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FINAL DEGREE PROJECT

"DERIVE A METHODOLOGY FOR THE DESIGN OF A BROADBAND (OVER 1 Gbps) MICROWAVE BACKHAUL LINK IN E-BAND"

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Abstract:

The goal of this project is to derive the methodology for the design of a broadband microwave backhaul link in the E-band, based on the ITU-R P.530 Recommendation and ETSI. The radio link designed will be placed in the city of Krakow and it will reach a rate of 1 Gbps.

For decades, microwave radios in the 6 to 50 GHz bands have been providing wireless communications. Recently, newer technologies at the 60 to 100 GHz mm-wave bands have taken advantage of new wireless regulations that are designed to enable ultra-high capacity communications. As we pursue this project, we are going to find out the latest details of multi-gigabit wireless communications in depth and review the currently technology available.

The project will cover both, generic aspects and E-band specific aspects. To estimate generic aspects of the radio link such as selection of the base stations, polarization, antenna height calculations; the software *Radio Mobile* will be used. Also a broad explanation of E-band will be exposed (channel plans aggregations, frequency planning process, specific licensing for E-band in Europe...). Finally, an evaluation of the availability and error performance of E-band will be carried out.

1. Introduction to E-band:

First of all, it is essential to do an introduction to E-band and its recent use that has supposed a revolution in multi gigabit wireless technology. The electromagnetic spectrum is divided in different frequencies and to each frequency it is assigned a telecommunications use. The ITU is the regulatory body of this spectrum, covering part of the radiofrequency spectrum and part of microwaves. According to the ITU the E-band is the range of radio frequencies from 60 GHz to 90 GHz in electromagnetic spectrum. These frequencies are equivalent to wave lengths between 5 mm and 3.333 mm. The E-band is in the EHF range of the radio spectrum.

[1] The popularity of multimedia applications and broadband Internet has created an ever increasing demand for achieving higher throughputs in cellular and wireless networks and as mobile operators need more and more bandwidth to satisfy their needs, spectrum at 71 to 76 GHz, 81 to 86 GHz and 92 to 95 GHz was available for high-density fixed wireless services. The 13 GHz allocated in this spectrum has clear technological and economic advantages. The frequencies allocated in 90 GHz are only for public use in USA; in Europe only can be used as part of E-band 70/80 GHz frequencies, so we are going to be focused on these 10 GHz.

Also multi-Gigabit per second capacities are allowed, without additional radio equipment and licensing fees. For the first time, true gigabit-speed wireless communications with carrier-class performances over distances of 1.5 km or more became realizable. In figure 1 is shown a scheme of microwave bands and especially we can notice about E-band:

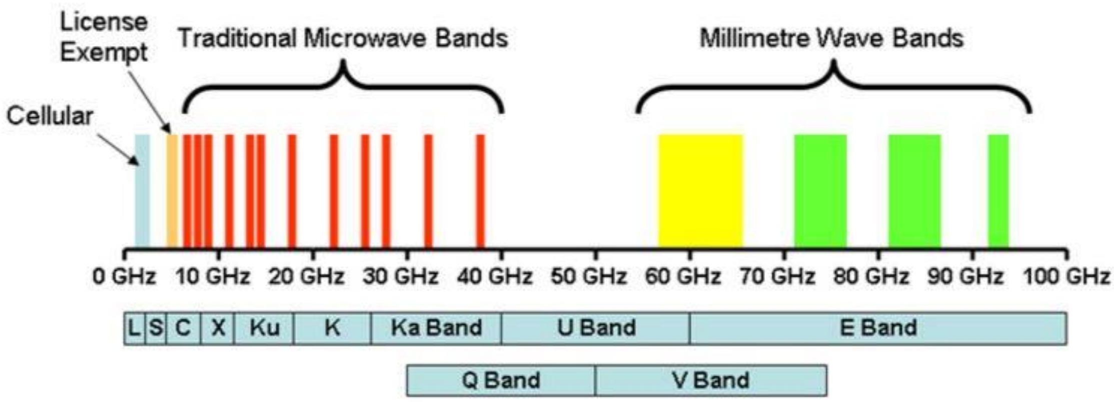


Figure 1: Representative diagram of E-band.

This project is focus on 80 GHz band, which along with 70 GHz band are widely viewed to hold the most interest, both are designed to co-exist. 81GHz to 86 GHz allow 5 GHz of full-duplex data rates in excess of 1 Gbps and even a carrier class of 99.999% can be achieved. Another advantage of 80 GHz band is that attenuation losses due to atmospheric conditions are not as unfavorable as in 60 GHz band. Even transmission distances can be many kilometers, but it depends on atmospheric attenuations, how attenuations affect this band will be explained in section 2.8.

[2] Until this moment these high speeds were achieved with fiber and microwave wireless in 60 GHz. The use of these new 10 GHz was a great revolution and very attractive because of the low costs comparing to fiber. Fiber-optic cable offers the widest bandwidth, allowing very high data rate to be transmitted over long distances. However, sometimes laying fiber can be difficult or even impossible due to substantial and prohibitive cost associated with digging trenches. As well, 60 GHz wireless was the alternative used, allowing data rates of 1 Gbps. Nevertheless, limited power requirements and the high attenuations losses in this band caused by atmospheric absorption by oxygen molecules limits distances and make 60 GHz a very short range communication (shown in section 2.5). In table data 1 we can see a comparative of the different broadband techniques and appreciate the various characteristics of E-band that are going to be discussed later in depth:

Table data 1: comparative of the different broadband techniques.

	WiFi	3/4G	60 GHz	FSO	Fiber	E-band
Data rate	about 1 Mbps, unstable	about 10 Mbps, unstable	100 ~ 1000 Mbps	100 ~ 1000 Mbps	up to 100s of Gbps	multiple Gbps
Transmission distance	18.3 m	3.2 km	457 m	183 m	up to 96.5 km	up to 19.3 km
Licensing	free for unlicensed use	licensed, spectrum very scare	free for unlicensed use	not regulated	N/A	Light licensing
Licensing cost	N/A	high	N/A	N/A	N/A	low
Licensing application period	N/A	months/years	N/A	N/A	N/A	minutes/hours
Guaranteed interference protection	No	Yes	No	No	Yes	Yes
Installation time	hours	months/years	hours/days	hours/days	months/years	hours/days
Installation cost	low	high	medium	medium	high	medium

It is also important to remark that a wide range of fixed services are realizable over E-band frequencies. Many high data rate applications can be satisfied with this technology such as IP and SONET backhaul, Gigabit wireless LANs and private networks and fiber backup for access/technology diversity. Also 3G cellular or WiMAX backhaul for dense urban networks and portable and temporary links for high definition video or HDTV transport can be realizable over these frequencies.

1.1 Frequency planning process and rules:

[3] The radio-frequency channel arrangement is regulated in Europe, which is the region concerned to this project, by the Conference of European Postal and Telecommunications (CEPT). Their approach is different from the other continents, they divide the 10 GHz of spectrum in the 70/80 GHz bands into 250 MHz channels with a guard band of 125 MHz at the top and bottom end of each band (to prevent potential interference to and from adjacent bands). Each 5 GHz band consists on 19 channels that can be used for both FDD and time-division duplex operation.

[4] The radio- frequency channel arrangements in the band 81-86 GHz according to the ITU-R Rec. 746 are:

Being:

- f_r the reference frequency of 81 GHz
- f_n the centre frequency of a radio-frequency channel in the band 81-86 GHz
- f_t the reference frequency of 86 GHz
- n the channel number

Then the centre frequencies of individual channel with 250 MHz separations are expressed by the following relationship:

$$f_n = f_r + 250 \cdot n \quad MHz \tag{1}$$

In reverse direction would be:

$$f_n = f_t - 250 \cdot (20 - n) \quad MHz \tag{2}$$

Where:

$$n = 1,2,3, \dots, 19$$

1.2 Channel plans aggregation:

Although ITU has released the E-band frequencies for fixed and mobile services, there has been no specific recommendations regarding the use of the E-band or sharing arrangements with other services. Nevertheless, many countries have issued their E-band channelization plans to promote its commercialization.

