Design of a Trans-Horizon Radio Link for Ultra High and Super High Frequencies

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Abstract. Cost considerations and availability of frequencies condition the feasibility of links at distances in which there is no line of sight between antennas. These trans-horizon links require precise design procedures to determine whether the intensity of the signal and its noise ratio allow reception with reasonable quality. The present work describes a procedure for radio electric link calculation to transmit voice and data signals through bandwidth at ultra high and super high frequencies.

Keywords: UHF, SHF, VoIP, IP/TCP, Links.

1   Introduction

In the framework of the Project *Communitarian Private Networks* [1] different technologies [2], [3], [4] to provide links to small and isolated communities have been analyzed and compared. These communities, with low population densities, hold no commercial interest to service providers. In addition, research focuses on links with a distance between antennas of about 70 km [5], [6] with the use of Radio Mobile, a freeware [7] developed by Roger Coudé. (Download address in the reference section.)

The present work aims to generalize the calculation of this type of links in a simple and practical way.

2   Trans-horizon Radio Link

At ultra-high and super-high frequencies, wave propagation takes the form of a direct wave. This type of propagation travels directly in a straight line from the transmitting antenna to the receiver hitting neither the ground nor the ionosphere. The height of the antennas and the distance between them is of core importance to establish the quality of the transmission and the possibility to establish an efficient link [8].

The following formula provides a simple way to calculate the distance to the horizon

given the height of an antenna at one endpoint:

$$D_{max} \text{ [in km]} = 3{,}61 \sqrt{H} \quad (1)$$

where: D_{max} is the maximum distance of the link to the horizon (in km) and H is the Antenna height in m.

Figure 1 shows an example of a link over the horizon limit in which both antennas have the same height H and establish a link at 2 D_{max} distance.
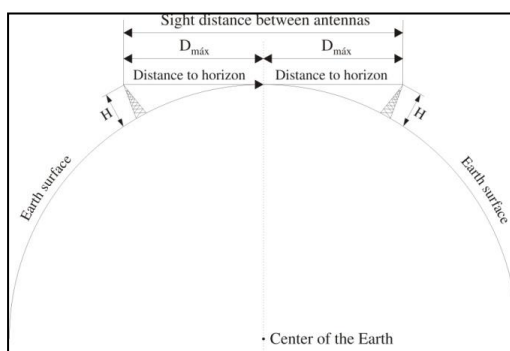

Figure 1. Horizon radio link at maximum distance

In practice, however, the real value for the maximum line of sight distance is greater than the value the formula yields, because of wave diffraction from the curvature of the Earth.

The phenomenon originates from the structure of the atmosphere. In areas close to the surface of the Earth, the beam curves slightly downward, increasing the distance and following the expression:

$$D_{max} \text{ [in km]} = 4{,}14 \sqrt{H} \quad (2)$$

for values such that the distance between the two endpoints is,

$$D > 2 D_{max} \quad (3)$$

Such link is called a trans-horizon link. Note that there is no direct line of sight between antennas. Figure 2 depicts two antennas of height H where both are at a distance greater than 2 D_{max}.

The present work aims to analyze this problem and to determine the values that can be obtained at these distances as a function of the electromagnetic field generated in the transmitting antenna and the effects that the atmosphere produces on the signal.
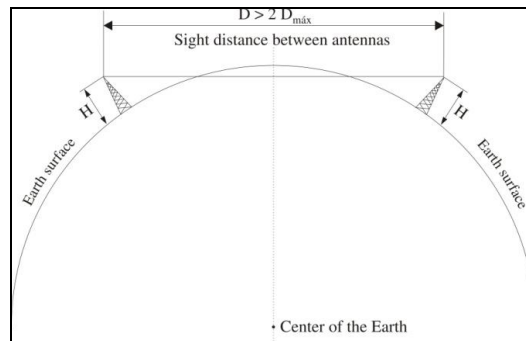
Figure 2. Trans-horizon radio link

3 Fresnel Zone

In Optics, as well as in radio electric communication systems, a **Fresnel zone** is the zone of additional clearance that needs to be considered in the calculation of these types of links, in addition to the direct line of sight between the antennas.

The Fresnel Zone generates an additional element derived from the theory of electromagnetic waves when signals are transmitted in free space. The expansion results from reflections and phase changes when travelling through an obstacle. The result is an increase or decrease in the intensity level of the received signal. In this sense, the curvature of the Earth (K) has to be taken into account, which generally take the values of K=2/3 (worst case scenario) and K=4/3 (best case).

