***minimum received signal level*** of the receiving radio, then a link is possible.
- The difference between the minimum received signal level and the actual received power is called the ***link margin***.
- The link margin must be positive, and should be maximized (should be at least 10dB or more for reliable links).

Do not confuse the link budget with the cost to obtain the equipment! We are not dealing with money here but with dB.
The link budget reflects the impact of different variables in the ultimate power that reaches the receiver.
Keep in mind that the receiver sensitivity is strongly dependent on the transmission rate: the higher the transmission rate
the higher the receiver power required for acceptable performance.
If one cannot obtain an acceptable margin at a given transmission rate it might be required to work at a lower transmission rate.
The free space loss applies when there is a completely unobstructed path between the transmitter and the receiver, with clearance of at least 60% of the first Fresnel Zone.
Partial obstruction of the 1st Fresnel Zone or the presence of walls or other objects will cause additional losses to be added to the free space loss to calculate the total path attenuation.

BULLET2 DATASHEET

UBIQUITI NETWORKS

BULLET2

UBIQUITI NETWORKS

Zero Variable Outdoor Wireless Deployment

SYSTEM INFORMATION	
Processor Specs	Atheros MIPS 4KC, 180MHz
Memory Information	16MB SDRAM, 4MB Flash
Networking Interface	1 X 10/100 BASE-TX (Cat. 5, RJ-45) Ethernet Interface

REGULATORY / COMPLIANCE INFORMATION	
Wireless Approvals	FCC Part 15.247, IC RS210, CE
RoHS Compliance	YES

RADIO OPERATING FREQUENCY 2412-2462 MHz

TX SPECIFICATIONS			
	DataRate	TX Power	Tolerance
802.11b	1Mbps	20 dBm	+/-1dB
	2Mbps	20 dBm	+/-1dB
	5.5Mbps	20 dBm	+/-1dB
	11Mbps	20 dBm	+/-1dB
802.11g OFDM	6Mbps	20 dBm	+/-1dB
	9Mbps	20 dBm	+/-1dB
	12Mbps	20 dBm	+/-1dB
	18Mbps	20 dBm	+/-1dB
	24Mbps	20 dBm	+/-1dB
	36Mbps	18 dBm	+/-1dB
	48Mbps	16 dBm	+/-1dB
	54Mbps	15 dBm	+/-1dB

RX SPECIFICATIONS			
	DataRate	Sensitivity	Tolerance
802.11b	1Mbps	-95 dBm	+/-1dB
	2Mbps	-94 dBm	+/-1dB
	5.5Mbps	-93 dBm	+/-1dB
	11Mbps	-90 dBm	+/-1dB
802.11g OFDM	6Mbps	-92 dBm	+/-1dB
	9Mbps	-91 dBm	+/-1dB
	12Mbps	-89 dBm	+/-1dB
	18Mbps	-88 dBm	+/-1dB
	24Mbps	-84 dBm	+/-1dB
	36Mbps	-81 dBm	+/-1dB
	48Mbps	-75 dBm	+/-1dB
	54Mbps	-72 dBm	+/-1dB

Here is a example of a manufacturer's data sheet showing the transmit power and receive sensitivity at various modulations and data rates. A data sheet is required for any serious outdoor work, and some data sheets are more complete than others. Avoid manufacturers who do not publish the detailed specifications of their equipment.

Note that the minimum RSL is dependent upon rate, and the 1 Mbps rate is used for maximum range. TX power is usually also rate dependent, but manufacturers rarely indicate this.

As the received signal drops, devices will automatically reduce their speed to attempt to maintain a stable link.

Note that the manufacturer specifies the frequency range from 2412-2462 MHz. The spectrum usage of each channel is 20 MHz, and the manufacturer is referring to the center frequency.