[5] Channel aggregation consists on aggregating several carriers of a frequency plan, with the aim of using larger bandwidths for each single radio channel. Europe divides each of the two 4.75 GHz bands (5 GHz with two band guards of 125 MHz each) into nineteen 250 MHz channels and allows aggregation of any number of channels from 1 to 19. Furthermore, the specified channels may be used for either time division duplex (TDD) or frequency division duplex (FDD) systems either within the single band or in combination with other bands. In figure 2 we can see the commonly used channelization for E-band in Europe that consists on a single duplex FDD with duplex separation of 10 GHz:

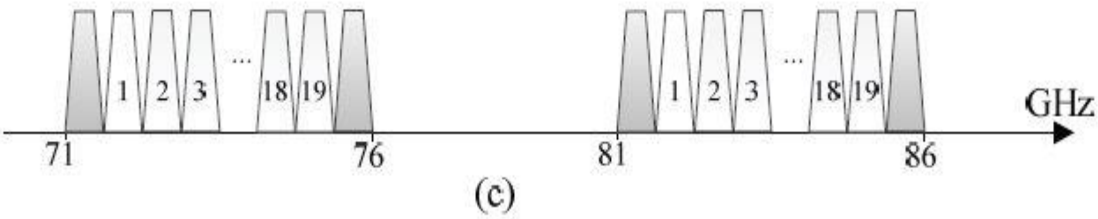
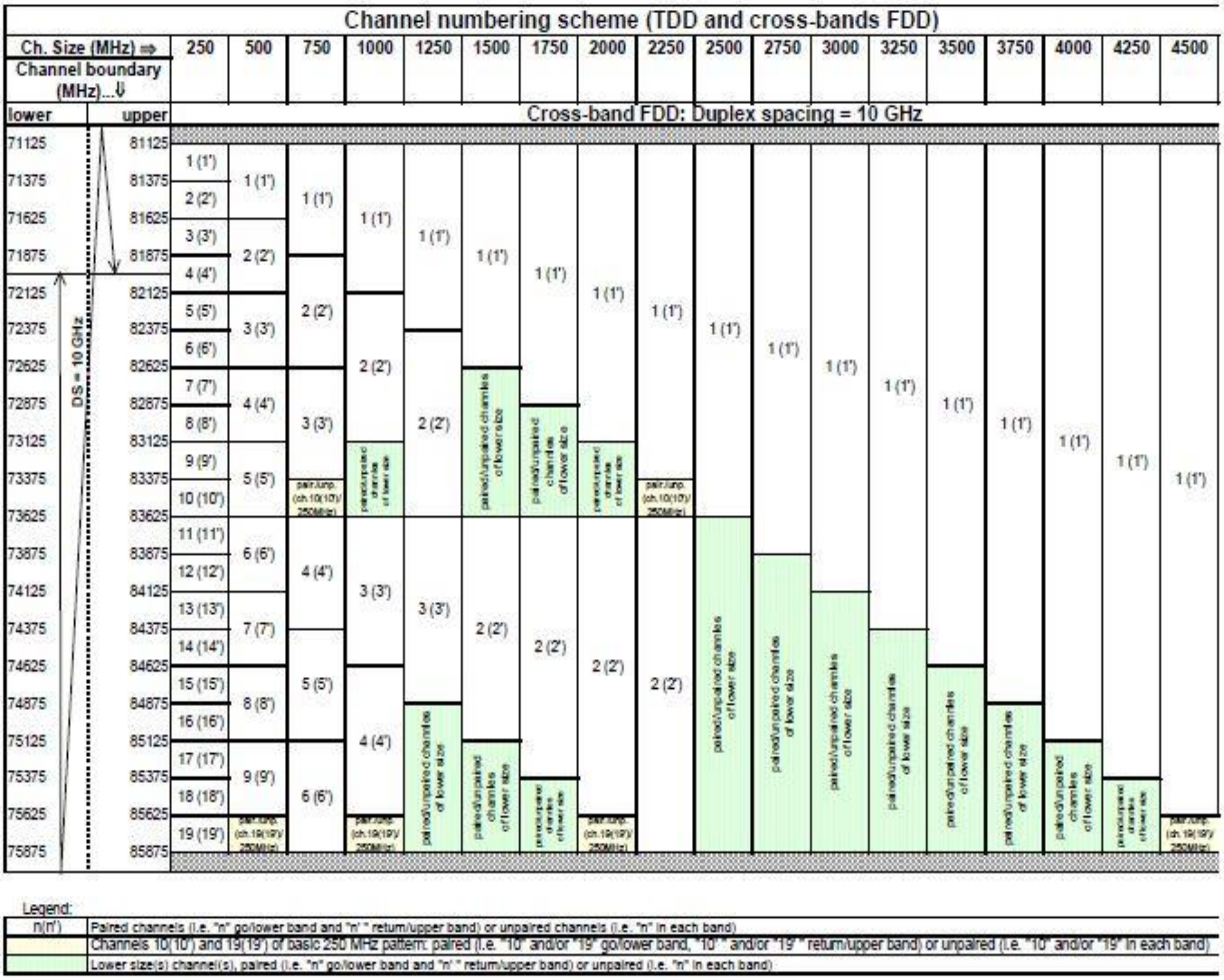


Figure 2: Typical E-band channelization in Europe.

[6] One enterprise that provides hardware that supports this channel aggregation is *Harmony E-band* from *Dragon Wave*. It operates in frequency division duplex transmission mode with a duplex spacing of 10 GHz. The "transmit low" radio transmits over the complete 71-76 GHz sub-band and receives over the complete 81-86 GHz sub-band. *Harmony E-band* transmits a single carrier in 250 MHz channels.

[7] Channels of larger size are obtained through aggregation of individual 250 MHz channels according the arrangements shown in table data 2. It is applicable for what concerns FDD systems, when the bands 71-76 GHz and 81-86 GHz are jointly used providing paired channels bandwidths from 250 MHz to 4500 MHz with duplex spacing 10 GHz.

Table data 2: Channel positions for TDD and cross-bands FDD applications.



1.3 Specific licensing in Europe for E-band:

As mentioned before, the body responsible for European normative is CEPT. [8] Although the 71-76 and 81-86 GHz bands are established for wireless links throughout the world, the International Telecommunication Unions (ITU) and CEPT regulate the channelization and regulations of this spectrum because it differs in different regions and countries.

Moreover, the regulations of E-band in Europe are more stringent than the FCC rules, which is the North American regulator. Specifically, in Europe the specifications are:

Table data 3: Collection of specifications in Europe.

Europe EIRP	55 dBW
Maximum transmit power	30 dBm
Minimum antenna gain	38 dBi
Maximum out of band emissions	-30 dBm

To promote E-band commercialization, the national wireless link regulators and administrators in many European countries have introduced innovative and streamlined "*light licensing*" schemes for managing this band, enabling the E-band an attractive alternative to existing licensed frequency bands. The "*light licensing*" policy allows E-band licenses to be applied for in minutes and costs of a few tens of Euros per year, thanks to this policy thousands of fixed E-band radios have been registered and installed quickly. Despite the name " *light licensing*", the possession of such a license still gives the link operator the same full benefits of a traditional link license, including link registration, "*first come first served*" rights and full interference protection.

[9] In some European countries the deployment under a license exempt basis could result in unacceptable interference and would be unlikely to lead to optimal use of the spectrum, particularly considering the high availability applications proposed to be used in the band. [10] This policy is also important due to the declining of interferences. The high frequencies at E-band allow the systems to adopt highly directional antennas and communicate via highly focused transmissions, leading to dense configuration of communication links without interference concern and thus a high degree of frequency reuse. Besides, the E-band frequencies are configured as a single pair of 5 GHz channels, which makes the traditional frequency planning and coordination unnecessary and the related interference analysis significantly simplified. A simple mechanism which enables individual 70/80 GHz links to gain protection from interference can be accomplished by the implementation of a centralized database with a registration system with a "*first come first served"* data forming the basis for protection

1.4 Equipment currently available supporting multi-gigabit communication in E-band:

[9] It is of great interest for the development of this project, a review of the companies that are currently developing equipments supporting multi-gigabit communication in this band. The following tables compare the equipment manufactured by these companies. Once we can see the comparatives of all the features, we will choose the equipment for developing our project.

- Loea Corporation:

Table data 4: Features of L2500 transceiver.

[11] L2500 transceiver characteristics	
Operating frequency	71-76 GHz and 81-86 GHz
Throughput	2.48832 Gbps full duplex
Receiver Sensibility for 10^{-6} B.E.R	- 53 dBm
Transmitter power output	20 dBm
Antenna	Parabolic design, 61 cm, 51 dBi, beam width 0.4 º

- **Elva-1:**

Table data 5: Features of Elva PCP-10G equipment.

[12] Elva PCP-10 G characteristics	
Operating frequency	71-76 GHz and 81-86 GHz
Throughput	Up to 10 Gbps Full duplex
Receiver Sensibility for 10^{-6} B.E.R	-79 dBm
Transmitter power output	45.44 dBm
Antenna	Parabolic designs, 51 dBi

- **E-band Corporation:**

Table data 6: Features of E-band Corporation equipment.

[13] E-link 1000-Q 4G Characteristics	
Operating frequency	71-76 GHz and 81-86 GHz
Throughput	1.25 Gbps full duplex (Ethernet)
Receiver Sensibility for 10^{-6} B.E.R	-66 dBm
Transmitter power output	46.43 dBm
Antenna	30 cm flat plate with 45 dBi gain or 30 cm with 52 dBi

- **BridgeWave**:

The family of products is specifically designed for LTE mobile backhaul. The features of the products are multi-gigabit capacity, advanced Ethernet switch capabilities, high power operation and spectral efficiency at the longest distances. Some characteristics of the equipment are in data table 7:

Table data 7: Features of Flex4G-1250 equipment developed by BridgeWave.

[14] Flex4G-1250 Characteristics	
Operating frequency	81-86 GHz
Throughput	1.25 Gbps in a 250 MHz channel
Receiver Sensibility for 10^{-6} B.E.R	-59 dBm
Transmitter power output	14 dBm
Antenna	Parabolic antenna 60 cm. 51 dBi gain, 0.4º beamwidth

Thanks to their features and the integrated Silicon-Germanium technology used that provides performance, this is going to be the equipment used for this project.

Figure 3: Flex4G shown with integrated flat panel antenna.

Parabolic antennas are both use for transmitter and receiver. Thus two of them are going to be used in the design of this radio link. With this equipment we can achieve the desirable rate for this project of 1 Gbps using a 32 QAM modulation. Also 99.999% availability can be achieved. With the equipment configuration shown in table data 7, the design will be accomplish in next section.