A Fresnel zone is an ellipsoid of concentric revolution, infinite in theory, defining volumes in the pattern of radiation in the circular aperture (generally). The cross section of the first Fresnel zone is circular. The subsequent zones take a ring-like form in the cross section, and are concentric to the previous zones.

The concept of Fresnel zone can also be applied to the analysis of interference from obstacles near the trajectory of a radio antenna. This zone needs to be determined to keep it obstruction free. The maximum *tolerable* obstruction to consider it negligible is 40% in the first Fresnel zone. The maximum *recommended* obstruction is 20%.

In the case of radio communications, the values depend on K (the curvature of the Earth), considering that for K=4/3 the first Fresnel Zone should be clear in 100%, while with K=2/3 60% should be clear in the first Fresnel zone.

To establish a Fresnel zone, the link line of sight needs to be determined, i.e., the straight line between the transmitter and the receiver antenna. Once the line of sight is established, the Fresnel zone becomes the area surrounding it. The cross section radius of the first Fresnel zone has a maximum in the center of the link.
In this point, radius *r* is:

$$r = 547.723\sqrt{\frac{d}{4f}} \qquad (4)$$

where [r] = Radius in [m]; [d] = Distance in [km]; [f] = Transmission frequency in [MHz].

The generic formula of the Fresnel zones is:

$$r_n = 547.723\sqrt{\frac{nd_1 d_2}{fd}} \qquad (5)$$

where: $[r_n]$ = Radius of the nth Fresnel zone[m]; $[d_1]$ = Distance from the transmitter to the object in [km]; $[d_2]$ = Distance between the object and the receiver in [km]; [d] = Total distance of the link [km]; [f] = Frequency in [MHz].

4 General Calculation of a Trans-Horizon Radio Link.

4.1 General Link Calculation

The general case to solve is to establish a trans-horizon link of approximately 60 km using low cost technologies[1]. Wireless communication links are chosen; in particular those in the unlicensed ranges of 2.4 GHz or 5.7 GHz. Microwave links are dismissed due to cost considerations. Section 4.2 establishes link requirements and Section 4.3 analyzes operative options for the 2.4 GHz and 5.7 GHz frequencies.

4.2 General Conditions

A link design between the towns of Bowen, the base, and Ovejería, the link endpoint and slave, is presented as an example of the model. Both cities are located in the south of the Province of Mendoza, in Argentina.

The design suggests the construction of two 30 meter high antennas on both endpoints. Note that the town of Bowen has broadband internet and telephone access. Hence, the link will also provide VoIP technology. The town infrastructure consists of merely a rural school and a primary health care facility.

Equation (2) yields a distance to the optical horizon to be 22.6 km. Thus, total link distance for a line of sight link is 45.3 km.

The distance obtained from the coordinates of both cities is 54.13 km. The distance between the link endpoints does not render possible a line of sight link. In addition, potential frequencies are selected under the criteria that this type of link is feasible if refraction of the wave front in the atmosphere is taken into account.

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[1] Any other distance meeting the requirements of a trans-horizon link could have been chosen.

An alternative to enhance the link is to use one or several relay stations.

In this particular case, the area is a desert without electrical power which does not meet minimum safety requirements. Hence, relay stations are not considered even with the use of solar energy devices. This option increases costs and, hence, the low cost objective is not met.

On the other hand, 2.4 GHz and 2.5 GHz bands, called S-Band ISM and C-Band ISM respectively, provide a feasible solution. Both are unlicensed frequencies.

The coordinates of the station locations are found using Google Earth [9], determining the altitude of the link endpoints as well. (See Table 1)

Table 1: Coordinates of the link endpoints.

ENDPOINT	Latitude				Longitude				Height
Bowen	35º	00´	4´´	S	67º	30´	38´´	O	460,50
Ovejeria	34º	32´	56´´	S	67º	25´	11´´	O	459,78

To calculate link values, the following elements are taken into account: 1) electromagnetic field generated in the transmission antenna propagated perpendicularly to the link direction; 2) vacuum propagation; 3) atmospheric effects on the signal. All these elements have a strong influence on the quality of the received signal.

Propagation conditions of electromagnetic waves are determined using simple concepts and simplified models, given the complexity of their behavior.

