

SHORT-RANGE DEVICES, INDOOR RADIO PROPAGATION

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Observe precautions! Electrostatic sensitive devices!

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Packing: Please use the recycling operators known to you.

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1 Introduction

Short-range radio devices, such as wireless switches, sensors and actuators, are often installed inside buildings. In indoor environments, walls, floors, furniture and other objects attenuate and reflect the radio signal. Therefore, the range that can be achieved depends strongly on the building and is difficult to predict.

This application note explains the basic terms and gives simple rules of thumb for planning reliable indoor radio installations. It covers the relationship between power and dBm, the frequency bands, antenna basics, indoor propagation and path loss, receiver performance, radio noise, fade margin, the link budget, repeaters and cable loss.

All values in this document are typical values for reference. They do not replace a check at the installation site.

1.1 References

[1] Recommendation 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 from 300 MHz to 450 GHz

[2] ERC Recommendation 70-03: Relating to the use of Short Range Devices (SRD)

2 Power, dBm and range

Radio signals are electromagnetic waves. The signal becomes weaker the further it travels. In free space, the received power decreases with the square of the distance. This means that the received power drops by 6 dB each time the distance doubles.

Radio frequency (RF) output power is given in milliwatts (mW) or, more usefully, on a logarithmic scale in decibels (dB). The unit dBm is the power in decibels relative to 1 mW:

$$P [\text{dBm}] = 10 \cdot \log_{10}(P [\text{mW}])$$

With the logarithmic scale, calculations are simple: gains and losses in dB are just added or subtracted. Table 1 shows how the two scales relate.

Table 1 Relation between power in mW and dBm

Power [mW]	Power [dBm]	Relation
1	0	Reference level
2	3	2 times the power adds 3 dB
4	6	6 dB more power doubles the range in free space
10	10	10 times the power adds 10 dB
100	20	100 times the power adds 20 dB

In the same way, every additional 6 dB of loss reduces the range in free space to half.

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3 Frequency bands and general limitations

Short-range wireless applications typically operate in license-free frequency bands with limited transmit power. These bands are often called ISM bands (Industrial, Scientific and Medical) or SRD bands (Short Range Devices). The allowed frequencies and power levels vary from country to country. For Europe, they are listed in [2]. The most common license-free bands for short-range devices are:

- **2.4 GHz band:** available nearly worldwide
- **868 MHz band:** Europe and some other countries (sub-GHz band)
- **900 MHz bands:** for example North America, Japan and some other countries (sub-GHz band)

Independent of the frequency and the technology used, the bit error rate (BER) of a wireless link is always orders of magnitude higher than the BER of a wired link. Wireless systems must therefore be planned with sufficient reserve (see section 8).

4 Antenna basics

The antenna converts the RF power of the transmitter into a radio wave. At the receiver, it converts the radio wave back into RF power. The design and the placement of the antenna have a large effect on the range. The main points are:

- **Frequency:** The antenna must be tuned to the operating frequency. For example, a quarter-wave ($\lambda/4$) whip antenna is about 86 mm long at 868 MHz and about 31 mm long at 2.4 GHz.
- **Matching:** The antenna must be matched to the impedance of the radio circuit, usually 50 Ω . A mismatch reflects part of the power and reduces the radiated power.
- **Efficiency:** Efficiency is the ratio of radiated power to input power. Small or integrated antennas often have a low efficiency. Every dB lost in the antenna reduces the link budget in the same way as a cable loss.
- **Polarization:** For best results, the antennas of the transmitter and the receiver should have the same orientation, for example both vertical.
- **Environment:** Housing, mounting surface, batteries, cables and nearby metal detune the antenna and absorb energy. Keep the antenna away from metal parts and never place it inside a metal enclosure.

The antenna gain cannot be increased without limit. The radiated power, including the antenna gain, must stay within the limits of the local radio regulations.