2. Radiolink design:

In this section the technique design is going to be implemented. The design will be accomplished with the software *Radio Mobile*. This free radio propagation simulation program is based on the ITS (Longley-Rice) propagation model and in ITU Recommendations.

This radio link is engineered to get a data rate of 1.25 Gbps using a 32 QAM modulation in one channel and without channel aggregation.

Although later will be analyzed in depth, let's open up seeing approximately where to settle the base stations. As in this design we want to give coverage to old Krakow city centre; the transmitting antenna will be placed on the top of a building which is located about 0.63 km from the city center in *Zwierzyniecka* Street. The receiver will be placed on the top of City Hall tower, which is located in Main Square. In table data 8 we can see the coordinates and features of both points:

Table data 8: T_x and R_x coordinates.

T_x Location: *Ulica Zwierzyniecka*	**R_x Location:** *Stare Miasto*
Latitude: 50° 3' 25.73"N Longitude: 19°55' 50.28"E Altitude: 232 m Building Height: 25 m	Latitude: 50º 3’ 42’’ N Longitude: 19º 56’ 11’’ E Altitude: 219 m Tower Height: 45 m
Distance between T_x and R_x: 0.63 km	

The radio link we want to implement in this project is shown in figure 4:

Figure 4: *Google Maps* radio link overall.

Before starting with technical aspects, it is important to remark that the aim of this design is getting an availability of 99.999 % for the radio link which is being designed. This carrier-grade availability is supposed to be given with *Bridgewave's* equipment selected in section 1.4. In following steps, all calculations are done to make sure that the radio link shown in figure 4 can be designed with the selected equipment and obtaining the desired availability.

2.1 Diffraction fading:

Variations in atmospheric refractive conditions cause changes in the effective Earth's radius or *k*-factor from its median value of approximately 4/3 for a standard atmosphere. In this design *k* value, which procedure is going to be explained in section 2.3, is approximately 4/3. For sub-refractive atmospheres the ray paths will be bent in such a way that the Earth appears to obstruct the direct path between transmitter and receiver, giving risk to the diffraction fading. This factor will determine the antenna heights. Diffraction loss will depend on the type of terrain and vegetation, it will be crucial for diffraction fading an obstruction in the path.

[15] Some criteria have been taken into account while trying to find a place to settle the antennas to have path clearance. Diffraction fading of this type can be alleviated by installing antennas that are sufficiently high, so that the most severe ray bending would not place the receiver in the diffraction region. Diffraction theory indicates that the direct path between the transmitter and the receiver needs a clearance above ground of at least 60 % of the radius of the first Fresnel zone to achieve free-space propagation conditions. Fresnel zone is the radius that may be clear around the line of sight of a link to reduce the interference caused by reflection of the wave and interference produced by nearby objects. For practical purposes it is important to calculate the first Fresnel zone F_1:

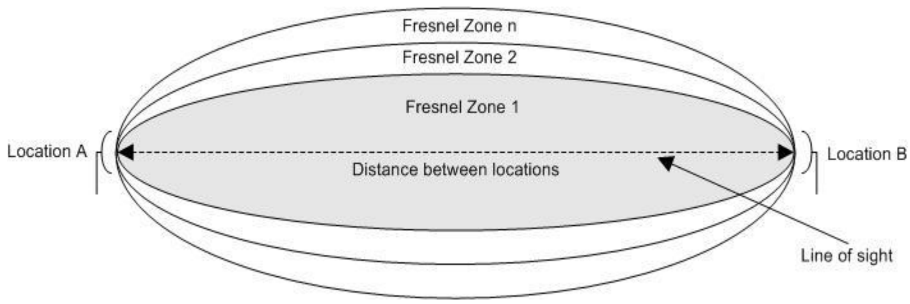


Figure 5: Representative scheme of Fresnel zones.

$$F_1 = 17.32\sqrt{\frac{d(km)}{4\cdot f(GHz)}} \quad m \tag{3}$$

$$F_1 = 17.32\sqrt{\frac{0.63}{4\cdot 80}} = 0.77\ m \tag{4}$$

In this case, 0.77 meters may be clear. Otherwise, the designer should assume a presence of diffraction fading in link budget calculations. What we get from equation 4 is the maximum radius of Fresnel ellipsoid considered in the middle of the path between the transmitter and the receiver. Actually, the radius of the ellipsoid should be calculated for each point of the path profile. In normal design process the radius of the first Fresnel zone should be calculated individually for each point along the transmission path using the formula:

$$F_1 = 17.32\sqrt{\frac{(d-d_1)d_1}{4 \cdot d \cdot f(GHz)}} \quad m \qquad (5)$$

Where d and d_2 are the distances (km) from the terminals to the path obstruction.

The procedure explained of the 60% clearance of the first Fresnel zone is correct but, however nowadays different methodology is used. [15] As explained in ITU-R P.530, recently with more statistics of k_e it is possible to do statistical predictions to install antennas at heights that will produce some small known outage. This planning criterion for path clearance would be estimate the antenna heights for 1.0F1 clearance over the highest obstacle (for temperate climate). After, from figure 6, a value of k_e for a the path length should be extracted:

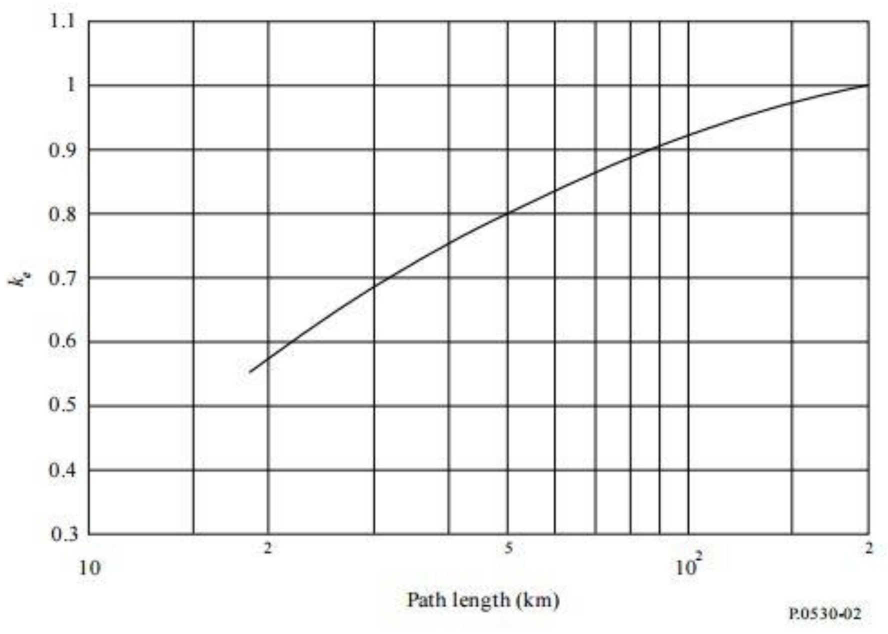


Figure 6: Value of k_e exceeded for approximately 99.99% of the worst moth for continental temperate climate.

The value obtained is the *k*-factor exceeded for approximately 99.99 % of the worst month. With this k_e value, would be necessary to recalculate the antenna heights (before it was used *k*=4/3), in this case the heights should be estimated for $0.0F_1$ or $0.3F_1$ (depending if there is obstruction in the path or not). Finally, we would have to use the larger of the antenna heights obtained in both procedures. This criterion is used as a plan for alleviating diffraction fading, but also we can find in the same recommendation a formula to approximate diffraction loss over average terrain for losses greater than about 15 dB:

$$A_d = -20\,\frac{h}{F_1} + 10 \qquad dB \tag{6}$$

Where F_1 is the first Fresnel zone radius (formulas 3 and 5) and h (m) is the height difference between most significant path blockage and the path trajectory. Also in recommendation ITU P-530 a curve referred to A_d, based on equation 6 is given. However, this curve is only valid for losses larger than 15 dB and for obstructed line-of-sight radio paths.

We have simulated this design in section 2.7 and it is confirmed that the radius of the first Fresnel zone is not obstructed because, as we can see in formulas 3 or 5, the radius decrease with frequency. As this radio link is design for a high frequency, 80 GHz, diffraction fading is not going to severely limit communications in E-band due to it is more difficult to obstruct Fresnel zones. That is why diffraction fading is not going to be considered in this design so it will not be included in the link budget.

2.2 Multipath fading:

One of the other propagation losses is fading due to multipath, beam spreading and scintillation. Various clear-air fading mechanisms caused by extremely refractive layers in the atmosphere must be taken into account in the planning of links. Beam spreading (defocusing), antenna decoupling, surface multipath and atmospheric multipath are some of these problems. [15] They are caused when beam spreading of the direct signal combines with surface reflected signal to produce multipath fading. However, ITU-R P.530 indicates that multipath fading only needs to be calculated for path lengths longer than 5 km and can be set to zero for shorter paths. So, as in this design our distance is shorter than this, we may not consider multipath fading.

Although multipath fading is not going to limit our design that much, we are going to do a review of some techniques for alleviating the effect of multipath propagation. Some of them can be used without the needed of using diversity. They are quite interesting for this design because, whenever possible, avoiding diversity is a good choice due to economic costs. Also the distance of this radio link is too short for using diversity. Some of these techniques are presented below:

- Increase of path inclination: Links should be sited to take advantage of rough terrain in ways that will increase the path inclination helping to reduce the occurrence of significant surface reflections.