Example link budget calculation

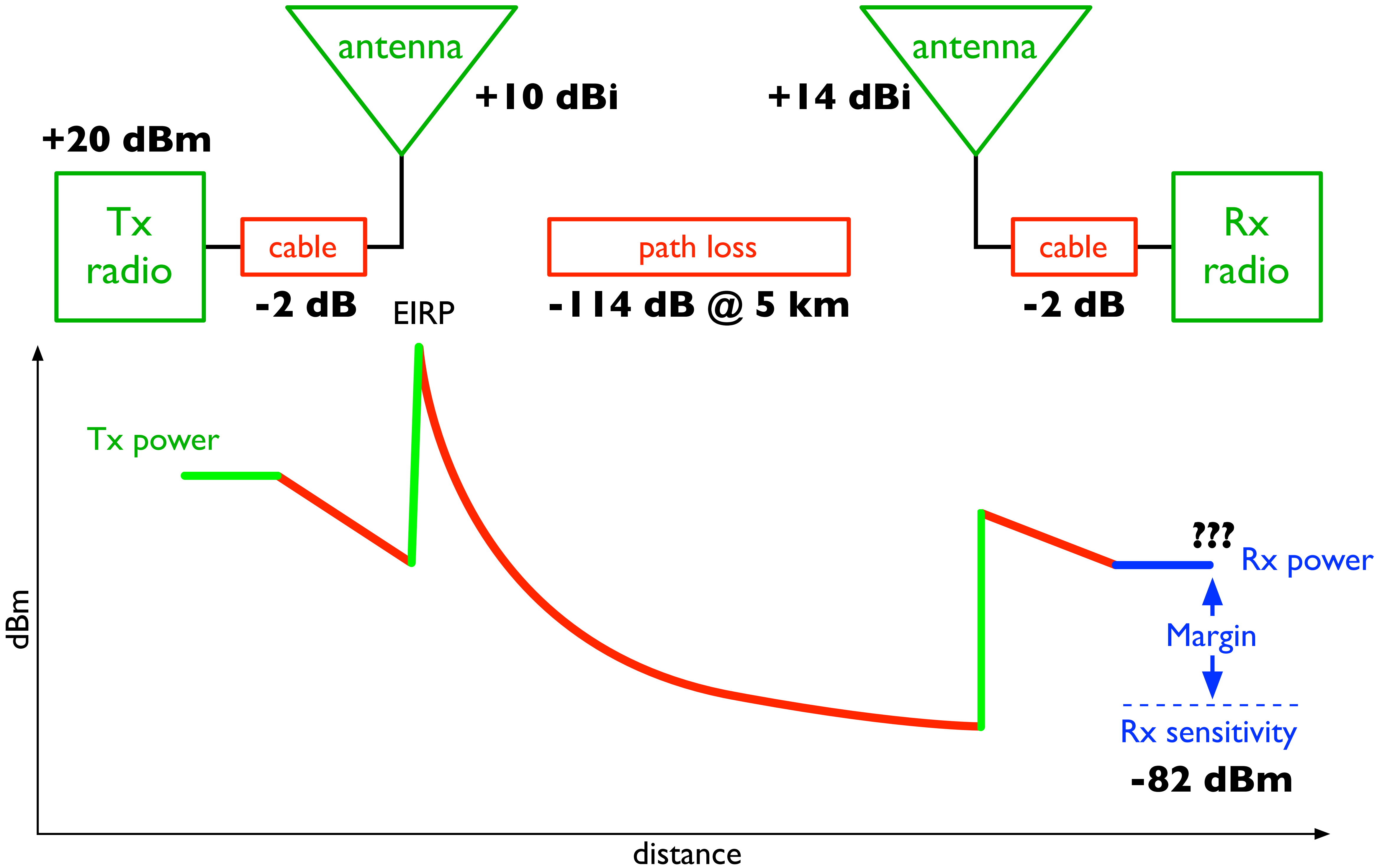
Let's estimate the feasibility of a **5 km** link, with one access point and one client radio.

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 2.4 GHz frequency of operation.

AP to Client link



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Here is the graph from the previous slide, with values filled in for the AP and client.

