WHITE PAPER

LoRaWAN® Gateways: Radio Coexistence Issues and Solutions

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1 INTRODUCTION

When deploying a low-power wide-area network (LPWAN), as any radiocommunications network, the choice of the gateway installation site is critical. An optimized site provides the operator several benefits, such as a better coverage area, a better quality of service, and an optimized number of deployed gateways. This results in a cost reduction for the deployment itself and an improved quality of service during the exploitation of the network.

In any defined area, the number of available sites offering optimal coverage is obviously limited. Site sharing is often favored in urban and suburban areas where there is a shortage of available sites or complex radio planning requirements. These sites are, in most cases, already being used by other radio systems, such as cellular base stations (GSM/UMTS/LTE) or TV emitters.

In many use cases, the LoRaWAN® gateways are therefore colocated with those emitters, and special care must be taken during the installation to avoid any interference. More generally, when deploying LoRaWAN gateways, especially in urban areas, it is necessary to consider all the radio systems in the near environment.

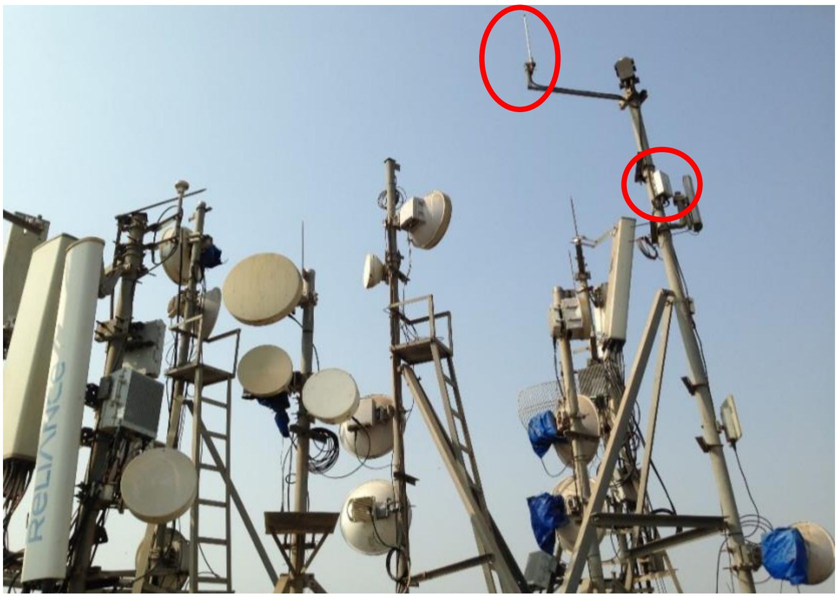

Figure 1: Example of Kerlink Wirnet™ iBTS Compact gateway deployed in Mumbai, India

This white paper details the phenomena which could cause desensitization of LoRaWAN gateways because of the colocated transmitters, such as:

- Out-of-band blocking
- In-band blocking
- Third-order intermodulation
- Generation of out-of-band noise (spurious emissions)

The paper also provides some recommendations to avoid desensitization by using:

- Radio frequency (RF) filters by design – embedded in the gateway
- External cavity filters, for specific harsh environments
- Installation recommendations to minimize interference

2 FUNDAMENTALS OF INTERFERENCE

2.1 RECEIVER DESENSITIZATION BASICS

Going back to radio basics, a radio receiver requires the wanted received signal to have an amplitude that is a minimum number of dB above the noise floor, often expressed in terms of signal-to-noise ratio (SNR).

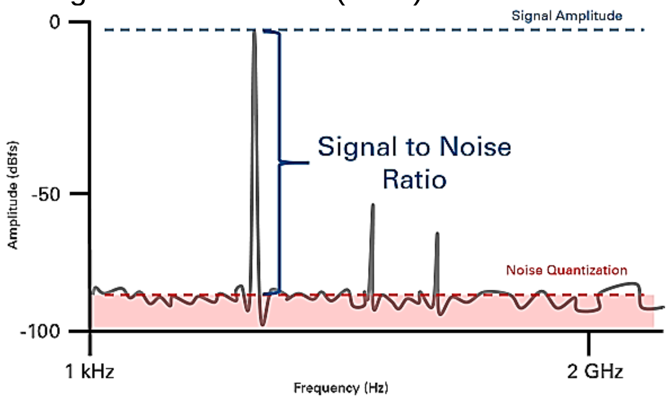

Figure 2: Signal-to-noise ratio (SNR)

Receiver sensitivity and SNR are important points of background information when considering RF interference. Desensitization of a receiver is generally defined as an additive noise phenomenon which degrades the receiver sensitivity or SNR, measured in dB.

A receiver could be desensitized in different ways:

- Out-of-band blockers
- In-band blockers (co-channel, adjacent channels, etc.)
- In-band spurious emissions
- Intermodulation distortion (IMD)

These phenomena are detailed in the following sections.

2.2 OUT-OF-BAND BLOCKERS

Out-of-band blockers provide strong interference outside the useful band, causing saturation of the receiver. The consequence of this saturation is a degradation of the SNR, leading to desensitization. High-power blockers obviously generate more saturation and therefore more desensitization.

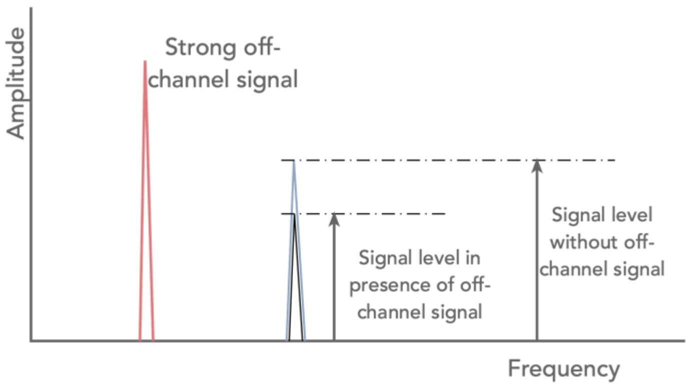

Figure 3: Receiver out-of-band blocking and desensitization

Out-of-band blockers could be eliminated, or reduced, by using high-rejection filters (high-pass, low-pass, or band-pass, depending on the frequency range of the blockers) and high-linearity receivers (low-noise amplifier [LNA], switch). Out-of-band blockers close to the useful band are obviously more difficult to eliminate due to lower rejection of the RF filters.

Examples of out-of-band blockers for LoRaWAN gateways include 2G/3G/4G base stations, TV transmitters, FM or digital audio broadcasting (DAB+) transmitters, radar transmitters, and others.

2.3 IN-BAND BLOCKERS

In-band blockers are generally sources of low-level interference caused by other radio systems operating in the same band. As LoRaWAN operates in unlicensed bands, there are numerous radio systems operating in the band for specific or non-specific uses. Radio frequency identification (RFID) often operates in the same band and is always a source of in-band interference to be considered.

In-band interference can occur on the same operating channel (co-channel), on adjacent channels, or on quite far channels, depending on the available bandwidth. The different interference may use different modulation techniques, such as narrow-band or wide-band, according to the local regulations.

Here is an example of a spectrogram in the 902 – 928MHz band in North America:

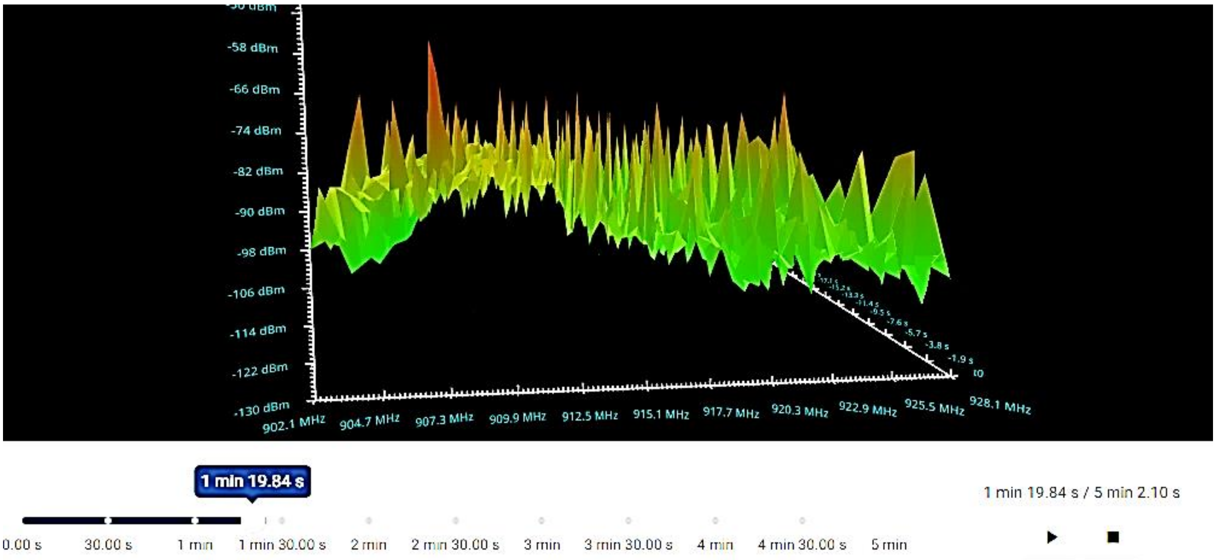

Figure 4: Example of in-band interference in the 902 – 928MHz band

Blocking this interference is achieved by the channel filters integrated in the transceiver and demodulator. Linearity of the receiver is also important, but it has lower impact compared with out-of-band blockers.

The impact on co-channels is obviously worse compared with the impact on adjacent channels and farther-removed channels.

2.4 RECEIVER LINEARITY

Intermodulation distortion (IMD) occurs when several sources of out-of-band or in-band interference generate additional interference within the band due to nonlinearities of the receiver. The IMD can be mitigated by using high-linearity receiver (LNA, switch) and high out-of-band rejection filters.

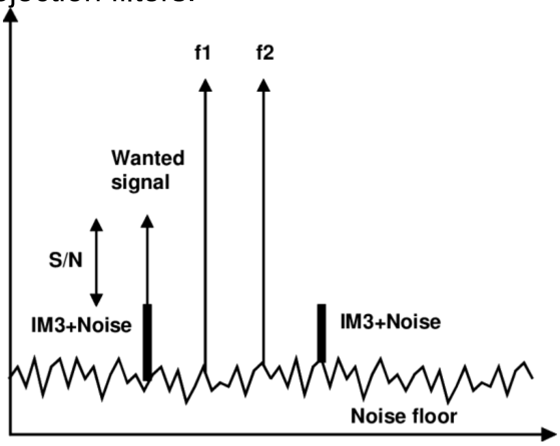

Figure 5: Receiver desensitization due to IMD

The nonlinear elements of the receiver are characterized by their third-order output intercept point (OIP3) (or third-order input intercept point [IIP3]) performance to determine the overall IMD performance of the whole receiver. The IMD level can be determined using the following mathematical formulas:

- $IM3_{right} = P_{f1} - 2x(OIP3 - P_{f2})$
- $IM3_{left} = P_{f2} - 2x(OIP3 - P_{f1})$

Online calculators are also available as detailed in [3].

Note that amplitude-modulated wideband signals such as wideband code division multiple access (WCDMA) and long-term evolution (LTE) would generate intermodulation products when injected into a nonlinear receiver. Constant amplitude-modulated signals such as Gaussian minimum-shift keying (GMSK) do not generate intermodulation products when injected into a nonlinear receiver.

2.5 OUT-OF-BAND SPURIOUS EMISSIONS

Spurious emissions are unexpected radiations in the receive band generated by other transmitters. These transmitters may be other radio systems operating in the same band or in different bands. In this case, there is no way to avoid the desensitization except by moving the receiver far away from the transmitter causing the interference.

The receiver also may be desensitized by spurious emissions generated by other transmitters from the same equipment. This may occur when a device embeds multiple radio systems. In this case, the manufacturer must reduce the level of the spurious emissions to ensure radio coexistence within the device.

The spurious emissions may be of different kinds:

- A continuous wave (CW) generated by a harmonic of an internal clock, for instance
- A modulated signal generated by an external transmitter or a harmonic of an external transmitter
- Noise (white or pink) generated by an external out-of-band high-power transmitter

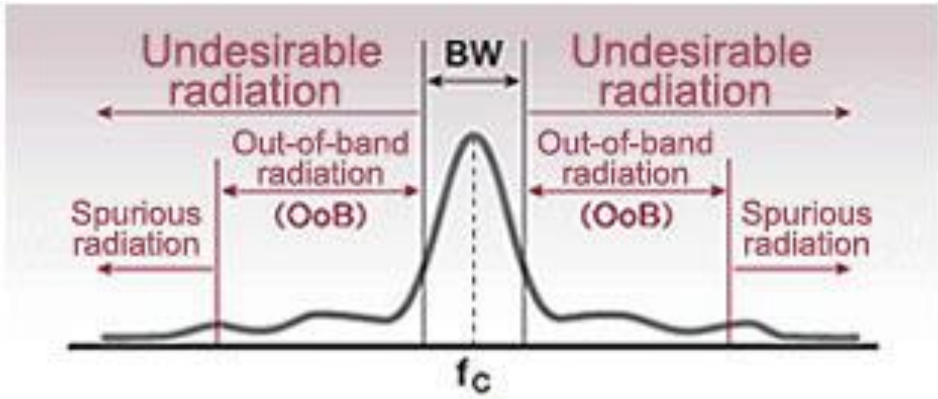

Figure 6: Out-of-band spurious emissions of transmitter

For LoRaWAN gateways, the most critical transmitters regarding out-of-band noise generation are:

- High-power TV transmitters
- Cellular base stations operating in 3rd Generation Partnership Project (3GPP) bands close to the LoRaWAN unlicensed bands

Any radio transmitter must meet out-of-band spurious emission specifications according to the local regulations. The specification depends on the application, the maximum radiated power (equivalent isotropically radiated power [EIRP]), the frequency range, etc. The specifications are intended to provide fair sharing of the spectrum and to avoid mutual interference between the different radio systems. However, when radio systems are colocated or sharing the same installation, the specifications may be not stringent enough. In this case, specific actions must be considered at the installation site.

2.6 TRANSMIT INTERMODULATION

The transmit intermodulation performance is a measure of the capability of the transmitter to inhibit the generation of signals in its nonlinear elements caused by presence of the wanted signal and an interfering signal reaching the transmitter via the antenna. The intermodulation products (IP) are mainly generated by the single pole double throw (SPDT) and power amplifier (PA), as nonlinear components, in the presence of both the transmit (Tx) signal and reverse interfering signal.

