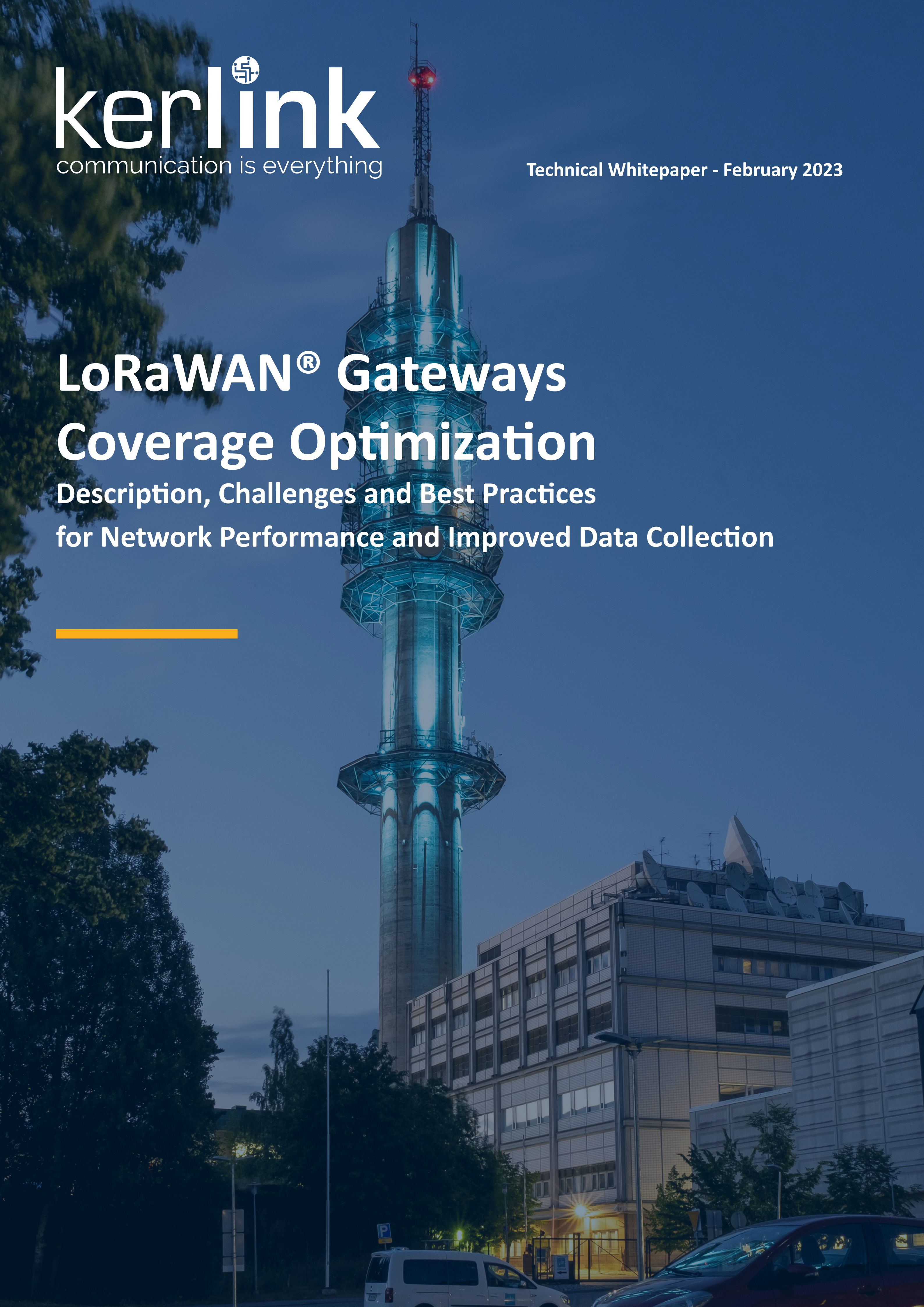

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Technical Whitepaper - February 2023

LoRaWAN® Gateways Coverage Optimization

Description, Challenges and Best Practices for Network Performance and Improved Data Collection

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1 Introduction

Low Power Wide Area Network (LPWAN) technology is gaining popularity in industry because of its energy saving, long range, and cost-efficient communication characteristics. LPWAN is very suitable for internet of Things (IoT) applications that only need to transmit small amount of data in long range, supposedly up to 10 - 40 km in rural zones and 1 – 5 km in urban areas. Many LPWAN technologies have arisen in the licensed as well as unlicensed frequency bands. Among them, LoRaWAN®, Sigfox and NB-IoT are today's leading technologies with some technical differences.

LoRa® is a physical layer technology that modulates the signals in sub-GHz unlicensed band using a proprietary chirp spread spectrum modulation (CSS) technique which spreads a narrow-band signal over a wider channel bandwidth. LoRa uses six spreading factors (SF7 to SF12) to adapt the data rate and range as a tradeoff. Higher spreading factor allows longer range at the expense of lower data rate, and vice versa. The LoRa® data rate is between 300 bps and 50 kbps, depending on spreading factor and channel bandwidth.

What is LoRaWAN® radio coverage?

Simple answers are sometimes provided to this question such as "typical outdoor LoRaWAN® network is expected to cover from 2 to 5km in urban areas while it can reach beyond 10 to 15km in rural areas". In some cases, extremely long range can be attained: 766km!

The reality is LoRaWAN® radio coverage depends on many factors such as obstacles in the line-of-sight, environment (urban area, sub urban areas, rural areas), elevation of the gateway and devices, choice of the antenna, etc.

This Technical Whitepaper provides some basics to understand how to determine the radio coverage and, moreover, how to optimize it thanks to an appropriate installation.

2 Budget link

2.1 Definition

When designing a complete end-to-end radio communications system, it is necessary to calculate the radio link budget. The link budget is a summary of all the gains and losses in a transmission system. The radio link budget sums the transmitted power along with the gains and losses to determine the signal strength arriving at the receiver input.
The link budget will take the form of the equation below:

Received power (dBm) = Transmitted power (dBm) + Gains (dB) – Losses (dB)

Once the link budget has been calculated, then it is possible to compare the calculated received level with the parameters for the receiver to discover whether it will be possible to meet the overall system performance requirements of signal to noise ratio, bit error rate, etc.

To devise a radio link budget formula, it is necessary to investigate all the areas where gains and losses may occur between the transmitter and the receiver. A typical link budget equation for a radio communications system may look like the following:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_{P} - L_{RX}$$

Where:

- P_{RX} = received conducted power (dBm)
- P_{TX} = transmitter conducted power (dBm)
- G_{TX} = transmitter antenna gain (dBi)
- G_{RX} = receiver antenna gain (dBi)
- L_{TX} = transmit feeder and associated losses (feeder, connectors, etc.) (dB)
- L_{FS} = free space loss or path loss (dB)
- L_{P} = miscellaneous signal propagation losses (these include fading margin, polarization mismatch, losses associated with medium through which signal is travelling, other losses...) (dB)
- L_{RX} = receiver feeder and associated losses (feeder, connectors, etc.) (dB)

In the next paragraphs (§2.2 to §2.4), several LoRaWAN® radio budget links are presented. Both uplink (from end-devices to gateway, aka UL) and downlink (from gateway to end-devices, aka DL) budgets are calculated. The budgets correspond to the (L_p+L_{FS}) losses as defined above.

2.2 Budget link – European use case

In Europe, the budget links are driven by some specific regulation aspects:

- Effective Radiated Power (ERP) is limited to +14dBm (25mW), i.e. +16dBm Effective Isotropic Radiated Power (EIRP), in 863-870MHz sub-bands according to ERC 70-03 recommendation;
- 27dBm (500mW) ERP, i.e. +29dBm EIRP, is allowed in 869.4-869.65MHz sub-band according to ERC 70-03 recommendation.

LoRaWAN® specification has considered these ERC 70-03 aspects and defined two downlink transmissions: RX1 in the 863-870MHz range (16dBm EIRP) and RX2 in the 869.4-869.65MHz range (29dBm EIRP). The RX1 and Rx2 budget links are obviously different as shown below.
For the uplink budget links, we have considered two use cases: the first one with a 3dBi gateway antenna gain and the second one with a 6dBi antenna gain.

UL budget link #1:

End-point conducted power (Ptx)	14dBm
End-point feeder losses (Lrx)	0dB
End-point antenna gain (Gtx)	2dBi
Gateway Rx antenna gain (Grx)	3dBi
Gateway Sensitivity (125KHz, SF12) (Prx)	-140dBm
Gateway feeder losses (Lrx)	0.5dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	158.5dB

UL budget link #2:

End-point conducted power (Ptx)	14dBm
End-point feeder losses (Lrx)	0dB
End-point antenna gain (Gtx)	2dBi
Gateway Rx antenna gain (Grx)	6dBi
Gateway Sensitivity (125KHz, SF12) (Prx)	-140dBm
Gateway feeder losses (Lrx)	0.5dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	161.5dB

For the downlink, we have considered only a 3dBi gateway antenna gain. The impact of the gateway antenna gain is null as increasing the antenna gain would cause a decrease of the gateway conducted power to meet the maximum EIRP regulation.

DL budget link #1 (RX1):

Gateway conducted power (Ptx)	13.5dBm
Gateway feeder losses (Lrx)	0.5dB
Gateway antenna gain (Gtx)	3dBi
End-point Rx antenna gain (Grx)	2dBi
End-point Sensitivity (125KHz, SF12) (Prx)	-136dBm
End-point feeder losses (Lrx)	0dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	152dB

DL budget link #2 (RX2):

Gateway conducted power (Ptx)	26.5dBm
Gateway feeder losses (Lrx)	0.5dB
Gateway antenna gain (Gtx)	3dBi
End-point Rx antenna gain (Grx)	2dBi
End-point Sensitivity (125KHz, SF12) (Prx)	-136dBm
End-point feeder losses (Lrx)	0dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	165dB

Comparing UL and DL budget links, we can see there are not symmetrical, especially considering RX1. Only RX2 provides symmetrical budget. Symmetrical budget links is important when “confirmed uplinks” are required.
Note that increasing the gateway antenna gain would improve the UL budget link but would have no impact on the DL budget link. A 6dBi gateway antenna gain is therefore an excellent trade-off.

2.3 Budget link – North America use case

In North America (USA, Canada) the budget links are driven by specific FCC regulation aspects:

- Unlicensed band is 902-928MHz,
- Digital modulation is allowed for modulation bandwidth greater than 500KHz,
- Conducted power is allowed up to +30dBm (1W) for digital modulation systems, assuming a 6dBi antenna gain,
- Frequency hopping is mandatory for modulation bandwidth of less than 500KHz,
- Transmit time on frequency hopping channel is limited to 400ms, and
- Conducted power is allowed up to +30dBm (1W) for 50 channels (or more) frequency hopping systems but limited to 24dBm (250mW) for less than 50 channels.

LoRaWAN® specification has considered the FCC regulation aspects as follows:

- Uplink uses 125KHz BW CSS modulation, so:
  - Frequency hopping is required,
  - Output power is limited to 24dBm,
  - Transmit time is limited to 400ms, and
  - SF12 and SF11 cannot be used in this case.
- Downlink uses 500KHz BW CSS modulation, so:
  - Output power is limited to 30dBm, and
  - 6dBi antenna is assumed.

For the uplink budget links, we have considered two use cases, the first one with 14dBm output power (using SX1261 transceiver) and the second one with 20dBm output power (using SX1262 transceiver). The choice of output power is driven mainly by the application and battery lifetime.

UL link budget #1:

End-point conducted power (Ptx)	14dBm
End-point feeder losses (Lrx)	0dB
End-point antenna gain (Gtx)	2dBi
Gateway Rx antenna gain (Grx)	6dBi
Gateway Sensitivity (125KHz, SF10) (Prx)	-135dBm
Gateway feeder losses (Lrx)	0.5dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	156.5dB

UL link budget #2:

End-point conducted power (Ptx)	20dBm
End-point feeder losses (Lrx)	0dB
End-point antenna gain (Gtx)	2dBi
Gateway Rx antenna gain (Grx)	6dBi
Gateway Sensitivity (125KHz, SF10) (Prx)	-135dBm
Gateway feeder losses (Lrx)	0.5dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	162.5dB

DL link budget #1:

Gateway conducted power (Ptx)	30dBm
Gateway feeder losses (Lrx)	0.5dB
Gateway antenna gain (Gtx)	6dBi
End-point Rx antenna gain (Grx)	2dBi
End-point Sensitivity (500KHz, SF12) (Prx)	-130dBm
End-point feeder losses (Lrx)	0dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	167.5dB

Comparing UL and DL budget links, we can see there are not symmetrical. The DL budget link is better than UL budget link, which is excellent when “confirmed uplinks” are required. There is then a benefit when increasing the end-device output power. The counterpart is obviously an increase of current drain and a reduction of battery life.

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2.4 Budget link – Peru use case

In some countries, the IoT regulation is limited to minimum requirements such as a defined frequency band and a maximum EIRP. This is a benefit for the budget link as there is no constraint of transmit time, allowing 125KHz BW / SF12 modulation.

For example, the regulation in Peru (DECRETO SUPREMO N° 006-2013-MTC) allows:

- Unlicensed bands are 915-928MHz and 916-928MHz.
- Maximum EIRP is +30dBm (1W) in 915-928MHz band.
- Maximum EIRP is +36dBm (4W) in 916-928MHz band.

For the uplink budget links, we have considered the most favourable use case, with 20dBm output power (usage of SX1262 transceiver). This is just for example, to demonstrate the benefits on the uplink budget.