- Shielding of the reflection point: Using advantage of hills, mountains or building along the path to shield the antennas from more specularly-reflective surfaces along the path. One example is shown in the figure below, where the own mountain shape is shielding from reflection:

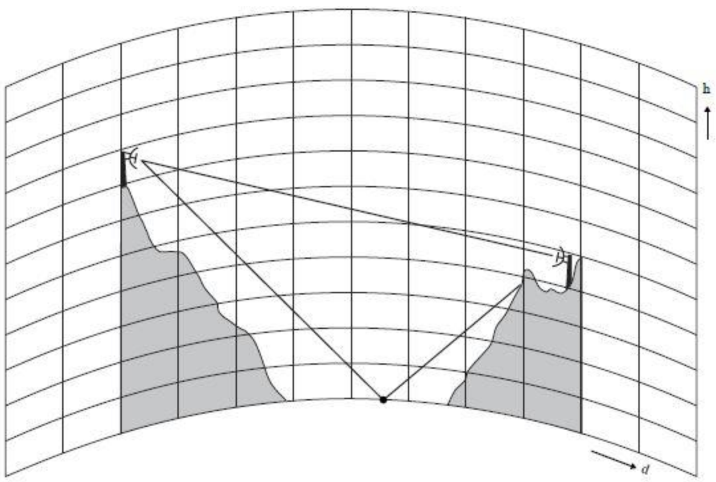


Figure 7: Example of shielding of antenna from specular reflection.

- Moving of reflection point to poorer reflecting surface: Sometimes adjusting the antenna height at one or both ends it is possible to move the reflection point to poorer reflecting surface. For example moving overwater paths into a land surface rather than on water or even it would be better a land surface covered by vegetations to use it for shielding of the reflection point as explained in the paragraph above.

2.3 Effective Earth radius: k factor

[16] Basing on digital maps provided by the ITU-R P.453-8 we are going to estimate the effective Earth radius for our exact location. In radio propagation studies, a value for the radius of the Earth may be used in place of the actual radius to correct refraction by the atmosphere. The effective Earth radius is a convenient fiction that makes straight the actual curved path of a radio ray in the atmosphere by presenting it relative to an imaginary Earth with a radius larger than the radius of the real Earth, thus maintaining the relative curvature between Earth and radio ray. For the standard atmosphere, the effective Earth radius is $^4/_3$ that of the actual Earth radius.

In the digital maps provided by the recommendation, we can find the value of the gravity gradient refractive factor. Thanks to these tabulated maps, the exact *k* value factor for a location can be easily calculated by simply using the latitude and longitude of the point. In these maps, the scale of both latitude and longitude varies very slowly. Due to this insignificant variation of the scale, there will be no little variation all over our design so; the *k*-factor is going to be estimated for the coordinates of the transmitter, which are:

Table data 9: Transmitter coordinates.

T_x Location:
Latitude: 50° 3' 25.73" N Longitude: 19°55' 50.28" E

With this location, the value of the gradient we get from the tabulated maps is:

$$\Delta N = \frac{dN}{dh(Km)} = -40.6 \quad (7)$$

Where:

$$k = \frac{157}{157 + \Delta N} = \frac{157}{157 - 40.6} \simeq 1.34 \qquad (8)$$

As $k > 0\ \ and\ \Delta N - 157\ ,\quad$ It is an Earth curve model

The Earth curve model is applied for links lengths such that the arrows due to the Earth curvature are above about 5 m. This usually corresponds to wavelengths of the order of radio electric visibility distance or higher. It is considered a straight path and a fictitious Earth model with a radius of KR_0, these models are shown in figure 8:

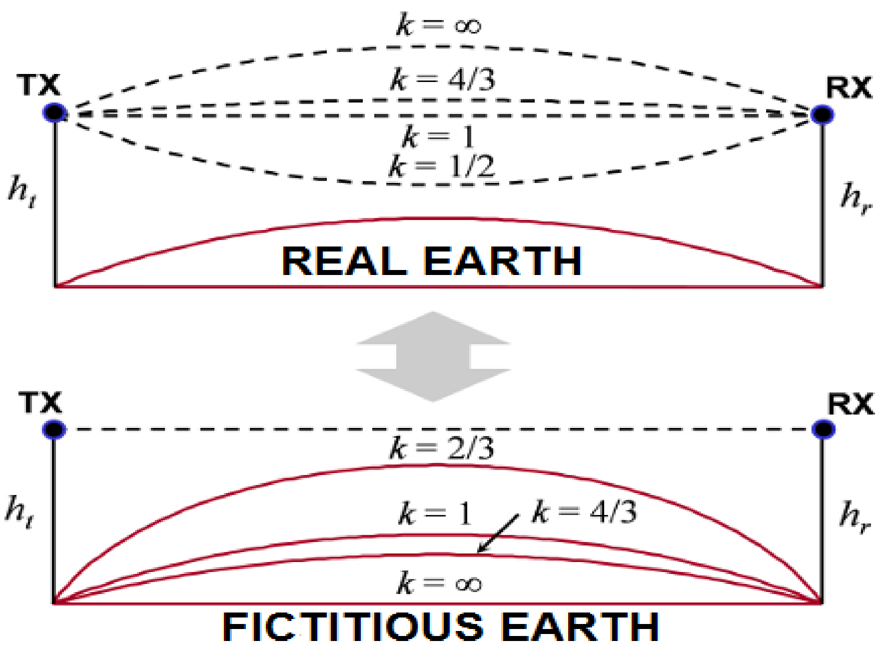


Figure 8: Real Earth and fictitious earth model.

$$As \quad k > {}^{4}/_{3} \;, \quad \text{It is a super} - \text{refractive troposphere}$$

A super-refractive troposphere will cause multipath fading. How multipath affect this design has been discussed in section 2.2.

2.4 Signal polarization:

[17] The radio wave is an electromagnetic waveform composed of both electric and magnetic fields**.** In free space, the fields are mutually perpendicular and are also perpendicular to the direction of propagation.

The term polarization commonly refers to the electric field component of the radio wave. In terrestrial microwave antennas, the polarization of the radio waves will be either horizontal or vertical. That is, the electric field will be either horizontal or vertically orientated. Although they are rarely used in DRRS, is noteworthy that there also exist circular polarizations. In this type of polarization, the extreme of the electric vector describes a circle. It may be considered as a particular case of the elliptic polarization in which both components, vertically and horizontally polarized, with the same amplitude are combined in phase quadrature.

As mentioned before, regarding this case of terrestrial microwave antennas, the polarizations used are either horizontal or vertical. The transmission characteristics of both polarizations are very similar at microwave frequencies. However, the effects of obstacles and reflections within the microwave link are more likely to degrade system performance in horizontal polarization than in vertical polarization and thus vertical polarization tends to be the first polarization of choice.

[15] As indicated in the ITU-R P.530 recommendation, at frequencies above 3 GHz, it is advantageous to choose vertical polarization over horizontal polarization. Even for angles greater than about 0.7º, a reduction in the surface reflection of 2 to 17 dB can be expected over that at horizontal polarization. Therefore, the polarization of this microwave design will be vertical.

A single polarized antenna is one that responds only to one orientation of polarization, either horizontal or vertical. Thus radio waves that are received or transmitted by a single polarized antenna will be either horizontal or vertical polarized. With our single polarized antennas there will be a single waveguide connection point, or port, at the customer interface. The polarization (vertical or horizontal) is sometimes denoted by an arrow placed adjacent to the port. The orientation of the waveguide cable will determine the polarization; if the broad wall of the guide is in the horizontal plane, the antenna is vertically polarized, and if the broad wall is in the vertical plane, the antenna is horizontally polarized.

From *Matlab* script that can be found in *Annex 1*, a behavior graphic of the amplitude for the reflection coefficient may be seen in figure 9. It shows the behavior of both polarizations for a typical earth surface and 80 GHz frequency.

As mentioned before, for an incidence angle greater than about 0.7 º we can see in figure 9 the great difference between both polarizations that derives in a difference of about 2 to 17 dB.

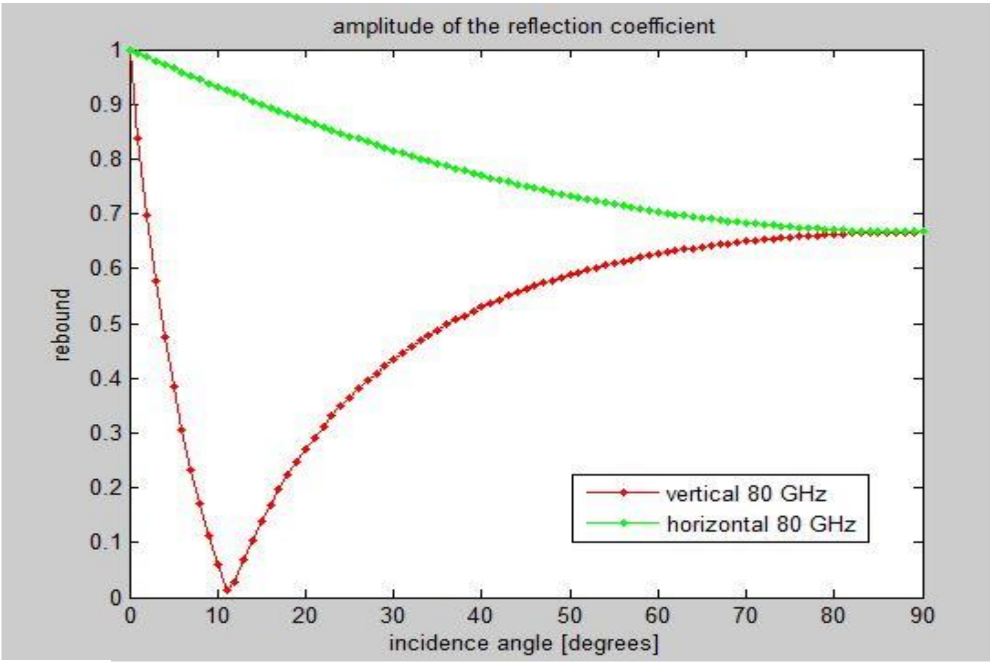


Figure 9: Behavior of the reflection coefficient amplitude.