5 Indoor radio propagation and path loss

Indoor radio propagation depends strongly on the shape and the structure of the building. It is therefore very difficult to predict, and the result is rarely exactly as planned. Keep in mind that planned distances are often based on ideal conditions. If the distance is made as long as possible, the link quality is always close to its limit.

Buildings contain many objects that reflect radio waves. The signal therefore travels from the transmitter to the receiver on many different paths (multipath propagation, see Figure 1 a). Unlike in free space, the received signal is a mix of these paths. Depending on their

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phase, the signals add up or cancel each other at the receiver input. Moving the antenna by only a small distance, for example a quarter wavelength (about 9 cm at 868 MHz), can change the received signal strength significantly.

Some obstacles move, for example people and doors, and the environment can change over time. Metal objects block and reflect radio waves very strongly.

The attenuation of an obstacle depends on its material, its thickness and the angle at which the radio wave passes through it. At an oblique angle, the path through the wall is longer (see Figure 1 b). The attenuation of a material also depends on the wavelength: the higher the frequency, the higher the attenuation. Sub-GHz frequencies are therefore clearly better suited for indoor installations than 2.4 GHz.

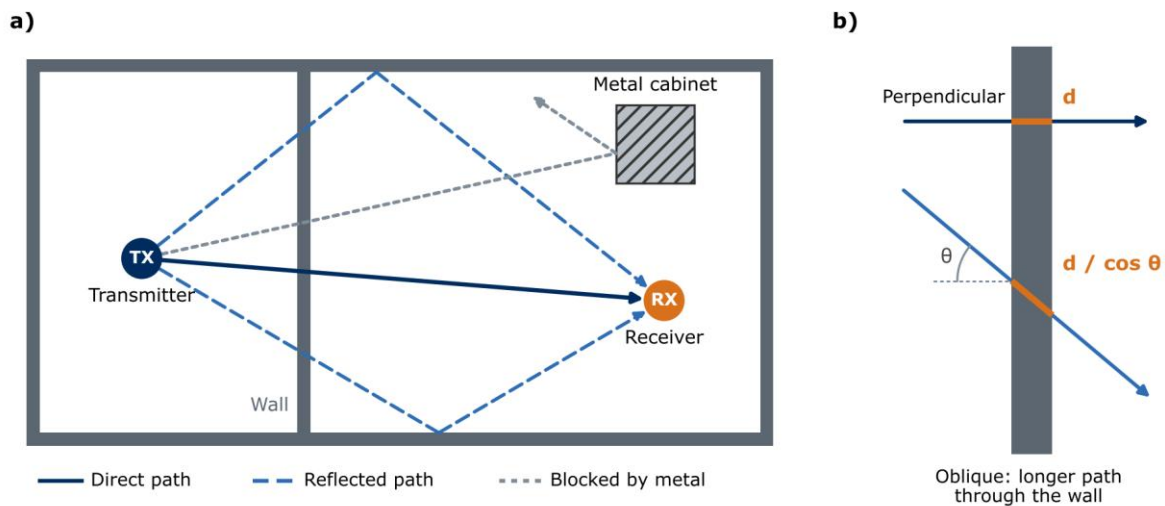


Figure 1 Multipath propagation (a) and path through a wall at an angle (b)

Table 2 gives typical values for common building materials in the 900 MHz bands. Use them for reference only.

Table 2 Typical attenuation of building materials in the 900 MHz bands

Material	Range reduction [%]	Attenuation [dB]
Wood, plaster, uncoated glass	5 to 10	3 to 5
Brick, pressboard	10 to 30	6 to 10
Reinforced concrete (200 mm)	20 to 80	15 to 20
Metal, aluminum lining	80 to 95	90

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5.1 Rules of thumb for indoor planning

- In free space, an additional loss of 6 dB reduces the range by half.
- Within one room, the area within 5 m around the antenna can, in the best case, be treated as quasi line of sight (LoS). Beyond this distance, the radio paths become more complex, and the planning rules must be more conservative.
- In a line-of-sight application, never plan more than 50 % of the maximum range specified by the manufacturer. This alone gives a fade margin of 6 dB, which is the minimum requirement.
- Indoors, beyond the first 5 m, each doubling of the distance increases the path loss by 10 dB to 15 dB. The increase becomes larger with the distance, because more obstacles are in the way.