These conditions are:

✓ The electromagnetic field has electrical field vectors E and magnetic field vectors H which are perpendicular to each other. When E and H fields meet far enough from the transmitting antenna they can be considered to be a different wave front plane. The plane containing field E and the propagation direction is called plane of polarization.

✓ The propagation medium is non-dispersive; hence, the phase velocity of the spectral components does not depend on the frequency.

✓ At a first stage, a direct beam may join the antennas. However, problems derived from multiple paths need to be taken into account.

✓ The model can contemplate two cases: 1) isotropic antennas with the same signal strength transmitted in all directions; 2) antennas with certain directivity. They are considered to gain signal strength when compared to isotropic antennas.

If the transmitting antenna is isotropic, the signal level transmitted per unit of surface of a sphere (power density) is:

$$\mathbf{Pd\ [w] = Pt\ /\ 4.\pi.d^2} \tag{6}$$

where: $[P_t]$ = Signal level transmitted by the antenna; [d] = Distance between the antennas and the point under study (radius of the sphere).

   The receiver antenna effective area is defined as the surface of the wave front plane with signal level Pd, which has a strength equivalent to the level delivered by the antenna.

For an isotropic antenna, the effective area is:

$$\mathbf{A_e\ [m^2] = \lambda^2/4.\pi} \tag{7}$$

where: $[\lambda]$ = Wavelength of the radio electric field [m].

Hence, the low signal level registered is understood.

Relating both elements yields the reception strength of P_r in function of P_t for isotropic antennas:

$$\mathbf{Pr\ [w] = Pt.\ \{\lambda/4.\pi.d\}^2} \tag{8}$$

where: λ denotes frequency in MHz and d distance in km.

        The reception strength is less than the transmitting signal level due to the impossibility of capturing the entire level generated. It can be considered as attenuation due to propagation in free space without obstacles between isotropic antennas.

        According to ITU-R, recommendations RC 525 and RC 341, the value for free space attenuation Ao (in dB) is:

$$\mathbf{Ao\ [dB] = 10.\ log\ Pt/Pr = 32,5\ dB + 20.\ log\ (f.d)} \tag{10}$$

   Transceiver kits have among their features: 1) transmission power; 2) lack of frequency drift; 3) sensitivity (which is the minimum magnitude of an input signal required to produce an output signal, also called threshold level of the receiver Pu).

        We define the *Fading Margin* as the difference [dB] between the signal level received Pn and the minimum signal level Pu which yields a low error rate.

$$\mathbf{FM\ [dB] = Pn - Pu} \tag{11}$$

Nominal reception signal level, shown in eq. (12), is obtained by subtracting from the transmitted signal level, Pt in dBm, the attenuation from the kit circuits (Ab), the coaxial cable (Ag), and the propagation of free space (Ao), and then adding antenna gain (Ga)

$$Pn \ [dB] = Pt - Ab1 - Ag1 + Ga1 - Ao + 2\ Ga - 2\ Ag - 2\ Ab \qquad (12)$$

Ab depends on the number of components, but it is estimated in the range of 0.2 dB per associated filter and circuit.

Coaxial cable attenuation is stated in [dB/100 m] and is a direct function of the working frequency.

The antenna gain is stated in the direction of maximum directivity and is a direct function of the frequency.

With these parameters, in a practical and simplified way, the features of the link can be determined. In addition, other elements appear, affecting the behavior of the signal in its propagation through the atmosphere and originating additional attenuation such as:

- ✓ Atmospheric refraction (elevated horizon)
- ✓ Fresnel zone diffraction (obstacle attenuation)
- ✓ Attenuation due to terrain reflection
- ✓ Multiple trajectory fading (duct formation)
- ✓ Absorption from vegetation close to the antenna
- ✓ Absorption from gases or hydrometeors (fog, snow, and others)
- ✓ Energy dispersion from rainfall
- ✓ Wave polarization decoupling

In the case of digital links, the error rate is measured in [BER]. Hence, the Pu is be the receiver level threshold which can assure a BER of 10^{-6} and 10^{-9}

With these error rates, an error bit in 10^6 or 10^9 bits transmitted is acceptable. In the case of digital links, the modulation system used is also relevant – directly associated to link capacity.

4.3   Link Calculation

When working with the simplified model described, software can be developed to obtain the following parameters:

1) Antenna height;
2) Attenuation from obstruction;
3) Beam curvature from atmospheric refraction; among others

Field experiences show that the obtained values are satisfactory in determining characteristics required for these applications.