2.5 Atmospheric attenuation:

[1] At conventional microwave frequencies (up to 38 GHz), atmospheric attenuation is reasonably low at a few tenths of a dB/km. A large peak is seen at around 60 GHz where absorption by oxygen molecules seriously limits radio transmission distances (shown is figure 10). After this peak, however, a large window opens up where attenuation drops back to ½ dB/km, not much worse than at the popular microwave frequencies. Above 100 GHz, atmospheric attenuation generally worsens and there are numerous molecular effects (O_2 and H_2O absorption at higher

frequencies). It can be seen that the spectrum from around 70 GHz to 100 GHz exhibits low atmospheric attenuation and is, therefore, suitable for wireless transmission.

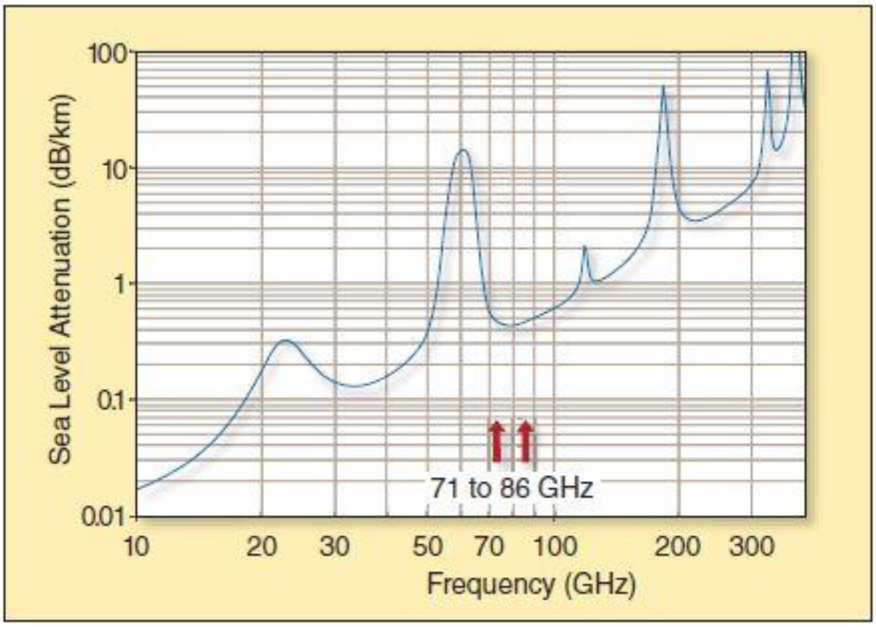


Figure 10: Atmospheric and molecular absorption.

At these high frequencies the short wavelengths give the radiation a very directional quality, similar to visible light. Many molecules possess rotational and vibrational states excited by very specific wavelengths in this band, thus the atmospheric gasses such as oxygen, water vapor, carbon dioxide and nitrogen can absorb, and be excited causing variable beam attenuation effects depending on meteorological and atmospheric conditions.

Specifically in E-band this is not a negligible value. [18] To estimate the attenuation caused by gas and atmospheric vapors we have to look on the ITU-R P.676, where the attenuation of the radio electric signal may be calculated as:

$$A_g = (\gamma o + \gamma w) \cdot d \quad (9)$$

Where *d* is path length (km), γ_0 and γ_w are the specific attenuations (dB/km) due to dry air and water vapor respectively. As seen in figure 10 and in the graphics provided by ITU-R P.676, for a frequency of 80 GHz the atmospheric attenuation is approximately:

$$A_g = 0.5\ \frac{dB}{km} \cdot d\ \ (km) \quad (10)$$

2.6 Link budget:

The length of the proposed link is 0.63 km. In this section we are pursuing the maximum link range taking into account the characteristics of the equipment selected from *BridgeWave*'s and then analyze if the distance proposed can be realized or not with this equipment. Considering free space loss and atmospheric attenuation, we are going to obtain an approximate value of the maximum distance reachable. In scheme 11 is shown the radio link design with the power values in transmission and reception, with this scheme we are going to carry out the calculus:

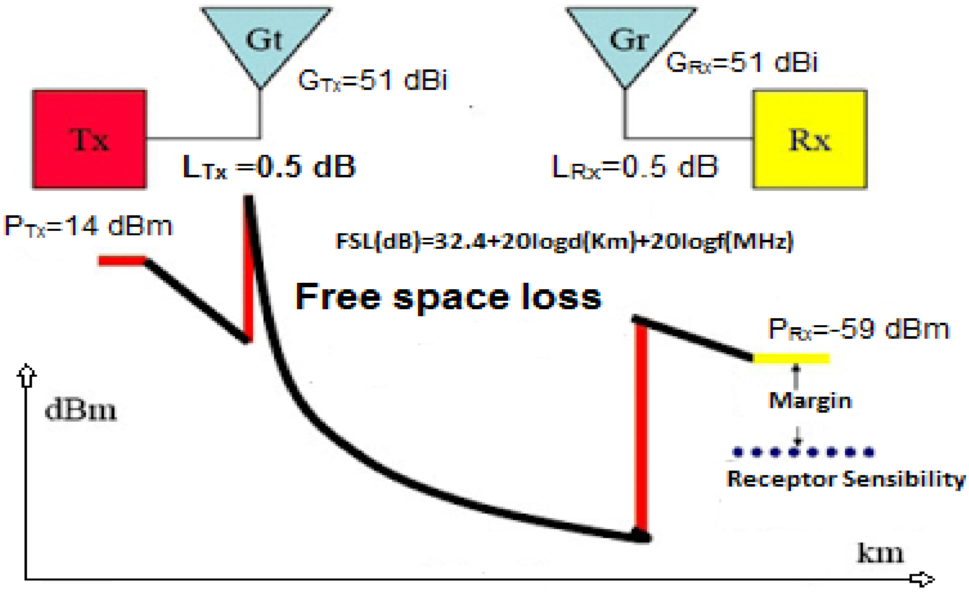


Figure 11: T_x and R_x scheme with the equipment parameters.

[19] FSL are, as indicated in ITU-R P.525-2, the losses due to free space path. They are the losses suffered by the signal as it propagates straight through space without any absorption or reflection. *Friis* equation is:

$$FSL(dB) = 32.4 + 20\log d(Km) + 20logf(MHz) \qquad (11)$$

Finally, adding to equation 11 the rest of the losses, the link budget is as follows:

$$\mathrm{P_{Tx}(dBm) - L_{Tx}(dB) + G_{Tx}(dBi) - FSL(dB) - A_g(dB) + G_{Rx}(dBi) - L_{Rx}(dB) = S_{Rx}(dBm)} \qquad (12)$$

Where:

- A_g has been explained is section 2.5. For the frequency of this design we are going to consider an atmospheric attenuation of 0.5 dB/km:

$$A_g = 0.5\ \frac{dB}{km} \cdot d(km)$$

- $\mathrm{L_{Tx}}$ and $\mathrm{L_{Rx}}$ are the line losses. This approximation is done by the software used and it includes cable, cavities and connectors losses.

$$\mathrm{L_{Tx} = L_{Rx} = 0.5\ dB}$$

Finally, replacing these values in equation 12, we end up with a non-linear equation that looks like:

$$43.43 - 20logd(Km) - 0.5d(km) = 0 \qquad (13)$$

Solving equation 13 with *Matlab*, we get a maximum distance reachable of *d*=28.6 km. This distance can seem to be very high, but without intermediate obstacles the maximum distance between both antennas can reach 150 km. Actually with repeaters, obviously, and taking advantage of the Earth curvature the distance can be even higher.

Of course this is not realizable because a fade margin of zero has been considered for the calculus, so the availability is not sufficient for any practical application. With any radio link installation, it is desirable to have signals strong enough to maintain communications regardless of weather conditions. Every radio link will have a threshold signal strength below which the wanted signals are too far buried in the noise of the radio channel to be received clearly. Ideally, radio links should be engineered to be working with signal levels at least 100 times (20 dB) stronger than the absolute minimum workable signal. In this way, even with severe weather extremes or environmental factors that can attenuate signal, 30 dB of fade margin (for temperate zone) will ensure that a working link is maintained. The fade margin of this design is:

$$\mathrm{P_{Tx}(dBm) - L_{Tx}(dB) + G_{Tx}(dBi) - FSL(dB) - A_g(dB) + G_{Rx}(dBi) - L_{Rx}(dB)} \\ = \mathrm{FM(dB) - S_{Rx}(dBm)} \qquad (14)$$

Replacing all the parameters explained and the distance of 0.63 km in eq. 14 we get a fade margin:

$$\mathrm{FM{=}47.22\ dB}$$

Our margin is the expected for temperate zones, however in high radio frequencies some extreme weather phenomena could cause temporary radio link failure. E-band is quite affected by rain attenuations; we are going to analyze these attenuations carefully in section 2.8 to see if this fade margin is high enough to allow communication with a high availability.