Link budget: AP to Client link

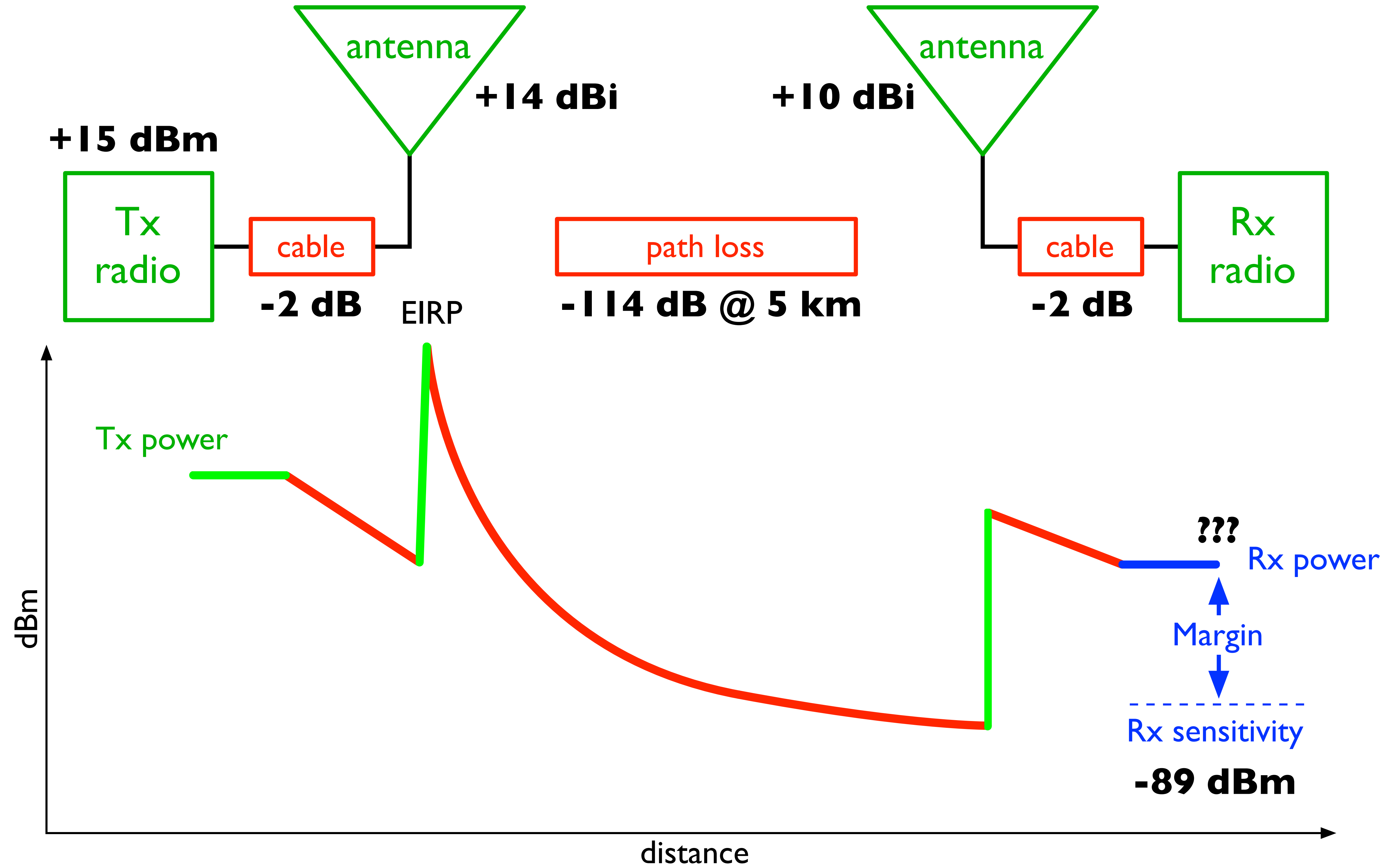
```
  20 dBm (TX Power AP)
+ 10 dBi (Antenna Gain AP)
-  2 dB  (Cable Losses AP)
+ 14 dBi (Antenna Gain Client)
-  2 dB  (Cable Losses Client)
__________
  40 dB  Total Gain
-114 dB  (free space loss @5 km)
__________
 -74 dBm (expected received signal level)
--82 dBm (sensitivity of Client)
__________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


The AP to Client link is possible, but below 10 dB. This link could be improved.

Remember that Free Space Loss is different than the link budget. FSL refers to the loss due to geometric spreading of signal in free space, while the link budget calculation will take the FSL into account to determine whether a link is feasible.

Ask to participants how the link margin can be improved. Comment on the answers; they may suggest use of higher gain antennas, shorter/better cables, higher TX power, better receiver, or amplifiers. You may point out that the use of amplifiers is not an optimal solution for different reasons: they are expensive, cause more interference, consume more power, create asymmetry in TX/RX power (unless used on both ends of a link) while antennas work in both directions, the amplifier is one more point-of-failure, etc…

Opposite direction: Client to AP



This shows the calculation to be performed, but in the opposite direction.

Link budget: Client to AP link

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