In this case, Radio Mobile [7] software is used. This freeware was developed by Roger Coudé and can be downloaded from the web address shown in the references.

The software requires the location coordinates and yields a satellite map of the area. It can also enhance the area to show the vegetation with the use of LANDSAT[2] [10], which shares high definition satellite images for research and academic purposes.

Once the working area is determined, the link endpoints are defined through the following parameters, among others:

1) Coordinates;
2) Weather conditions (desert, tropics, etc.),

and other technical data such as

3) Working power;
4) Frequency of operation;
5) Receiver sensitivity;
6) Coaxial cable attenuation;
7) Antenna height over the land;
8) Type of antenna;
9) Antenna gain.

Figure 3 shows a satellite image of the working area for this particular case, showing link stations.

The figure shows at the bottom the point coordinates and altitude where the cursor is located.

Regarding the features of the transceiver kits, a kit under standard 802.11 is considered, such as model NanoStation from Ubiquiti 2 [11], working at 2.4 GHz as well as 802.11 b/g and the kit of the same company, model NanoStation 5 [12], working at 5.7 GHz under standard 802.11a.
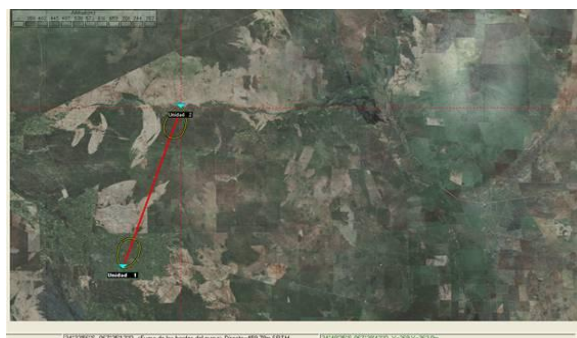

Figure 3: Satellite map of the area Bowen – Ovejeria

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[2] www.landsat.org.

The use of these kits implies the need for an access point (AP) in the same tower to avoid coaxial cable attenuation due to the low signal level in which they work.

Given that the frequency link is either 2.4 GHz or 5.7 GHz, both frequencies are analyzed to determine the range granting the best signal level with an availability of 70% of the time – required by the software.

Receiver signal is the sum of the beams which travel directly between the transmitter and the receiver. They follow the curvature of the Earth due to refraction at the low layers of the atmosphere, to the beams reflected at the high layers of the atmosphere, and to the beams reflected on the terrain.

The software delivers a profile picture, Figure 4, where the attenuation levels from free space and from obstructions are shown; as well as the worst obstruction ratio from the first Fresnel radius, the link distance, and the signal level measured in [dBm] and in [μV] at the receiver.
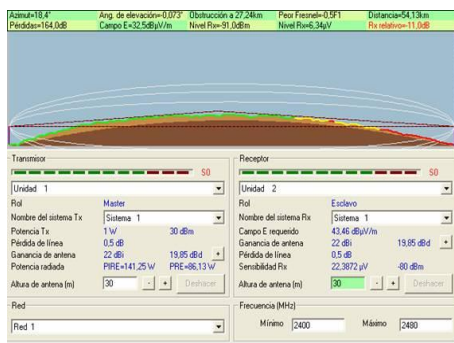

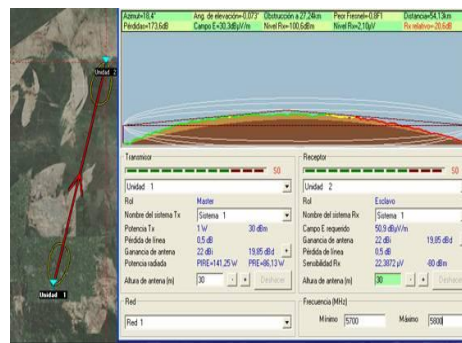**Figure 4**: Result of the link at 2.4 GHz   **Figure 5:** Result of the link at 5,7 GHz

In addition, Fresnel zones are shown. The obstruction to the fist Fresnel zone (F1) becomes clear in the graph and represents a value equivalent to the attenuation produced on the pair Fresnel zones against the odd zones. Finally, the reception level is equivalent to the value obtained in the **area free of obstacles.**

In the same figure, a graph shows endpoint locations. It also reveals that the link is of No Line of Sight type. The same occurs at 2.4 GHz and 5.7 GHz frequencies in Figures 4 and 5 respectively. In figure 5, the software shows in a red line the non feasibility of the link.

