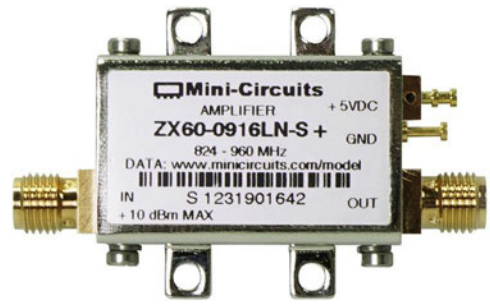
Range improvement with preamplifiers



White paper 902931

90293100T87Z001K000

V1.00/EN/00710001

Contents

Contents

1.1 The range of a wireless transmission path

The range of a wireless transmission path is determined by the emitted transmission power, the receiver's sensitivity, and the properties of the medium between the transmitter and receiver. The equation (1) provides the path attenuation SD between the transmitter and receiver antenna in dB:

$$SD(d) = 20 \bullet \lg \frac{4\pi \bullet 1\,m}{\lambda} + 10 \bullet n \bullet \lg \frac{d}{1\,m} \qquad (1)$$

In this equation, λ is the wavelength, d is the distance between the transmitter and receiver antenna, and n is something known as the loss exponent.

In a clear space free from objects, this means that the loss exponent n equals 2 when the transmitter and receiver antennas are set up high off the ground without any obstacles between them.

Fig. 1-1 shows the path attenuation in a clear space as a function of distance d for three frequently used, license-free frequency bands.

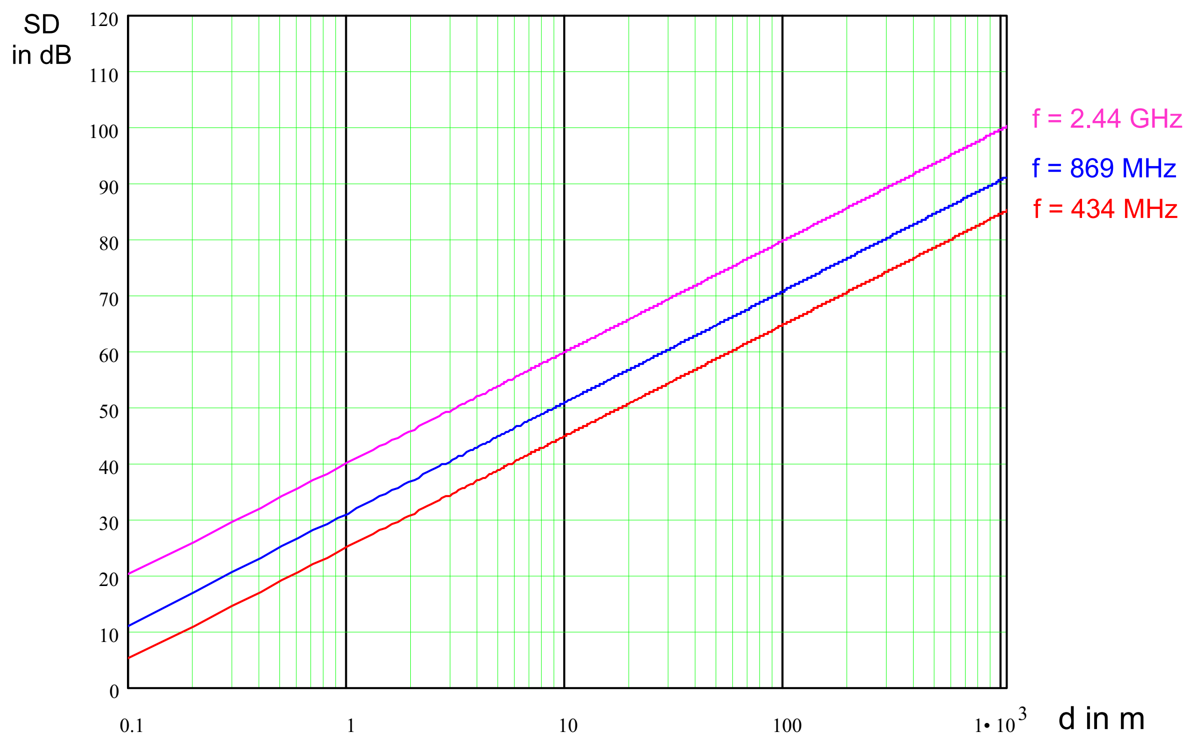


Fig. 1-1 Path attenuation in a clear space (n = 2)