The Client to AP link is better, at 10 dB, even though the transmit power is lower. This link is might work but it could be improved by using higher gain antennas, more sensitive radios, or more powerful transmitters.

Fresnel Zone

- The First Fresnel Zone is an ellipsoid-shaped volume around the Line-of-Sight 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.

Fresnel zone calculations are independent of the free space loss. A link with plenty of link budget but a blocked Fresnel zone can have many problems, or not work at all.

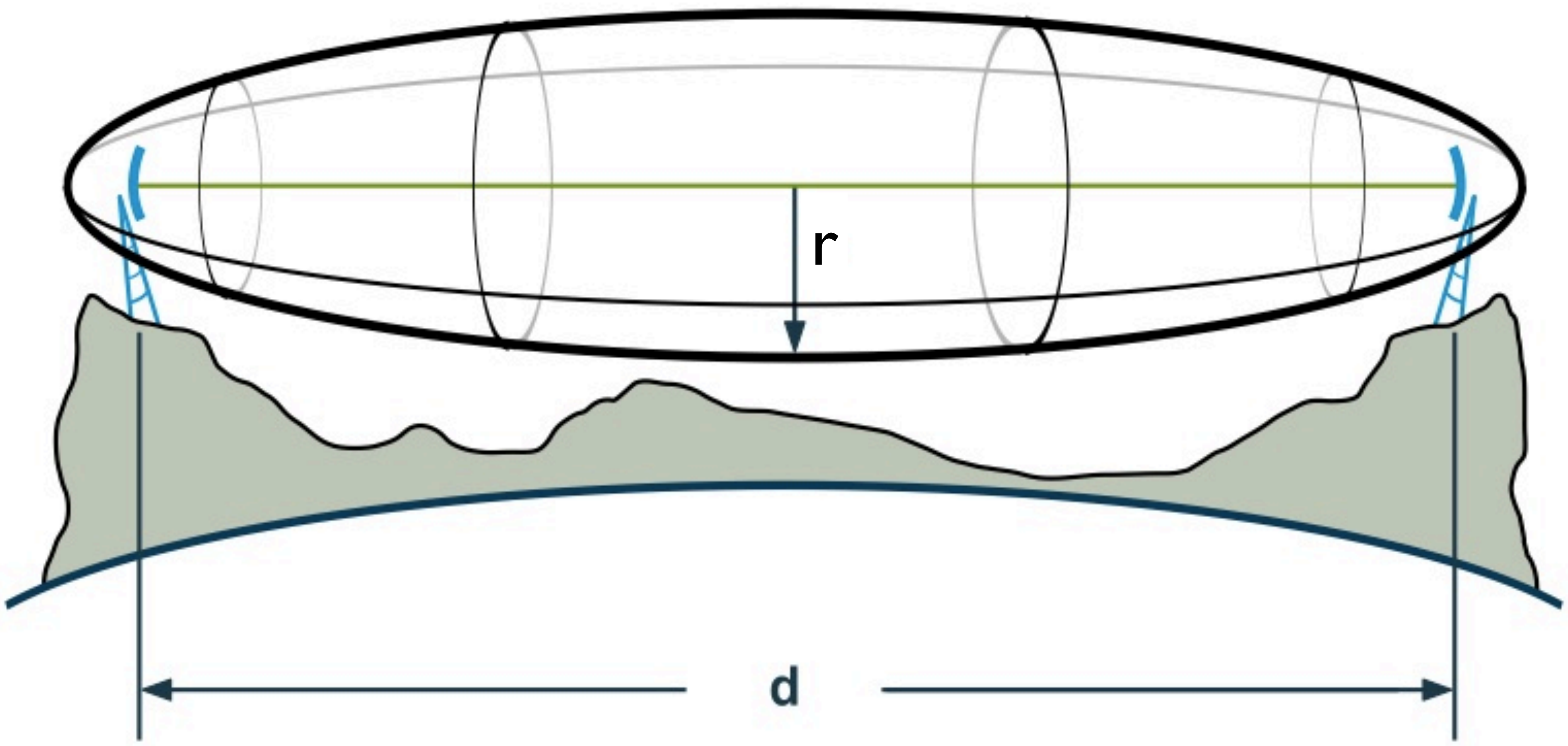
The shape of the Fresnel zone is similar to a cigar, it is a 3D object, so one has to mind also the possible obstruction of the Fresnel zone by objects in the horizontal plane as well, for instance, two close buildings adjacent to a clear optical LOS might cause a significant loss.

Optical and Radio LOS

Optical signals also possess 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.

Line of Sight and Fresnel Zones



a free line-of-sight **IS NOT EQUAL TO** a free Fresnel Zone

Simply draw a line between two points, and if nothing is in the way, we have optical **line of sight**.

But radio waves are not confined to a perfectly straight line, they occupy a volume in space. **Fresnel zone** theory describes how a propagating wave can cause interference with itself. If the first Fresnel zone is partially blocked by an obstruction, the signal arriving at the far end would be diminished.