2.7 Antenna heights:

Now we have the antennas placed and the equipment chosen, we are going to simulate with the software *Radio Mobile* to see how high the antennas should be to get, with the distance we have planned, an availability of 99.999%.

To guarantee a reasonably high successful link connection probability between the transmitter and the receiver and provide sufficiently good coverage, it is preferable to equip transmitter equipment densely to combat both the severe path attenuation experienced by E-band signals and the possible block of LOS transmissions caused by surrounding buildings or obstacles. The antennas could be located adaptively according to the topography and architectural construction of the severing area, e.g., on the surface of buildings or the top of lampposts. In this design, to take advantage of buildings, the transmitter will be settle on the top of a building and the receiver on the top of a 45 meters tower.

To start with the simulation, first of all, we are going to create a network. Some of the features of the network are: frequency range of 81 GHz to the maximum frequency of 86 GHz, vertical polarization (explained in 2.4), continental temperate climate (it is common in most areas in the temperate zone; it is characterized by extremes in temperature and daily changes. Also is defined by pronounced seasons. It is the typical situation in most part of the European continent.), surface refractivity of 301 N-units, ground conductivity of 0.05 S/m and relative ground permittivity of 15 units. In this network we will configure two types of units: transmitter and receiver. The equipment chosen was fabricated by *BridgeWave*, so following the features of this equipment given in 1.4, the configuration of the T_x and R_x will look like figure 12.

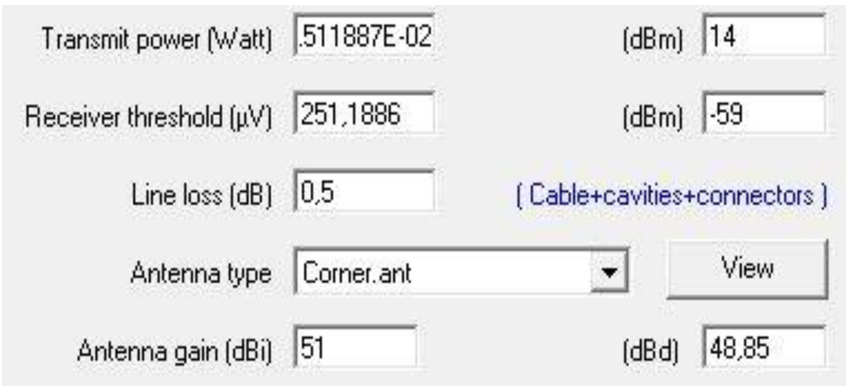


Figure 12: Transmitter and receiver configuration.

The antenna is parabolic with a diameter of 60 cm and 51 dBi gain. Parabolic antennas are typically used in microwaves designs. They are very directive because they transmit a very narrow beam that have to be perfectly focused into the receptor antenna. Both antennas are fixed to each other so the azimuth and elevations angles are determined by this position. The radiation diagram of a directive antenna, which appears in figure 13, is the same in vertical and horizontal:

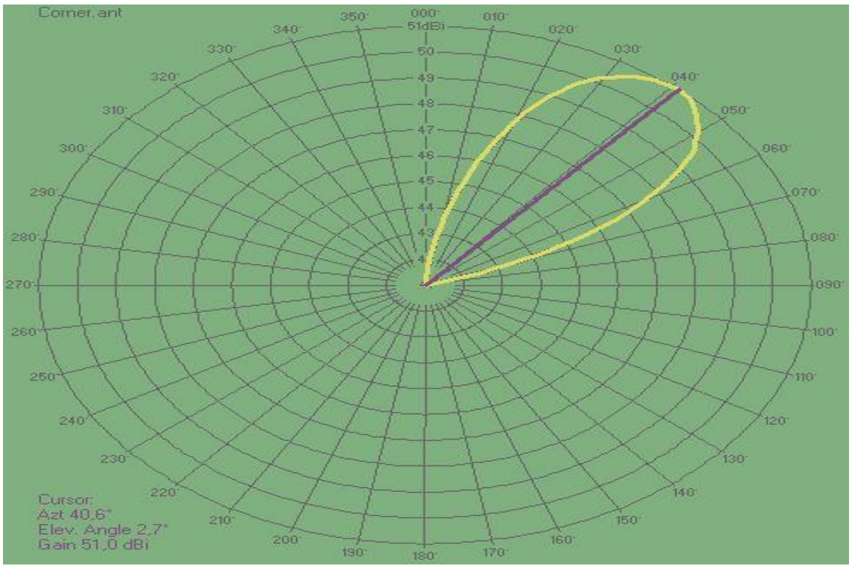


Figure 13: Radiation diagram of a directive antenna.

Finally we can have an overall view of the radio link. Thanks to the software, we are allowed to adjust the height of the antennas until we can provide the best coverage diagram. At last, the link design and the path is:

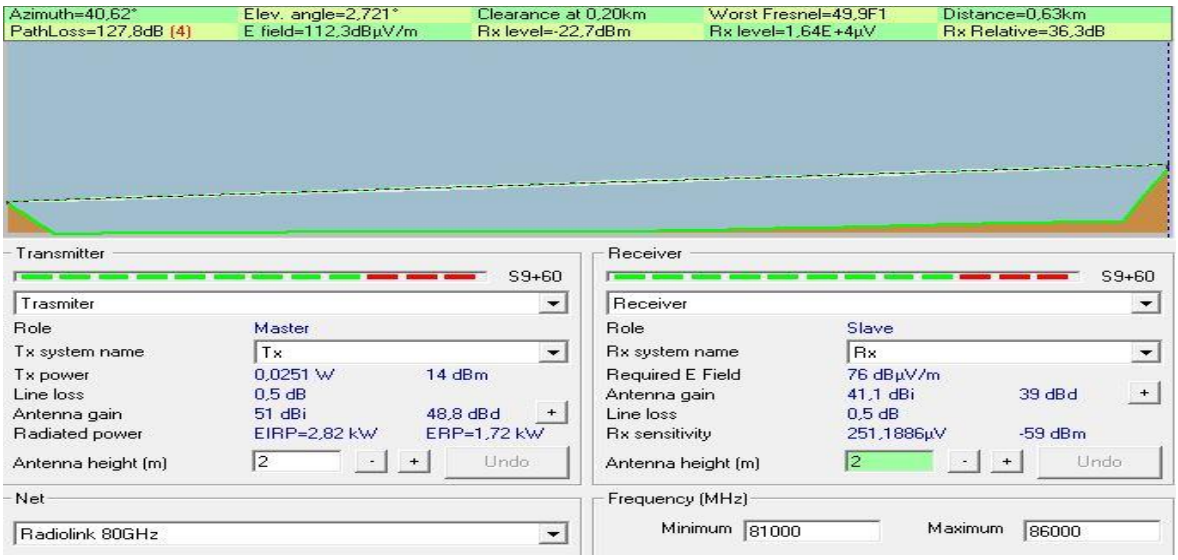


Figure 14: Antenna high calculation and path view.

The T_x antenna height is 2 m and it is placed on the top of a 25 m high building. R_x antenna is 2 meter high and it is settle on the top of a 45 m high tower. There exists coverage all the path long, because the R_x signal level is at least -22.7 dBm, which is higher than the receptor sensibility.

2.8 Atmospheric phenomena in E-band:

Now that we have the height of the antennas, the last point is to do a review of the availability. In E-band the availability is going to be determinedly limited by rain attenuation. In order to complete this project, we are going to do a review of the specific phenomena affecting E-band and also see those which have to be included in the design process and which can be neglected.

During propagation, in tropospheric radio links some signal attenuations are produced due to absorption and scattering cause by hydrometeors such as rain, snow, hail or fog.

[20] One strong benefit of E-band is that it is unaffected by many transmission deteriorations. Thick fog, for example, at a density of 0.1 g/m^3 (about 50 m visibility) has just 0.4 dB/km attenuation at 70/80 GHz, compared to more than 225 dB/km at visible wavelengths. [21] Furthermore E-band wireless is similarly unaffected by dust, sand, snow and other transmission path impairments. [15] Although snow does not affect this band, it should be taken into account that the recommendation ITU-R P.530 does not consider practicable to formulate a global model for the effect of ice formation on an antenna which can cause large additional attenuations. For reliable operation under freezing conditions, as in this case, antennas should be kept clear of icing.

[22] However, the recommendation ITU-R 838 indicates that attenuations produced by rain grow rapidly for frequencies above 10 GHz. Despite they are negligible for frequencies below 5 GHz; E-band transmissions can experience large attenuation when in presence of rain. As with all high frequency radio propagation, rain attenuation will place practical limits on link distances. So it will be significantly important in the design of this project.