Fig. 1-1 can be used as an initial indication for the expected range for a wireless transmission path. It is important to note that doubling the distance in a clear space results in the path attenuation increasing by 6 dB. Vice versa, increasing the transmission power by 6 dB doubles the range.

In practice, however, the loss exponent n rarely equals 2. Inside buildings, n can be between 3 and 4. If the distance is doubled, the path attenuation then rises to between 9 and 12 dB. A common rule of thumb tends be that increasing the transmission power by 10 dB (or improving the sensitivity by 10 dB) doubles the range.

If the transmission power, the antenna gains, and the properties of the transmission path are fixed, the only way to increase the range is to improve the receiver sensitivity. The next section will therefore look at the variables that can be used to influence the sensitivity of a receiver.

1.2 Additional noise, noise factor, and sensitivity of a wireless receiver

In the frequency range observed here, the thermal noise sets a theoretical limit on the sensitivity of wireless receivers. The thermal noise is the result of the Brownian motion of the load carriers, which generates a random voltage at the connections for each resistor at temperatures above the absolute zero point. At room temperature, the spectral density of the thermal noise is -174 dBm/Hz.

The thermal noise can be regarded as white noise with a consistent spectral density. The noise power therefore equals the noise power spectral density multiplied by the bandwidth. Wireless receivers for small data rates can therefore be more sensitive than those for quick data transmission rates.

Every module (even ideal noise-free ones) has an input noise level, which cannot be below the thermal noise power of -174 dBm at a 1 Hz bandwidth at room temperature. At a power density of -174 dBm/Hz, the thermal noise is present at each point in an electrical circuit or system.

Unfortunately, every amplifier used in practice adds additional noise on top of the unavoidable thermal noise. This additional noise is the result of factors such as surface effects, contamination, or contact effects. Fig. 1-2 shows the effect of additional noise on an amplifier's signal-noise ratio.