Fresnel Zone

- The radius of the first Fresnel Zone at a given point between the transmitter and the receiver can be calculated as:

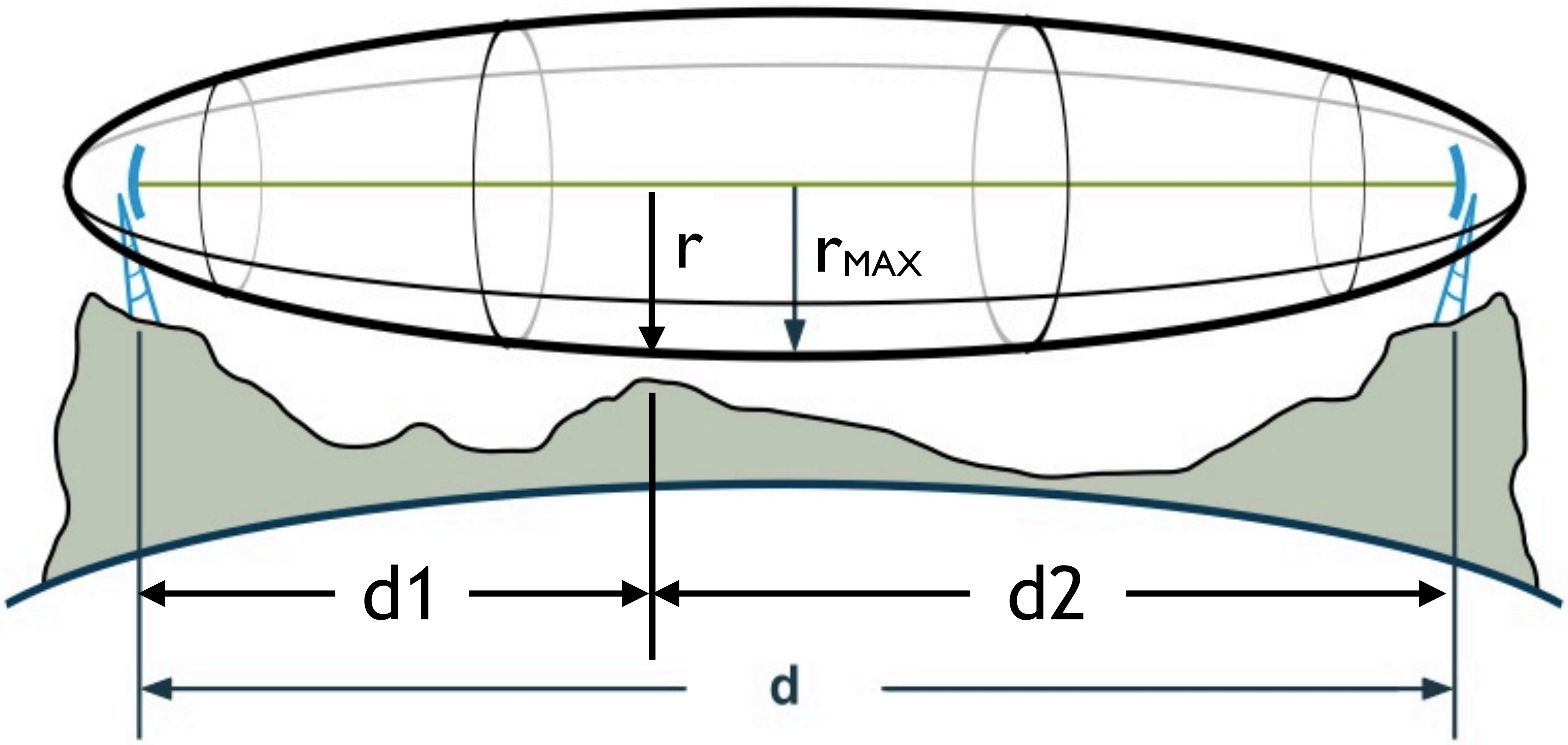
```
r = sqrt(λ*(d1*d2)/(d))
```

- ...where **r** is the radius of the zone in meters, **d1** and **d2** are distances from the obstacle to the link end points in meters, **d** is the total link distance in meters, and λ is the wavelength in m.
- Note that this gives you the radius of the zone, not the height above ground. To calculate the height above ground, you need to subtract the result from a line drawn directly between the tops of the two towers.

It is not strictly necessary to clear the whole of the first Fresnel zone for an acceptable link.
Standard engineering practice is to clear 60 to 70% of the first Fresnel zone; the resulting loss over the 100% clearance is negligible.
There is an infinite number of Fresnel zones that surround the first one, but we are not concerned with them since the clearance of the second Fresnel zone will actually reduce the amount of power reaching the receiver.
So we strive for clearance of just 60% of the first Fresnel zone for optimum performance.
In terms of the frequency in MHz, this equation can be written as:
r = 17.31 * sqrt((d1 * d2) / (f * d)), where the distances are in meters
sqt(x) is the square root of x.