The software also yields other relevant information; for instance, the signal level, with a sweep over the 360° azimuth from the main unit, increasing one degree at a time. Figure 6 shows the result of signal level exploration for 2.4 GHz with a sweep from 40° azimuth to 90° azimuth. On the upper side, the signal levels of the selected area are shown. The information obtained confirms the non feasibility of the link.

The program allows the user to modify different parameters such as antenna height, transceiver sensitivity, and transmission levels. Final values can be obtained for a feasible

link. As a first step, the link height is modified to obtain a feasible value when the heights of the endpoints are: 60 m in Bowen and 80 m in Ovejería. Figure 7 shows the results indicating the reception value. Link feasibility is shown in a green line.

Maintaining antenna heights at the feasibility level, but changing the frequency to the 5.7 GHz range, the link arrives to a critical level – shown in the yellow line – because the reception level is equal to or is greater than -3 db but is less than 3 db. These values cannot grant the availability of 70% required by the software. (Figure 8)

The results can be explained by an obstruction suffered at the Fresnel zone at 5.7 GHz, considering that the first zone is much smaller than in the 2.4 GHz case. The difference in size results from the curvature of the terrain separating both endpoints.
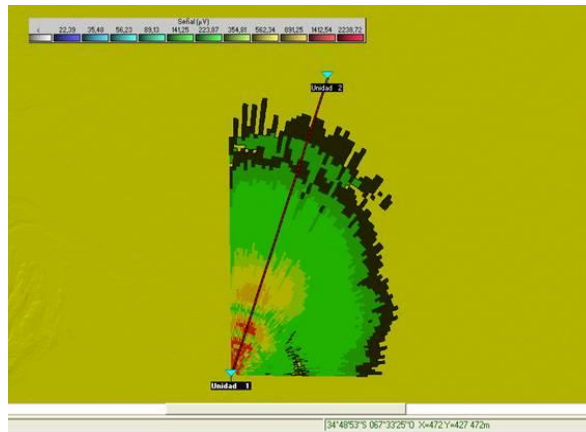

Figure 6: Representation of the signal level at 2.4 GHz

Certainly, the solution presented is not convenient under economic or practical considerations because of the space required in Bowen for tower anchoring, as well as the presence of nearby buildings in Ovejería, the space required, and the safety measures needed to avoid accidents with tower anchoring.
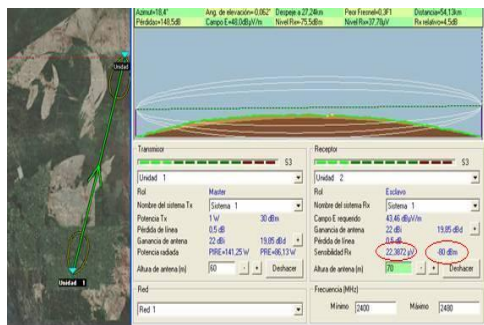

Figure 7: Results from elevating antenna height at frequency 2.4 GHz

Figure 8: Results from elevating antenna height at frequency 5.7 GHz
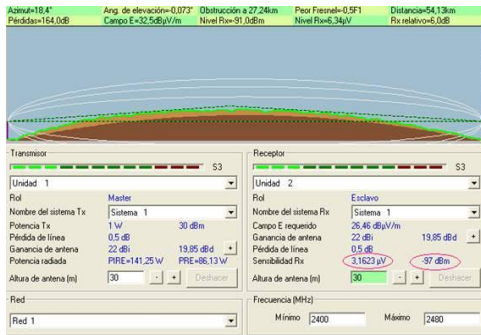
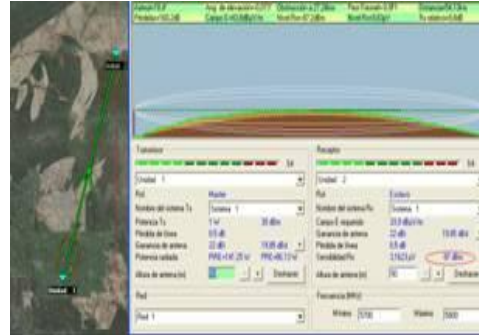**Figure 9**: Link with sensitivity 97 dBm at 2,4 GHz   **Figure 10**: Solution at 5.7 GHZ, modifying height and sensitivity

Thus, the most convenient alternative, which needs to be studied for each particular case, is to lower the minimum signal level of the receiver sensitivity to -97 dBm, instead of the -80 dBm originally established. It implies to work at lower transmission speeds: approximately 1 Mbps instead of 24 or 36 Mbps originally considered.