UL link budget #1:

End-point conducted power (Ptx)	20dBm
End-point feeder losses (Lrx)	0dB
End-point antenna gain (Gtx)	2dBi
Gateway Rx antenna gain (Grx)	6dBi
Gateway Sensitivity (125KHz, SF12) (Prx)	-140dBm
Gateway feeder losses (Lrx)	0.5dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	167.5dB

DL link budget #1:

Gateway conducted power (Ptx)	30dBm
Gateway feeder losses (Lrx)	0.5dB
Gateway antenna gain (Gtx)	6dBi
End-point Rx antenna gain (Grx)	2dBi
End-point Sensitivity (125KHz, SF12) (Prx)	-136dBm
End-point feeder losses (Lrx)	0dB
UL Link budget (Lp+Lfs=Ptx+Gtx+Grx-Ltx-Lrx-Prx)	173.5dB

Comparing UL and DL budget links, we can see there are not symmetrical. The DL budget link is better than UL budget link by 5dB, which is excellent when “confirmed uplinks” are required. Comparing the budget links with North America use case, we have 5dB improvement.

2.5 How to optimize the budget link?

The different use cases considered above show that, depending on the local regulation, the UL budget link varies from 161.5dB to 167.5dB and the DL budget link varies from 165dB to 173.5dB. The uses cases also demonstrated that some parameters of the budget link are defined by regulation and therefore cannot be changed nor improved. Other parameters can however be optimized.

UL budget link:

- P_{RX} = gateway received conducted power (dBm)
  This is the sensitivity of the gateway. It cannot be modified or improved.
  However, this value can be degraded due to a poor design of the gateway or due to interferences.
- P_{TX} = end-device transmitter conducted power (dBm)
  The conducted power is limited by local regulation (25mW for instance).
  Some countries may allow up to 1W but LoRaWAN® transceivers (SX1262 based) do not reach such output power. This is also a penalty for current consumption and duration life. A trade-off shall be considered in this case.
- G_{TX} = end-device transmitter antenna gain (dBi)
  The end-device antenna gain shall be ideally comprised between 0dBi and 2dBi.
  Below 0dBi, the end-device would not be able to transmit the maximum EIRP allowed by regulation. Above 2dBi would be great but this is hardly achievable in a small for factor device.
- L_{TX} = transmit feeder and associated losses (feeder, connectors, etc.) (dB)
  This value is generally set to zero as the antenna is directly implemented on the PCB of the end-device.
- G_{RX} = gateway receiver antenna gain (dBi)
  This is a key parameter. The antenna gain shall be as high as possible. 6dBi antenna gain is a good trade-off but higher values can be used, depending on the Lrx losses.
- L_{RX} = gateway receiver feeder and associated losses (feeder, connectors, etc.) (dB)
  This is another key parameter. The losses between the gateway antenna and the RF input port shall be limited to minimum values. It includes obviously the RF coaxial cable but also all additional losses such as lightning surge protection and cavity filters, for instance.
- L_{FS} = free space loss or path loss (dB)
  This value depends directly on the distance between the end-device and the gateway. This is assumed not to be changed or improved in direct line of sight situations but in real conditions the value can be optimized as detailed in §3.
- L_{P} = miscellaneous signal propagation losses(dB)
  These include fading, polarization mismatch, losses associated with medium through which signal is travelling, other losses... This value can be optimized as detailed in §3.

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DL budget link:

- P_{RX} = end-device received conducted power (dBm)
  This is the sensitivity of the end-device. It cannot be modified nor improved.
  However, this value can be degraded due to a poor design of the gateway or due to interferences.
- P_{TX} = gateway transmitter conducted power (dBm)
  The conducted power is usually limited by local regulation (25mW or 1W for instance).
  The gateway shall be able to reach the maximum conducted power. If not, this is a penalty for the budget link
- G_{TX} = gateway transmitter antenna gain (dBi)
  This is a key parameter. The antenna gain shall be as high as possible to ensure transmission at the maximum EIRP allowed by local regulation. 6dBi antenna gain is a good trade-off but higher values can be used, depending on the Ltx losses.
- L_{TX} = transmit feeder and associated losses (feeder, connectors, etc.) (dB)
  This is another key parameter. The losses between the gateway antenna and the RF output port shall be limited to minimum values. It includes obviously the RF coaxial cable but also all additional losses such as lightning surge protection and cavity filters for instance.
- G_{RX} = end-device receiver antenna gain (dBi)
  The end-device antenna gain shall be ideally comprised between 0dBi and 2dBi. Above 2dBi would be great but this is hardly achievable in a small for factor device.
- L_{RX} = receiver feeder and associated losses (feeder, connectors, etc.) (dB)
  This value is generally set to zero as the antenna is directly implemented on the PCB of the end-device.
- L_{FS} = free space loss or path loss (dB)
  This value depends directly on the distance between the end-device and the gateway. This is assumed not to be changed or improved in direct line of sight situations but in real conditions the value can be optimized as detailed in §3.
- L_{P} = miscellaneous signal propagation losses (dB)
  These include fading, polarization mismatch, losses associated with medium through which signal is travelling, other losses... This value can be optimized as detailed in §3.

3 Factors impacting the propagation losses

The previous paragraph provided some calculations of the budget links (UL and DL) i.e., the (Lp+Lfs) losses of LoRaWAN® networks. In this paragraph, we are going to detail how the (Lp+Lfs) losses are affected by factors such as obstacles in the line-of sight, environment, etc. This is known as the propagation channel.

3.1 Fresnel zone

In point-to-point wireless communications, it is important for the Line of Sight (LoS), between two wireless systems, to be free from any obstacles (terrain, vegetation, buildings and a lot of other obstructions). Any interference or obstruction in the LoS can result in a loss of signal. To minimize the losses, obstacles in a "Fresnel ellipsoid" shall be avoided.

The Fresnel ellipsoid is a theoretical ellipsoid located between the transmitter and the receiver. The radius of the ellipsoid is defined as follows:

$$r1 = \sqrt{\frac{d1 * d2 * c}{f * (d1 + d2)}}$$

Where:

- *d1* = distance from Tx antenna
- *d2* = distance from Rx antenna
- *f* = frequency
- *c* = celerity (3E8m/s)
- *r1* = radius at the distance d1

A global rule is that 60% of the Fresnel ellipsoid shall be clear of obstacles.

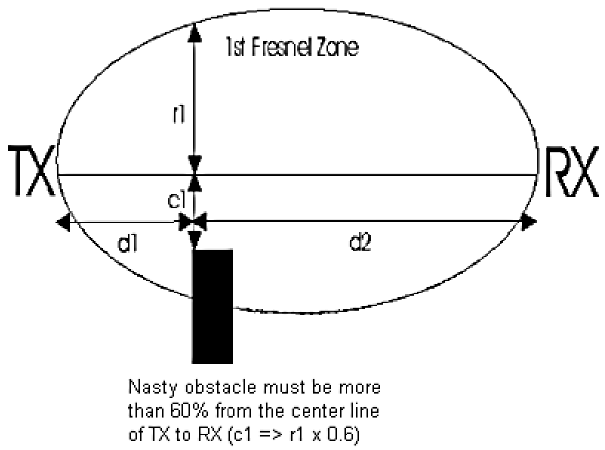

Figure 1 : Fresnel ellipsoid clearance

When considering long distance communications, such as LPWAN, the earth curvature shall be considered. Because, the antennas heights are not sufficient, then the ground (earth curve) is inside the Fresnel ellipsoid and overrule the 60% criteria.

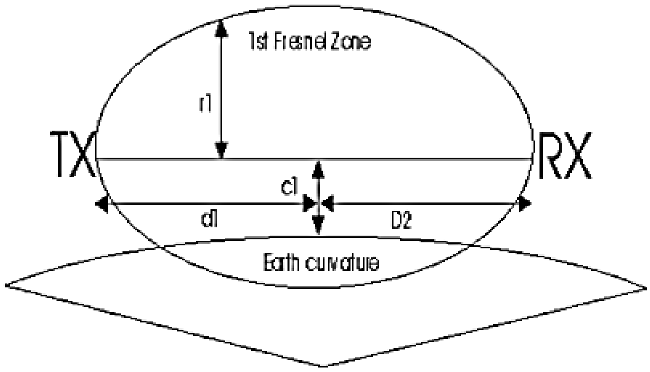

Figure 2 : Fresnel ellipsoid and earth curvature

Assuming a perfect sphere with no terrain irregularity, the distance (*d*) to the horizon from a high transmitter (*h*) can readily be calculated as follows:

$$d = 3570\sqrt{h}$$

If *h*=30m then *d* = 19.5km

3.2 Multipath losses

Radio waves generally travel in a straight line from the emitter to the receiver. This is obviously true when there are no obstacles between the transmitter and the receiver. However, there are, most of the time, some obstacles between the transmitter and the receiver. Then, the radio waves bump into the obstacles and are reflected or diffracted with dephasing. These diffracted waves when arriving on the receiver can cause phase cancelling with the straight-line signals reducing the received power (fading). The fading effect depends on the distance between the receiver and the emitter, the nature of the obstacles and the associated out of phase.

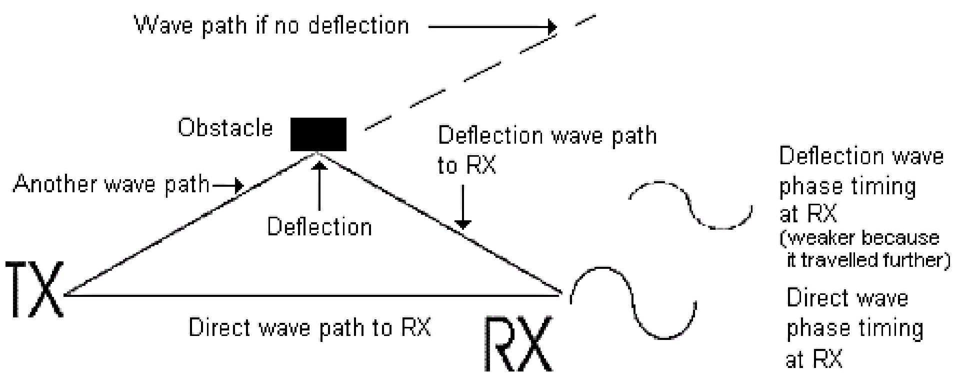

Figure 3 : Fading effects due to obstacles

Fading refers to the fluctuations in strength of the received signal at the demodulator input. Multipath fading occurs in any environment where there is multipath propagation, and the paths change because of the three propagation mechanisms:

- Reflection,
- Diffraction, and
- Scattering.

This will change not only their relative strengths, but also their phases, as the path lengths will change. The multiple signal paths may sometimes add constructively or sometimes destructively at the receiver input.

3.2.1 Reflection losses

It is possible for radio waves to be reflected in the same way as light waves. As both light and radio waves are forms of electromagnetic waves, they are both subject to the same basic laws and principles. Visual examples of light reflection are everywhere from specific mirrors to flat reflective surfaces like glass, polished metal, and the like.

When a radio wave or in fact any electromagnetic wave encounters a change in medium, some or all of it may propagate into the new medium and the remainder is reflected. The part that enters the new medium is called the transmitted wave and the other the reflected wave.
The rules that govern the reflection of radio waves are simple and are the same as those that govern light waves.

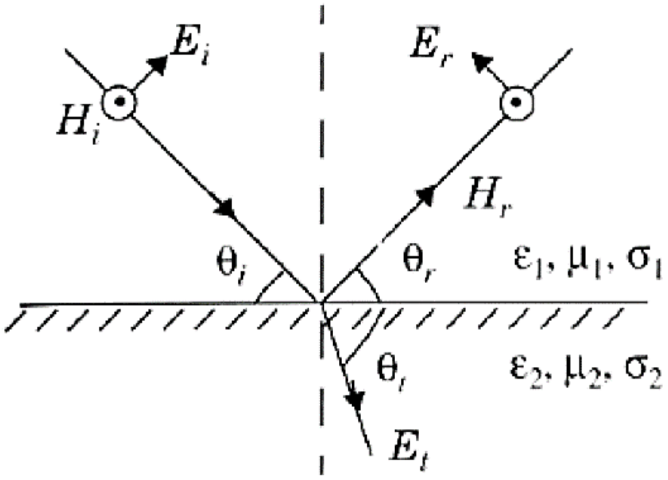

Figure 4 : Reflection and refraction

When a reflection occurs, the angle of incidence, θ1 is the same for the incident ray as for the reflected ray. Additionally, there is normally some loss, because of absorption, or signal passing into the medium.

Conducting media provides the optimum surfaces for reflecting radio waves. Metal surfaces, and other conducting areas provide the best reflections. It is noticeable that for HF ionospheric propagation, when signals are returned to earth and are reflected again by the earth's surface, areas of good conductivity provide the best reflections. Desert areas give poor reflected signals, but the sea is much better, and the differences are very noticeable, despite the variations in the ionosphere and overall propagation path.

3.2.2 Diffraction losses

As radio waves undergo diffraction, it means that a signal may be received from a transmitter even though it may be "shaded" by a large object between.

To understand how this happens it is necessary to look at **Huygen's Principle**. This states that each point on a spherical wave front can be considered as a source of a secondary wave front.

Even though there will be a shadow zone immediately behind the obstacle, the signal will diffract around the obstacle and start to fill the void. It is found that diffraction is more pronounced when the obstacle becomes sharper and more like a "knife edge".

For a radio signal the definition of a knife edge depends upon the frequency, and hence the wavelength of the signal.