5.2 Estimating the indoor path loss

As a first empirical rule, the path loss L at 0.9 GHz in typical indoor environments within a radius of 20 m can be estimated with the following equation:

$$L [\text{dB}] = L_{\text{FS}} [\text{dB}] + k [\text{dB/m}] \cdot D [\text{m}]$$

where L_{FS} is the free space loss, D is the distance and k is a frequency-dependent constant. At 0.9 GHz, $k = 0.9 \text{ dB/m}$. The free space loss is calculated as follows:

$$L_{\text{FS}} [\text{dB}] = 20 \cdot \log_{10}(D [\text{m}]) + 20 \cdot \log_{10}(f [\text{MHz}]) - 27.55$$

Table 3 gives rough estimates of the indoor path loss in the 0.9 GHz band without walls between the transmitter and the receiver. Figure 2 shows the same estimate as a function of the distance.

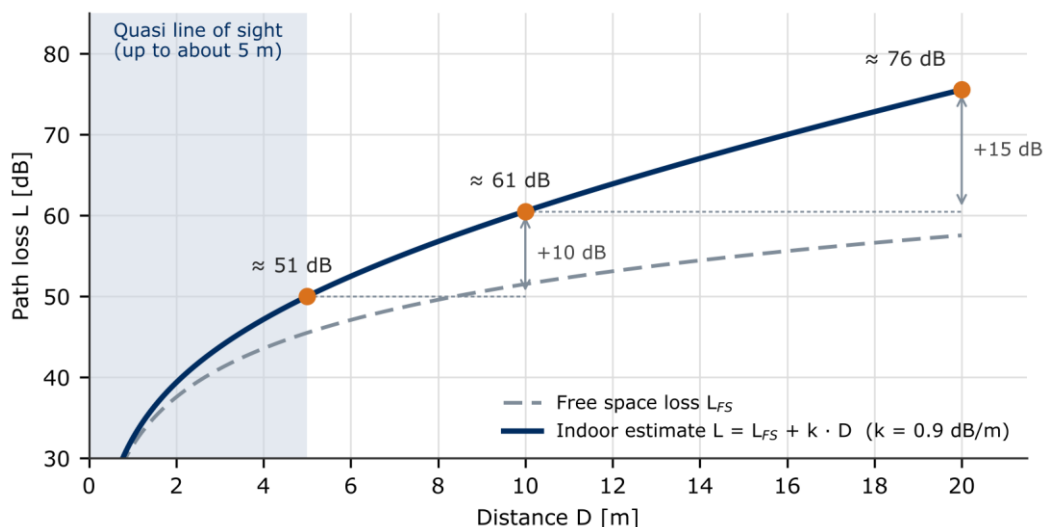


Figure 2 Estimated indoor path loss versus distance at 0.9 GHz

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Table 3 Estimated indoor path loss at 0.9 GHz without walls in the radio path

Distance D	L_{FS}	$k \cdot D$	Path loss L
5 m	46 dB	4.5 dB	51 dB
10 m	52 dB	9 dB	61 dB
20 m	58 dB	18 dB	76 dB

Each wall between the transmitter and the receiver adds its attenuation from Table 2 to this estimate.

6 Receiver sensitivity and selectivity

The range does not only depend on the antennas and the transmit power. The receiver is just as important.

The more sensitive the receiver, the weaker the signal that it can still receive successfully. The lower limit is the noise floor: the signal must be above the noise by a certain signal-to-noise ratio (S/N) to be decoded correctly.

Receiver sensitivity is specified in many different ways, so it is difficult to compare products directly. The most common specification refers to a certain bit error rate (BER), measured in an ideal environment that is shielded from external noise.