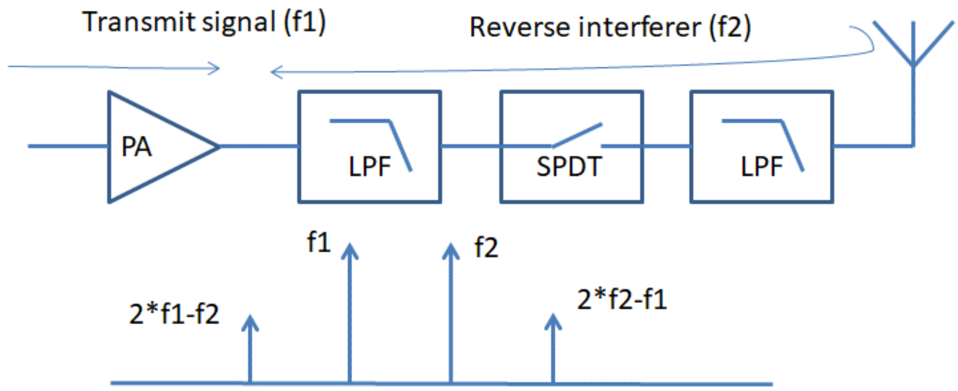

Figure 7: Transmit intermodulation principle. LPF, low pass filter; PA, power amplifier; SPDT, single pole double throw.

The principle of IMD on the transmitter is basically the same as the one described for the receiver in §2.4. The IMD level can be determined using the following mathematical formulas:

- IM3 $_{right}$ = P_{f1}-2x(OIP3-P_{f2})
- IM3 $_{left}$ = P_{f2}-2x(OIP3-P_{f1})

Intermodulation product levels can be estimated based on PA (or SPDT) OIP3, interferer level at PA (or SPDT) output (Pf2), and useful signal level at PA (or SPDT) output (Pf1). Intermodulation product frequencies depend on the f1 and f2 frequencies.

Considering a LPWAN gateway, the consequences of transmit intermodulation could be:

IM3 product falling in the LoRaWAN receive band, causing desensitization of the LoRaWAN gateway. (Note that this is only possible in full-duplex configuration, because in the half-duplex configuration, transmitter and receiver are not active simultaneously.)

- IM3 product falling in the cellular uplink (UL) band, causing desensitization of the colocated cellular base station.
- IM3 product falling in the cellular downlink (DL) band, causing desensitization of the LoRaWAN gateway cellular backhaul.
- IM3 product falling in any receive (Rx) band, causing desensitization of a colocated radio system.

3 COLOCATION WITH GSM/UMTS/LTE TRANSMITTERS

3.1 LoRaWAN COEXISTENCE ISSUES DUE TO CELLULAR NETWORKS

LoRaWAN end-devices and gateways communicate in the unlicensed frequency bands. This is a benefit for the operator or customer, who does not need to apply and pay for a license from the government to transmit on these frequencies.

The most common LoRaWAN frequency bands used worldwide are:

- 433MHz (Europe, Middle East, and Africa [EMEA])
- 863 – 870MHz (EMEA)
- 902 – 915MHz (North America)
- 915 – 928MHz (Latin America [LATAM] and Asia-Pacific [APAC])

However, it is important to note that unlicensed frequencies are country-specific. Although some zones (as described above) share similar frequency bands, some countries may have specific usage. This could relate to the allowed frequencies but also time on air, duty cycle, EIRP, etc.

At the same time, the gateway communicates to the network server via a 3G or 4G backhaul operating in the 3GPP cellular bands. The LoRaWAN gateway may be also colocated with 3G or 4G base stations, sharing the same tower or mast. In the past years, the number of 3G and 4G bands has significantly increased. At the beginning of 2020, the number of LTE bands used worldwide exceeded 70, as detailed in [2]. The bands are mainly spread from 400MHz to 3800MHz.

So, considering the overall picture of LoRaWAN bands and LTE bands, we have then a few LoRaWAN bands among a large number of LTE bands. When scrutinizing the bands, we can see that some LTE bands and LoRaWAN bands are very close to each other. The guard band is sometimes very limited (few MHz) or even reduced to null. Some examples are provided below, for different continents or countries (uplink [UL] and downlink [DL]):

<table>
<tr><th>Zone/Countries</th><th>Unlicensed Bands</th><th>LTE UL Bands</th><th>LTE DL Bands</th></tr>
<tr><td rowspan="4">Europe</td><td>868 – 870MHz</td><td rowspan="2">832 – 862MHz (B20)</td><td rowspan="2">791 – 821MHz (B20)</td></tr>
<tr><td>863 – 873MHz</td></tr>
<tr><td>915 – 918MHz</td><td rowspan="2">880 – 915MHz (B8)</td><td rowspan="2">925 – 960MHz (B8)</td></tr>
<tr><td>915 – 921MHz</td></tr>
<tr><td>North America</td><td>902 – 928MHz</td><td>824 – 849MHz (B5)</td><td>869 – 894MHz (B5)</td></tr>
<tr><td rowspan="2">Australia/New Zealand</td><td rowspan="2">915 – 928MHz</td><td>880 – 915MHz (B8)</td><td>925 – 960MHz (B8)</td></tr>
<tr><td>825 – 845MHz (B5)</td><td>870 – 890MHz (B5)</td></tr>
<tr><td>Asia/ Thailand, Taiwan, and Singapore</td><td>920 – 925MHz</td><td>885 – 915MHz (B8)</td><td>930 – 960MHz (B8)</td></tr>
<tr><td>Asia/Malaysia</td><td>919 – 924MHz</td><td>880 – 915MHz (B8)</td><td>925 – 960MHz (B8)</td></tr>
</table>

Colocalizing LoRaWAN gateways with LTE (or 3G, 2G) base stations may cause some issues if the RF filters and the installation are not carefully considered. The main issues to be faced are:

- Out-of-band spurious emissions generated by a LTE transmitter falling in the LoRaWAN unlicensed band, causing desensitization of the LoRaWAN gateway
- Out-of-band spurious emissions generated by a LoRaWAN transmitter falling in the LTE UL band, causing desensitization of the LTE base station
- An LTE transmitter acting as an out-of-band blocker, causing desensitization of the LoRaWAN gateway
- LTE transmitter intermodulation in the LoRaWAN receiver, causing desensitization of the LoRaWAN gateway
- LTE transmitter intermodulation in the LoRaWAN transmitter, causing desensitization of the LTE base station or any other receiver
- The total amount of radiated power by an LTE base station in the installation site may damage the LoRaWAN receiver

To mitigate these potential issues, RF filters and antenna isolation must be carefully managed before and during the installation of the LoRaWAN gateway.

The LTE DL is a major concern for radio coexistence with LoRaWAN. However, the LTE UL must be also considered. An outdoor LoRaWAN gateway embeds a LoRaWAN modem supporting one or more of the above unlicensed bands and a cellular 3G or 4G modem supporting several LTE bands. The global market trend is cellular modem to support a maximum of LTE bands to reach worldwide coverage. Each modem is connected to a dedicated antenna, one for the cellular modem and one for the LPWAN modem. These antennas could be designed based on different technologies and are separated by a defined distance, leading to a certain isolation or mutual coupling between both antennas.

Distance between antennas is a key factor for antenna isolation. Obviously, this is less critical for outdoor LoRaWAN gateways, because the gateways are generally based in a large or medium-size enclosure. It is then naturally possible to optimize the antenna isolation when placing antennas at a sufficient distance, or even by deporting the antennas using coaxial cable and antenna brackets. However, even for outdoor LoRaWAN gateways, if no special care is taken during the design phase, isolation may be not enough.

3.2 LoRa®/LTE ANTENNA ISOLATION

The antenna isolation considered in this section is the isolation measured between the LoRaWAN gateway RF port and the LTE base station RF port. Isolation includes, therefore, the LoRa antenna gain, the LTE antenna gain, and the propagation losses.

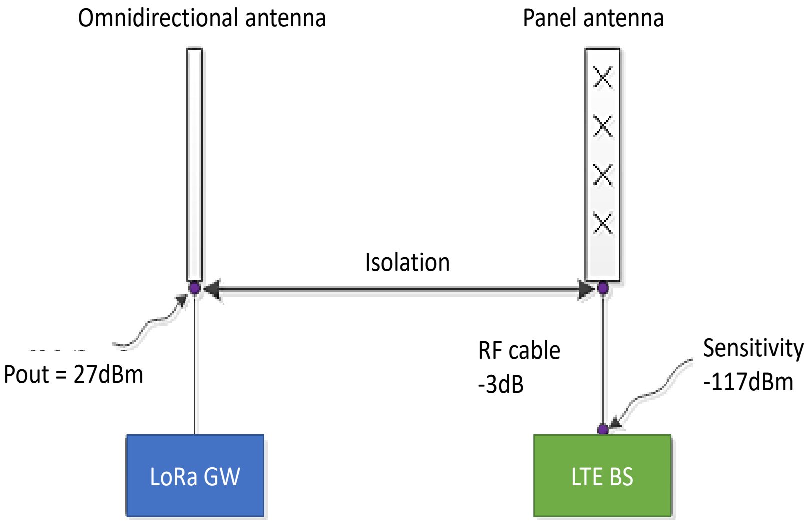

Figure 8: Isolation between LTE and LoRa antennas. BS, base station; GW, gateway; RF, radio frequency.

The measured isolation between two panel antennas has been investigated in Report ITU-R M.2244 (see [8]). The methodology used here is almost identical; correction factors are applied to the antenna gain to consider the gain variation depending on the directions.

Antenna isolation can be optimized via installation parameters because both LoRa antennas and base station antennas are directive antennas. This means that the antenna gain is not identical depending on the direction. The installation can be then optimized, favoring the ideal direction to improve isolation.

3.2.1 LTE BASE STATION ANTENNAS

LTE base station antennas have about 15 to 20dBi antenna maximum gain. Here is an example of an antenna pattern:

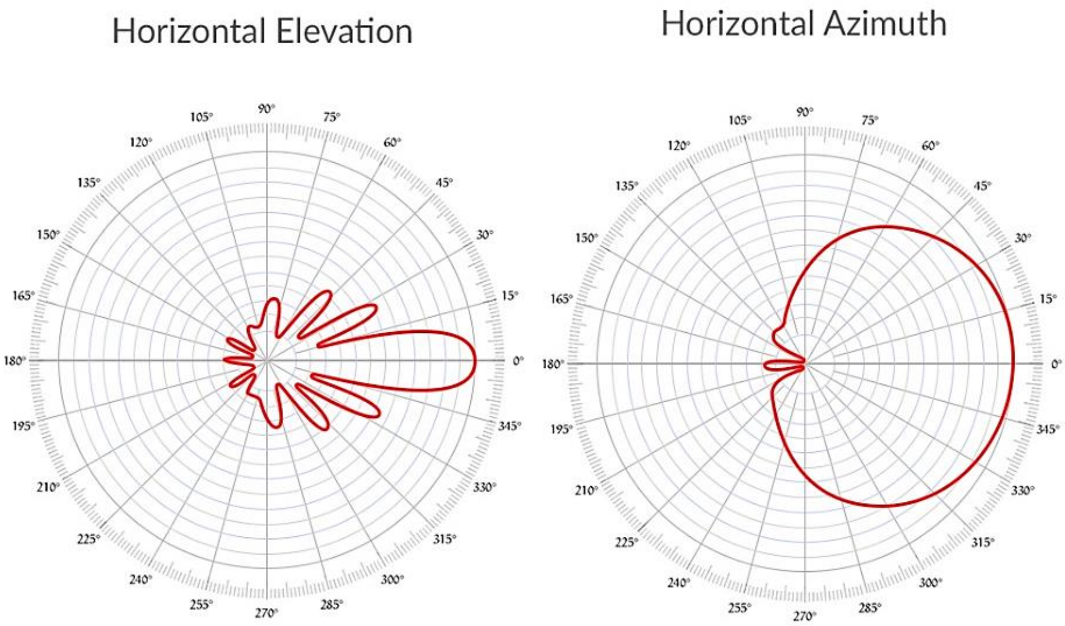

Figure 9: Example of antenna gain pattern of an LTE base station

The antenna pattern shows that:

- The gain above (90°) or below (270°) the antenna in the vertical plane is reduced by 20dB to 30dB.
- The gain beside (90° or 270°) or behind (180°) the antenna in the horizontal plane is reduced by 20dB to 30dB.

For the next calculations, we are going to consider a typical LTE antenna with the following performance at 900MHz:

- Max gain: 20dBi
- Horizontally 90°: 20dB loss
- Horizontally 180°: 30dB loss
- Vertically 90°: 25dB loss
- Vertically 270°: 25dB loss

3.2.2 6DBI LoRa ANTENNA

LoRa antennas are usually considered omnidirectional antennas. This is true in the horizontal plane but not in the vertical plane.

When increasing the gain of the LoRa antenna, the directivity is also improved.
Higher vertical isolation can be therefore obtained as shown here

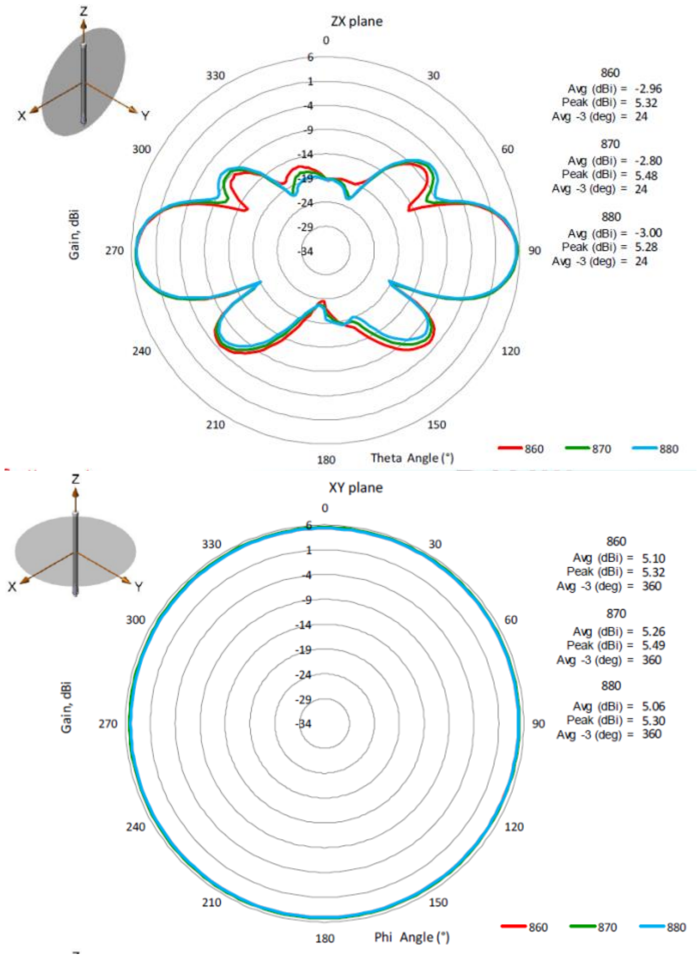

Figure 10: Typical gain of 6dBi omnidirectional antenna

We can see that the gain on the top of the antenna or below the antenna is about -10dB to -15dB compared with maximum gain.