For low frequency signals, a mountain ridge may provide a sufficiently sharp edge. A more rounded hill will not produce such a marked effect. It is also found that low frequency signals diffract more markedly than higher frequency ones. It is for this reason that signals on the long wave band can provide coverage even in hilly or mountainous terrain, where signals at VHF and higher would not.

The effect may also be important for very high frequency signals where items of furniture in the home may have a sufficiently sharp edge to enable diffraction to be seen. This may give slightly better coverage.

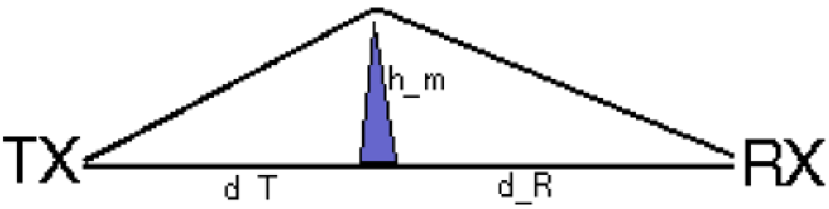

Figure 5 : Diffraction

The diffraction parameter v, also known as **Fresnel-Kirchoff diffraction parameter**, is defined as:

$$v = h_m \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_t} + \frac{1}{d_r}\right)}$$

Where:

- h_m is the height of the obstacle,
- d_t is distance transmitter – obstacle,
- d_r is distance receiver – obstacle, and
- λ is the wavelength.

The diffraction loss L_d, expressed in dB, is approximated by:

$$L_d = \begin{cases} 6 + 9v - 1.27v^2 & 0 < v < 2.4 \\ 13 + 20\log v & v > 2.4 \end{cases}$$

When d_t -> 0 or d_r-> then v -> ∞ and L_d -> ∞.

- At 900MHz, if h_m=30m, d_t =300m and d_r=1000m then v=0.78 and L_d=12.2dB
- At 900MHz, if h_m=100m, d_t =300m and d_r=1000m then v=2.6 and L_d=21.3dB

3.2.3 Scattering losses

In addition to diffracted rays, there may be also rays that are diffracted multiple times, or rays that are both reflected and diffracted. A scattered ray, as shown in the figure below by the segments s and s', has a path loss proportional to the products of s and s'. This multiplicative dependence is due to the additional spreading loss experienced by the ray after scattering.

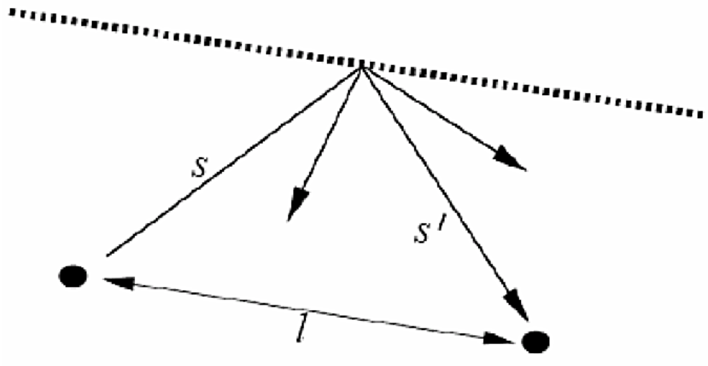

Figure 6 : Scattering

The path loss associated with scattering is:

$$P_r \,\mathrm{dBm} = P_t \,\mathrm{dBm} + 10\log_{10}(G_s) + 20\log_{10}(\lambda) + 10\log_{10}(\sigma) - 30\log(4\pi) - 20\log_{10} s - 20\log_{10}(s')$$

Where:

- σ = radar cross section of the scattering object (in m^2), and
- Gs = antenna gain.

The model assumes that the signal propagates from the transmitter to the scatter based on free space propagation and is reradiated by the scatter with a transmit power equal to σ times the received power.

3.2.4 Multipath Fading

In real transmission paths, radio waves are often reflected by a variety of different surfaces. Although ionospheric reflections are caused by refraction, they can often be considered as reflections. Also, for VHF / UHF communications the signals undergo many reflections. These multiple reflections lead to the signal arriving at the receiver via several paths. Radio wave reflections normally give rise to multi-path effects.
The multiple reflections and multi-path effects give rise to distortion of the signal and fading.
When a signal arrives by two paths, one is longer than the other and will take longer to arrive than the other. This can mean that the signals either add together if they are in phase, or they can tend to cancel each other out. This results in fading of anything moves of changes, or dead spots in certain areas if the reflective surfaces are fixed.
Additionally, the delays in some signal paths can give rise to distortion of the modulation. For digital signals, it can result in data becoming corrupt as the data from one path may be delayed compared to the other and the receiver not being able to distinguish where data bits start and stop.

Fading can be classified into two types:

- Fast fading, and
- Slow fading.

Fast fading refers to the rapid fluctuations in the amplitude, phase, or multipath delays of the received signal over very short distances. This is due to scattering from nearby objects.
Slow fading is characterized by slow variations the amplitude, phase, or multipath delays of the received signal. This is due to scattering from large distant objects.

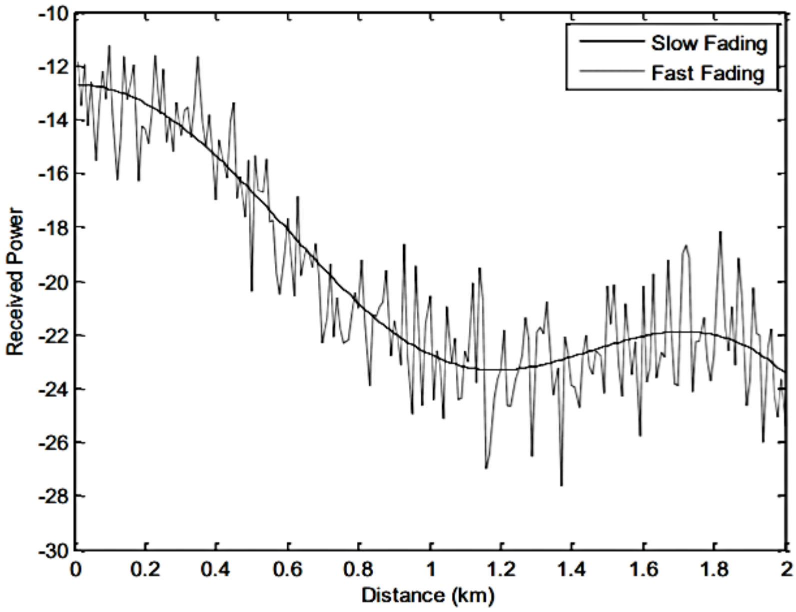

Figure 7 : Slow and Fast Fading

3.3 Penetration in materials

3.3.1 Building materials

Radio waves impinging on a building will enter the building by various mechanisms. The influence of the electrical properties of building materials on each mechanism is different. Material properties have a dominant effect on the reflection and transmission of radio waves through building materials and on the absorption of radio wave energy in those materials. Other mechanisms include diffraction from the edges of materials and scatter from rough surfaces.
All normal building materials are non-magnetic and non-ionized. This means that we only need to consider the dielectric properties of building materials. Most building materials behave as lossy dielectrics. Even metals can be characterized in this way, although the RF losses through metal are very high.

Recommendation of the International Telecommunication Union (ITU) ITU-R P.2040 can be used to describe the "effects of building materials and structures on radio wave propagation".

Attenuation, depending on the material, in dB/m, can be expressed as:

$$A_{dielectric} = 1636 \frac{\sigma}{\sqrt{\eta'}}$$

$$A_{conductor} = 545.8\sqrt{\sigma f_{\text{GHz}}}$$

Where:

- σ = conductivity (S/m), and
- η' = real part of the relative dielectric permittivity.

Material properties are dependent on the frequency.
For the conductivity, there is usually statistically significant evidence for an increase with frequency. In this case the trend has been modelled using:

$$\sigma = c\, f_{\text{GHz}}^{d}$$

For the relative permittivity one can assume similar frequency dependency:

$$\eta' = a\, f_{\text{GHz}}^{b}$$

a, b, c, and d are constants characterizing the material. Some values are expresses below for different materials:

Material class	Real part of relative permittivity		Conductivity S/m		Frequency range
	a	*b*	*c*	*d*	GHz
Vacuum (≈ air)	1	0	0	0	0.001-100
Concrete	5.31	0	0.0326	0.8095	1-100
Brick	3.75	0	0.038	0	1-10
Plasterboard	2.94	0	0.0116	0.7076	1-100
Wood	1.99	0	0.0047	1.0718	0.001-100
Glass	6.27	0	0.0043	1.1925	0.1-100
Ceiling board	1.50	0	0.0005	1.1634	1-100
Chipboard	2.58	0	0.0217	0.7800	1-100
Floorboard	3.66	0	0.0044	1.3515	50-100
Metal	1	0	10^7	0	1-100

Figure 8 : Material properties

When applying above formulas, the attenuation (dB/m) of the different material vs frequency can be represented by the following curves:

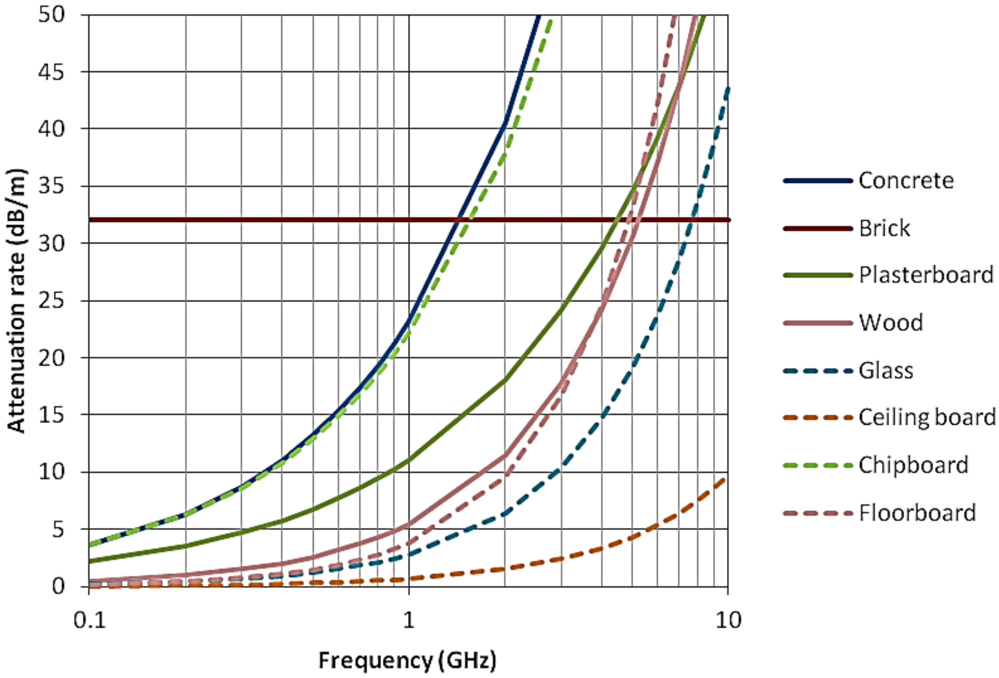

Figure 9 : Attenuation (dB/m) depending on building material

As explained above, the penetration in material depends on the propagation phenomenon (reflection, transmission, scattering). The radio wave angle of incidence in the material has obviously a significant impact as shown below:

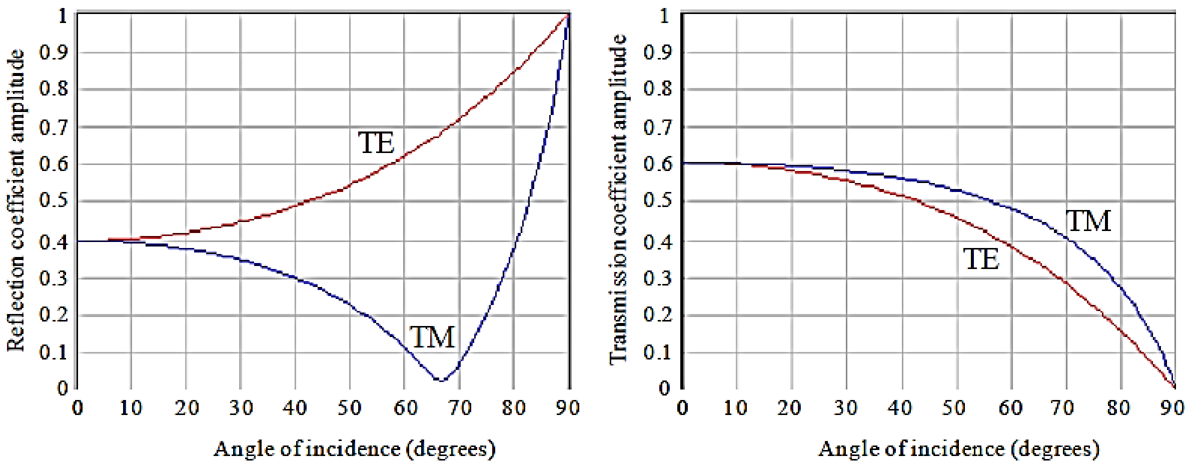

Figure 10 : Reflection and transmission coefficients for air/concrete interface at 1GHz

The above reflection and transmission coefficient are calculated for both transverse electric (TE) polarization (electric vector is perpendicular to the plane of incidence) and transverse magnetic (TM) polarization (electric vector is parallel to the plane of incidence).