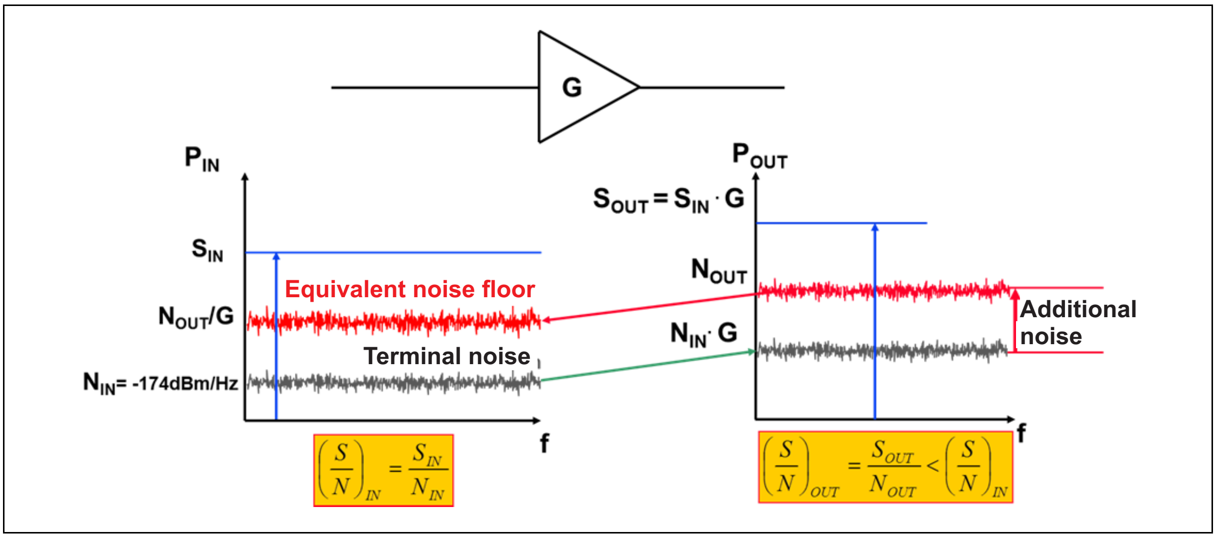


Fig. 1-2 Deterioration of the signal-noise ratio due to additional noise

Additional noise means that the signal-noise ratio at a module's output is always worse than at the input. This deterioration can be described in quantitative terms using the noise figure:

$$F = \frac{\left(\frac{S}{N}\right)_{IN}}{\left(\frac{S}{N}\right)_{OUT}} \qquad (2)$$

The noise factor NF is often used as a logarithmic element:

$$NF = 10 \bullet \lg F \qquad (3)$$

The noise factor describes the inherent noise generated by the module and is synonymous with the deterioration of the signal-noise ratio caused by the module, on the condition that only the thermal noise at the module's input is taken into account. The signal-noise ratio at a module's output can never be higher than the ratio at its input; due to the module's unavoidable additional noise, it is always lower than at the input.

All sources of noise for a receiver – related to its input – generate the equivalent noise floor. The noise factor indicates in dB how much higher the equivalent noise floor at a module's input is than the thermal noise of -174 dBm/Hz.

The sensitivity of a wireless transmitter then equals the equivalent noise floor at the input plus the signal-noise ratio, which, for example, is required for a certain bit error rate.

The noise figure of an attenuator can be used as an example (Fig. 1-3).

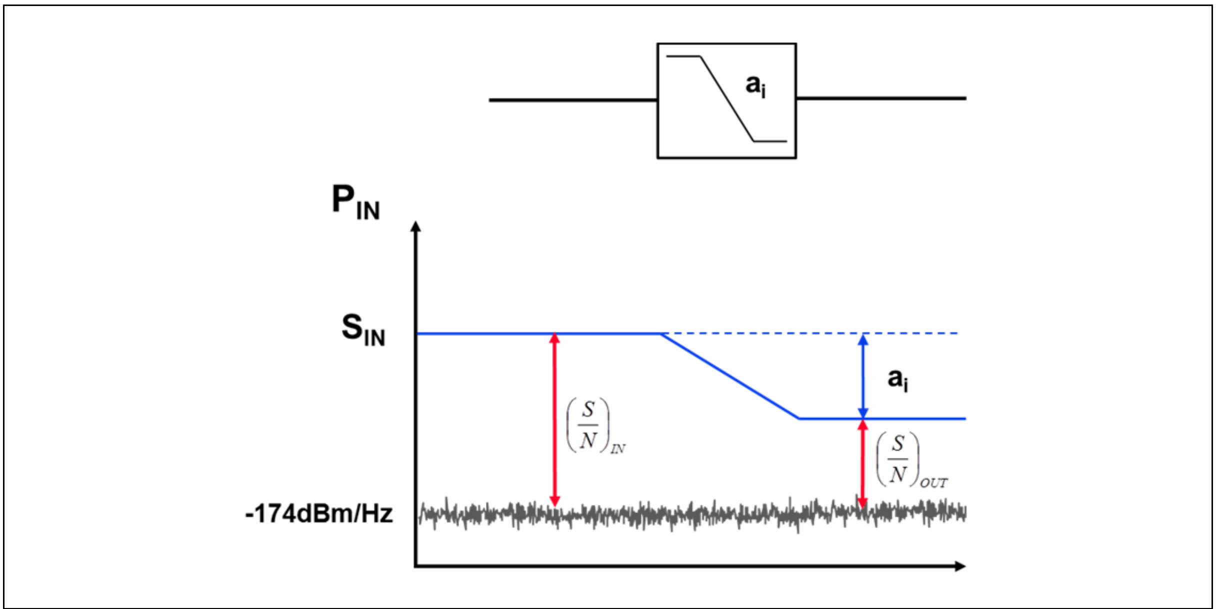
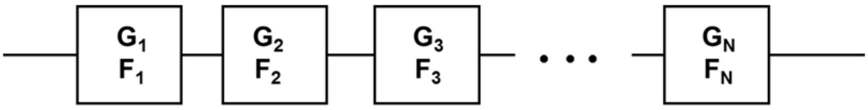