Receiver sensitivity is given in dBm as a negative number. The larger the absolute value, the better the sensitivity. For example, a sensitivity of -98 dBm is 3 dB better than a sensitivity of -95 dBm, which is a factor of two. At the same frequency and data rate, a receiver with -98 dBm sensitivity can receive signals with half the power of the signals that a receiver with -95 dBm sensitivity needs.

Selectivity is another important factor, especially in a noisy environment. It describes how well the receiver suppresses unwanted signals. Avoiding and filtering radio interference, for example from the device's own power supply, from heavy loads such as ballasts, dimmers and motors, or from digital circuitry, improves the receiver performance.

In summary, an efficient antenna is essential for good transmission, because the transmitted signal is not affected by the noise floor. However, a good antenna alone does not guarantee good reception.

7 Radio noise and interference

RF background noise comes from many sources: power supplies, heavy loads, high-frequency digital products and all other kinds of radio communication. This background noise sets the noise floor. Weak radio signals below the noise floor are lost. In the worst case, interference corrupts the data.

The noise floor is not constant and varies with the frequency. Usually, the noise floor is lower than the receiver sensitivity, so it is not an important factor. However, in an environment with strong RF noise in the operating frequency band use the noise floor instead of the receiver sensitivity in the calculation (see section 9).

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If such an environment is suspected, a simple site survey, for example with a spectrum analyzer, shows the actual noise floor. This small investment often pays off. Some sources of interference are not obvious. Even the receiver or actuator itself can be a source of interference.

8 Planning with sufficient reserve

Fade margin is a critical factor for wireless success. Fading is a temporary drop of the received signal, caused for example by people moving, doors opening or closing, or reflected signals canceling each other. The fade margin describes by how many dB the received signal can drop before the system performance falls below an acceptable level. Leaving a newly commissioned installation without knowing its fade margin is the most common cause of wireless problems.

A link budget reserve of more than 6 dB gives a high degree of confidence that the system will continue to work reliably, even when the environmental conditions change.

The fade margin can be checked without special equipment. For example, insert a small 6 dB attenuator into the antenna line of the transmitter or the receiver. If the communication fails with the attenuator, the fade margin is not sufficient.

9 Link budget calculation

The range of a radio link can be estimated with simple calculations. Based on the propagation basics described above, the following rule applies. A wireless link works reliably if:

$$\text{TX power} + \text{TX antenna gain} - \text{path loss} - \text{cable loss} + \text{RX antenna gain} - 6 \text{ dB} \\ \text{fade margin} > \text{RX sensitivity (or RF noise floor)}$$

All values are given in dB or dBm. Most parameters can be found in the manufacturer's specifications. Only the path loss and, in case of strong interference, the RF noise floor must be estimated, or covered by a sufficient safety margin in the installation.

Table 4 shows an example with typical values for a link over 20 m indoors through one brick wall. Figure 3 shows the same calculation as a level diagram.

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Table 4 Link budget example

Parameter	Value
TX power	+5 dBm
TX antenna gain	-2 dBi
Path loss: 20 m indoors (76 dB) plus one brick wall (10 dB)	-86 dB
Cable loss	-1 dB
RX antenna gain	0 dBi
Received signal level	-84 dBm
Fade margin	-6 dB
Result compared with RX sensitivity	-90 dBm > -95 dBm: link OK