In this section, we are going to consider the 6dBi omnidirectional LoRa antenna and the following performance:

- Max gain: 6dBi
- Horizontally 90°: 0dB loss
- Horizontally 180°: 0dB loss
- Vertically 90°: 20dB loss
- Vertically 270°: 20dB loss

3.2.3 LoRa/LTE ANTENNA ISOLATION CALCULATION

Considering the LoRa antenna gain and LTE antenna gain, the correction factor for horizontal isolation is:

Correction H [0^0] = (6dBi - 0dB) + (20dBi – 0dB) = +26dB
Correction H [90^0] = (6dBi - 0dB) + (20dBi – 20dB) = +6dB
Correction H [180^0] = (6dBi - 0dB) + (20dBi – 30dB) = -4dB

Considering the LoRa antenna again and LTE antenna gain, the correction factor for vertical isolation is:

Correction V [0^0] = (6dBi - 0dB) + (20dBi –0dB) = +26dB
Correction V [90^0] = (6dBi - 20dB) + (20dBi –25dB) = -19dB
Correction V [180^0] = (6dBi - 20dB) + (20dBi –25dB) = -19dB

Now, considering free-space attenuation between antenna, the total isolation between antennas, depending on the separation distance, is:

Distance (m)	Free space attenuation (dB)	Isolation Horizontal 180°	Isolation Vertical 90°/180°	Isolation H=0°, V=0°
1	-31.22	-35.22	-50.22	-5.22
2	-37.24	-41.24	-56.24	-11.24
3	-40.76	-44.76	-59.76	-14.76
4	-43.26	-47.26	-62.26	-17.26
5	-45.19	-49.19	-64.19	-19.19
6	-46.78	-50.78	-65.78	-20.78
7	-48.12	-52.12	-67.12	-22.12
8	-49.28	-53.28	-68.28	-23.28
9	-50.30	-54.30	-69.30	-24.30
10	-51.22	-55.22	-70.22	-25.22
15	-54.74	-58.74	-73.74	-28.74
20	-57.24	-61.24	-76.24	-31.24
25	-59.17	-63.17	-78.17	-33.17
30	-60.76	-64.76	-79.76	-34.76
35	-62.10	-66.10	-81.10	-36.10
40	-63.26	-67.26	-82.26	-37.26
45	-64.28	-68.28	-83.28	-38.28
50	-65.19	-69.19	-84.19	-39.19
55	-66.02	-70.02	-85.02	-40.02
60	-66.78	-70.78	-85.78	-40.78
70	-68.12	-72.12	-87.12	-42.12
80	-69.28	-73.28	-88.28	-43.28
90	-70.30	-74.30	-89.30	-44.30
100	-71.22	-75.22	-90.22	-45.22
200	-77.24	-81.24	-96.24	-51.24
300	-80.76	-84.76	-99.76	-54.76
400	-83.26	-87.26	-102.26	-57.26
500	-85.19	-89.19	-104.19	-59.19
600	-86.78	-90.78	-105.78	-60.78
700	-88.12	-92.12	-107.12	-62.12
800	-89.28	-93.28	-108.28	-63.28
900	-90.30	-94.30	-109.30	-64.30
1000	-91.22	-95.22	-110.22	-65.22
2000	-97.24	-101.24	-116.24	-71.24
3000	-100.76	-104.76	-119.76	-74.76
4000	-103.26	-107.26	-122.26	-77.26
5000	-105.19	-109.19	-124.19	-79.19
6000	-106.78	-110.78	-125.78	-80.78
7000	-108.12	-112.12	-127.12	-82.12
8000	-109.28	-113.28	-128.28	-83.28
9000	-110.30	-114.30	-129.30	-84.30
10000	-111.22	-115.22	-130.22	-85.22

Figure 11: Isolation between LTE and 6dBi LoRa antenna vs distance separation vs horizontal and vertical plane.

Vertical isolation is therefore the best solution for LTE coexistence. A 3-meter separation allows 59dB isolation in this case.

3.3 OUT-OF-BAND SPURIOUS EMISSIONS GENERATED BY CELLULAR BASE STATIONS

Out-of-band spurious emissions calculations detailed in this section are extracted from the European Telecommunications Standards Institute (ETSI) TS 136 104 V15.8.0 (see [5]) detailing LTE base station radio transmission and reception specifications.

The output RF spectrum emissions for the LTE transmitter consist of three components: the occupied bandwidth (channel bandwidth), the out-of-band (OOB) emissions, and the far-out spurious emission domain (see Figure 12):

- Channel bandwidth: range occupied by the LTE channel

- Out-of-band emission: unwanted emissions immediately outside the nominal channel, in a range from the user channel limits to Δf_{OOB} (depending on the channel bandwidth; for example, Δf_{OOB} = 15MHz for a channel bandwidth of 10MHz).
  Out-of-band emissions are specified in terms of a spectrum emission mask and adjacent channel leakage ratio (ACLR).
  Out-of-band emission is therefore used when the LoRaWAN unlicensed band is adjacent to the LTE band and up to 10MHz.
- Spurious emission: everything outside of Δf_{OOB}.
  Spurious emission is therefore used when the LoRaWAN unlicensed band is far from the LTE band (for example, 10MHz above and 10MHz below the band).

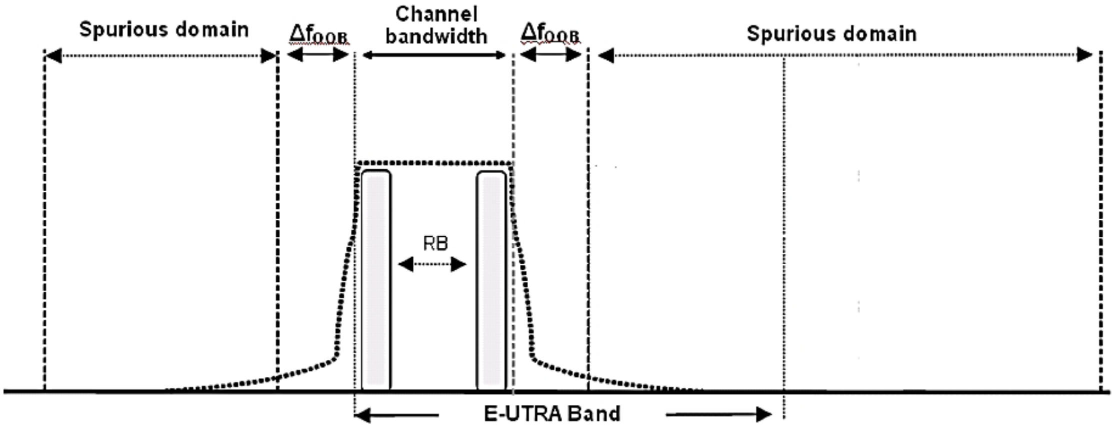

Figure 12: LTE output spectrum. E-UTRA, Evolved Universal Mobile Telecommunications System Terrestrial Radio Access

3.3.1 LTE BASE STATION CLASSES

LTE base station specifications define different classes of base stations:

- Wide-area base stations are characterized by requirements derived from macro-cell scenarios with a BS to UE minimum coupling loss equal to 70dB.
  Wide-area BS are typically deployed in rural or suburban environments, with large-cell deployment. They are installed on high towers or above rooftops.
- Medium-range base stations are characterized by requirements derived from micro-cell scenarios with a BS to UE minimum coupling loss equal to 53dB.
  Medium-range BS are typically deployed in urban or rural outdoor environments. They are often installed on rooftops or embedded in street furniture such as lighting fixtures, advertisement panels, bus shelters or street signs. They can also be deployed to extend the mobile network coverage and capacity on a localized area, such as isolated villages, industrial sites, or emergency situations.
- Local-area base stations are characterized by requirements derived from pico-cell scenarios with a BS to UE minimum coupling loss equal to 45dB.
  Local-area BS are typically deployed in indoor environments accessible to the general public such as stations, airports, and commercial centers.

- Home base stations are characterized by requirements derived from femto-cell scenarios.
  Home BS are used in residential settings to improve mobile network coverage and quality of service.

This document focuses on the wide-area BS (rural and suburban areas) and medium-range BS (urban areas), which inherently cause more coexistence issues with LoRaWAN gateways.

3.3.2 OUTPUT POWER/EIRP

The output power of LTE BS depends on the BS class, as follows:

BS class	$P_{rated,c}$
Wide Area BS	- (note)
Medium Range BS	$\leq$ + 38 dBm
Local Area BS	$\leq$ + 24 dBm
Home BS	$\leq$ + 20 dBm (for one transmit antenna port) $\leq$ + 17 dBm (for two transmit antenna ports) $\leq$ + 14dBm (for four transmit antenna ports) < + 11dBm (for eight transmit antenna ports)
NOTE: There is no upper limit for the rated output power of the Wide Area Base Station.	

Figure 13: LTE Base station rated output power

As indicated in the note, there is no upper limit for the wide-area BS. However, it is generally considered that 48dBm is the maximum output power.

As stated in §3.2.1, the LTE antenna gain may vary from 15dB to 20dB, so EIRP may reach up to 48 + 20 = 68dBm for wide-area BS. For medium-range BS, the EIRP is limited to +58dBm.

3.3.3. ADJACENT CHANNEL LEAKAGE RATIO

According to [5], the adjacent channel leakage power ratio (ACLR) minimum requirement is:

- For Category A wide-area BS, either 45dB or the absolute limit of -13dBm/MHz shall apply, whichever is less stringent.
- For Category B wide-area BS, either 45dB or the absolute limit of -15dBm/MHz shall apply, whichever is less stringent.
- For medium-range BS, either 45dB or the absolute limit of -25 dBm/MHz shall apply.

Considering a wide-area BS, the output power generated in the adjacent channel is therefore:
48dBm - 10*Log(10MHz/1MHz) - 45dB = -7dBm in 1MHz RBW = -17dBm in 100KHz RBW

For a medium-range BS, the output power generated in the adjacent channel is therefore:
38dBm - 10*Log(10MHz/1MHz) - 45dB = -17dBm in 1MHz RBW = -27dBm in 100KHz RBW

3.3.4 OPERATING BAND UNWANTED EMISSIONS

According to [5], the minimum requirement for unwanted emissions in operating band is detailed in the following table:

Frequency offset of measurement filter -3dB point, Δf	Frequency offset of measurement filter centre frequency, f_offset	Minimum requirement (Note 1, 2)	Measurement bandwidth (Note 8)
0 MHz ≤ Δf < 5 MHz	0.05 MHz ≤ f_offset < 5.05 MHz	$-7dBm-\frac{7}{5}\cdot\left(\frac{f\_offset}{MHz}-0.05\right)dB$	100 kHz
5 MHz ≤ Δf < min(10 MHz, Δf_{max})	5.05 MHz ≤ f_offset < min(10.05 MHz, f_offset_{max})	-14 dBm	100 kHz
10 MHz ≤ Δf ≤ Δf_{max}	10.05 MHz ≤ f_offset < f_offset_{max}	-13 dBm (Note 10)	100 kHz

NOTE 1: For a BS supporting non-contiguous spectrum operation within any operating band, the minimum requirement within sub-block gaps is calculated as a cumulative sum of contributions from adjacent sub blocks on each side of the sub block gap. Exception is Δf ≥ 10MHz from both adjacent sub blocks on each side of the sub-block gap, where the minimum requirement within sub-block gaps shall be -13dBm/100kHz.
NOTE 2: For BS supporting multi-band operation with Inter RF Bandwidth gap < 20MHz the minimum requirement within the Inter RF Bandwidth gaps is calculated as a cumulative sum of contributions from adjacent sub-blocks or RF Bandwidth on each side of the Inter RF Bandwidth gap.

Figure 14: Wide-area BS category A operating band unwanted emissions limits (E-UTRA bands < 1GHz)

Considering a wide-area LTE BS:

- The output power generated from 5 to 10MHz offset is -14dBm in 100KHz RBW.
- The output power generated from 10MHz to 15MHz offset is -13dBm in 100KHz RBW.

3.3.5 SPURIOUS EMISSIONS

According to [5], there are three types of minimum requirements for out-of-band spurious emissions:

1. Mandatory requirements
2. Additional spurious emissions for the protection of systems operating in frequency ranges other than the E-UTRA BS downlink operating band. The limits may apply as an optional protection of such systems that are deployed in the same geographical area as the E-UTRA BS, or they may be set by local or regional regulation as a mandatory requirement for an E-UTRA operating band.
3. Colocation with other base stations for the protection of other BS receivers when UTRA FDD, UTRA TDD, E-UTRA, and/or NR BS are colocated with an E-UTRA BS.

Mandatory requirements are defined in the following tables for both categories A and B:

<table>
<tr><th>Frequency range</th><th>Maximum level</th><th>Measurement Bandwidth</th><th>Note</th></tr>
<tr><td>9kHz - 150kHz</td><td rowspan="6">-13 dBm</td><td>1 kHz</td><td>Note 1</td></tr>
<tr><td>150kHz - 30MHz</td><td>10 kHz</td><td>Note 1</td></tr>
<tr><td>30MHz - 1GHz</td><td>100 kHz</td><td>Note 1</td></tr>
<tr><td>1GHz - 12.75 GHz</td><td>1 MHz</td><td>Note 2</td></tr>
<tr><td>12.75 GHz - 5th harmonic of the upper frequency edge of the DL operating band in GHz</td><td>1 MHz</td><td>Note 2, Note 3</td></tr>
<tr><td>12.75 GHz - 26 GHz</td><td>1 MHz</td><td>Note 2, Note 4</td></tr>
<tr><td colspan="4">NOTE 1: Bandwidth as in ITU-R SM.329 [2] , s4.1
NOTE 2: Bandwidth as in ITU-R SM.329 [2] , s4.1. Upper frequency as in ITU-R SM.329 [2] , s2.5 table 1
NOTE 3: Applies only for Bands 22, 42, 43, 48 and 49.
NOTE 4: Applies only for Band 46.</td></tr>
</table>

Figure 15: BS category A mandatory spurious emissions limits

Frequency range	Maximum Level	Measurement Bandwidth	Note
9 kHz ↔ 150 kHz	-36 dBm	1 kHz	Note 1
150 kHz ↔ 30 MHz	-36 dBm	10 kHz	Note 1
30 MHz ↔ 1 GHz	-36 dBm	100 kHz	Note 1
1 GHz ↔ 12.75 GHz	-30 dBm	1 MHz	Note 2
12.75 GHz ↔ 5th harmonic of the upper frequency edge of the DL operating band in GHz	-30 dBm	1 MHz	Note 2, Note 3
12.75 GHz ↔ 26 GHz	-30 dBm	1 MHz	Note 2, Note 4
NOTE 1: Bandwidth as in ITU-R SM.329 [2] , s4.1 NOTE 2: Bandwidth as in ITU-R SM.329 [2] , s4.1. Upper frequency as in ITU-R SM.329 [2] , s2.5 table 1 NOTE 3: Applies only for Bands 22, 42, 43, 48 and 49. NOTE 4: Applies only for Band 46.			