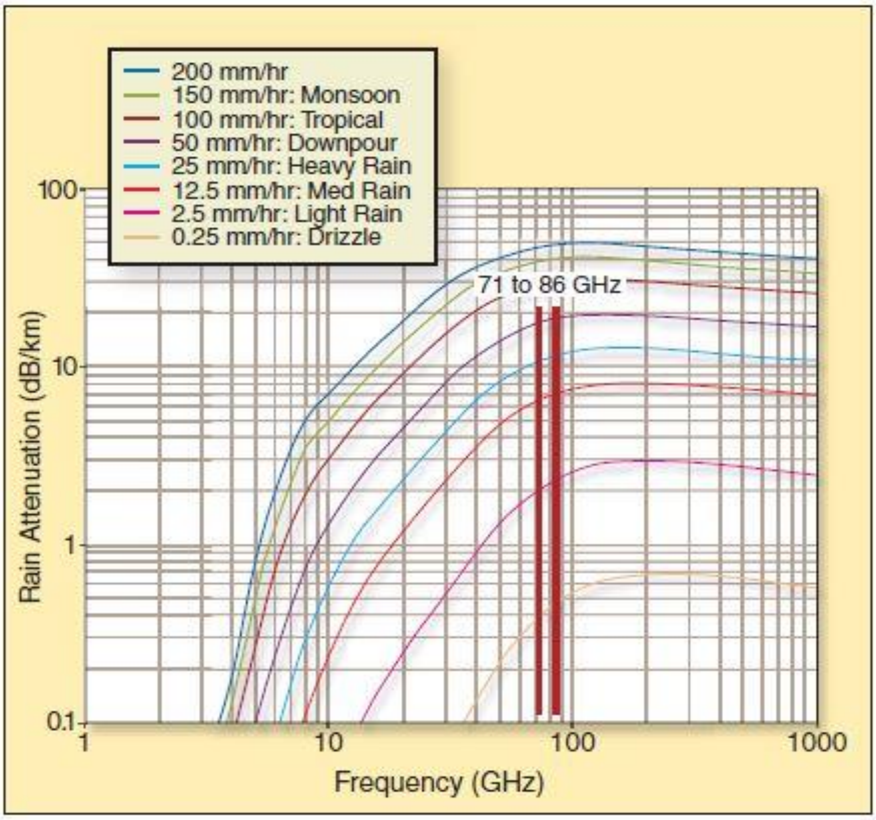


Figure 15: Rain attenuation at microwave and millimeter-wave frequencies.

Although *Radio Mobile* software calculates these losses itself, to calculate the availability after, the following technique may be used for estimating the long-term statistics of rain attenuation:

The specific attenuation due to rain(γ_R) can be calculated from the ITU-R P.838 recommendation. The specific attenuation, γ_R (dB / km) is obtained from the rain rate R (mm / h) by the exponential law:

$$\gamma_R = kR^{\alpha} \ , \tag{15}$$

where *k* and α are constants depending on the frequency and polarization of the electromagnetic wave.

In Recommendation ITU-R 838, values of *k* and α for different frequencies and linear polarizations (horizontal and vertical) are provided. For example, the values taken by these constants for our design of 80 GHz are:

Table data 10: Regression coefficients to estimate the value of the specific attenuation.

Frequency (GHz)	k_H	α_H	k_V	α_V
80	1.1704	0.7115	1.1668	0.7021

Vertical polarization values will be taken because, as it is explain before, is the one used in this design.

Finally, it should be taken into account that in all the above calculations, horizontal propagation paths and linear polarizations are considered. If there exists an inclination of polarization with respect to the horizontal one, or there is an elevation angle along the path, then the values of *k* and α have to be modified by correction formulas included in the same recommendation:

$$k = \frac{k_H + k_V + (k_H - k_V)\cos^2\theta \cos 2\tau}{2} \tag{16}$$

$$\alpha = \frac{k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta \cos 2\tau}{2k} \tag{17}$$

Where θ is the elevation path angle and τ is the inclination of polarization with respect to the horizontal.

[23] The next step is to obtain the rain rate $R_{0.01}$ exceeded for 0.01% of the time (with an integration time of 1 min). In figure 16 a climatic global map of Poland with $R_{0.01}$ rates for different cities is shown.

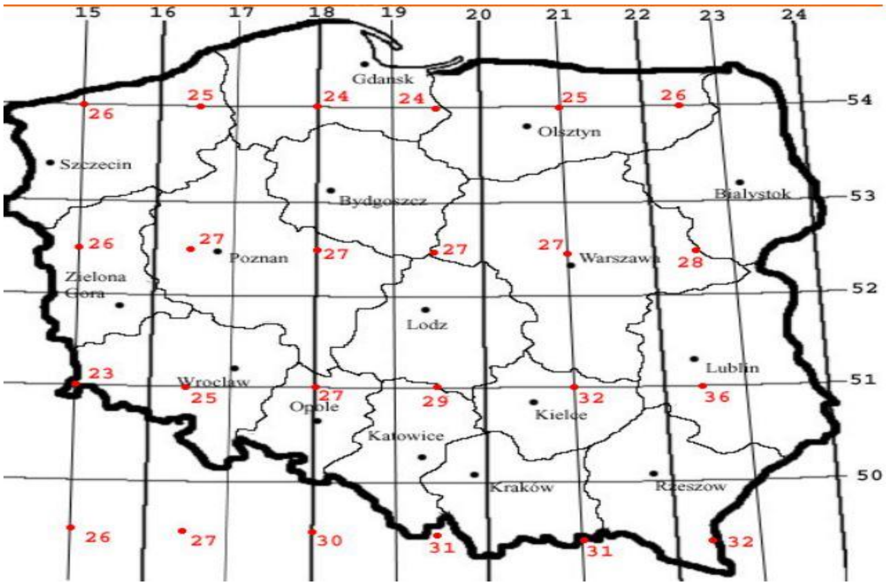


Figure 16. Climatic global map of Poland.

Krakow city, where this project is developed, has a value of $R_{0.01}$ approximated of 32 mm/h. For example, in this case, it means that it rains more than 32 mm/h during less than 0.01% of the time. So, if we want our system to have an availability of 99.99% it would be necessary to develop this design considering a rain intensity of R=32 mm/h and take it into account while estimating attenuation.

Finally, the ITU-R P.530 Recommendation sets out the procedure for calculating long-term attenuation by rain. An estimate of the path attenuation exceeded for 0.01% of the time is given by equation 18:

$$A_{0.01} = \gamma_R d_r \quad , \tag{18}$$

Where d_r is the effective path length, d_{eff}, of the link multiplying the actual path length *d* by a distance factor *r*. An estimation of this factor is given by:

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1 - e^{-0.024d})} \quad (19)$$

In the recommendation also is given a power law to estimate the attenuation exceeded for other percentages of time (ρ).

In *Annex 2* there is a *Matlab* script that calculates the procedure explained in the recommendation ITU-R 837 (rainfall rate exceeded for p% of an average year). The input parameters of the function are:

```
function [RainRate,p0] = Rec837_5(p,lat,lon)
```

Where *p* is the probability level and the other ones are the latitude and longitude of the radio link emplacement. When it is compiled, the function returns the rain rate exceeded for 0.01% of the time which is 37.5547 mm/h.

Foliage losses are significant at E-band frequencies and may be a limiting propagation impairment for E-band transmissions. For example, the foliage loss at 80 GHz for a penetration of 8 meter (roughly equal to the diameter of a large tree) is about 20 dB. However, in our design there are no vegetations between the transmitter and the receiver so these losses should not be taken into account.

In summary, E-band propagations exhibit comparable characteristics to those at the widely used microwave bands, and with well characterized weather characteristics allowing rain fade to be understood, link distances of several kilometers can confidently be realized.

2.9 Multigigabit link availability and error performance:

It has been shown in section 2.8 that meteorological phenomena cause considerable attenuations of radio wave transmission; especially in E-band these attenuations are caused by rain. It is demonstrated that in E-band outages caused by rain fades are relatively long, of order minutes and longer. Wireless links need to be designed and installed with a fade margin to provide protection against such rain fades. The question concerned every link designer is how much fade margin should be engineered into each link. If the fade margin chosen is too big, the link will be over engineered and the cost spent on large antennas and higher power transmitters may be wasteful. On the other hand, if the fade margin chosen is too low, the link will experience more outages that perhaps can be tolerated. The correct fade margin is therefore a tradeoff between technical performance, cost and desired link performance. This radio link FM has been calculated in section 2.6.

It is usual to quote link performances in terms of weather availability, it means the statistical amount of time that the link is operating with better than a given performance. If the fade exceeds the link's fade margin, an outage will occur and the link is said to be unavailable.

[24] Safety standards of operation in microwave systems have reached high rigidity. For example, a 99.999% of link availability can be reach. A link with 99.999 % availability would experience 0.001% outages. This is often known as carrier-class availability, because it has long been the telecom operators' benchmark for wired and wireless telecommunications. This is equivalent to a maximum of 5 minutes of interruptions during a year.

[15] As said before, in E-band the unavailability is directly connected to rain attenuation. However, multipath fading is not going to be considered because ITU-R P.530 says that multipath fading only need to be calculated for path lengths longer than 5 km and can be set to zero for shorter paths. As the distance of this radio link is much shorter than this margin (0.63 km), it is not necessary to take into account multipath fading for estimating the outage of this design.

So as we do not have to consider multipath fading, the unavailability of this radio link is going to be defined by rain attenuation. In following steps we are going to calculate the outage probability due to rain following the procedure explained in ITU P-530 Recommendation.