For an optical signal, λ =10^-6 m, whereas at 2.4 GHz is 0.12 m so the Fresnel zone is about 300 times smaller, that is why we do not see it

Line of Sight and Fresnel Zones



$r = sqrt(\lambda*d1*d2/d)$

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

where all the dimensions are in meters

λ = lambda is the wavelength = c/f, where c = 300 000 km/s

or in terms of frequency:

r = 17.31 * sqrt((d1 * d2) / (f * d))

with f in MHz, d in km and r in meters.

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

Comment on the values for one or two cases. This table is computed for a frequency of 2.4 GHz.
Note that the indicated values refer to the midpoint of the trajectory between the transmitter and the receiver. Assuming flat ground, the indicated value corresponds to the height of the towers needed for this link.
A good figure to remember is that at 30 km distance over flat land one would need towers about 30 m tall in order to clear the earth curvature and 60 % of the first Fresnel Zone.

Fresnel Zone

- Considering the importance of the Fresnel Zone, it is important to quantify the degree to which it can be blocked.
- Typically, 20% - 40% Fresnel Zone blockage introduces little attenuation into the link.
- It is better to err to the conservative side allowing no more than 20% blockage of the Fresnel Zone.

Ways to improve the clearance: higher antennas, repeaters, higher freq., plan higher margin, relocate the link to avoid the obstacle, etc.