In Figure 9, the red circle shows the change in the sensitivity value. Antenna heights remain at the same value of 30 m at both endpoints, at a frequency of 2.4 GHz. The upper side of Figure 9 shows that the receiver levels are higher than the established minima, guaranteeing the link. The green line joining the endpoints represents the feasibility condition. Figure 10 shows once again that the solution is not satisfactory only for a link at 5.7 GHz and the antennas need to be elevated to 50 m for the link to become feasible.

In addition, transmission speed cannot be determined because the value cannot be predicted with the equipment used. It can be assumed that it would be within the previous range.

The analysis confirms the feasibility of a link at 2.4 GHz requiring only a change in the level of sensitivity expected, as can be seen in Figure 11.

Figure 12 represents the signal distribution and the success rate of a 6.4 dB link. They show that the signal level for a frequency of 2.4 GHz is above the receiver threshold level.
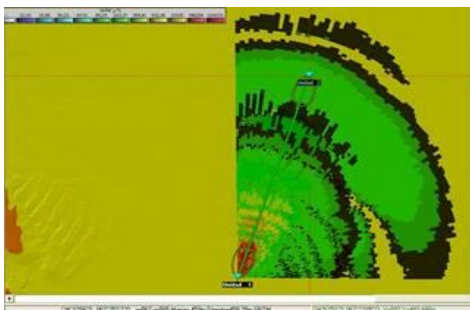

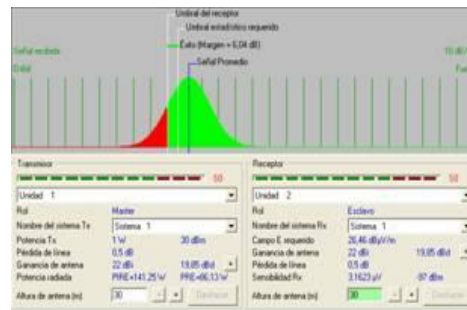**Figure 11**: Signal level for 2.4 GHZ and -97   **Figure 12**: Signal range of the link at 2.4 GHz

5 Conclusions

The work analyzes the design of a wireless link between two towns, both in the southeast of the Province of Mendoza, in Argentina, located beyond the optical horizon.

The link is studied as a typical case to solve the general problem of populations with isolation problems. Hence, it can be extrapolated later to be applied in similar situations. In these cases, the distance to cover with the link ranges between 60 to 70 kilometers and the terrain is desertic or semi-desertic.

Coordinates and terrain conditions are detailed between the two endpoints. Estimates for different bandwidths are established, i.e. 2.4 GHz and 5.7 GHz.

Note that the distance between the endpoints (60 km) is greater than regular distances contemplated in the theory for the application of standard 802.11.

In addition, analysis focuses on the fact that, in practice, transmitted signals in rural areas behave differently from those in urban settings because the former suffer less from noise spectrums. Radio Mobile software is considered to be a valuable tool in the design of radio electric links.

It can be downloaded from the internet and used to obtain satellite information of the area under study. With this software, signal levels are determined for Fresnel zones in free space, granting the use of the equipment in the frequencies at 2.4 and 5.7 GHz.

At a 5.7 GHz frequency, the obstruction of the first Fresnel zone is significant and could deteriorate further with the presence of obstacles such as trees. They could attenuate the transmitted signal to values leading to critical values or to a low transference rate. The same problem applies to 2.4 GHz frequencies.Therefore, the obtained results suggest the advisability to work primarily with links at the 2.4 GHz bandwidth, which in theory may have some advantages.

In this sense, field tests have been scheduled with equipment at both frequencies to verify their behavior.

In addition, and to establish the scope, tests will be conducted to analyze the results obtained from the 802.11 standard using antennas with a significant gain.

These field experiences will follow the present analysis. Different parameters like antenna gain and equipment range will be tested at the setup of the link.

The results from these experiences will be presented in a forthcoming article.

6 Acknowledgements

acknowledged. The authors acknowledge the interest and collaboration of Engineer Walter López, Director of the General Alvear campus of the Instituto Tecnológico Universitario (ITU) towards the project. They also wish to thank the City Hall of General Alvear for its assistance in the field.

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