Figure 16: BS category B mandatory spurious emissions limits

Considering wide-area and medium-range BS, the output power generated from 10MHz outside the LTE DL band is -13dBm in 100KHz RBW for category A, which is in accordance with ACLR and unwanted emissions in the operating band. For category B, the output power generated from 10MHz outside the LTE DL band is -36dBm in 100KHz RBW.

Additional requirements may apply when other systems operate in the same geographical area. However, these requirements may not be mandatory, and the bands defined in this section are only the 3GPP bands, which limits the considered coexistence systems! Depending on the UTRA band, the maximum levels vary from -47dBm to -61dBm in 100KHz RBW.

When colocated with other wide-area BS, the spurious emissions limits are:

Type of co-located BS	Frequency range for co-location requirement	Maximum Level	Measurement Bandwidth	Note
Macro GSM900	876-915 MHz	-98 dBm	100 kHz	
Macro DCS1800	1710 - 1785 MHz	-98 dBm	100 kHz	
Macro PCS1900	1850 - 1910 MHz	-98 dBm	100 kHz	
Macro GSM850 or CDMA850	824 - 849 MHz	-98 dBm	100 kHz	
WA UTRA FDD Band I or E-UTRA Band 1 or NR Band n1	1920 - 1980 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band II or E-UTRA Band 2 or NR Band n2	1850 - 1910 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band III or E-UTRA Band 3 or NR Band n3	1710 - 1785 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band IV or E-UTRA Band 4	1710 - 1755 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band V or E-UTRA Band 5 or NR Band n5	824 - 849 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band VI, XIX or E-UTRA Band 6, 19	830 - 845 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band VII or E-UTRA Band 7 or NR Band n7	2500 - 2570 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band VIII or E-UTRA Band 8 or NR Band n8	880 - 915 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band IX or E-UTRA Band 9	1749.9 - 1784.9 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band X or E-UTRA Band 10	1710 - 1770 MHz	-96 dBm	100 kHz	
WA UTRA FDD Band XI or E-UTRA Band 11	1427.9 –1447.9 MHz	-96 dBm	100 kHz	This is not applicable to E-UTRA BS operating in Band 50 or 75
WA UTRA FDD Band XII or	699 - 716 MHz	-96 dBm	100 kHz	

Figure 17: BS spurious emissions limits for wide-area BS colocated with another BS

Type of co-located BS	Frequency range for co-location requirement	Maximum Level	Measurement Bandwidth	Note
Micro/MR GSM900	876-915 MHz	-91 dBm	100 kHz	
Micro/MR DCS1800	1710 - 1785 MHz	-91 dBm	100 kHz	
Micro/MR PCS1900	1850 - 1910 MHz	-91 dBm	100 kHz	
Micro/MR GSM850	824 - 849 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band I or E-UTRA Band 1 or NR Band n1	1920 - 1980 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band II or E-UTRA Band 2 or NR Band n2	1850 - 1910 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band III or E-UTRA Band 3 or NR Band n3	1710 - 1785 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band IV or E-UTRA Band 4	1710 - 1755 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band V or E-UTRA Band 5 or NR Band n5	824 - 849 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band VI, XIX or E-UTRA Band 6, 19	830 - 850 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band VII or E-UTRA Band 7 or NR Band n7	2500 - 2570 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band VIII or E-UTRA Band 8 or NR Band n8	880 - 915 MHz	-91 dBm	100 kHz	
MR UTRA FDD Band IX	1749.9 - 1784.9 MHz	-91 dBm	100 kHz	

Figure 18: BS spurious emissions limits for medium-range BS colocated with another BS

This performance can be achieved thanks to cavity duplexers.

3.3.6 REQUIRED ISOLATION BETWEEN ANTENNAS

Depending on the minimum requirement considered (i.e. ACLR, operating band unwanted emissions, and moreover spurious emissions when colocated), we can see a huge variation of out-of-band emissions requirements in the unlicensed band.

In a real use case, an LTE BS embeds a cavity duplexer, which significantly reduces the out-of-band spurious emissions. The performance of the LTE BS is then very close to the ACLR requirement at the edge of the UTRA DL band but meets colocated spurious emissions at 20MHz offset from the UTRA DL band.

According to Report ITU-R SM.2421-0 (see [9]), a typical LTE BS output spectrum, without external filtering (Tx1 and Tx3), is as follows:

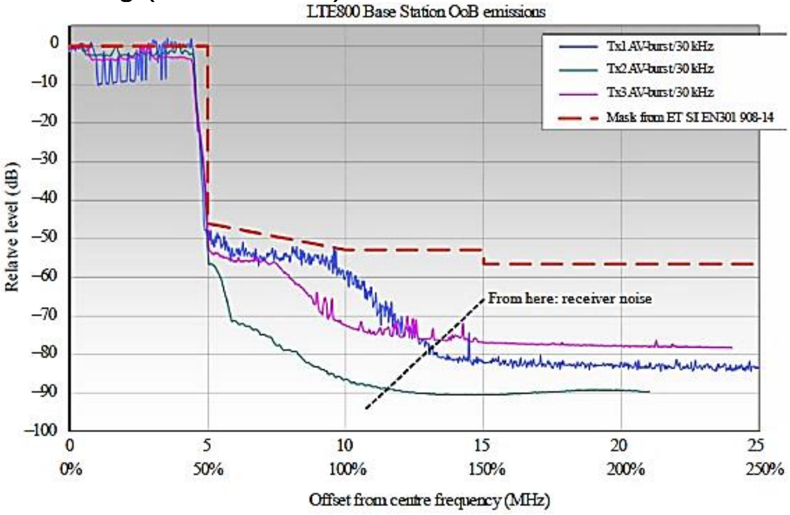

Figure 19: Typical emissions from an LTE800 BS without external filter

According to Report ITU-R SM.2421-0 (see [9]), a typical LTE BS output spectrum, including external cavity filter, is as follows:

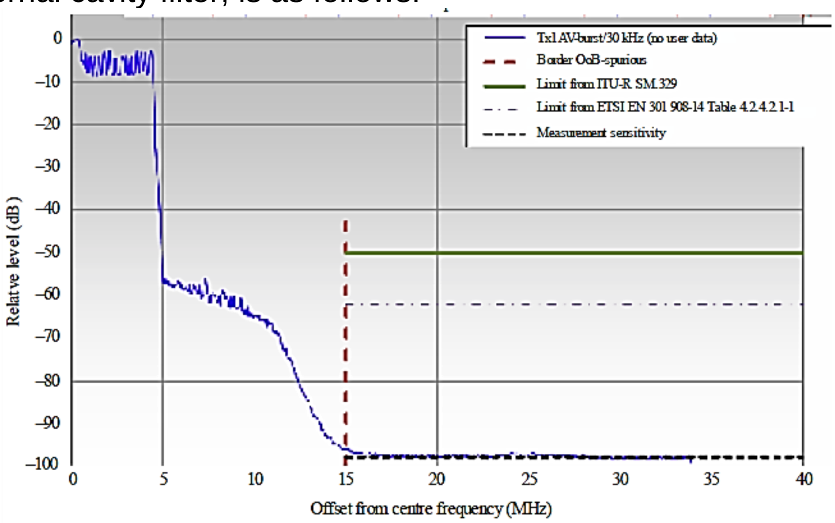

Figure 20: Typical emissions from an LTE800 BS with external filter

Of course, the out-of-band emissions depend on the performance of the external cavity filter. The performance depends on the LTE band, the installation site, and the operator's choices. A typical performance of duplexer is presented here:

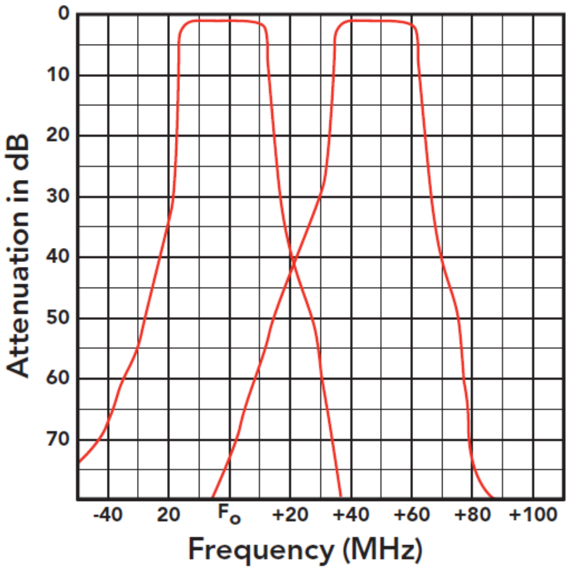

Figure 21: Typical frequency response of external BS duplexer

Typical attenuations can be obtained at the edge of the LTE bands:

- 20dB@5MHz offset
- 30dB@7.5MHz offset
- 40dB@10MHz offset
- 60dB@20MHz offset

The following performance at the LTE BS antenna port can be achieved:

Frequency Offset from UTRA DL Band	Relative Level (spectrum mask)	External Cavity Filter Attenuation	Absolute Level for Wide-area BS (48dBm)	Absolute Level for Medium-range BS (38dBm)
0MHz	-55dB	0dB	-27dBm/100KHz	-37dBm/100KHz
2MHz	-57dB	5dB	-34dBm/100KHz	-44dBm/100KHz
5MHz	-65dB	20dB	-57dBm/100KHz	-67dBm/100KHz
7.5MHz	-75dB	30dB	-77dBm/100KHz	-87dBm/100KHz
10MHz	-80dB	40dB	-92dBm/100KHz	-102dBm/100KHz
20MHz	-80dB	60dB	-112dBm/100KHz	-122dBm/100KHz

To avoid desensitization, the noise generated in the LoRaWAN band must be lower than -124dBm/100KHz.

The required vertical isolation is therefore:

Frequency Offset from UTRA DL Band	Required Isolation for Wide-area BS (48dBm)	Required Isolation for Medium-range BS (38dBm)
0MHz	97dB	87dB
2MHz	90dB	80dB
5MHz	67dB	57dB
7.5MHz	47dB	37dB
10MHz	32dB	22dB
20MHz	12dB	2dB

According to Figure 11, the corresponding distance between the LTE BS antenna and the LoRaWAN gateway antenna is therefore:

Frequency Offset from UTRA DL Band	Min. Vertical Separation for Wide-area BS (48dBm)	Min. Vertical Separation for Medium-range BS (38dBm)	Min. Horizontal Separation for Wide-area BS (48dBm)	Min. Horizontal Separation for Medium-range BS (38dBm)
0MHz	200m	70m	>10Km	>10km
2MHz	100m	30m	>10km	6km
5MHz	7m	2.5m	1500m	400m
7.5MHz	1m	1m	150m	40m
10MHz	1m	1m	25m	7m
20MHz	1m	1m	2.5m	1m

The separation distance may be mitigated, as line of sight is never obtained in real situations. However, a guard band less than 5MHz may cause a desensitization issue at the edge of the LTE DL band. It is then preferable to use LoRaWAN channels far out of the LTE DL band.

The above tables show that a 45dB isolation between the LTE antenna and LoRa antenna is a good trade-off. This isolation can be achieved with minimum vertical separation (1m or 2m) and acceptable horizontal separation (150m maximum). This isolation also ensures no sensitivity degradation of the LoRaWAN gateway by the LTE BS when the band guard is greater than 5MHz. We can then consider the 45dB antenna isolation as a minimum requirement and a good assumption to define the LoRaWAN gateway's requirements.

Assuming 45dB isolation also means that the maximum LTE BS power at the gateway RF port is 48dBm - 45dB = +3dBm.

An example is provided here, considering a colocated LoRaWAN gateway with a CDMA 800 base station in India. The CDMA band edge is 869MHz, whereas the LoRaWAN band is 865 – 867MHz. A cavity filter is used to reject the CDMA DL band, and we can measure the noise generated by the CDMA 800 BS at the LoRaWAN gateway input.

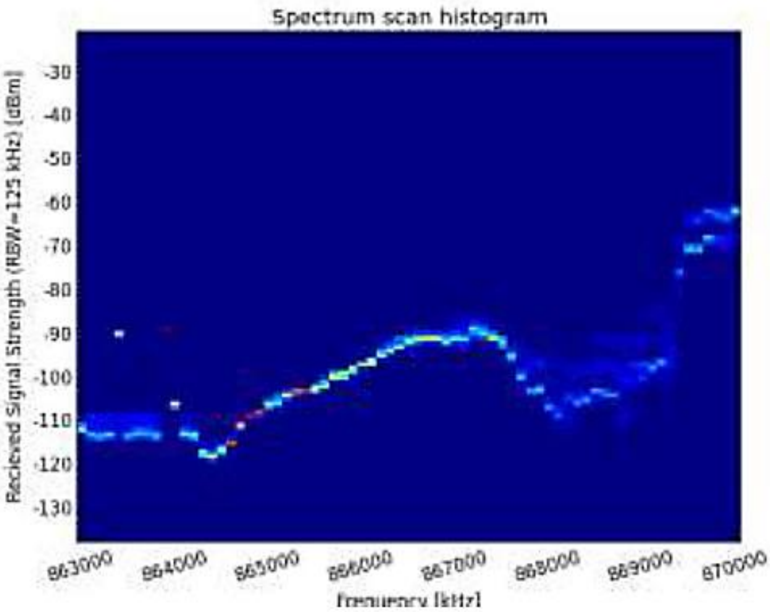

Figure 22: Example of Out-of-band emissions from a CDMA800 base station in India

At 867MHz the noise is ~-90dBm/125KHz, which causes about 30dB desensitization.

According to the above table, about 90dB isolation are required between the BS antenna and LoRaWAN antenna. The 2- or 3-meter separation provides only 60dB maximum isolation. There is therefore a lack of 30dB isolation, explaining the 30dB desensitization.

3.4 BLOCKING OF LTE EMITTERS

LTE BS transmitters act as an out-of-band blocker for the LoRaWAN receiver. The output power of the LTE BS depends on the class of the BS, according to §3.3.2, but assuming 45dB isolation between LTE antenna and LoRa antenna, the maximum LTE DL power at the LoRa RF port is +3dBm, according to §3.3.6. Considering a LoRaWAN gateway sensitivity of -140dBm, therefore the LTE rejection must be better than +3dBm - (-140dBm) = 143dB. We will consider a requirement of 150dB minimum rejection for LTE band in this section.