3.3.2 Surfaces of the earth

Earth surfaces (soil, water) could be considered as any material as detailed in §3.3.1 with their own permittivity and conductivity parameters.
Recommendation [ITU-R P.527](ITU-R P.527) specifically addresses the "Electrical characteristics of the surface of the Earth" by considering:

- Water,
- Sea Water,
- Dry and Wet Ice, and
- Dry and Wet Soil (combination of sand, clay, and silt).

The penetration depth of the radio energy (δ) is defined as the depth at which the amplitude of the field strength of electromagnetic radiation inside a material falls to 1/e (about 37%) of its original value just beneath the surface.
The penetration depth, as a function of frequency, for different types of Earth's surface components is presented below:

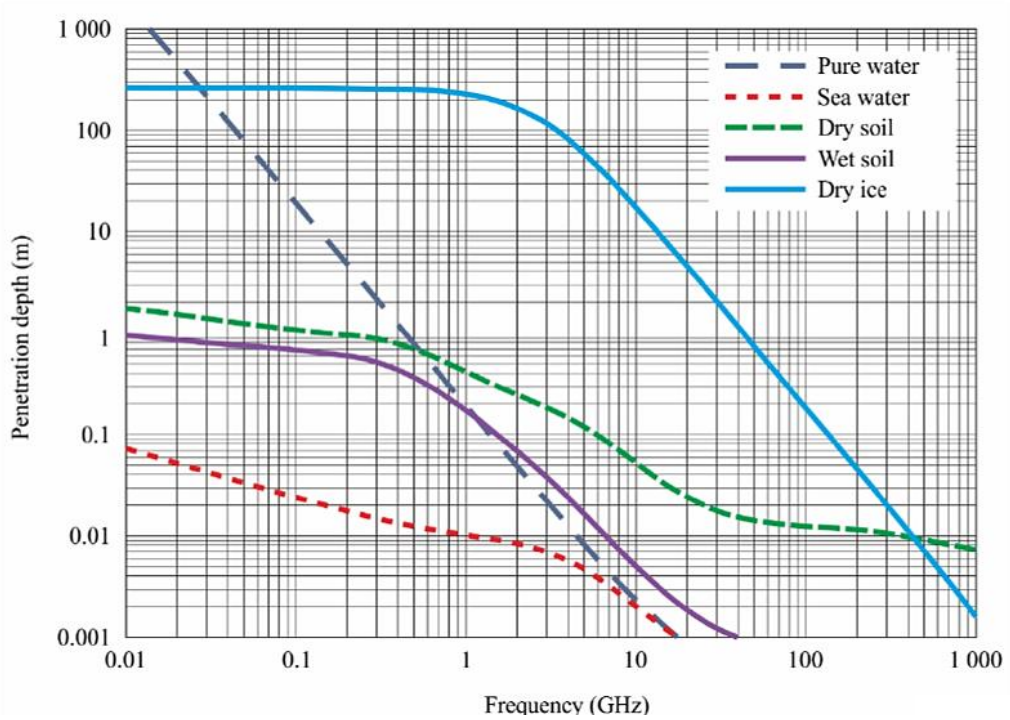

Figure 11 : Penetration depth of surface types as a function of frequency

Note: 37% reduction of field strength is equivalent to -8.6dB (20*Log0.37).

At 1m depth, at 900MHz, we can then consider the following attenuation:

- 43dB in pure water,
- 860dB in sea water!,
- 17.2dB in dry soil, and
- 43dB in wet soil.

The poor penetration in sea water is due to the salinity.

3.3.3 Vegetation

Attenuation in vegetation is detailed in Recommendation ITU-R P.833.

The attenuation depends on the type of foliage and density of the vegetation, so it is difficult to have accurate data.

The figure below shows typical values for specific attenuation derived from various measurements over the frequency range 30 MHz to about 30 GHz in woodland.

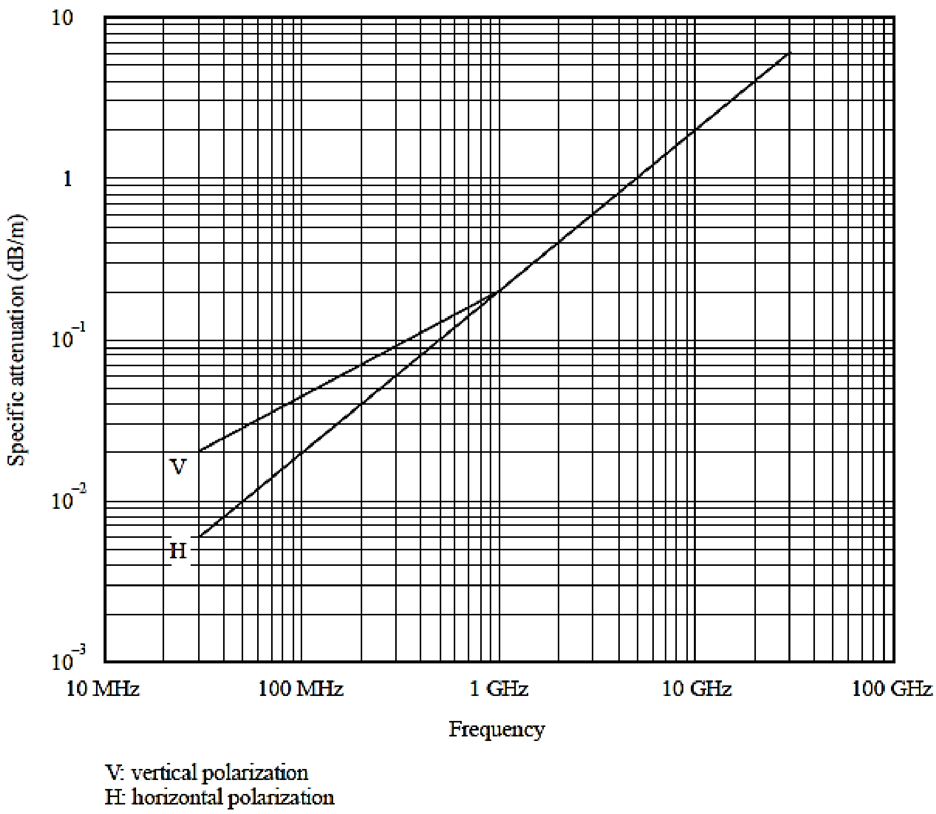

Figure 12 : Specific attenuation due to woodland

The values in the above figure should be viewed as only typical.

At frequencies of the order of 1 GHz the specific attenuation through trees in leaf appears to be about 20% greater (dB/m) than for leafless trees. There can be also variations of attenuation due to the movement of foliage, such as due to wind.

3.4 Noise

A key factor impacting the link budget is often underestimated or even neglected: radio noise. Recommendation ITU-R P.372 provides information on the background levels of radio-frequency noise in the frequency range from 0.1Hz to 100GHz. It takes account radiated radio noise emanating from sources external to the radio receiving system, and received through the reference antenna, which derives from the following causes:

- Natural noise:
  - emissions from atmospheric gases and hydrometeors,
  - the ground or other obstructions within the antenna beam,
  - radiation from celestial radio sources, and
  - radiation from lightning discharges (atmospheric noise due to lightning).
- Man-made noise:
  - particularly for outdoor antennas, aggregated unintended radiation from electrical machinery, electrical and electronic equipment and networks, power transmission lines, or from internal combustion engine ignition, and
  - indoors or for antennas near to obstructions, aggregated unintended radiation, as above, to the extent possible, but also including typical radiation levels from individual or small numbers of sources, in defined typical environments.

The following figure show the expected values of external noise figure (F_a) in the frequency range 100MHz to 100GHz along with different noise levels of interest.

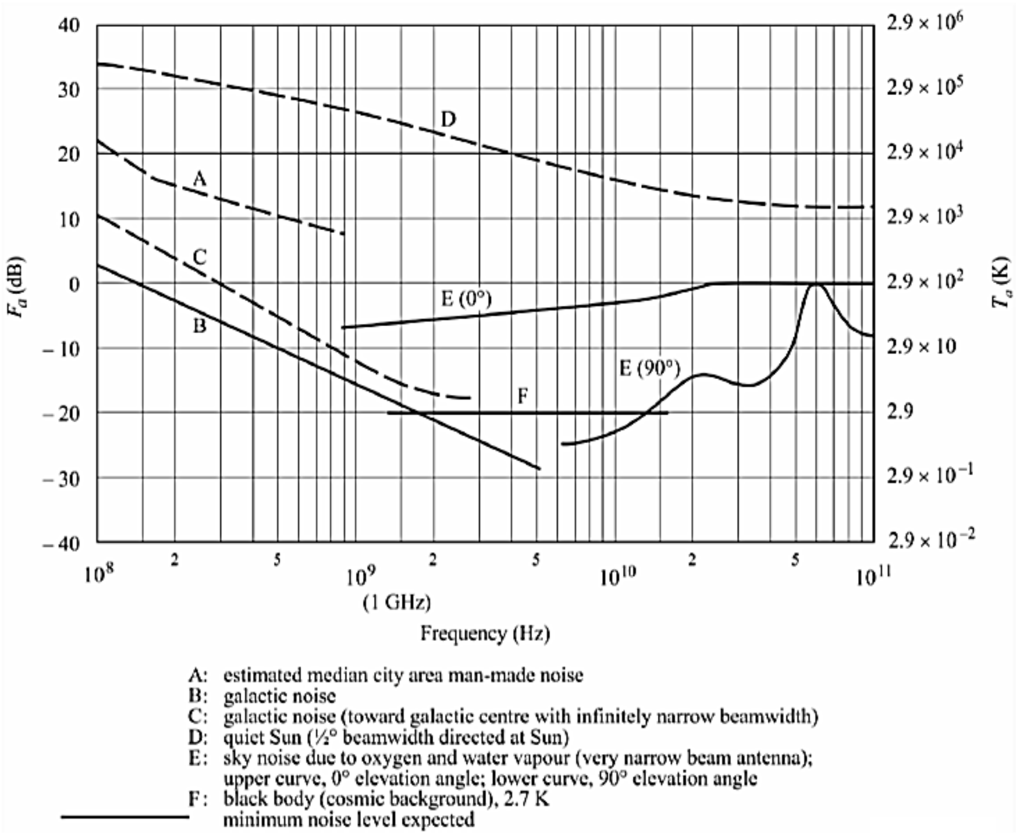

Figure 13 : External noise factor vs frequency (100MHz to 100GHz)

At 900MHz, the main contributors are then:

- Sun: ~25dB.
  Sun is a strong variable noise source depending on sun activity. Large increases occur when the sun is disturbed. The value can be however reduced because the antenna gain in direction to the sun is low for LPWAN applications. Using high gain directive antenna would also help to minimize the sun noise contribution.
- Urban noise (human origin): ~10dB.
  The value may vary depending on the cities.

At 433MHz, the external noise figure is significantly higher compared to 900MHz. The benefits of lower propagation losses at 433MHz (according to free space losses model as detailed in §4.1) are then demolished by the environmental noise.

4 Propagation models

The previous paragraph explained how the propagation channel is affected by obstacles in the "line-of sight", causing the Lfs losses. In this paragraph, some propagation models are detailed to estimate the propagation channel and therefore the (Lp+Lfs) losses. The list is obviously not exhaustive as many propagation models are available in the literature.
Path loss can be expressed as the ratio of power of transmitted signal to the power of the same signal received by the receiver on a given path. It is a function of the propagation distance.

4.1 Free space

The free space propagation model is the simplest path loss model in which there is a direct-path signal between the transmitter and the receiver with no atmosphere attenuation and no obstacles. In this model, assuming an isotropic antenna, the relationship between the transmitted power *Pt* and the received power *Pr* is given by:

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi d)^2}$$

Where:

- *Gt* is the transmitter antenna gain,
- *Gr* is the receiver antenna gain,
- *d* is the distance between the transmitter and receiver, and
- *λ* is the wavelength of the signal.

The path loss, expresses in dB, is therefore:

Lfs= 32.44 + 20 log (f /1 MHz) + 20 log (d / 1 km)

Considering the following "European" use case:

- *f* = 868.1MHz
- UL budget link = 161.5dB (see §2.2).

Then, <u>*d* = 3,268 km!</u>

4.2 Two-way model

The free space model detailed above assumes that there is only one single path from the transmitter to the receiver. It is experienced that the signal reaches the receiver through the multiple paths. The two-way model is intended to capture this phenomenon.
Two-way model, also called as two path models, is a widely used path loss model. The model assumes that the signal reaches the receiver through two paths, one a line-of-sight and the other the path through which the reflected wave is received.

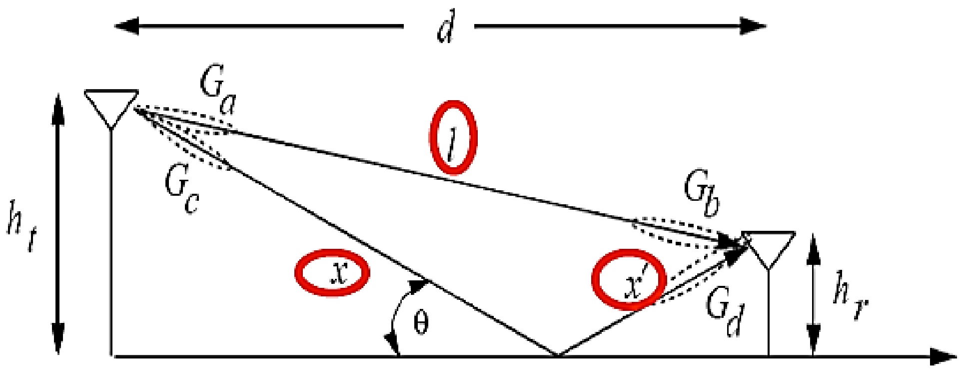

Figure 14 : Two-way model

According to the two-path model, the power which is received is given by:

$$P_r = P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2$$

Where:

- *Pt* is the transmitted power,
- *Gt* represent the antenna gain at the transmitter,
- *Gr* represents the antenna gain at the receiver,
- *d* is the distance between the transmitter and receiver,
- *ht* is the height of the transmitter, and
- *hr* is the height of the receiver.