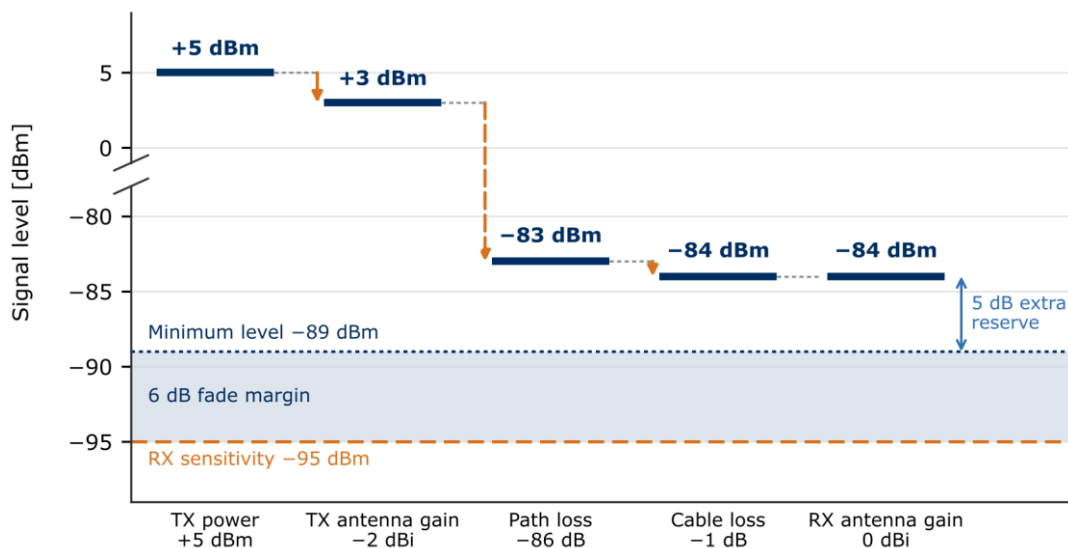


Figure 3 Level diagram of the link budget example

The received level of -84 dBm is 11 dB above the receiver sensitivity. After the 6 dB fade margin, 5 dB of extra reserve remain. If the brick wall is replaced by a reinforced concrete wall with 20 dB attenuation, the received level drops to -94 dBm. Only 1 dB then remains above the sensitivity, and the required fade margin is no longer available. In this case, change the device positions or use a repeater (see section 10).

10 Planning repeaters in advance

In critical environments, for example with long distances, many walls, reinforced concrete or large metal objects, plan the use of repeaters from the start. A repeater receives a radio telegram and transmits it again. This extends the range or bypasses an obstacle.

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- Place the repeater where it has a good link to both the transmitter and the receiver, for example around the middle of the path or at a corner around an obstacle.
- Apply the same planning rules to each repeater link. Every link needs a sufficient fade margin.
- Identify suitable mounting positions during the planning phase. Many line-powered devices, such as actuators and gateways, can also work as repeaters.
- Use only as many repeaters as needed. Each repetition adds radio traffic and increases the risk of telegram collisions.
- The EnOcean radio protocol supports one or two repeater levels. A telegram can therefore be repeated up to two times.

11 Avoiding cable loss

High frequencies do not propagate well through long cables and connectors. Use a short, low-loss RF coaxial cable with the correct impedance (for example 50 Ω) between the radio module and the antenna. Make sure that all connectors are of good quality and carefully installed. Always use the PCB footprint recommended by the connector manufacturer.

Calculate 0.3 dB loss per coaxial connector in addition to the attenuation of the cable itself. Table 5 lists typical attenuation values for three common 50 Ω coaxial cables.

Table 5 Typical cable loss in dB per 10 m cable length

Frequency	RG-174	RG-58	LMR-400
900 MHz	10	5 to 8	1
2.4 GHz	N/A	12	2

12 Summary

The following rules help to plan reliable installations and to avoid range problems in the field:

- Plan with no more than 50 % of the maximum range specified by the manufacturer, even with line of sight.
- Plan a link budget reserve (fade margin) of more than 6 dB.
- Take every wall and obstacle in the radio path into account, and keep antennas away from metal.
- Sub-GHz frequencies are preferred for indoor installations.
- Check the noise floor in environments with strong interference.
- Keep antenna cables short, and use low-loss cables and good connectors.
- Plan repeater positions in advance for critical environments.
- Check the fade margin after the installation, for example with a 6 dB attenuator.

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DISCLAIMER

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