Rejection of the in-band blockers depends on the frequency offset from the LoRaWAN channels. These following typical values are used:

- 75dB at +/- 0.2MHz
- 93dB at +/- 2MHz
- 100dB at +/- 5MHz
- 105dB at +/- 10MHz

The out-of-band rejection is completed by the RF filters of the LoRaWAN gateway receiver. The cumulated rejection of these RF filters, to achieve 150dB total attenuation, must be therefore as follows:

Frequency Offset from LoRaWAN Channel	Blocker Rejection (typical)	Required Attenuation in RF Filters to Achieve 150dB Total Attenuation
0.2MHz	75dB	75dB
2MHz	93dB	57dB
5MHz	100dB	50dB
10MHz	105dB	45dB

Obviously, it is not possible to achieve 75dB attenuation at 0.2MHz offset from the LoRaWAN band. No filtering technology can achieve such performance. The separation distance may be increased in this case, but it would be hardly possible to reach 75dB isolation, according to Figure 11. This means that guard band less than 2MHz must be strongly avoided.

Therefore, 57dB (60dB) is the minimum requirement for RF filter rejection of LTE DL bands.

Achieving 57dB attenuation at 2MHz offset is only possible when using cavity filters. Surface acoustic wave (SAW), bulk acoustic wave (BAW), and ceramic filter technologies would not be able to meet such sharp slopes. SAW filters could be only used when the guard band is greater than 5MHz.

When using SAW filters (or BAW or ceramic filters), the 60dB attenuation can be divided, for example, in 20dB in the first band-pass filter and 40dB in the second band-pass filter. Reducing the attenuation in the first band-pass filter minimizes insertion losses of the filter and therefore improves the sensitivity of the LoRaWAN receiver.

As opposite, when using a cavity filter as first band-pass filter, the maximum attenuation must be completed by the cavity filter (50dB or more), relaxing the required attenuation for the second band-pass filter (10dB or less).

3.5 OUT-OF-BAND SPURIOUS EMISSIONS GENERATED BY THE LoRaWAN EMITTER

Considering 45dB isolation between the LoRa antenna and LTE antenna, the transmitter of the LoRaWAN gateways should be designed to reduce the spurious emissions and the noise generated in the LTE BS UL bands below -124dBm + 45dB = -79dBm in a 100KHz-resolution bandwidth.

This is typical noise performance, depending on the gateway and LTE UL band. All LoRaWAN gateways do not meet the -79dBm out-of-band noise in LTE bands due to the architecture of the gateway or due to the guard band between LoRaWAN band and LTE band.

Depending on the noise performance of the gateway, the gateway manufacturer has basically two options:

- Use a cavity filter (external or internal) to attenuate the out-of-band noise in the LTE BS UL band.
- Increase isolation between the LTE and LoRa antennas, according to the following vertical and horizontal separation distance:

Noise in LTE UL Band	Required Isolation	Min. Vertical Separation	Min. Horizontal Separation
-70dBm/100KHz	54dB	2m	300m
-75dBm/100KHz	49dB	1m	150m
-80dBm/100KHz	44dB	1m	90m
-85dBm/100KHz	39dB	1m	50m
-124dBm/100KHz	0dB	1m	1m

The vertical and horizontal separation distance is evaluated according to Figure 11.

3.6 INTERMODULATION OF LTE EMITTERS

An LTE BS signal is an OFDM signal based on QPSK, 16QAM, or 64QAM modulation. This modulation is a non-linear modulation; injecting the OFDM into signal in a non-linear receiver would cause generation of IM3 products, as explained in §2.4.

When the LTE BS signal is injected into the LoRa receiver, IM3 (or even IM5) products may be generated, falling into the LoRaWAN band as shown here:

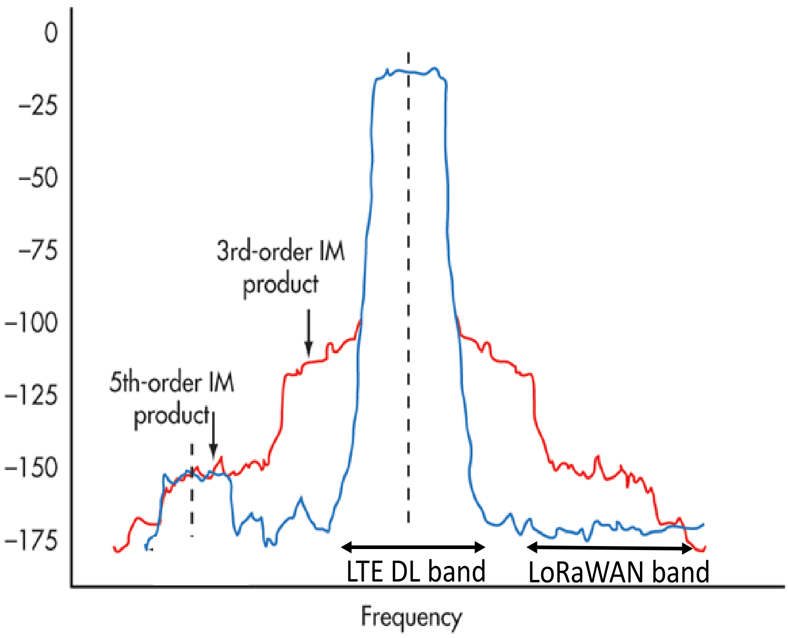

Figure 23: Intermodulation of LTE BS signal in LoRa receiver

The level of the IM3 products depends on the level of the LTE BS signal at the input of the receiver, the attenuation of the LTE BS signal in the Rx chain, and the IIP3 of the receiver.

According to the §3.4, an attenuation of 57dB (60dB) is expected from the RF filters to avoid desensitization of the LoRaWAN gateway due to LTE BS as an out-of-band blocker. Also, the maximum input power of LTE BS at the LoRaWAN gateway RF port is +3dBm, according to §3.3.6.

To estimate the required IIP3 of the receiver, we can assume:

- An LTE BS channel of 5MHz BW
  The power is therefore +3dBm -10*Log(5/0.1) = -14dBm in 100KHz BW.
- IM3 products must be below -124dBm/100KHz to avoid desensitization.

Considering the above assumptions, the **IIP3 of the receiver must be better than -43dBm.**

This calculation assumes that all the RF attenuation (57dB) is available at the antenna port, before any active part (single-pole X-throw SPxT , LNA, transceiver). Usually the RF attenuation is split in two RF filters, so the IIP3 of each active part and attenuation of each RF filter has to be carefully selected to minimize the IM3 products.

If we consider no RF filtering, the required IIP3 of the receiver would be +42dBm minimum.

3.7 TRANSMIT INTERMODULATION

In this section, only close LTE BS interferers are considered when mixing with a LoRaWAN transmitter. This is considered as a worst case due to the proximity with the LoRa band. Three regional use cases are detailed, depending on the LTE bands and LoRaWAN band available.

Then, we are going consider and evaluate the transmit intermodulation products falling in:

- LoRaWAN receive band, causing desensitization of any LPWAN gateway. The desensitization of its own LoRaWAN gateway is only possible in full-duplex configuration, as in half-duplex configuration, transmitter and receiver are not active simultaneously.
- LTE UL band, causing desensitization of the colocated cellular base station
- LTE DL band, causing desensitization of the LoRaWAN gateway cellular backhaul

For the IM3 product estimation, we are going to consider the following assumptions:

- The LoRaWAN transmitter is configured at maximum output power, i.e.:
    - +14dBm or +27dBm at RF port in Europe
    - +30dBm at RF port in North America
    - +27dBm at RF port in APAC and LATAM
- OIP3 at the LoRa RF port is +40dBm.
- LTE BS level at the LoRaWAN gateway RF port is +3dBm, according to §3.3.6.
- An LTE BS channel of 5MHz BW. The power is therefore +3dBm - 10*Log(5/0.1) = -14dBm in 100KHz BW.
- Isolation between the LTE BS antenna and LoRa antenna is 45dB, according to §3.3.6.
- Isolation between the LoRa antenna and LTE backhauling ports of the LoRaWAN gateways is 35dB.
- LTE UL level (from gateway backhaul) at the LoRaWAN gateway RF port is +21 - 35 = -14dBm
- An LTE UL channel of 5MHz BW. The power is therefore -14dBm - 10*Log(5/0.1) = -31dBm in 100KHz BW.
- IMD3 products are evaluated with RBW = 100KHz.
- IMD3 is calculated according to calculator [3].
- IMD3 products must be below -124dBm/100KHz in a receive band of any receiver port to avoid desensitization.
- IMD3 products must be below -54dBm/100KHz in the 470 – 790 MHz band at the LoRa RF port to meet ETSI EN 300 200.
- IMD3 products must be below -36dBm/100KHz or -30dBc/100KHz in other bands at the LoRa RF port to meet ETSI EN 300 200 and 47 CFR FCC Part 15 specifications.

3.7.1 EUROPEAN USE CASE

We consider in this use case the mixing of the 863 – 870MHz LoRa band with LTE bands 8 and 20. IMD3 products are generated in B20 UL/DL and B8 UL/DL bands.

The estimated IMD3 products at the receiver's ports are:

F1	F2	IM3 Left	IM3 Right	IM3 at LTE BS Receiver Port	IM3 at GW LTE Receiver Port
869.525MHz (27dBm)	925 – 960MHz (LTE 900 DL)	LTE 800 DL -40dBm/100KHz	-81dBm/100KHz	N/A	LTE 800 DL -75dBm/100KHz
	880 – 915MHz (LTE 900 UL)	LTE 800 UL/DL -57dBm/100KHz	LTE 900 UL -115dBm/100KHz	LTE 800 UL -102dBm/100KHz LTE 900 UL -150dBm/100KHz	LTE 800 DL -92dBm/100KHz
	832 – 862MHz (LTE 800 UL)	LTE 800 UL/DL -115dBm/100KHz	LTE 900 UL -57dBm/100KHz	LTE 800 UL -150dBm/100KHz LTE 900 UL -102dBm/100KHz	LTE 900 DL -140dBm/100KHz
	791 – 821MHz (LTE 800 DL)	-81dBm/100KHz	LTE 900 UL/DL -40dBm/100KHz	LTE900 UL -85dBm/100KHz	LTE900 DL -75dBm/100KHz
863-870MHz (14dBm)	925 – 960MHz (LTE 900 DL)	LTE 800 DL -66dBm/100KHz	-94dBm/100KHz	N/A	LTE 800 DL -101dBm/100KHz
	880 – 915MHz (LTE 900 UL)	LTE 800 UL/DL -83dBm/100KHz	LTE900 UL -128dBm/100KHz	LTE 800 UL -128dBm/100KHz LTE 900 UL -173dBm/100KHz	LTE 800 DL -118dBm/100KHz
	832 – 862MHz (LTE 800 UL)	LTE 800 UL/DL -128dBm/100KHz	LTE900 UL -83dBm/100KHz	LTE 800 UL -173dBm/100KHz LTE 900 UL -128dBm/100KHz	LTE 900 DL -163dBm/100KHz
	791 – 821MHz (LTE 800 DL)	-94dBm/100KHz	LTE 900 UL/DL -66dBm/100KHz	LTE900 UL -111dBm/100KHz	LTE900 DL -101dBm/100KHz

IMD3 products due to LTE BS in bands 8 and 20 may significantly desensitize the LTE BS in bands 8 and 20. The LTE backhaul of the gateway may be also impacted. Therefore, a band-pass filter is required on the gateway Tx path to attenuate LTE 900 DL (B8) and LTE 800 DL (B20) signals.

The IMD products at the LoRa RF port can reach up to -40dBm/100KHz, which is very marginal to ETSI EN 300 200 specification (-36dBm/100KHz).

A cavity filter is therefore required in this case. It must provide 40dB or more attenuation in the LTE 900 DL and LTE 800 DL bands.

3.7.2 NORTH AMERICA USE CASE

We consider in this use case mixing of the 923 – 928MHz LoRa band with LTE bands 27, 5, 12, and 13. The IMD3 products are generated in the B27 UL/DL, B13 UL, and B5 UL/DL bands.

The estimated IMD3 products at the receiver's ports are:

F1	F2	IM3 Left	IM3 Right	IM3 at LTE BS Receiver Port	IM3 at GW LTE Receiver Port
923–928MHz	852 – 869MHz (LTE SMR DL)	SMR UL 700c UL -78dBm/100KHz	-34dBm/100KHz	SMR UL -123dBm/100KHz 700c UL -123dBm/100KHz	N/A
	807 – 824MHz (LTE SMR UL)	700c UL -112dBm/100KHz	-51dBm/100KHz	700c UL -157dBm/100KHz	N/A
	869-894MHz (LTE 850 DL)	SMR UL/DL LTE 850 UL -78dBm/100KHz	-34dBm/100KHz	SMR UL -123dBm/100KHz LTE 850 UL -123dBm/100KHz	SMR DL -113dBm/100KHz
	824 – 849MHz (LTE 850 UL)	SMR UL LTE 850 UL -112dBm/100KHz	-51dBm/100KHz	SMR UL -157dBm/100KHz LTE 850 UL -157dBm/100KHz	N/A
	777 – 787MHz (LTE 700c UL)	700a UL -112dBm/100KHz	-51dBm/100KHz	700a UL -157dBm/100KHz	N/A

IMD3 products due to LTE BS in bands 27, 5, 12, and 13 may not cause any degradation of the LTE BS and LTE backhaul. IMD3 right product may be somewhat high (-34dBm/100KHz) but is compliant with 47 CFR FCC Part 15 specification.

3.7.3 APAC AND LATAM USE CASES

We consider in this use case mixing of the 915 – 928MHz LoRa band with LTE bands 8, 5, and 28. The IMD3 products are generated in B27 UL/DL, B13 UL, and B5 UL/DL bands.

The estimated IM3 products at the receiver port are:

F1	F2	IM3 Left	IM3 Right	IM3 at LTE BS Receiver Port	IM3 at GW LTE Receiver Port
915 – 928MHz	935 – 960MHz (LTE 900 DL)	LTE 850 DL LTE 900 UL LoRa -78dBm/100KHz	-34dBm/100KHz	LTE 900 UL -123dBm/100KHz	LTE 850 DL -113dBm/100KHz
	890 – 915MHz (LTE 900 UL)	LTE 850 UL/DL LTE900 UL -112dBm/100KHz	LTE 900 DL -51dBm/100KHz	LTE 850 UL -157dBm/100KHz	LTE 850 DL -147dBm/100KHz LTE 900 DL -86dBm/100KHz
	860 – 890MHz (LTE 850 DL)	LTE 850 UL LTE 700 DL -78dBm/100KHz	LTE 900 DL -34dBm/100KHz	LTE 850 UL -123dBm/100KHz	LTE 700 DL -113dBm/100KHz LTE 900 DL -69dBm/100KHz

IMD3 products due to LTE BS in bands 8, 5, and 28 may not cause any degradation of the LTE BS but may impact LTE backhaul in LTE B8 DL. Also, IMD3 right product may be somewhat high (-34dBm/100KHz), which is very marginal to ETSI EN 300 200 specification (-36dBm/100KHz).
A cavity filter is therefore required in this case. It must provide **40dB or more attenuation in the LTE 900 UL/DL and LTE 850 DL bands**.