It can be noticed that the two-way model is independent of the wavelength and therefore of the frequency.

The path loss, expresses in dB, is therefore:

$$Lfs = 40 \log (d) - 20 \log (h_t h_r)$$

Considering the following "European" use case:

- *ht*=1m
- *hr*=30m
- UL budget link = 161.5dB (see §2.2).

Then, *d* = 59.7km

4.3 Log-Distance Path Loss

The log-distance path loss model is derived from the free space path loss but assumes the path loss variations takes place exponentially with distance. The path loss in dB is given by the following equation:

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

Where:

- *n* is the path loss exponent,
- *d* is the distance between the transmitter and receiver,
- d_0 is the close-in reference distance, and
- $PL(d_0)$ is calculated using the free space path loss equation as detailed in§4.1.
  The value d_0 should be considered such that it is in the far-field of the transmitting antenna.

The path loss exponent value n varies according to the environment. In free space environment, *n* is equal to 2. In practice, the value of *n* is calculated using empirical data:

Environments	Path Loss Exponent, *n*
Free space	2
Urban area	2.7 to 3.5
Shadowed urban area	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Although using empirical data, the log-distance path loss model has the advantage to predict indoor coverage, which was not the case for previous propagation models.

4.4 Okumura and Hata models

Okumura model is one of the most widely used models for signal prediction in urban areas. This model is applicable for frequencies in the range 150MHz to 2000MHz and distances of 1km to 100 km. It can be used for gateway antenna ranging from 30m to 1,000m.
Okumura developed a set of curves giving the median attenuation relative to free space (A_{mu}) in an urban area over a quasi-smooth terrain with a gateway effect antenna height (h_{te}) of 200m and the height of end-device antenna (h_{re}) of 3m.
To determine path loss using Okumura's model, the free space path loss between the points of interest is first determined, and then the value of $A_{mu}(f,d)$ is added to it along with correlation factors to account for the type of terrain. The model can be expressed as:

$$L_{50}\,(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

Where:

- L_{50} = 50th percentile value of propagation path loss,
- L_F = free space propagation loss,
- $A_{mu}(f,d)$ = median attenuation relative to free space,
- $G(h_{te})$ = transmit antenna height gain factor,
- $G(h_{re})$ = receiver antenna height gain factor, and
- G_{AREA}=gain due to the type of environment.

The antenna height correction factors are determined as follows:

$$G(h_{te}) = 20\log_{10}(h_{te}/200), \quad 30\text{ m} < h_{te} < 1000\text{ m}$$
$$G(h_{re}) = 10\log_{10}(h_{re}/3), \quad h_{re} < 3\text{m}$$
$$G(h_{re}) = 20\log_{10}(h_{re}/3), \quad 3\text{ m} < h_{re} < 10\text{ m}$$

The correction factor G_{AREA} for different types of terrain is determined as follows:

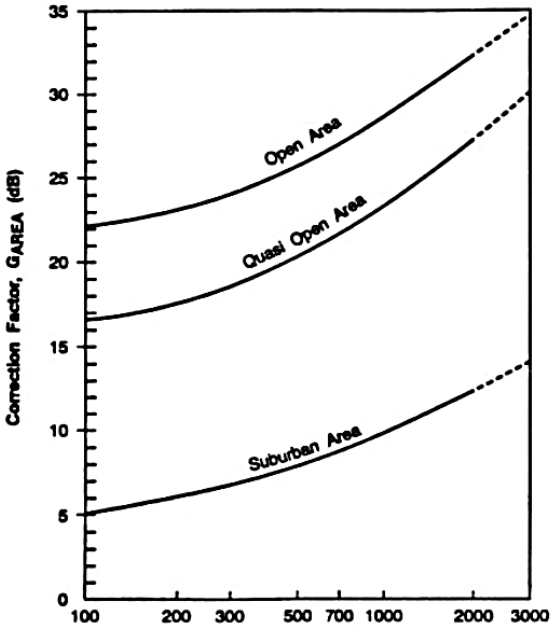

Figure 15 : Correction factor G_{AREA} vs different types of terrain

Hata Model is a popular easy to use model, also known as **Okumura-Hata**. It is an empirical formulation of graphical path loss data provided by Okumura and is valid from 150MHz-1500MHz. Hata's formulation is limited to certain ranges of input parameters and is applicable only over quasi-smooth terrain. The mathematical expression and their ranges of applicability are as follows:

$$L_{50}(urban) = 69.55 + 26.16\log_{10} f_c - 13.82\log_{10} h_{te} - a(h_{re}) + (44.9 - 6.55\log_{10} h_{te})\log_{10} d$$

Where:

- Carrier frequency: $150\text{MHz} \le f_c \le 1500\text{MHz}$,
- Gateway antenna height (h_{te}): $30\text{m} \le h_{te} \le 200\text{m}$,
- End-device antenna height (h_{re}): $1\text{m} \le h_{re} \le 10\text{m}$, and
- Transmission distance (d):$1\text{km} \le d \le 20\text{km}$.

For small to medium city size:

$$a(h_{re})=(1.1\log_{10}f_c-0{,}7)h_{re}-(1.56\log_{10}f_c-0.8)$$

For large city size:

$$a(h_{re})=8.29(\log_{10}1.54h_{re})^2-1.1, \qquad f_c<300\ \text{MHz}$$
$$a(h_{re})=3.2(\log_{10}11.75h_{re})^2-4.97, \qquad f_c>300\ \text{MHz}$$

For suburban area, the original expression is modified as:

$$L_{50}(suburban)=L_{50}(urban)-2\left[\log(f_c/28)\right]^2-5.4$$

For open or rural environments (pastures, farms, etc.), the original expression is modified as:

$$L_{50}\ (rural) \quad =L_{50}(urban)-4.78\left[\log(f_c)\right]^2+18.33\log_{10}(f_c)-40.94$$

The Okumura-Hata model is quite good in urban and suburban environments, but not as good in rural areas, because it does not consider neither terrain relief, nor the effects derived from the degree of urbanization along the propagation path.

The figures below show the Received Signal Strength Indication (RSSI) of the signal (dBm) vs. the distance to the end point (meters) vs. the type of area (urban, suburban, countryside, desert). The height of the gateway antenna (h_{re}) is 30 meters. The frequency is 868MHz in this case but performance and conclusions at 915MHz would be almost identical. The RSSI is the received signal by the gateway. The end point EIRP is assumed to be 25mW. The height (h_{te})of the end point is 1m.

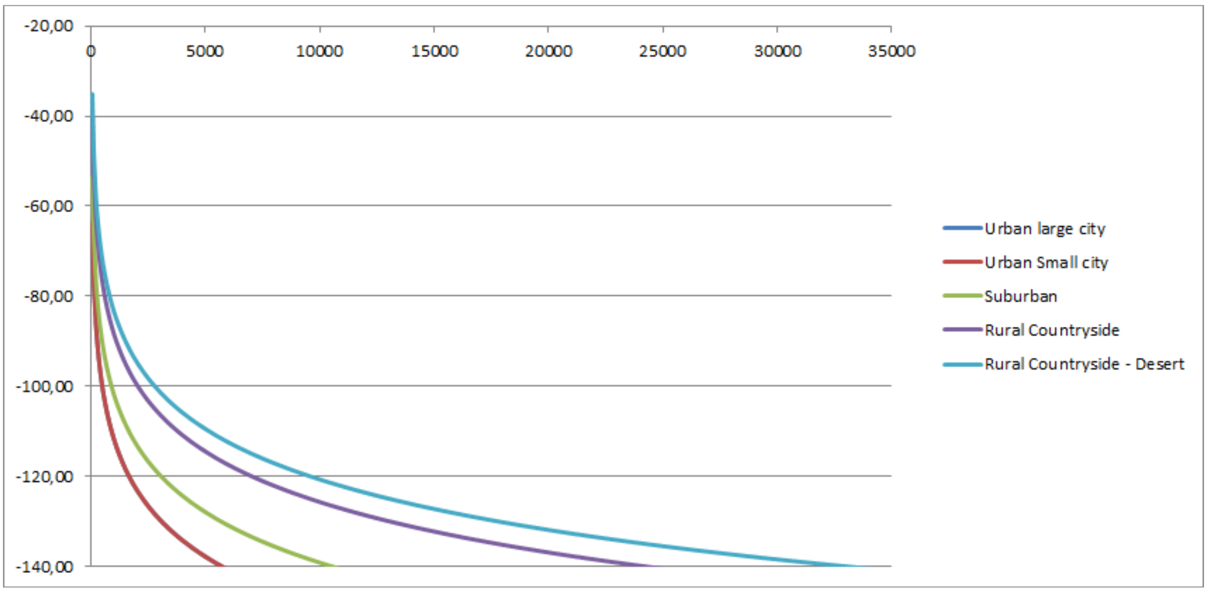

Figure 16 : Hata propagation model vs area configuration (Height = 30m) – RSSI (dBm) vs distance (m)

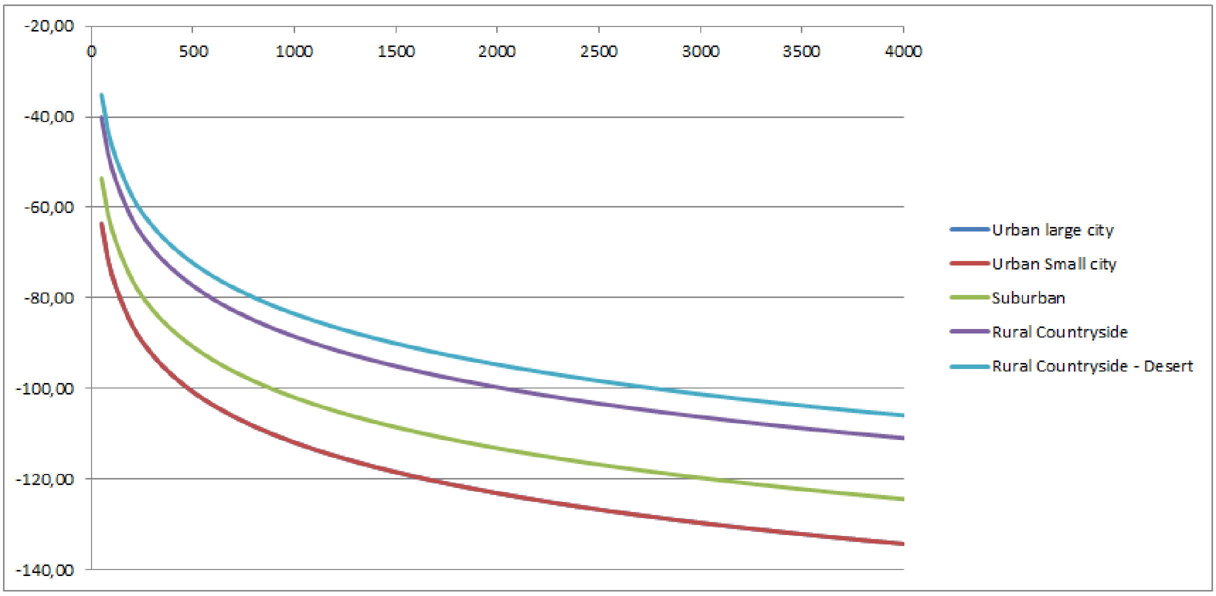

Figure 17 : Hata propagation model vs area configuration (Height = 30m) – RSSI (dBm) vs distance (m)- detail in the 4km range

The coverage radius of the gateway, depending on the area type can vary from 3km (urban areas), up to 30km (countryside).

4.5 ITU-R P radio wave propagation predictions

Radiocommunication sector of ITU has published for many years several recommendations, regarding the radio wave propagation, known as "P series". Some of these recommendations are listed in the §7 for information.

A "Guide to the application of the propagation methods of Radiocommunication" (Recommendation ITU-R P.1144) is available to help users to find the most appropriate methods for particular applications.

For LoRaWAN® propagation predictions, the more adequate recommendations are the followings:

Method	Title	Application	Type	Frequency	Distance
ITU-R P.530	Propagation data and prediction methods required for the design of terrestrial line-of-sight systems	Line-of-sight fixed links	Point-to-point line-of-sight	150MHz to 100GHz	Up to 200 km if line-of-sight
ITU-R P.1238	Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz	Mobile RLAN	In-building propagation methods	300MHz to 450GHz	Within buildings
ITU-R P.1411	Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz	Mobile	Short-path propagation methods	300MHz to 100GHz	< 1 km
ITU-R P.1546	Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz	Terrestrial services	Point-to-area	30MHz to 4GHz	1 to 1000 km

For outdoor propagation predictions, recommendation ITU-R P.1546 can be used. It is initially intended for use on tropospheric radiocommunications over land paths, sea paths and/or mixed land-sea paths up but calculation procedure also includes empirical corrections to the results obtained from this interpolation/extrapolation to account for terrain clearance and terminal clutter obstructions. ITU-R P.1546 produces similar results to the Okumura-Hata method for distances up to 10km. It will not be detailed further in this document.