From previous steps in section 2.8 we have:

- Rain rate: $R_{0.01\%}$=37.5547 mm/h.
- Specific attenuation:

$$A = \gamma_r = k \cdot R^{\alpha} = 14.87\frac{dB}{km} \quad (20)$$

Where *k* and α depend on the polarization and have been extracted from table data 10 and R is the rain rate.

- Effective path length:

$$deff = d \cdot r = 1.083\ km \quad (21)$$

Where:

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1 - e^{-0.024d})} = 1.72 \quad (22)$$

- Path attenuation exceeded for 0.01% of the time:

$$A_{0.01\%} = \gamma_r \cdot deff = 16.11\ dB \quad (23)$$

The attenuation exceeded for other percentage of time *p* in the range 0.001% to 1 % may be deduced from the following power law:

$$\frac{A_p}{A_{0.01}} = C_1 \cdot p^{-(C_2 + C_3 \cdot log_{10} p)} \quad (24)$$

Where, $if\ f \geq 10\ GHz$:

$$C_0 = 0.12 + 0.4[log_{10}(\frac{f}{10})^{0.8} = 0.488 \quad (25)$$

$$C_1 = (0.07^{C_0})\left[0.12^{(1-C_0)}\right] = 0.092 \quad (26)$$

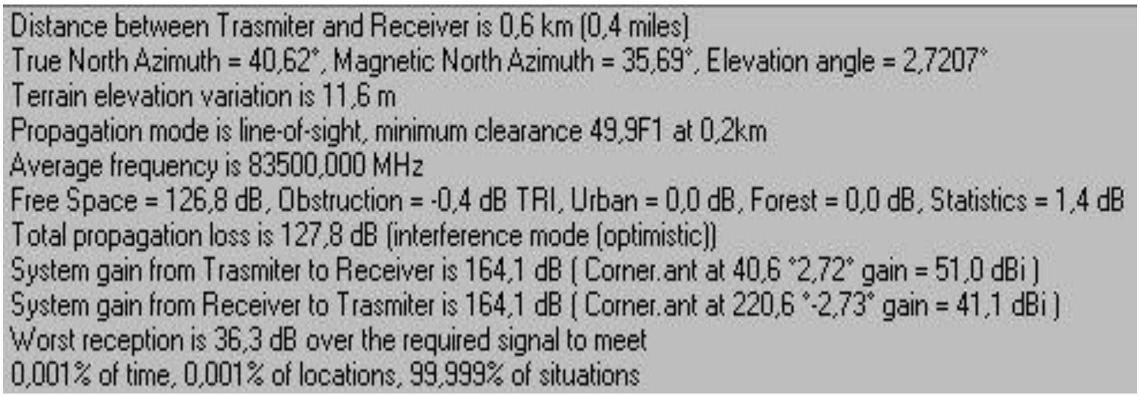
$$C_2 = 0.855C_0 + 0.546(1 - C_0) = 0.696 \quad (27)$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0) = 0.089 \quad (28)$$

Replacing in equation 24 these constants (from equations 26, 27 and 28), we are going to solve equation 29 for the percentage of 0.001. We will get a value of $A_{0.001\%}$ that will be the attenuation exceeded for 0.001 % of the time. If this attenuation is lower than the FM, the link will be over engineered and an availability of 99.999% may be achieved. On the other hand, if this attenuation is higher it means that the FM is too low and we could not get the availability pursued all along the project.

$$\frac{A_{0.001\%}}{10^{1.611}} = 0.092 \cdot 0.001^{-0.696-0.089log_{10}(0.001)} \quad (29)$$

Solving equation 29 we get a value of $A_{0.001\%}$ =18.61 dB. Although the FM of this design is over engineered we can conclude that with this equipment and emplacement we can obtain an availability of 99.999%, which was the value we have been pursuing all along the design. To finalize, we can see in figure 19 an extract from all the simulation parameters and calculations. It can be appreciated that the availability of this system is 99.999 %, which in E-band is equivalent to a maximum of 5 minutes of interruptions during a year.



Distance between Trasmiter and Receiver is 0,6 km (0,4 miles)
True North Azimuth = 40,62°, Magnetic North Azimuth = 35,69°, Elevation angle = 2,7207°
Terrain elevation variation is 11,6 m
Propagation mode is line-of-sight, minimum clearance 49,9F1 at 0,2km
Average frequency is 83500,000 MHz
Free Space = 126,8 dB, Obstruction = -0,4 dB TRI, Urban = 0,0 dB, Forest = 0,0 dB, Statistics = 1,4 dB
Total propagation loss is 127,8 dB (interference mode (optimistic))
System gain from Trasmiter to Receiver is 164,1 dB (Corner.ant at 40,6 °2,72° gain = 51,0 dBi)
System gain from Receiver to Trasmiter is 164,1 dB (Corner.ant at 220,6 °-2,73° gain = 41,1 dBi)
Worst reception is 36,3 dB over the required signal to meet
0,001% of time, 0,001% of locations, 99,999% of situations

Figure 17: Profile details view.

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Annex 1:

```
e0=1/(36*pi*1e9);
mi0=4*pi*1e-7;
mir=1;
er=25;
sigma=1e-2;
w=2*pi*80e9; %frequency=80 GHz

z1=(mi0/e0)^0.5;
z2=((i*w*mi0*mir)/(sigma+i*w*er*e0))^0.5;
gama1=i*w*((mi0*e0)^0.5);
gama2=(i*w*mi0*mir*(sigma+i*w*e0*er))^0.5;
teta_i=[0:(pi/180):pi/2];
teta_t=acos((gama1*cos(teta_i))/gama2);

%Amplitude calculation:
for k=1:length(teta_i)
wsp_odbicia_r(k)= (z2*sin(teta_t(k))-
z1*sin(teta_i(k)))/(z2*sin(teta_t(k))+z1*sin(teta_i(k)));
wsp_odbicia_p(k)= (z2*sin(teta_i(k))-
z1*sin(teta_t(k)))/(z2*sin(teta_i(k))+z1*sin(teta_t(k)));
end

plot(teta_i*180/pi,abs(wsp_odbicia_r),'r.-');
hold on
plot(teta_i*180/pi,abs(wsp_odbicia_p),'g.-');

title('amplitude of the reflection coefficient');
xlabel('incidence angle [degrees]')
ylabel('rebound');
legend('vertical 80 GHz','horizontal 80 GHz',2);



% Phase estimation:
figure
plot(teta_i*180/pi,(180/pi)*angle(wsp_odbicia_r),'b.-');
hold on
plot(teta_i*180/pi,(180/pi)*angle(wsp_odbicia_p),'k.-');


title('phase of the reflection coefficient');
xlabel('incidence angle [degrees]')
ylabel('reflection phase [degrees]');
legend('vertical 80 GHz','horizontal 80 GHz',2);
```

Annex 2:

```
function [RainRate,p0] = Rec837_5(p,lat,lon)

%   Check latitude and longitude arrays are the same size
if sum( size(lon) ~= size(lon) ) ~=0
    error('The lat and lon vectors must be the same size');
end

%   Ensure all longitudes are between 0 and 360
lon = mod(lon,360);

%
%            *********************************
%            ** Input Climate Parameters     **
%            *********************************

% load input meteorological paramaters
load ESARAIN_LAT_v5.TXT -ascii ; lat_e40 = ESARAIN_LAT_v5 ;
load ESARAIN_LON_v5.TXT -ascii ; lon_e40 = ESARAIN_LON_v5 ;
load ESARAIN_MT_v5.TXT -ascii ; mt = ESARAIN_MT_v5 ;
load ESARAIN_BETA_v5.TXT -ascii ; conv_ratio = ESARAIN_BETA_v5 ;
load ESARAIN_PR6_v5.TXT -ascii ; pr6 = ESARAIN_PR6_v5 ;

%
%            ****************************
%            ** Perform calculation     **
%            ****************************


% bi-linear interpolation of parameters @ the required coordinates
pr6i  = interp2(lon_e40,lat_e40,pr6,lon,lat,'linear');
mti   = interp2(lon_e40,lat_e40,mt,lon,lat,'linear');
betai = interp2(lon_e40,lat_e40,conv_ratio,lon,lat,'linear');

% extract mean annual rainfall amount of stratiform type
msi = mti.*(1 - betai);

% percentage probability of rain in an average year
p0 = pr6i.*(1 - exp(-0.0079.*(msi./pr6i)));

% Loop over each (lat,lon) point and calculate rain rate exceedance

nPoint = numel(lat);              % number of (lat,lon) points
nProb = numel(p);                 % number of exceedances
RainRate = zeros(nProb,nPoint); % Declare array to hold rain rates

for iPoint = 1:nPoint

    rr = zeros(numel(p),1);       % Array to hold rain rates for this
point
    if isnan(p0(iPoint))          % catch the case where P0 is not
defined
       p0(iPoint) = 0;
    else
```

```
        % P0 is defined so do the calculation
        ThisP0 = p0(iPoint);
       ix = find(p > ThisP0);
       if ~isempty(ix),
          rr(ix) = 0;
       end;
       ix = find(p <= ThisP0);
       if ~isempty(ix),
          a = 1.09;
          b = mti(iPoint)/(21797*ThisP0);
          c = 26.02*b;
          A = a*b;
          B = a + c*log(p(ix)/ThisP0);
          C = log(p(ix)/ThisP0);
          rr(ix) = (-B + sqrt(B.^2 - 4*A*C))/(2*A);
       end
    end
    RainRate(:,iPoint) = rr;

end
```