3.8 TOTAL POWER RECEIVED BY A LoRaWAN GATEWAY

In urban areas, the LoRaWAN gateway may be surrounded by many LTE or high-speed packet access (HSPA) base stations. For example, three or four operators may share the same mast or may be located very close to each other on neighboring rooftops:

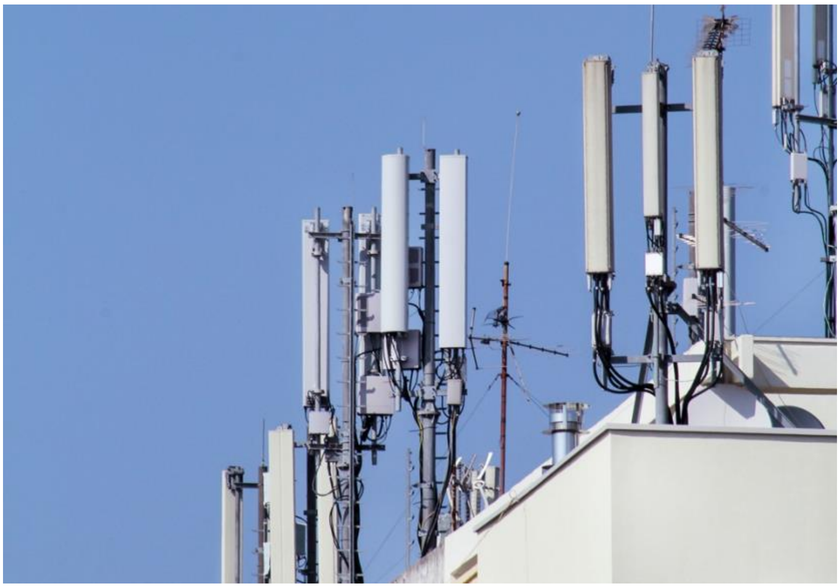

Figure 24: Example of multiple 3G/4G base stations located on the same site

Fortunately, in dense urban areas, the LTE or HSPA base stations are rarely wide-area BS, but medium-range or local-area BS. Therefore, the radiated power of the BS is usually limited from 20W to 100W. However, the numerous BS surrounding the LoRaWAN gateway may generate a huge amount of radiated power.

In the example of Figure 24, more than 12 three-sector BS are identified. Assuming a 100W radiated power for each, we have a total of 100 x 3 x 12 = 3600W or more radiated power in the vicinity of the LoRaWAN gateway.

Although isolation between the LTE/HSPA BS and the LoRaWAN gateway antennas can be expected, a significant amount of power can be inserted into the gateway RF port, impacting both Tx and Rx paths.

On the LoRaWAN receiver path, the LNA and the band-pass SAW filters have usually very low maximum input power, such as +13dBm, for example. There is obviously a high risk of damage to the LoRaWAN in the case of high radiated power in the vicinity. The LoRaWAN receiver could be protected using RF power limiters, for instance, but saturation or intermodulation of the receiver could occur then.

On the LoRaWAN Tx path, the power amplifier may be also damaged due to high power in reverse mode.

Therefore, considering the potential damage to the LoRaWAN gateway, cavity filters are recommended to mitigate the risk. A cavity filter having about 40dB attenuation in the LTE UL bands would ensure no damage to the gateway, even in case of poor installation.

3.9 SUMMARY

Colocation of LoRaWAN gateways with LTE BS imposes several constraints on the gateway installation and design:

- At least 45dB isolation is required between the LTE BS antenna and LoRa antenna to minimize impact of LTE BS out-of-band spurious emissions.
- A minimum attenuation of 57dB (60dB) of the LTE BS DL band is expected from Rx RF filters of the LoRaWAN gateways, to mitigate LTE BS blocking.
- A minimum IIP3 of -33dBm for the LoRaWAN receiver is required to mitigate LTE BS intermodulation.
- A minimum attenuation of 40dB of LTE BS UL/DL band is expected of the LoRaWAN Tx path, between the PA and antenna port, to reduce transmitted out-of-band spurious emissions and minimize the transmit intermodulation.

The minimum separation distance between an LTE BS and a LoRaWAN gateway equipped with a 6dBi LoRa antenna is summarized in this table:

Gateway Type	Min. Vertical Separation for Wide-area BS (48dBm)	Min. Vertical Separation for Medium-range BS (38dBm)	Min. Horizontal Separation for Wide-area BS (48dBm)	Min. Horizontal Separation for Medium-range BS (38dBm)	Recommendation
EU868-870 version	1m	1m	150m	150m	Cavity filter
US902-928 version	1m	1m	150m	40m	Cavity filter
AU915-928 version	1.5m	1m	200m	150m	Cavity filter
AS923 version Guard band <2MHz	**100m**	**40m**	**10km**	**7km**	Cavity filter + increase guard band
AS923 version Guard band <5MHz	7m	2.5m	1500m	400m	Cavity filter + increase guard band
AS923 version Guard band <10MHz	1.5m	1m	200m	150m	Cavity filter

A cavity filter is recommended in all use cases, as detailed in the last column. The cavity filters are described in §7.

For AS923 versions of the gateway, it is recommended to add a cavity filter (see §7) and increase the guard band between the LoRaWAN channels and the edge of the LTE UL band. A guard band of 2MHz or less must be avoided unless accepting huge desensitization of the LoRaWAN gateway and significant reduction of the coverage area.

Moreover, due to the very high power in the proximity (LTE BS or other) that could cause damage to the gateway, cavity filters are recommended to mitigate the risk. A cavity filter having about 40dB attenuation in the LTE UL band would ensure no damage of the gateway, even in case of poor installation.

4 COLOCATION WITH OTHER LPWAN GATEWAYS

Nowadays, colocation of LPWAN gateways on a shared site is rare, but as massive Internet of Things (IoT) deployment is approaching, the probability is increasing significantly. LPWAN gateways could then share the same site or eventually could be installed on close rooftops, for instance. LPWAN gateways could be LoRaWAN gateways but also Sigfox gateways, Qowisio gateways, or any other LPWAN gateways sharing the same unlicensed band.

The issue when colocating LPWAN on the same site or on a nearby site is that they use the same bands and, most of the time, the same channels. Therefore, RF filtering cannot be used to avoid interference. Of course, if gateways are configured in Rx mode only (no transmission), no issues are encountered. Issues are observed when a gateway emits on a dedicated channel, causing desensitization of the other gateways, as in-band blockers.

It must be noted that in the case of colocated full-duplex LoRaWAN gateways (North America use case), there is no in-band blocking issue. This is because the US902 – 928MHz regional parameter (see [1]) defines separated bands for UL and DL frequencies as follows:

- UL: 902 – 915MHz
- DL: 923 – 928MHz

The duplexer used to separate UL and DL bands prevents any desensitization of the receiver while transmitting. This is valid for full-duplex gateways and, therefore, for all the gateways located on the same site.

However, transmit intermodulation may occur when two full-duplex gateways are transmitting at the same time. IM3 products may be generated in or outside the ISM band. According to CFR 47 FCC part 15.247, the IM3 product must be lower than -30dBc. A 30dB isolation is therefore enough to meet this requirement.

In the case of half-duplex gateways, the probability of issues is more significant. The transmitted gateway is considered as an in-band blocker for the other gateway's receivers. Different use cases must be considered depending on:

- The gateway EIRP, according to the local regulation. It may vary from 16dBm EIRP to 36dBm EIRP.
- The frequency separation between the DL (Tx) and the UL (Rx) channel frequencies. We may consider the following uses cases: co-channel, adjacent and alternate channels, and 2MHz offset.
- The sensitivity and acceptable desensitization of the gateways.

In the following table, we have considered the following typical performance:

- Sensitivity = -140dBm, and we may allow maximum 3dB degradation
- Co-channel rejection = 25dB
- Adjacent channel rejection = 75dB
- 2MHz offset rejection = 95dB

Therefore, the required isolation, depending on the allowed EIRP, is:

Required Isolation	**Co-channel**	**Adjacent Channel +/- 200KHz**	**+/- 2MHz**
In-band blocker rejection	*25dB*	*75dB*	*95dB*
In-band blocker max. level (relative to -140dBm)	*-115dBm*	*-65dBm*	*-45dBm*
Gateway Tx EIRP = 16dBm	131dB	81dB	61dB
Gateway Tx EIRP = 29dBm	144dB	94dB	74dB
Gateway Tx EIRP = 36dBm	151dB	101dB	81dB

The co-channel required isolation is very high, from 131dB to 151dB. This basically means that desensitization on the same channel is inevitable. The required isolation for adjacent channels, alternate channels, and up to 2MHz offset varies from 61dB to 101dB.

The required isolation must be translated into distance separation. Two use cases are considered: vertical separation and horizontal separation.

Vertical separation is obviously recommended, as we can benefit from the antenna pattern characteristic of the antenna. About 30dB isolation can be achieved with the vertical position for a 6dBi antenna gain, whereas no improvement can be achieved in the horizontal plane. High antenna gain (6dBi or more) is therefore highly recommended in the case of colocation of LPWAN gateways.

In the following table, the distance is converted into isolation (dB) assuming direct line of sight (LoS). The frequency used for the calculations is 868MHz, but results would not be very different using 915MHz, for instance.

Vertical separation:

	Vertical Antenna Separation (m)					
	1m	3m	6m	15m	30m	60m
Antenna isolation (vertical)	30dB	30dB	30dB	30dB	30dB	30dB
Antenna separation (LoS)	31dB	41dB	47dB	55dB	61dB	67dB
Total isolation	61dB	71dB	77dB	85dB	91dB	97dB

Horizontal separation:

	Horizontal Antenna Separation (m)					
	30m	50m	100m	300m	1000m	2000m
Antenna isolation (horizontal)	0dB	0dB	0dB	0dB	0dB	0dB
Antenna separation (LoS)	61dB	65dB	71dB	81dB	91dB	97dB
Total isolation	61dB	65dB	71dB	81dB	91dB	97dB

Based on these calculations, we can provide the following recommendations regarding antenna separation of LPWAN gateways:

Gateway Type	Min. Vertical Separation	Min. Horizontal Separation
EU868-870 version	5m	200m
US902-928 version	1m	20m
AU915-928 version	10m	300m
AS923 version	**50m**	**1500m**

The probability of interference may be mitigated, however, by the duty cycle of the LPWAN gateway transmitter (1% to 10%). The probability is therefore low.

5 COLOCATION WITH A HIGH-POWER TRANSMITTER

LoRaWAN gateways may be colocated with high-power transmitters. These transmitters could consist of radio broadcasting equipment (FM radio, TV), radars, satellite stations, military applications, etc. All the different uses cases cannot be addressed in this document, but any LoRaWAN deployment must consider all the high-power transmitters in the area.

In this section, we are going to consider one of the most critical high-power transmitters, digital terrestrial TV:

- DVB-T/T2 in EMEA and APAC regions
- ATSC in North America
- ISDB-T in Japan and LATAM

DVB-T/T2 transmitters are critical due to their high radiated power and also the operating UHF band (470 – 694MHz), which is close to the unlicensed bands used by LPWAN gateways. The DVB-T/T2 transmitters may degrade LoRaWAN gateway receiver performance due to:

- Out-of-band spurious emissions falling in the unlicensed band
- High-power carrier causing out-of-band blocking

If not sufficiently protected (RF filtering), the DVB-T/T2 transmitters may also damage the gateways, and especially the radio front end.

5.1 LoRa/DVB-T ANTENNA ISOLATION

The antenna isolation considered in this section is the isolation measured between the LoRaWAN gateway RF port and the DVB-T emitter RF port. Isolation includes, therefore, the LoRa antenna gain, the DVB-T/T2 antenna gain, and the propagation losses.

In this section we are going to consider a 6dBi LoRa antenna, as detailed in §3.2.2.

DVB-T/T2 emitters antennas have about 5dBi to 15dBi antenna maximum gain. An example of a 15dBi antenna pattern is presented here:

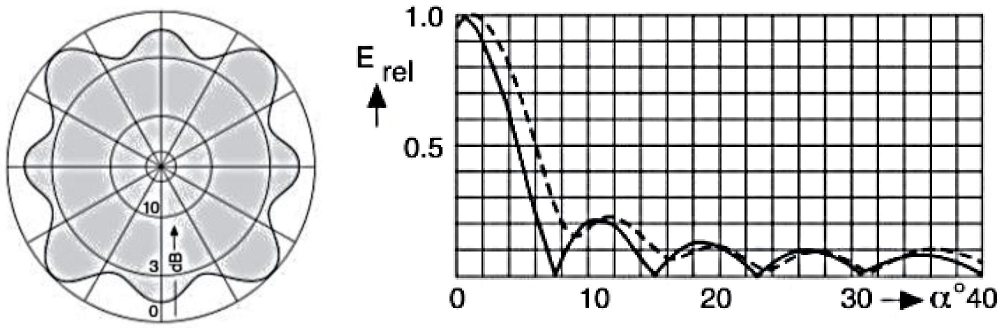

Figure 25: Example of antenna gain pattern (H and V) of DVB-T emitter

The antenna pattern shows that:

- The gain above (90°) or below (270°) the antenna in the vertical plane is reduced by 20*Log(0.1) = -20dB.
- The gain in the horizontal plane is almost omnidirectional, with only 3dB variation depending on the azimuth.