For indoor propagation predictions, recommendation ITU-R P.1238 can be used.
The basic model, expresses in dB, has the following form:

$$L_{total} = L(d_o) + N \log_{10} \frac{d}{d_o} + L_f(n)$$

Where:

- N = distance power loss coefficient,
- f = frequency (MHz),
- d = separation distance (m) between the gateway and end-device (where d > 1m),
- d_0 = reference distance (m),
- $L(d_0)$ = basic transmission loss at d_0 (dB), for a reference distance d_0 at 1 m, and assuming free-space propagation $L(d_0)$ = 20 log10(f) −28 where f is in MHz,
- L_f = floor penetration loss factor (dB), and
- n = number of floors between the gateway and end-device (n > 0), L_f = 0 dB for n = 0.

Power loss coefficient N, for indoor coefficient can be estimated as follows:

Frequency (GHz)	Residential	Office	Commercial	Factory	Corridor
0.8	-	22.5 (open office)	-	-	-
0.9	-	33	20	-	-
1.25	-	32	22	-	-
1.9	28	30	22	-	-
2.1	-	25.4 (computer room)	20	21.1	17 (LoS)
2.2	-	20.7 (open office)	-	-	-
2.4	28	30	-	-	-
2.625	-	44 (ceiling)	-	33 (semi shielded)	-
3.5	-	27	-	-	-
4	-	28	22	-	-
4.7	-	19.8 (open office)	-	-	-
5.2	30 (apartment) 28 (house)	31	-	-	-
5.8	-	24	-	-	-

The floor penetration loss factors, L_f (dB) with n being the number of floors penetrated, for indoor transmission loss calculation (n > 1) can be estimated as follows:

Frequency (GHz)	Residential	Office	Commercial
0.9	-	9 (1 floor) 19 (2 floors) 24 (3 floors)	-
1.8-2	4 n	15 + 4 (n – 1)	6 + 3 (n – 1)
2.4	10 (apartment) 5 (house)	14	-
3.5	-	18 (1 floor) 26 (2 floors)	-
5.2	13 (apartment) 7 (house)	16 (1 floor)	-
5.8	-	22 (1 floor) 28 (2 floors)	-

It should be noted that there may be a limit on the isolation expected through multiple floors. The signal may find other external paths to complete the link with less total loss than that due to the penetration loss through many floors.

The indoor shadow fading statistics are log-normal and standard deviation values (dB) are given in the following table:

Frequency (GHz)	Residential	Office	Commercial	Factory	Corridor
0.9	-	3.4 (open space)	-	-	-
1.8-2	8	10	10	-	
2.4	-	2.3 (open space)	-	-	-
3.5	-	8	-	-	-
4.7	-	2.7 (open space)	-	-	-
5.2	-	12	-	-	-
5.8	-	17	-	-	-

Although available measurements have been made under various conditions which make direct comparisons difficult and only select frequency bands have been reported upon, a few general conclusions can be drawn, especially for the 900-2000MHz band.

- Paths with a line-of-sight (LoS) component are dominated by free-space loss and have a distance power loss coefficient (N) of ~20.
- Large open rooms also have a distance power loss coefficient (N) of ~20; this may be due to a strong LoS component to most areas of the room. Examples include rooms located in large retail stores, sports arenas, open-plan factories, and open-plan offices.
- Corridors exhibit basic transmission loss less than that of free space, with a typical distance power coefficient (N) of ~18. Grocery stores with their long, linear aisles exhibit the corridor loss characteristic.
- Propagation around obstacles and through walls adds considerably to the loss which can increase the power distance coefficient (N) to ~40 for a typical environment. Examples include paths between rooms in closed-plan office buildings.
- For long unobstructed paths, the first Fresnel zone breakpoint may occur. At this distance, the distance power loss coefficient (N) may change from ~20 to ~40.

- The decrease in the basic transmission loss coefficient (N) with increasing frequency for an office environment is not always observed or easily explained. On the one hand, with increasing frequency, loss through obstacles (e.g., walls, furniture) increases, and diffracted signals contribute less to the received power; on the other hand, the Fresnel zone is less obstructed at higher frequencies, leading to lower loss. The actual basic transmission loss is dependent on these opposing mechanisms.

4.6 3D Ray-tracing models

The empirical and theoretical models presented above, cannot accurately predict the radio propagation channel in urban environments as the scatterers determine the radio propagation. Ray tracing models consider all the scatterers to compute the dominant paths through which the radio energy propagates. Computer programs are used for ray tracing, taking 3D database (LIDAR for instance), frequency and transmitter and receiver antennas characteristics as inputs to compute the channel parameters. Ray tracing models become computationally intensive if there are large number of objects in the environment or a higher order of ray interaction is considered. Immense computational resources including higher CPU time and larger computing memory are required to model such scenarios. The ray tracing models are approximate methods and have inherently limited accuracy. However, it is quite accurate at UHF frequencies for network planning, when computing a higher order of rays.
Recent years have seen a tremendous increase in the use of ray tracing for radio networks planning and this trend seems set to continue in future. Being a high-frequency phenomenon makes ray tracing tool a better candidate for channel modeling. The accuracy of the 3D buildings database and terrain properties is critical for prediction accuracy.
In the future, technologies such as big data and machine learning will be embedded into ray tracing tools for intelligent and accurate channel predictions.

5 Examples of radio coverage planning tools

5.1 Okumura-Hata Excel spreadsheet

Okumura-Hata Model is an easy-to-use model, providing quite good predictions in urban and suburban environments, but not as good in rural areas. The main weakness is the fact that it does not consider neither terrain relief nor the effects derived from the degree of urbanization along the propagation path.
Predictions can be provided by using a simple Excel spreadsheet including the formulas detailed in §4.4. The different terrain configuration shall be then considered i.e., urban large city, urban small city, suburban and rural areas.

An example is presented below. The spreadsheet is presented as a budget link and space attenuation is calculated according to §2.1. Then the distance of coverage is estimated according to Okumura-Hata formulas:

	Hata		Urban large city	Urban Small city	Suburban	Rural Countryside
Pout end-device (conducted)	14	dBm				
Antenna Gain End-device	0	dB				
Cable losses end-device (between transmitter and antenna)	0	dB				
EIRP (dBm)	14	dBm				
Height of end-device	2	m				
Frequency	868,3	MHz				
Antenna Gain gateway	6,00	dBi				
Cable losses gateway (between antenna and receiver)	0,50	dB				
Height of the gateway	30	m				
Received level at gateway input	-140,00	dBm				
Additional losses (ground penetration, ...)	20,00	dB				
Space attenuation	139,50	dB				
Distance		m	2586	2626	4999	12085

Figure 18 : Example of Okumura-Hata prediction: distance vs. RSSI

An alternate option is to estimate the RSSI of the received signal at the gateway RF input port at a defined distance:

	Hata		Urban large city	Urban Small city	Suburban	Rural Countryside
Pout end-device (conducted)	14	dBm				
Antenna Gain End-device	0	dB				
Cable losses end-device (between transmitter and antenna)	0	dB				
EIRP (dBm)	14	dBm				
Height of end-device	2	m				
Frequency	868,3	MHz				
Distance	2000	m				
Space attenuation		dB	135,57	135,33	125,49	111,98
Additional losses (ground penetration, ...)	20,00	dB				
Antenna Gain gateway	6,00	dBi				
Cable losses gateway (between antenna and receiver)	0,50	dB				
Height of the gateway	30	m				
Received level at gateway input		dBm	-136,07	-135,83	-125,99	-112,48

Figure 19 : Example of Okumura-Hata prediction: RSSI vs. distance

It can be noted that additional losses are considered in the spreadsheet (20dB in the example). This is intended to take into consideration fading margin, penetration losses or any additional losses.
This spreadsheet can be used for rough estimation of coverage. Due to the limitation of the Okumura-Hata model, it is not recommended to use it for large scale deployments. More sophisticated planning tools shall be considered for this purpose.

5.2 Xirio

XIRIO is an example of quick and low-cost professional online simulation tool for wireless networks. Radio coverage can be done anywhere in the world using a high-resolution mapping. A profile of a radio study is defined including the main following parameters:

- The position of the transmitter on the high-resolution map,
- Characteristics of the transmitter: output power, feeder losses, antenna gain, elevation of the antenna, frequency, etc.
- Characteristics of the receiver: reception threshold, feeder losses, antenna gain, antenna height, etc.
- Calculation method: several propagation methods are proposed such as Okumura-Hata or ITU-R Rec (P526, P1411, P1546),
- Cartography layer.

An example is presented below using Okumura-Hata model and 10dB fading margin. The gateway is located on Kerlink building roof top.

Figure 20 : Example of Xirio simulation - Source: https://www.xirio-online.com

XIRIO offers some advantages compared to Okumura-Hata Excel spread sheet:

- Usage of high-resolution mapping, and
- Several propagation models available

It has however a major limitation: no 3D mapping is available.

The simulation tool can be then accurate in flat areas but not accurate in areas with hills relief or buildings for instance. XIRIO could be used it for low scale deployments, when only few gateways are deployed.

More sophisticated planning tools, using 3D mapping, shall be considered for large scale deployments.

5.3 Volcano S_IoT

Volcano S_IoT is a radio planning tool for Low Power Wide Area Networks (LPWA) provided by SIRADEL. S_IoT offers a large set of innovative features to cope with the challenges of LPWA network roll-out. It is available as SaaS with a flexible and scalable access, gives access to a large set of 2D and 3D geodata, worldwide. Moreover, thanks to Volcano, SIRADEL leading 3D-ray tracing propagation prediction tool, S_IoT can accurately estimate LPWAN metrics, such as global coverage, data rates and geolocation accuracy.
SIRADEL is an editor of high-resolution 3D cities with 50,000+ km2 off-the-shelf, and a large capability of production worldwide (existing cities or urban projects) from stereo satellite, aerial or terrestrial images, LiDAR or 3D graphics.
Volcano S_IoT is an ideal tool for massive LoRaWAN® network rollout, allowing the operator to select the best installation sites, to optimize the coverage, to minimize the number of gateways and finally reduce the costs of deployments.

An example of simulation is provided below. This represents the received levels for a LoRaWAN® deployment in Hong-Kong:

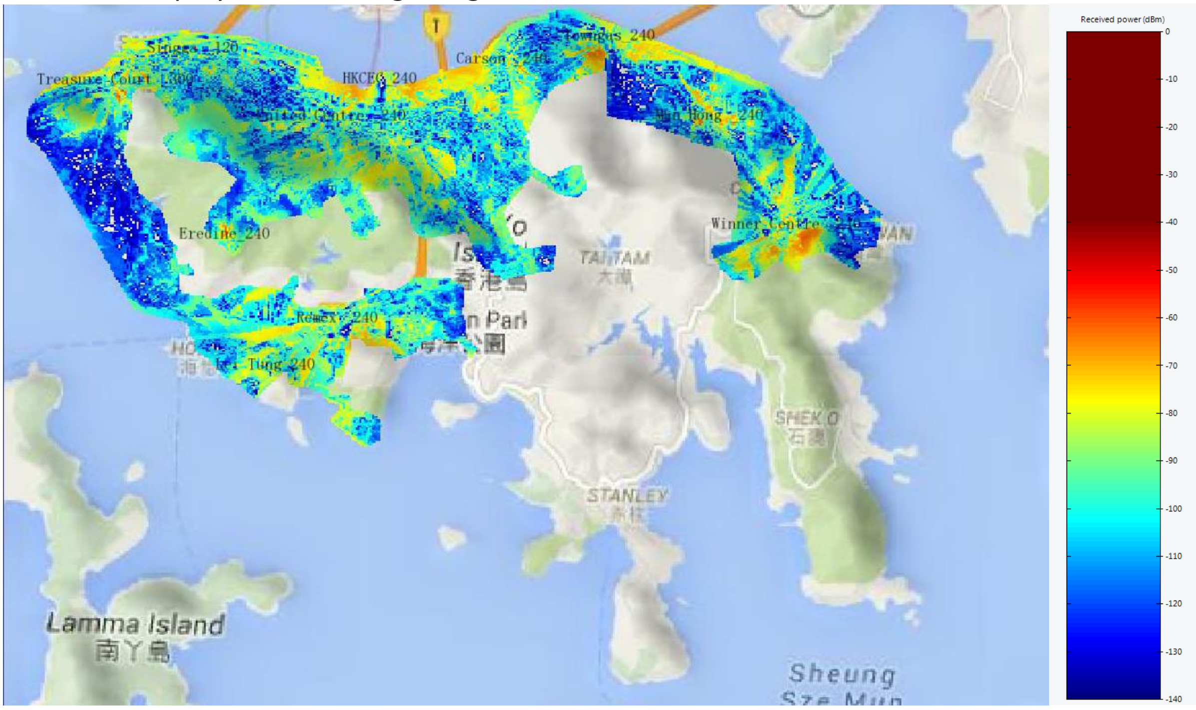

Figure 21 : Example of Volcano simulation for Hong-Kong

More examples and videos can be found on Siradel website.

kerlink
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6 Key parameters to optimize the radio coverage

6.1 Feeder losses

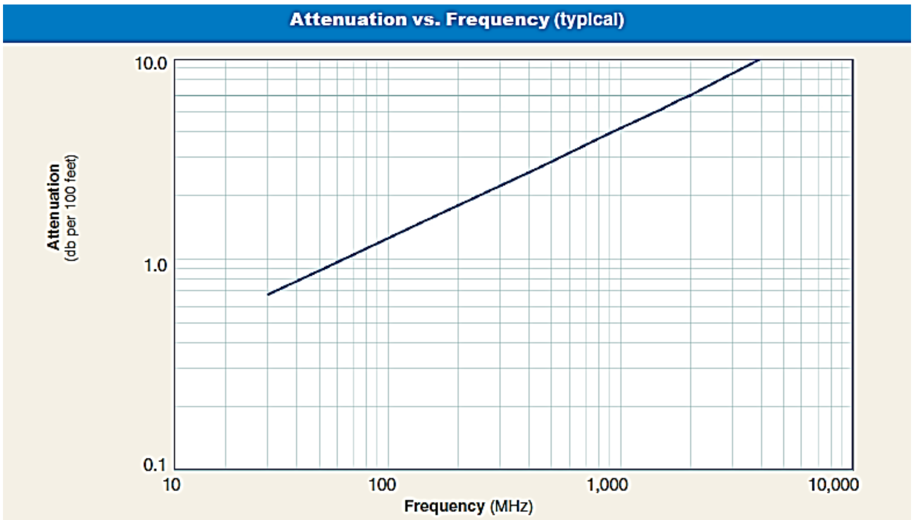
Feeder losses refers to all the losses between the antenna port and the gateway port. It includes:

- Coaxial cables losses,
- Coaxial lightning surge protection losses, and
- Cavity filter losses.