Keep in mind that the calculations shown refer to normal propagation conditions, which happen most of the time. For critical links, it is also necessary to consider **abnormal** propagation conditions in which radio waves will have a different trajectory, and higher antenna height will be required.

Radio Mobile

- Radio Mobile is a free tool to aid in the design and simulation of wireless systems.
- It can automatically calculate the power budget of a radio link, calculating the Fresnel zone clearance. It can use digital maps, GIS (Geographical Information Systems), or any other digital map, including maps provided by yourself.
- Runs on every version of Windows and can be used in Linux and Mac through Windows emulators

http://www.cplus.org/rmw/english1.html

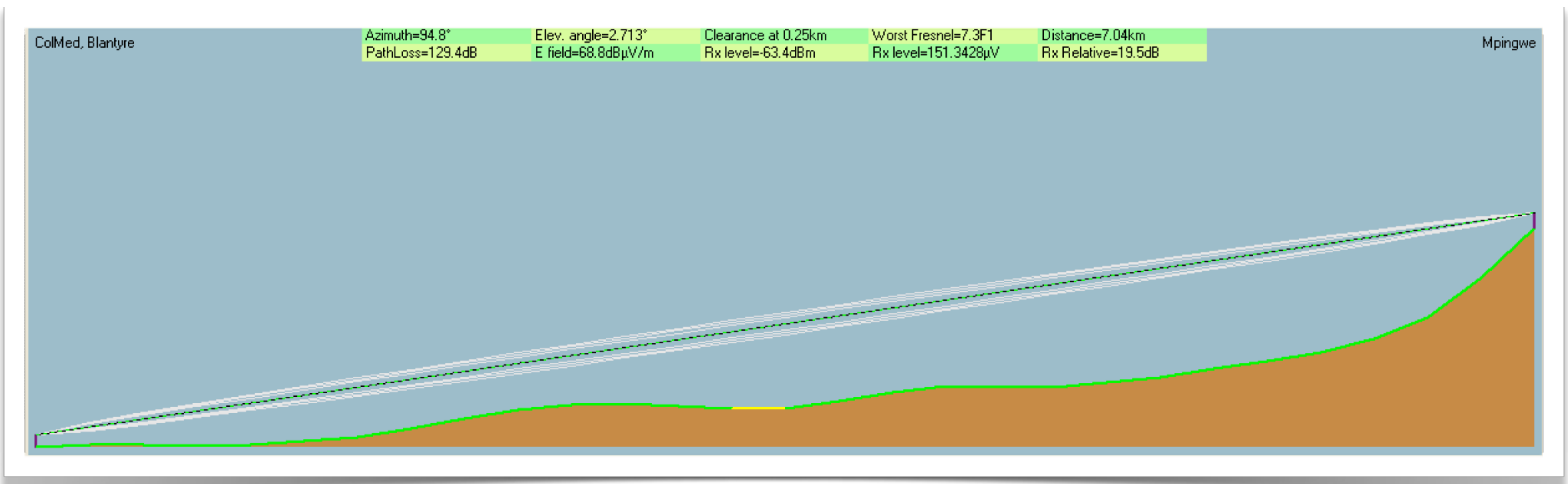
Radio Mobile

- From the same site, you can use radio mobile on-line
- You only need a browser, so it operating system independent
- You need to register in the site, choose a user name and password and start using the program
- There are some limitations in the on-line version, since you are only allowed to use radio ham frequencies, but you can choose the one closest to your real frequency and the result will be close enough.

http://www.cplus.org/rmw/rmonline.html

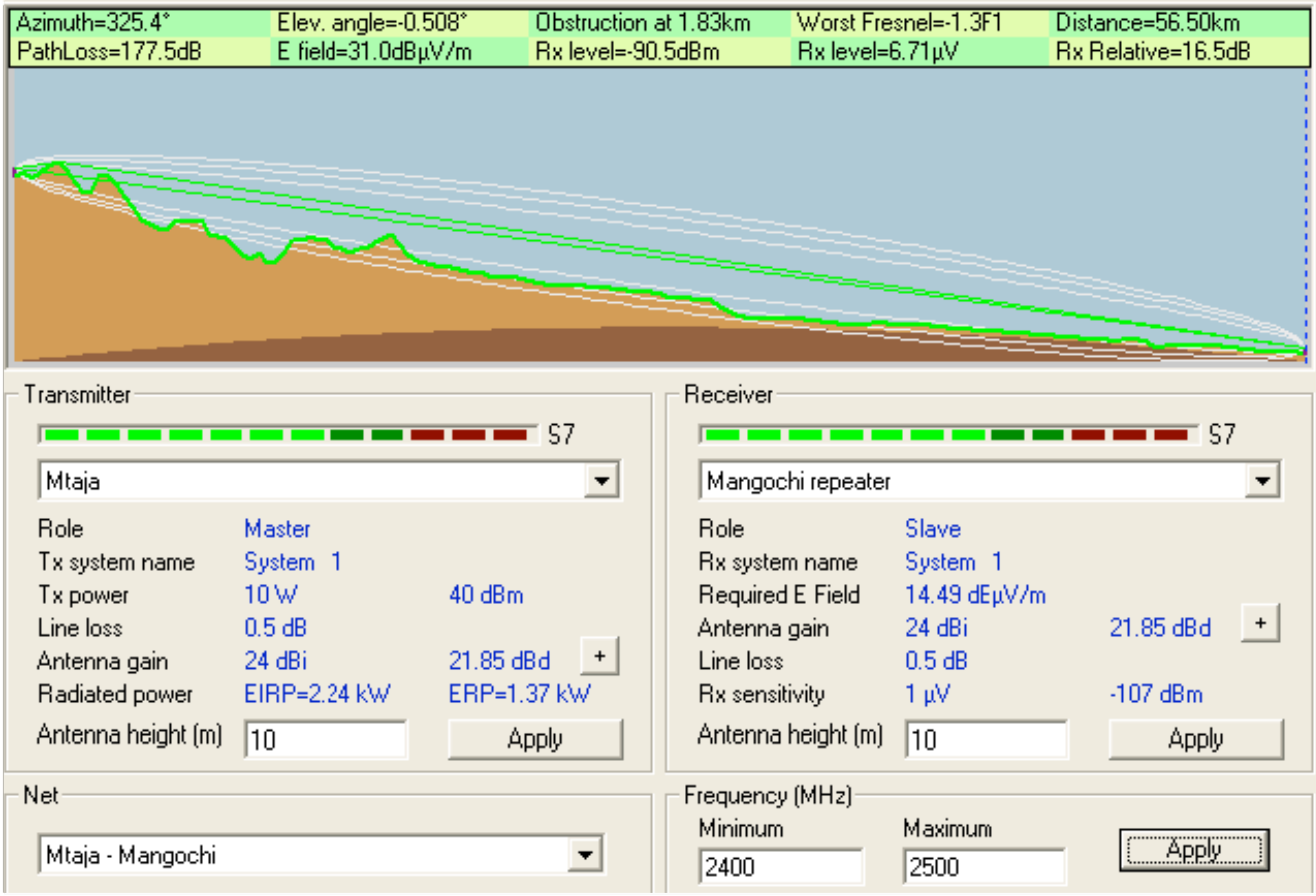
Radio Mobile

- Uses Digital terrain Elevation Model for the calculation of coverage, indicating received signal strength at various point along the path.
- Radio Mobile automatically builds a profile between two points in the digital map showing the coverage area and 1st Fresnel zone.
- Different antenna heights can be tried to achieve optimum performance.



This link has a clean line-of-sight and a free Fresnel zone.

Radio Mobile



In addition to the land cross-section view, Radio Mobile provides all of the hard numbers relating to the performance of your link: expected receive signal, link quality, EIRP, etc.
The software will tell you the azimut and elevation angles that the antennas should be pointed at, as well as the location of the most offending obstacle and which portion of the first Fresnel zone is blocking.

This particular link would not work due to obstacles in the path, indicated by the clearance of -1.3 F1, that is 130% of the first Fresnel zone is blocked. This means that even the portion of the first Fresnel zone ABOVE the line of sight is blocked.
Nevertheless, the simulation show a positive margin of 16.5 dB. This is because the transmitter power is set at an illegal value of 10 W and the receiver sensitivity is at an unrealistic value of -107 dBm.

Thank you for your attention

For more details about the topics presented in this lecture, please see the book ***Wireless Networking in the Developing World***, available as free download in many languages at:

http://wndw.net/

See Chapter 4 of the book for more detailed information about the material covered in this talk.