For our next calculations, we are going to consider a typical DVB-T/T2 antenna with the following performance at 900MHz:

- Max gain: 15dBi
- Horizontally 90°/180°: 0dB loss
- Vertically 90°/270°: 20dB loss

Considering the LoRa antenna gain and DVB-T/T2 antenna gain, the correction factor for horizontal isolation is:

Correction H [0^0, 90^0, 180^0] = (6dBi - 0dB) + (15dBi - 0dB) = +21dB

Considering the LoRa antenna again and DVB-T/T2 antenna gain, the correction factor for vertical isolation is:

Correction V [0^0] = (6dBi - 0dB) + (15dBi - 0dB) = +21dB
Correction V [90^0, 180^0] = (6dBi - 20dB) + (15dBi - 20dB) = -19dB

Now, considering free-space attenuation between antennas, the total isolation between antennas, depending on the separation distance, is:

Distance (m)	Free space attenuation (dB)	Isolation Vertical 90°/180°	Isolation H=0°, V=0°
1	-31.22	-50.22	-10.22
2	-37.24	-56.24	-16.24
3	-40.76	-59.76	-19.76
4	-43.26	-62.26	-22.26
5	-45.19	-64.19	-24.19
6	-46.78	-65.78	-25.78
7	-48.12	-67.12	-27.12
8	-49.28	-68.28	-28.28
9	-50.30	-69.30	-29.30
10	-51.22	-70.22	-30.22
15	-54.74	-73.74	-33.74
20	-57.24	-76.24	-36.24
25	-59.17	-78.17	-38.17
30	-60.76	-79.76	-39.76
35	-62.10	-81.10	-41.10
40	-63.26	-82.26	-42.26
45	-64.28	-83.28	-43.28
50	-65.19	-84.19	-44.19
55	-66.02	-85.02	-45.02
60	-66.78	-85.78	-45.78
70	-68.12	-87.12	-47.12
80	-69.28	-88.28	-48.28
90	-70.30	-89.30	-49.30
100	-71.22	-90.22	-50.22
200	-77.24	-96.24	-56.24
300	-80.76	-99.76	-59.76
400	-83.26	-102.26	-62.26
500	-85.19	-104.19	-64.19
600	-86.78	-105.78	-65.78
700	-88.12	-107.12	-67.12
800	-89.28	-108.28	-68.28
900	-90.30	-109.30	-69.30
1000	-91.22	-110.22	-70.22
2000	-97.24	-116.24	-76.24
3000	-100.76	-119.76	-79.76
4000	-103.26	-122.26	-82.26
5000	-105.19	-124.19	-84.19
6000	-106.78	-125.78	-85.78
7000	-108.12	-127.12	-87.12
8000	-109.28	-128.28	-88.28
9000	-110.30	-129.30	-89.30
10000	-111.22	-130.22	-90.22

Figure 26: Isolation between DVB-T and 6dBi LoRa antennas vs distance separation vs horizontal and vertical planes

Vertical isolation is therefore the best solution for DVB-T coexistence. A 2-meter separation allows 56dB isolation in this case.

5.2 DVB-T/T2 OUT-OF-BAND SPURIOUS EMISSIONS

The essential requirements of the digital terrestrial TV transmitters are detailed in the ETSI EN 302 296 documents (see [6]).

Considering the out-of-band spurious emissions, the limits are detailed in the following figure:

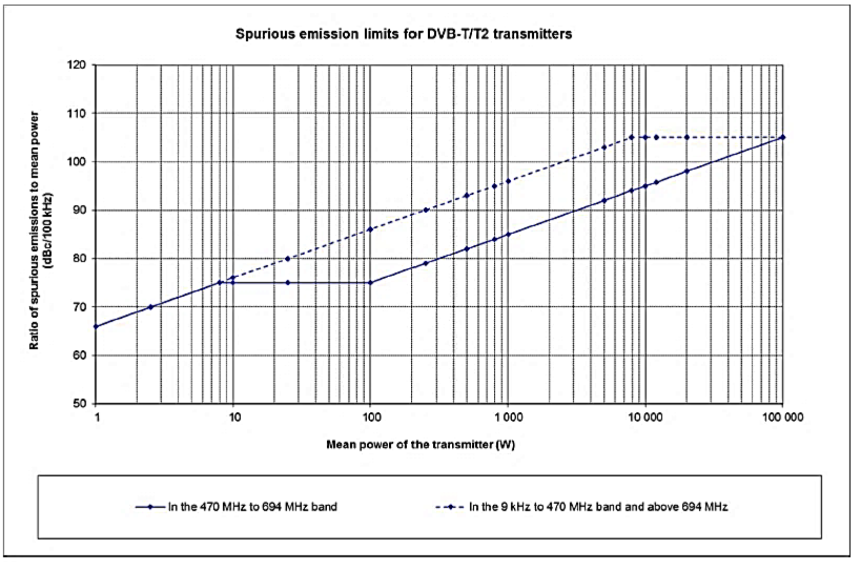

Figure 27: Spurious emissions limits for DVB-T/T2 transmitters (antenna port, RBW = 100KHz)

From 10KW to 100KW, the limit is then -105dBc in 100KHz RBW.
Considering a 69dBm output power (conducted) transmitter, the limit of spurious emissions in 100KHz RBW is then:
Spurious emissions = 69dBm - 10*Log(8MHz/100KHz) - 105 = -55dBm in 100KHz RBW

The required out-of-band limits are detailed in the following figure:

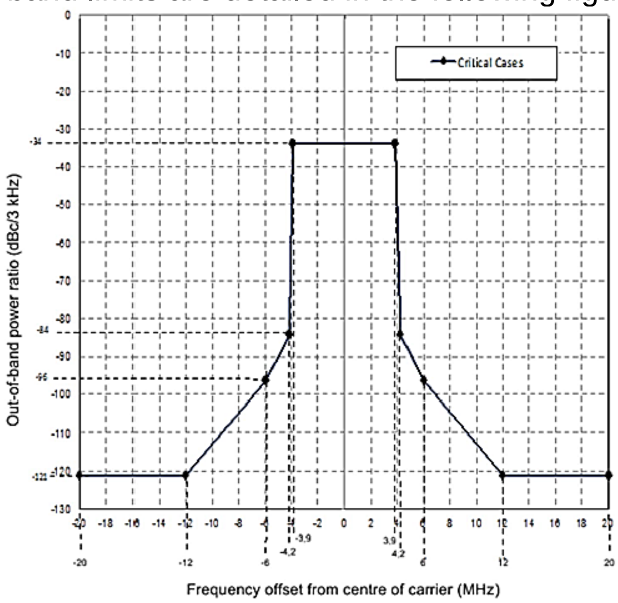

Figure 28: Out-of-band limits for H1 transmitter (antenna port, RBW = 3KHz)

The limit is then -121dBc in 3KHz RBW.

Considering a 69dBm output power (conducted) transmitter, the limit of spurious emissions in 100KHz RBW is then:
Spurious emissions = 69dBm - 10*Log(8MHz/3KHz) - 121 = -86dBm in 3KHz RBW or -71dBm in 100KHz BW

This requirement is therefore more stringent regarding out-of-band performance. We are going to consider this one for the following calculation, although some spurious emissions may degrade performance by 15dB, according to the spurious emissions limit.

The required isolation, considering out-of-band limits, is therefore:
Isolation = -71dBm - (-124dBm) = 53dBm

This isolation must be translated into distance separation. According to Figure 26, we can provide the following recommendations regarding antenna separation of LoRaWAN gateways with DVB-T/T2 transmitters:

Min. Vertical Separation	**Min. Horizontal Separation**
2m	150m

5.3 DVB-T/T2 OUTPUT POWER

According to [6], DVB-T/T2 transmitters are considered high-power transmitters when the conducted output power is greater than 25W. The conducted power may reach up to 10KW (69dBm) and the radiated power can reach up to 200KW ERP (85dBm EIRP) in Germany, but it is limited to 50KW ERP (79dBm EIRP) in France.

Considering 53dB isolation between antennas, as shown in §5.2, the maximum DVB-T/T2 power at the LoRaWAN RF port is 69dBm - 53dB = 16dBm.

According to §3.4, the receiver must provide at least 60dB attenuation of the LTE emitters as out-of-band blocker rejection. The same rejection is expected for DVB-T/T2 emitters. Therefore, the maximum blocker input level at the LoRa RF port is +10dBm.

Considering +16dBm DVB-T/T2 maximum input power at the LoRaWAN RF port, this means that 66dB to 70dB attenuation is required to avoid blocking due to DVB-T/T2. This is achievable using SAW filters in the LoRa receiver path, and no cavity filter is required for that purpose.

However, due to the very high power in the proximity that could cause damage to the gateway, the usage of cavity filters is recommended to mitigate the risk. The cavity filter may have about 40dB to 50dB maximum attenuation in the UHF band, ensuring no damage of the gateway, even in case of poor installation.

6 LoRaWAN GATEWAY RADIO PERFORMANCE

Knowledge of the LoRaWAN gateway performance is a prerequisite before colocating the gateway with other transmitters. The radio performance of the LoRaWAN gateway would help to understand the potential issues and the relevant solutions to prevent interference.

Each gateway manufacturer may have its own proprietary architecture, but most of the architectures available in the LoRaWAN ecosystem are derived from the following Semtech Reference Designs:

- Semtech Reference Design V1.0 based on SX1257 and SX1301
- Semtech Reference Design V1.5 based on SX1257, SX1301, and FPGA
- Semtech Reference Design V2.0 based on AD9363, SX1301, FPGA, and DSP
- Semtech SX1302CxxxGW1 – Corecell Reference Design for Gateway Applications Based on SX1302 and SX1250

The Reference Design architecture may be convenient for some installation sites, but it has some weaknesses in harsh environments, such as when colocated with high-power transmitters:

- Close out-of-band signals may generate intermodulation products that could fall into the LoRaWAN unlicensed band. The level of the intermodulation products would obviously depend on the IIP3 of the receiver.
- Close out-of-band signals may generate Tx intermodulation products that could fall into the LoRaWAN unlicensed band or in the LTE uplink bands, for instance, causing desensitization of the LoRaWAN gateway or cellular BS.
- Tx noise generated by the PA has no, or very limited, out-of-band spurious rejection. Spurious emissions or noise could fall into the LTE uplink bands, for instance, causing desensitization of the cellular BS.
- The gateway may be sensitive to lightning surges, which could damage the front-end chipsets.
- Maximum input power may be limited.

To fix potential issues regarding use of Semtech Reference Designs in harsh environments, a band-pass cavity filter shall be added at the antenna port. The cavity filter may be embedded in the gateway or connected outside the gateway.

Also, when designing a LoRaWAN gateway, the choice of the band-pass RF filters must be carefully investigated. This is often a trade-off between contradictory requirements. The main specifications to be considered are:

- Band-pass, driven by:
  - The usable unlicensed band according to the local regulation (country specific)
  - The LoRaWAN Regional Parameters that can be used for a LoRaWAN deployment in a dedicated country (see [8])
  - The number of LoRaWAN channels that can be used or needed
- The out-of-band rejection, driven by:
  - LTE UL and DL bands used in the dedicated country
  - Guard band between the LoRaWAN unlicensed band and LTE bands
- The maximum input power, which is often neglected but must be chosen as high as possible to reinforce the robustness of the receiver

Increasing RF filter bandwidth leads to lower rejection of the close LTE bands, and therefore the gateway's immunity is degraded. Increasing the RF filter rejection increases the insertion losses of the RF filters, and the bandwidth may be sacrificed to get the expected immunity.

Cavity filters offer the best option for RF filters, as this is the ideal trade-off between maximum input power, out-of-band rejection, insertion losses, and largest bandwidth.

See more details in [11].

7 CAVITY FILTERS

7.1 MAIN REQUIREMENTS

Previous chapters demonstrated that cavity filters are required when colocating LoRaWAN gateways with high-power emitters. Cavity filters improve performance of the LoRaWAN gateways regarding:

- Out-of-band blockers
- Transmit intermodulation
- Intermodulation of LTE BS emitters in the LoRaWAN receiver
- Out-of-band spurious emissions generated by the LoRaWAN transmitter
- Out-of-band maximum input power

However, cavity filters do not improve performance of the gateways regarding:

- In-band blockers
- Linearity of the receiver
- In-band maximum input power
- Out-of-band spurious emissions generated by other transmitters in the unlicensed band

When selecting a cavity filter, the gateway manufacturer or must consider:

- The usable unlicensed band for LoRaWAN
- The Regional Parameters to be used for LoRaWAN
- The cellular (LTE) bands colocated with the LoRaWAN gateway
- Guard band between unlicensed band (LoRaWAN) and LTE DL bands
- Attenuation of the main interfering bands (the colocation issues to be solved)
- Outdoor or indoor (embedded) versions depending on the gateways
- Typical insertion losses to evaluate impact on the budget link
- Dimensions
- Weight
- Connectors type
- Operating temperature range

The following table summarizes the main common characteristics of cavity filters when using an unlicensed band in the 860 – 928MHz range (EMEA, North America, LATAM, and APAC zones):

Characteristic	Specification
Connectors	IN N-Female/OUT N-Female (external version) IN SMA-Female /OUT SMA-Female (embedded version)
Power handling	10W CW min.
Impedance	50Ω@I/O
Operating temperature	-40℃～+85℃
Attenuation 10 – 800MHz	60dB min.
Attenuation 1000 – 2000MHz	60dB min.
Attenuation 2000 – 3000MHz	50dB min.
Attenuation in LTE DL bands	40dB min. if guard band greater than 10MHz 50dB min. if guard band greater than 5MHz 60dB min. if guard band greater than 2MHz
Attenuation in LTE UL bands	40dB min.

7.2 EMBEDDED OR EXTERNAL CAVITY FILTERS?

Gateway manufacturers or operators must choose whether to use embedded or external cavity filters.

Using an embedded cavity filter is an attractive choice, as it offers several advantages:

- Lower price of the cavity filter:
  - External cavity filters require specific powder coating to meet IP67.
  - Embedded cavity filters do not require such coating.
- Easier installation:
  - The installer only needs to connect a coaxial cable between the gateway RF port and the antenna.
  - External cavity filter mounting must be considered by the installer.

However, external cavity filters must be also considered, as they offer significant flexibility for the operators and installers. An embedded cavity filter is supposed to address all the possible interference uses cases in a specific country. This could be true in a dedicated country but untrue in another country or at another installation site. The external cavity filter would allow the installer to meet all the specificities of an installation site.

If we consider, for example, the EMEA zone, the unlicensed bands may vary depending on the countries as follows:

- 868 – 870MHz in Ivory Coast, Kenya, Nigeria, South Africa, Greece, Sweden, etc.
- 863 – 870MHz in Belgium, France, Germany, Italy, Netherlands, Lebanon, Oman, etc.
- 863 – 873MHz in Denmark, Finland, Hungary, United Kingdom, Iran, Somalia, etc.
- 863 – 876MHz in Kuwait, Qatar, Saudi Arabia, UAE, etc.
- 862 – 873MHz in Albania, Moldova, Slovenia
- 862 – 876MHz in Comoros
- 864 – 870MHz in Belarus

- 864 – 869.2MHz in Russia

It could be understood that a gateway manufacturer would want to avoid producing eight different versions of EMEA gateways to accommodate all the different above unlicensed bands. A unique gateway supporting the 863 – 876MHz band would be suitable for all the EMEA countries. One or more external cavity filters could be envisaged to accommodate each country's specifications regarding out-of-band emissions or out-of-band blocker rejection. Examples were provided in §7.1.

In North America, both LTE (band 5 mainly) and unlicensed bands (902 – 928MHz) are clearly defined and harmonized across countries (USA, Canada, Mexico, Bahamas, Panama, etc.). Using embedded filters makes complete sense in this zone.