The feeder losses shall be minimized to improve the budget link as detailed in §2.1.
If the feeder losses are not fully under control, the consequences are:

- Degradation of the LoRaWAN® UL budget
- Degradation of the LoRaWAN® DL budget, assuming the gateway would not be able to transmit at the maximum allowed EIRP.

Kerlink outdoor gateways are provided with a 1m length LMR195 coaxial cable equipped with 2 x N male IP68 connectors. The insertion losses are less than 0.5dB at 900MHz.
If longer coaxial cables are required, low insertion losses references shall be used. Kerlink recommend using LMR400 cables in this case. These cables are designed for 20-year service outdoor use and has low insertion losses as shown below:



Frequency (MHz)	30	50	150	220	450	900	1500	1800	2000	2500	5800
Attenuation dB/100 ft	0.7	0.9	1.5	1.9	2.7	3.9	5.1	5.7	6.0	6.8	10.8
Attenuation dB/100 m	2.2	2.9	5.0	6.1	8.9	12.8	16.8	18.6	19.6	22.2	35.5
Avg. Power kW	3.33	2.57	1.47	1.20	0.83	0.58	0.44	0.40	0.37	0.33	0.21

Calculate Attenuation =
$(0.122290) \cdot \sqrt{FMHz} + (0.000260) \cdot FMHz$ (interactive calculator available at http://www.timesmicrowave.com/cable_calculators)
Attenuation:
VSWR=1.0 ; Ambient = +25°C (77°F)
Power:
VSWR=1.0; Ambient = +40°C; Inner Conductor = 100°C (212°F); Sea Level; dry air; atmospheric pressure; no solar loading

Figure 22 : LMR400 coaxial cable - attenuation vs. frequency

The insertion losses of coaxial lightning surge are usually less than 0.3dB at 900MHz.

A major contributor for the feeder losses is the cavity filter. Depending on the used unlicensed band and country specificities, the cavity filters insertion losses could vary from 0.5dB to 4.0dB! It is obvious that a 4dB insertion losses cavity filter could have a huge impact on the coverage area. It is however possible to mitigate the impact of the cavity filter insertion losses by using an appropriate antenna. The choice of the antenna and the feeder losses are therefore a tradeoff that shall be considered before the installation of the gateway (see §6.2).

6.2 Gateway antenna gain

According to the budget link calculations, as shown in §2, there is a direct benefit when using high antenna gain. A 3dB gain increase would cause a 3dB improvement in the budget link and increase somewhat the coverage. In reality, observed benefits are not always so obvious.

When considering the LoRaWAN® DL budget, we need to ensure the gateway can transmit at the maximum allowed EIRP, according to the local regulation. The antenna gain shall be therefore adjusted depending on:

- The gateway maximum conducted power,
- The feeder losses including coaxial cable, lightning surge insertion losses and cavity filter losses (see §6.1), and
- The maximum allowed EIRP, according to the local regulation.

The following antenna gain are then recommended for different use cases:

Gateway max conducted power	Max EIRP (local regulation)	Feeder losses	Recommended antenna gain
≤27dBm	≤30dBm	≤1dB	3dBi (6dBi)
≤27dBm	≤30dBm	≥3dB	6dBi
≤27dBm	≥36dBm	≤1dB	9dBi
≤27dBm	≥36dBm	≥3 dB	12dBi
≤30dBm	≤30dBm	≤1dB	3dBi (6dBi)
≤30dBm	≤30dBm	≥3dB	6dBi
≤30dBm	≥36dBm	≤1dB	6dBi
≤30dBm	≥36dBm	≥3 dB	9dBi

When considering the LoRaWAN® UL budget, increasing the antenna gain would not systematically improve the coverage. In ideal conditions it would … but not necessarily in real conditions. The main reason for that is the environmental noise (see §6.5).
Because the gateway is installed in a “noisy” environment, the antenna amplifies not only the useful signal (LoRaWAN®) but also the noise in the receive band. Increasing the antenna gain would then result in increasing the environmental noise with no benefit on the signal to noise ratio. A high gain antenna is however less susceptible to noise compared to a low gain antenna. This is due to the antenna pattern. High gain antennas are more directive in the elevation plan as shown in Figure 23. Their gain in all direction is then limited and therefore they capture less noise.
The figure below shows the antenna patterns of 3dBi, 6dBi and 9dBi antennas from FT-RF (OA-868M03-NF, OA-868M03-NF and OA-868M09-NF respectively).

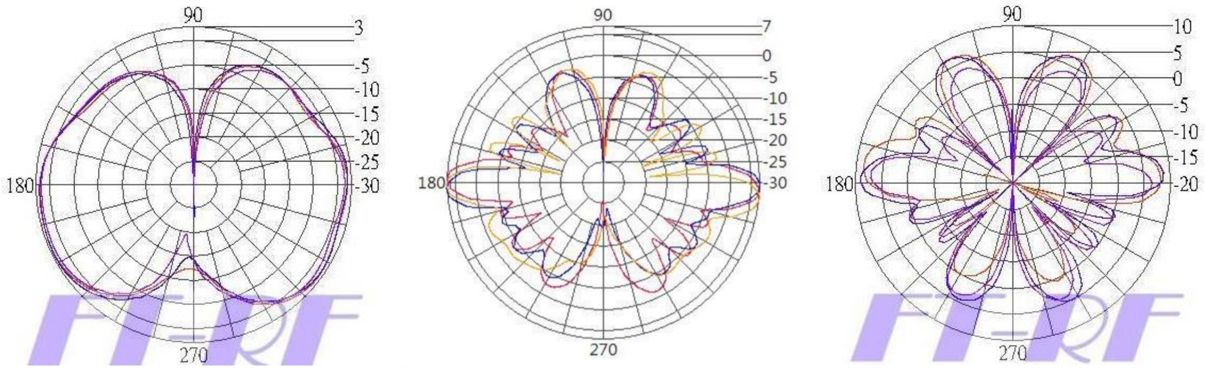


Figure 23 : FT-RF 3dBi, 6dBi and 9dBi omnidirectional antenna patterns

Consequently, using 9dBi or 12dBi antenna to improve UL budget would be a bad invest. High antenna gain are real benefits only to improve DL budget to meet the maximum allowed EIRP, as demonstrated before.

Also, when choosing the antenna, the following criteria shall be considered:

- <u>Size, weight and easy installation:</u>
  A 3dBi antenna is about 0.3m length and 0.3Kg weight.
  A 12dBi antenna is about 3m length and 2Kg weight.
  Installation constraints are obviously very different considering the two antennas.
- <u>Cost:</u>
  A 3dBi antenna is a low-cost antenna (< 50 euros).
  A 12dBi antenna cost could reach up to 200 euros.
  Sometimes the rental cost of the installation site is linked to the size of the gateway and therefore the size of the antenna. Increasing the size of the antenna would have a huge impact on operational costs.
- <u>Location of the end-devices:</u>
  Increasing the antenna gain helps to increase the coverage area, so the gateway can receive end-devices located at long distances (see §6.3). However, the gain in maximized in the horizon plan but gain at 220° elevation could be very low. A 3dBi gain antenna may have a higher gain at 220° elevation compared to a 9dBi gain antenna as shown in Figure 23. About 10 to 20dB gain difference could be obtained for specific directions or angles. This means, for example, that a gateway would not be able to receive water meters in a 1m depth pit, just below the tower, with a 9dBi gain antenna whereas it could be possible with a 3dBi antenna gain. At the same time, the gateway with 9dBi gain antenna would be able to receive water meters at 10km distance whereas it would be impossible with the 3dBi gain antenna.

Kerlink Indoor gateways (Wirnet™ iFemtoCell and Wirnet™ iFemtoCell-evolution) are provided with a 3dBi swivel dipole antenna. For indoor usage, it is recommended to keep this antenna as is. Using a higher gain antenna would not provide any benefits due to:

- **Antenna pattern**: gain is expected to be as omnidirectional as possible for indoor antenna, in azimuth plan but also in elevation plan, because end-devices are located in all directions (same floor, upstairs floors, downstairs floors)
- **Environmental noise**, as detailed in §6.5.

6.3 Height of the gateway

A key factor to have an optimized outdoor LoRaWAN® gateway reception is the height of installation site and moreover the height of the LoRa® antenna. The gateway shall be installed as high as possible to have the better reception and wider coverage area.
When increasing the height of the gateway, the number of obstacles in the Fresnel zone are limited and therefore the propagation channel is likely a free-space path.

Considering the Okumura-Hata propagation model, the benefits of the height are obvious. The figure below shows the RSSI of the signal (dBm) vs. the distance to the end point (meters) for different heights of the gateway (15m, 30m, 50m and 100m). Two uses cases are presented: one for a small city configuration (urban area) and one for suburban area.

- The frequency is 868MHz in this case but performance and conclusions at 915MHz would be almost identical.
- The RSSI is the received signal by the gateway.
- The end point EIRP is assumed to be 25mW.
- The height of the end point is 1m.

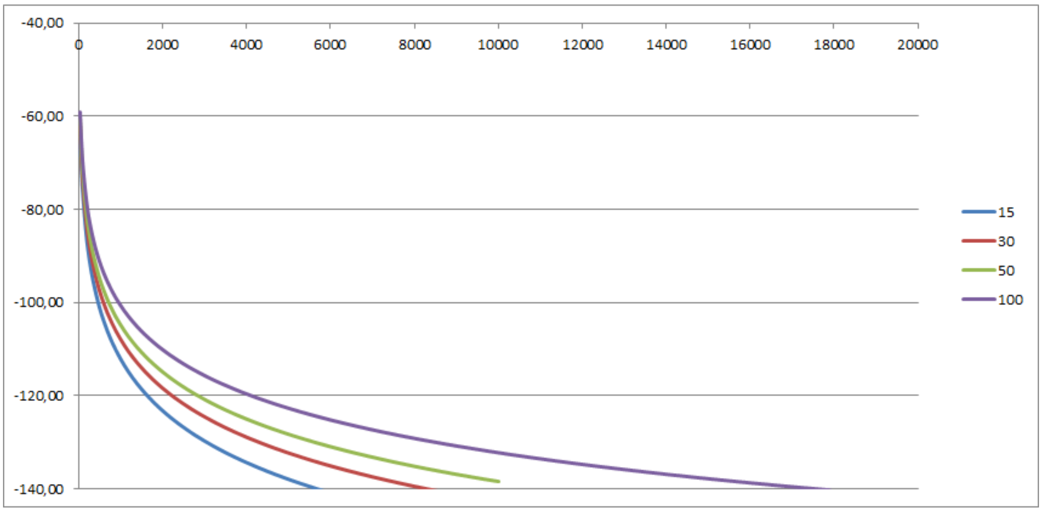


Figure 24 : Urban (small city) Hata propagation model – RSSI (dBm) vs distance (meters) vs height of the antenna

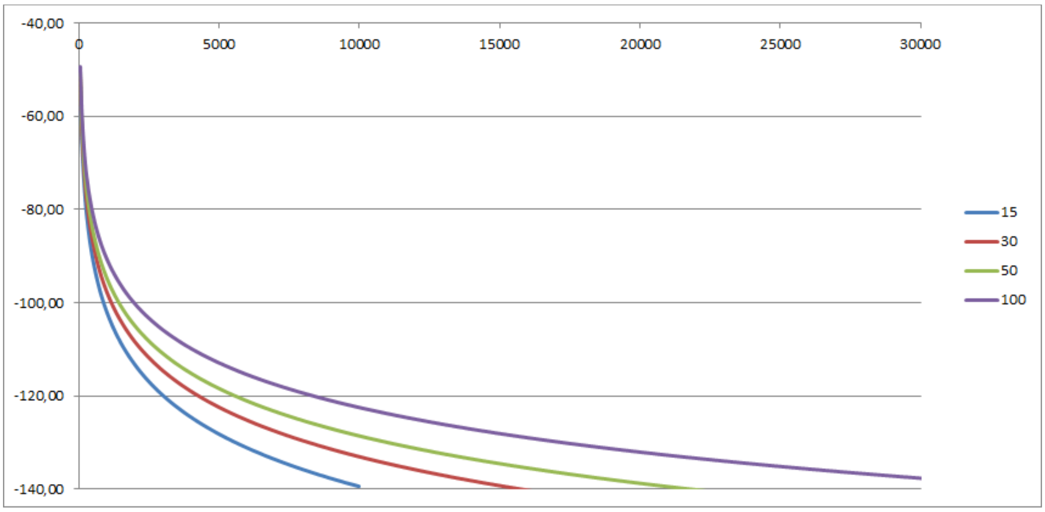


Figure 25 : Suburban Hata propagation model - RSSI (dBm) vs distance (meters) vs height of the antenna

What is noticeable is that the coverage distance at a fixed RSSI is:

- multiplied by 2 from 15m height to 50m height
- multiplied by 3 from 15m height to 100m height

Up to 30km coverage can be obtained when using towers of 100m height or plus. This was demonstrated for instance in Germany, where Digimondo used telecom towers to install their Kerlink gateways with only a 3dBi antenna.