The situation is more complex in the APAC zone, as we have different unlicensed bands in the 915 – 928MHz range but also different usages of the LTE bands 8, 5, and 20, as detailed in the table below:

Unlicensed Band	LTE DL Band	Countries	LoRaWAN Regional Parameters
915 – 928MHz	870 – 890MHz 935 – 960MHz	Australia New Zealand Tonga	AS923-1 AU915
915 – 918MHz	870 – 880MHz 925 – 960MHz	Philippines	AS923-3
917 – 923.5MHz	864 – 894MHz 950 – 960MHz	South Korea	KR920
918 – 923MHz	869 – 880MHz 925 – 960MHz	Vietnam	AS923-2
918 – 925MHz	869 – 894MHz 925 – 960MHz	Solomon Islands	AS923-1
919 – 924MHz	870 – 880MHz 925 – 960MHz	Malaysia Myanmar	AS923-1
920 – 923MHz	869 – 880MHz 925 – 960MHz	Indonesia	AS923-2
920 – 924MHz	925 – 960MHz	Sri Lanka	AS923-1
920 – 925MHz	870 – 890MHz 869 – 894MHz 930 – 960MHz	Brunei Hong Kong Macao Singapore Taiwan Thailand	AS923-1
920 – 928MHz	860 – 890MHz 935 – 960MHz	Japan New Zealand	AS923-1
922 – 925MHz	870 – 885MHz 930 – 960MHz	Bangladesh	AS923-1
923 – 925MHz	870 – 880MHz 927 – 960MHz	Cambodia Laos	AS923-1

It could be difficult for a gateway manufacturer to accommodate all the specific requirements of each country regarding unlicensed bands vs. LTE DL bands (12 configurations). A unique gateway supporting the 915 – 928MHz bands would be suitable for all the APAC countries. Several external cavity filters could be envisaged to accommodate each country’s specifications regarding out-of-band emissions or out-of-band blocker rejection. Examples were provided in §7.1.

In LATAM, 915 – 928MHz unlicensed bands are mostly harmonized across countries (Brazil, Argentina, Chile, Colombia, Honduras, Paraguay, Peru, Uruguay, etc.), but there are some exceptions:

- Bolivia: 915 – 930MHz
- Costa Rica: 920.5 – 928MHz
- Curaçao: 920 – 925MHz
- Venezuela: 922 – 928MHz

Moreover, LTE deployments (bands 5 and 8) may vary by country.

Using embedded filters (915 – 928MHz band) would be satisfactory for most of the LATAM countries, but external cavity filters would be more convenient for Venezuela, Costa Rica, and Curaçao.

7.3 IMPACT OF CAVITY FILTERS ON LINK BUDGET

Cavity filter losses must be included in the feeder losses in the link budget calculation. The losses obviously have an impact on both the uplink and downlink budget.

Depending on the used unlicensed band and country specifications, the cavity filter insertion losses could vary from 0.5dB to 4.0dB. It is quite obvious that a 4.0dB insertion loss could have a huge impact on the coverage area. However, it is possible to mitigate the impact of cavity filter insertion losses by using an appropriate antenna gain. The choice of antenna gain and feeder losses therefore constitutes a trade-off that must be considered before the installation of the gateway.

Also, when considering the LoRaWAN DL budget, we need to ensure the gateway is able to transmit at the maximum allowed EIRP, according to the local regulation. The antenna gain therefore must be adjusted depending on:

- The gateway’s maximum conducted power
- The feeder losses including coaxial cable, lightning surge insertion losses, and cavity filter losses
- The maximum allowed EIRP, according to the local regulation

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

Gateway Max. Conducted Power	Max. EIRP (local regulation)	Feeder Losses	Recommended Antenna Gain
≤27dBm	≤30dBm	≤1dB	3dBi or 6dBi
≤27dBm	≤30dBm	≥3dB	6dBi
≤27dBm	≥36dBm	≤1dB	9dBi
≤27dBm	≥36dBm	≥3 dB	12dBi
≤30dBm	≤30dBm	≤1dB	3dBi or 6dBi
≤30dBm	≤30dBm	≥3dB	6dBi
≤30dBm	≥36dBm	≤1dB	6dBi
≤30dBm	≥36dBm	≥3 dB	9dBi

8 GATEWAY GNSS RECEIVER

Like any other receiver of the LoRaWAN gateway, the GNSS receiver, when colocated with other emitters, can be desensitized due to:

- Out-of-band spurious emissions generated by emitters falling in the GNSS band, causing desensitization of the GNSS gateway
- High-power emitters acting as out-of-band blockers, causing desensitization of the LoRaWAN gateway

Fortunately, GNSS antennas have a narrow bandwidth, which significantly increases the isolation with high-power emitters, such as LTE BS and DVB-T/T2 emitters. Separation distance then can be lowered but still must be considered.

A typical GNSS radio architecture of a LoRaWAN gateway is presented here:

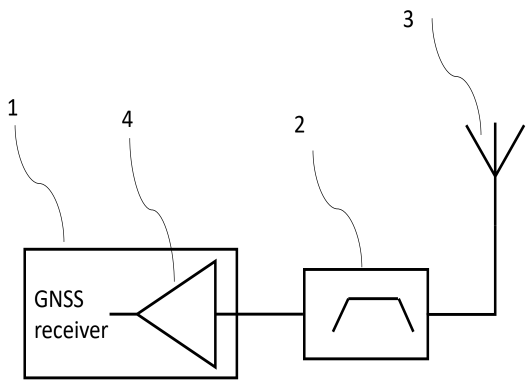

Figure 29: GNSS front-end block diagram of LoRaWAN gateway

A band-pass SAW filter (2) shall be inserted between the LNA (4) of the GNSS receiver (1) and the GNSS antenna port (3), ensuring excellent out-of-band blocker rejection.

Usually, the LNA (4) and the band-pass filter (2) have very low maximum input power, such as +10dBm, for example. When colocated with high-power emitters, there is obviously a high risk of damage to the GNSS front end. Protecting the GNSS receiver with RF power limiters, for instance, is recommended.

Issues may occur when adding an external active GNSS antenna due to potential linearity issues of the LNA or poor out-of-band rejection, causing desensitization of the GNSS receiver.

The best architectures using GNSS antennas are therefore:

- Passive antenna
- Active antenna with SAW-LNA-SAW (
- Figure 30) or SAW-LNA architecture. The LNA gain shall be also minimized (15dB, for instance, instead of the usual 30dB) to optimize linearity performance.

Other types of GNSS antenna are not recommended.

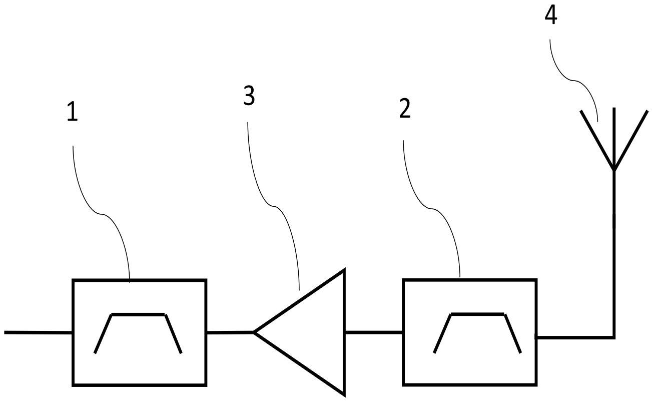

Figure 30: Recommended GNSS active antenna block diagram

9 GATEWAY CELLULAR BACKHAUL

The outdoor LoRaWAN gateways usually embed a cellular 3G or 4G modem for backhauling. The global market trend is a cellular modem to support a maximum of LTE bands to reach worldwide coverage. The performance of this cellular modem inside the gateway is obviously critical, as the backhauling must be reliable to ensure connectivity with the network server.

The cellular modem is also subject to environmental interference. In case of colocation with LTE BS, the main causes of desensitization are:

- The LoRaWAN transmitter of the gateway, which may:
    - Generate out-of-band spurious emissions in the LTE DL band
    - Act as an out-of-band blocker for the LTE UE receiver
- The LTE BS transmitter (LTE BS DL), which may:
    - Generate out-of-band spurious emissions in the LTE DL band
    - Act as an out-of-band blocker for the LTE UE receiver
    - Generate intermodulation products in the LTE UE receiver
- Any other high-power emitter (DVB-T/T2 or other), which may:
    - Generate out-of-band spurious emissions in the LTE DL band
    - Act as an out-of-band blocker for the LTE UE receiver

The outdoor LoRaWAN gateways, therefore, embed at least two modems: a cellular modem and a LoRaWAN modem. Each one is connected to its own dedicated antenna. These antennas could be designed based on different technologies and are separated by a defined distance, leading to a certain isolation or mutual coupling between both antennas.

Mutual desensitization may occur due to either out-of-band blocking effect or out-of-band spurious emissions generated in the receive bands. The blocking effects are usually not the major concern, as both the cellular receiver and the LoRaWAN receiver have enough out-of-band rejection for that purpose.
The main concern is essentially out-of-band spurious emissions. Considering the out-of-band spurious emissions generated by a LoRaWAN gateway (see §3.5), about 40dB to 50dB isolation between antennas is required.

Distance between antennas is a key factor for antenna isolation. Obviously, this is less critical for an outdoor LoRaWAN gateway, because the gateways are generally based on large or medium-size enclosures. It is then naturally possible to optimize the antenna isolation when placing the antenna at a sufficient distance or even by deporting the antennas using coaxial cable and antenna brackets. However, even for outdoor LoRaWAN gateways, if no special care is taken during the design phase, isolation may be not enough.

Moreover, the colocation of the LoRaWAN gateways and LTE BS may cause some coexistence issues in the LTE UE module receiver, such as:

- High LTE BS power at backhaul RF port that may damage the cellular modem. RF power limiters may be recommended to mitigate this risk.
- Blocking due to LTE BS transmitter
- Intermodulation of LTE BS transmitter in the UE receive band

It must be noted that the LTE BS classes define also the minimum coupling between the BS and the UE:

- Wide-area BS: minimum coupling loss equal to 70dB
- Medium-range BS: minimum coupling loss equal to 53dB
- Local-area BS: minimum coupling loss equal to 45dB

About 40 – 50dB isolation can be obtained between the LTE BS antenna port and LoRaWAN gateway LTE port. Therefore, adding an attenuator at the gateway LTE RF port is recommended to increase the coupling loss and mitigate desensitization. The recommended value of the attenuator is provided in this table:

Attenuator to Be Added at Gateway LTE Port		
Wide-area Base Stations	**Medium-range Base Stations**	**Local-area Base Stations**
N/A	N/A	N/A
N/A	N/A	N/A
30dB	10dB or deported antenna	None
30dB	10dB or deported antenna	None
30dB	10dB or deported antenna	None

10 GATEWAY ENCLOSURE AND SHIELDS

In the previous chapters, we demonstrated that RF filtering is a key factor to ensure that a LoRaWAN gateway will not suffer from desensitization due to colocated emitters. The following filtering performance is expected:

- 70dB to 100dB attenuation in the channel filters of the transceiver and LoRa demodulator
- 60dB attenuation in the RF filters
- 40dB attenuation in an external or embedded cavity filter

Adding all the above attenuations, we can expect a significant amount of attenuation in the receiver path!

The LoRaWAN gateway, when colocated with other emitters, is surrounded by electromagnetic fields. The strength of these fields depends obviously on the proximity to these emitters and to their radiated power. These electromagnetic fields may leak directly into the electronic components of the LoRaWAN receiver.

For example, we may experience direct electromagnetic field leakage between LTE BS transmitter and the LoRa transceiver. In this case, the effects of RF filters and cavity filters are reduced to null! Electromagnetic interference (EMI) effects, therefore, must be carefully considered when designing an outdoor gateway.

In Europe, as part of the CE marking, LoRaWAN gateways must be compliant with ETSI EN 301 489-1 (see [10]), ensuring EMC compliance. Electromagnetic field immunity of the gateways is tested according to the EN 61000-4-3 procedure. A 3 V/m field is applied from 80MHz to 6GHz. This test may guarantee a good EMI performance of the gateway, but in the case of colocation with high-power emitters, this test is not sufficient, as stronger fields can be reached.

To optimize the EMC performance of the LoRaWAN gateway, effective shielding is required in colocated sites. The shields can be used at different levels:

- Enclosure: Using a metal enclosure is an easy and efficient way to improve EMC performance. However, some precautions must be considered to avoid degradation of performance:
    - Avoid or reduce aperture size
    - Use EMI gaskets
    - Connect all metal parts together (cover, frame, etc.)

  A plastic enclosure (ABS, polycarbonate) could be also envisaged, but internal shielding should be reinforced in this case.
- Module: A modular conception is especially convenient when using a plastic enclosure. Each module is inserted in a metal box, providing the required EMC protection.
- PCB: Effective PCB cans must be used to cover radio chipsets to avoid internal coupling inside the gateway and protect them from external interference.
- Cables: Efficiently shielded cables must be used to interconnect PCB.

Finally, the enclosure and the associated mounting kit, antenna brackets, etc., must be connected to the installation site's grounding system for effective EMI protection.

11 CONCLUSION

When colocating a LoRaWAN gateway with high-power transmitters and/or wide-area LTE base stations or medium-range LTE base stations, usage of cavity filters is recommended to mitigate blocker effects, intermodulation effects, and transmit intermodulation. This recommendation is driven by technical aspects, as shown in this application note, but also because the site environment is not under the control of the installer. LTE emitters or DVB-T emitters may be located close to the LoRaWAN gateway site without any possibility to modify it. Using a cavity filter may correct many potential issues. The additional cost of the cavity filter is very low compared with the intervention costs and improvement in quality of service on the installation site.

However, cavity filters do not fix all the possible issues. In particular, out-of-band spurious emissions generated by high-power transmitters, wide-area LTE base stations, or medium-range LTE base stations may cause desensitization of the LoRaWAN gateways if minimum vertical and horizontal separation are not respected. These distances are detailed in this white paper and can be roughly summarized by region:

- Europe: 2m vertical separation, 300m horizontal separation
- North America: 2m vertical separation, 150m horizontal separation
- LATAM (AU915-928): 2m vertical separation, 300m horizontal separation. Using UL channels 915 – 922MHz is recommended, rather than 922 – 928MHz.
- APAC (AS923): 7m vertical separation, 1500m horizontal separation. Selection of the channels must be carefully considered to optimize the frequency separation with the LTE DL band and mitigate potential desensitization.

Moreover, when installing a LoRaWAN gateway with another LPWAN gateway, a minimum vertical separation distance is required, depending on the region:

- Europe: 5m vertical separation, 200m horizontal separation
- North America: 1m vertical separation, 30m horizontal separation
- LATAM (AU915-928): 10m vertical separation, 300m horizontal separation. Using UL channels 915 – 922MHz is recommended, rather than 922 – 928MHz.
- APAC (AS923): 50m vertical separation, 1500m horizontal separation. Colocation is therefore not recommended unless using separate channelization.

The focus is usually put on the LoRa link, but the GNSS receiver and the LTE backhauling must be also considered. Choice of the antenna is key for better GNSS performance. Separation distance and attenuators (up to 30dB) may be considered to improve the LTE link.

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