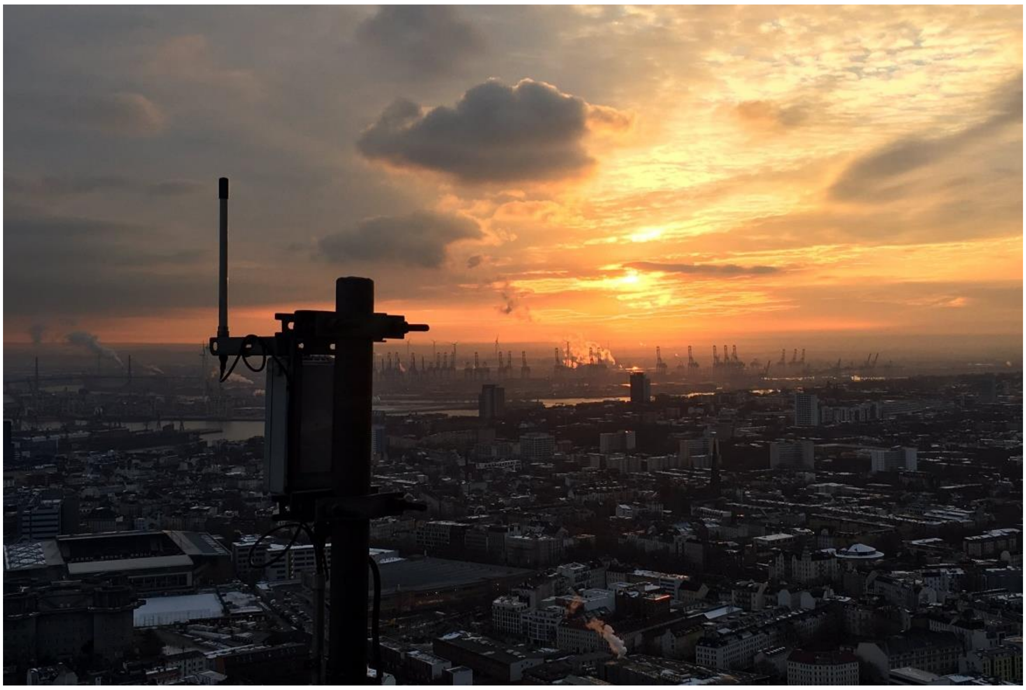


Figure 26 : Installation of Kerlink gateway in Hamburg

Some specific recommendations can be also applied depending on the area type:

- **Urban areas:** the roof top of highest building, or highest tower, in the area can be used to host the gateway. This site is likely already occupied by other transmitters so potential radio coexistence issues shall be considered (see §6.4).
- **Rural areas:** the highest tower in the area can be used to host the gateway. This site is likely already occupied by other transmitters so potential radio coexistence issues shall be considered (see §6.4).
- **Mountainous areas:** the highest mountain or hill in the area can be used to host the gateway. This site is likely already occupied by other transmitters, so potential radio coexistence issues shall be considered (see §6.4).
- **Woodland areas:** when deploying gateways in a woodland, it is recommended to identify a high point above the vegetation. This is because the attenuation is huge (0.2dB/m) in the vegetation as shown in §0. The distance of propagation in the vegetation shall be then minimized.

6.4 Colocalization of the gateway with other radio transmitters

As shown in the previous paragraph, height is a critical parameter for the radio coverage. In a defined area, the number of available sites, offering the best coverage, is obviously limited. These sites are, in most of the uses cases, already used by other radio systems such as cellular base stations (GSM/UMTS/LTE) or TV emitters for instance. In many use cases, the LoRaWAN® gateways are therefore colocalized with those emitters and special care shall be taken for the installation to avoid any interferences More generally, when deploying LoRaWAN® gateways, especially in urban areas, it is necessary to consider all the radio systems in the near environment.

These transmitters, colocalized with the LoRaWAN® gateways could cause desensitization of the gateways in different manners:

- Out of band blocking,
- In band blocking,
- Third order intermodulation, or
- Generation of out of band noise (spurious).

Desensitization could be avoided in different manners:

- RF filters by design - embedded in the gateway,
- External cavity filters, for specific harsh environments, and
- Installation recommendations to minimize interferences.

For more information, see [26].

6.5 Environmental noise

As detailed in §3.4, the gateway antenna receives radio noise emanating from external sources i.e., galactic noise (mainly sun) and human-made noise. The human-made noise is mainly due to machinery, electrical and electronic equipment's and networks. This noise has a tremendous impact on the budget link, especially in urban areas and obviously in indoor areas.
The additional noise can be assimilated to an equivalent noise figure to estimate the noise at the receiver input.

At 900MHz, the equivalent noise figure can be estimated as follows:

Area type	Equivalent noise figure (dB)
Dense Urban	8 to 15
Suburban	3 to 5
Rural	0.5
Indoor	20 to 30

The equivalent noise figure affects both UL and DL budgets i.e., both gateway and end-device.
The placement of the gateway and the end-device shall be chosen, as far as possible, in areas where the equivalent noise is limited to minimum values.
Increasing the height of the gateway helps reducing the human-made noise.
End-devices shall be placed as far as possible to other electric or electronic devices.

Environmental noise can be estimated using:
- A spectrum analyzer,
- The gateway “spectrum scan” functionality.

6.6 Indoor gateways

The placement of an indoor gateway shall take into consideration the following aspects:
- Type of building (residential, office, commercial, factory)
- Number of floors to be covered
- Materials used in the building

The placement shall be chosen to cover a maximum of floors when minimizing the losses, which is often contradictory.

ITU-R P.1238 recommendation, as detailed in §4.5, can be used to estimate the propagation losses in the different indoor areas and floor penetration losses.
Floor and walls penetration losses are further detailed in §3.3.1, depending on the materials used in the building. All the associated losses shall be taken into consideration of the budget link to estimate the coverage area.

Placement of the gateway and end-devices should be done considering some basic rules:
- Favor line-of-sight propagation in large open rooms.
- Corridors can be used as they exhibit lower losses.
- Ceiling boards exhibit lower losses compared to floorboards or concrete / brick walls.

6.7 End-device location

6.7.1 Indoor end-devices

When indoor end-devices are expected to be under coverage of outdoor gateways, then it is recommended to place them, when possible:
- On the top floors of the building rather than on bottom floors
- Close to the windows as glass exhibit lower losses compared to concrete walls

When indoor end-devices are expected to be under coverage of indoor gateways, then see §6.6.

6.7.2 Outdoor end-device

For outdoor end-devices, it is recommended to install them as high as possible. The principle is almost the same as for the gateways, although the height cannot be increased that much. When increasing the height of the end-devices, the number of obstacles in the Fresnel zone is limited, especially the ground, and therefore the propagation channel is getting closer to a free-space path. Considering the Okumura-Hata propagation model, the benefits of the end-device height are also obvious.
A height of 1m to 1.5m is usually a good tradeoff considering feasibility and propagation improvement.

6.7.3 Inground end-device

For inground end-devices, such as water meters, the ground penetration losses shall be added in the budget link. Ground penetration losses are detailed in §3.3.2. This corresponds to the "additional losses" as defined in the Okumura-Hata Excel spreadsheet as defined in §5.1.
Regarding water meters, considering the losses detailed in §3.3.2, it is then recommended to:

- Avoid deep depth of pits as attenuation increases with depth
- Avoid / remove water in pits

6.8 End-device antenna performance

Antenna design is always a critical parameter for end-devices. This is because the design of the antenna suffers from contradictory specifications:

- High gain is expected (2dBi ideally),
- Omnidirectional antenna pattern,
- Very small size, and
- Very low cost.

The final result is generally a small size, low-cost antenna but antenna gain and moreover antenna patterns are seriously affected.

A good choice for low cost and small size antenna is to use ceramic loop parts. Ceramic loop antenna should be preferred to monopole antennas as they are less susceptible to the close environment which may cause detuning of the antenna.

For example, we can consider Taoglas ILA.02 ceramic loop antenna. It is a 868MHz, 1.5dBi peak gain, antenna with dimensions of 10x3.2x0.5mm. The ILA.02 antenna performance was measured with a 80x40 mm ground plane and the radiation pattern is the following:

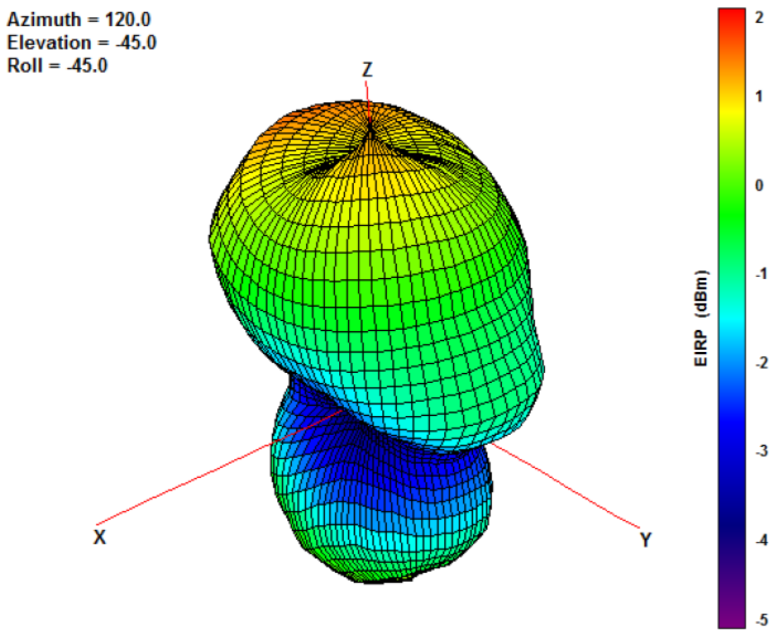


Figure 27 : Radiation Pattern at 868 MHz of the Taoglas ILA.02 antenna

The ILA.02 antenna pattern is obviously not omnidirectional. This means that the antenna gain may vary significantly depending on the direction i.e., depending on the position of the end-device, the gateway would receive different levels of signal. So, end-device antenna may have a huge impact on both UL and DL budgets.

The choice of the end-devices is therefore critical for the coverage distance. Criteria shall be, from less critical to most critical:

- Peak gain,
- Average gain,
- Susceptibility to the environment (detuning), especially for wearable devices, and
- Perfect knowledge of the radiation pattern to understand where the max gain is and how to orientate the end-device to the gateway to favor budget links.

6.9 Additional fading margin

As explained in §3.2.4., multiple radio waves, reflected or diffracted with dephasing, when arriving on the receiver can cause phase cancelling with the straight-line signals reducing the received power (fading).
Radio planning tools using 3D Ray-tracing may provide good estimation of the fading effects, but when using Okumura-Hata model, some extra-losses due to fading shall be added in the budget link. This corresponds to the "additional losses" as defined in the Okumura-Hata Excel spreadsheet as defined in §5.1.
Values from 10dB to 20dB can be used depending on the propagation channel.

7 Conclusion

Predicting the radio coverage area of a LoRaWAN® gateway could be completed using low-cost basic simulation tools based on typical propagation models such as Okumura-Hata. However, only sophisticated 3D Ray-tracing simulation tools provide the accuracy and confidence for large scale deployments.
The installation of the gateway, and the end-devices, shall be completed with a comprehension of the propagation medium i.e. the nature of the obstacles in the Fresnel ellipsoid. Some mistakes can be easily avoided to optimize the coverage area:

- The height of the gateway is a critical parameter,
- The budget link shall be be optimized by limiting feeder losses and using proper antenna gain,
- Interferences with other emitters shall be mitigated with a proper installation and usage of cavity filters (see [26]),
- Human-made noise environment should be characterized,
- Antenna performance of the end-devices matter, and
- Placement and installation of the end-devices shall be optimized.

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About Kerlink® Group

Founded in 2004, Kerlink® is a fast-growing, global and publicly traded provider of Internet of Things (IOT) connectivity solutions helping telecom operators, public authorities and private businesses to design, launch and operate public and private IOT networks. Kerlink® is a founding and Board member of the LoRa Alliance® and of the uCiFi Alliance™.

Based in France, with subsidiaries in the US, Singapore, India and Japan, Kerlink® offers a comprehensive portfolio of industrial-grade premium network equipment, best-of-breed network operations and management software, value-added applications and expert professional services to design, orchestrate and monetize tailored IoT networks.

In just over 10 years, more than 200,000 Kerlink® installations have been rolled out for more than 350 clients in 70 countries, with major deployments in Europe, South Asia, South America and Oceania, for tier-one telecom operators, major transportation companies and large utility players.

Kerlink® crystalizes a strong ecosystem of partners leveraging its connectivity solutions best in-class building blocks not only to design innovative connected device and conceive smart applications but also to unlock the real potential of IoT to improve the lives of people around the world.

Kerlink® is also constantly improving its efficiency, operations control and processes through its Quality Program and has been certified ISO 9001-2015 by AFNOR for its IoT network solutions overall design, development, and sales processes.