Fig. 1-3 Effect of an attenuator: the noise factor is the same as the attenuation

At the attenuator's output, the signal power is the input signal power minus a_i (total attenuation). However, the thermal noise power density is the same across the entire system at -174 dBm/Hz. The signal-noise ratio at the attenuator's output is therefore equal to the input ratio minus the total attenuation. An attenuator's noise factor is therefore equal to its attenuation. Over the signal path, the signal-noise ratio can never be higher than $(S/N)_{OUT}$ at the attenuator's output. In a practical example, the attenuator can be depicted by a cable, power section, or plug connector, for example.

In general, the noise figure for a chain of modules can be calculated with the noise figures F_i and the gains G_i according to the Friis formula (4):



$$F_{CHAIN} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \bullet G_2} + \dots + \frac{F_N - 1}{G_1 \bullet G_2 \bullet \dots \bullet G_{N-1}} \qquad (4)$$

Findings:

1) The noise figure for the first module in a chain is added straight to the total noise figure; the effect of the noise from the following stages is then reduced by the gain from the previous stages.
2) The improvement to the sensitivity caused by a preamplifier is not the same as its gain, but instead corresponds to the improvement to the total noise figure according to the Friis formula.

It is important to make sure that linear values are used in the formula (4) instead of dB values!

This is clarified by an example:

1 Basic principles: noise, sensitivity, and range

The sensitivity of a receiver with a noise factor of 6 dB is due to be improved by a preamplifier with a noise factor of 1 dB and a gain of 15 dB. How high is the expected improvement to receiver sensitivity in dB?

Solution:

First of all, the logarithmic values for the noise factor NF and the gain in the linear values for the noise figure F must be converted:

$$F_1 = 10^{\frac{NF_1}{10}} = 10^{\frac{1}{10}} = 1.259 \tag{5}$$

$$F_2 = 10^{\frac{NF_2}{10}} = 10^{\frac{6}{10}} = 3.981 \tag{6}$$

$$G_1 = 10^{\frac{15}{10}} = 31.6 \tag{7}$$

The Friis formula then generates:

$$F_{total} = 1.259 + \frac{3.981 - 1}{31.6} = 1.353 \tag{8}$$

The chain's noise factor is:

$$NF_{total} = 10 \bullet \lg 1.353 = 1.31\ dB \tag{9}$$

The improvement to sensitivity is therefore 6 dB - 1.31 dB = 4.69 dB.

2 Sensitivity improvement by a preamplifier

2.1 Specifications for the receiver and the recommended additional modules

The sensitivity of the receiver JUMO Wtrans T01.ECI with a data rate of 100 kBit/s and a frequency swing of ±50 kHz is normally -95 dBm. This roughly corresponds to a noise factor of NF = 13 dB or a linear noise figure of F = 20. The sensitivity can be increased significantly using a preamplifier.

The JUMO Wtrans T01.ECI was designed for use with the λ/4 antenna (part no. 00503151) on the wall-mounted antenna bracket (part no. 00482648). In electrical terms, this antenna is a monopole antenna with ground plane and a gain of around 5 dBi. If the antenna is mounted directly on the Wtrans T01.ECI instead of on the wall bracket, a range decrease of up to 40 % must be expected due to the lack of ground plane.

Preamplifier

To improve the sensitivity and range, JUMO recommends using the low-noise preamplifier **ZX60-0916LN-S+** by Mini-Circuits. In the 868 MHz bandwidth, this amplifier normally has the following performance figures:

Noise factor, typ.:	NF = 0.6 dB (corresponds to linear noise figure F = 1.15)
Gain, typ.:	G = 18 dB (corresponds to a linear power gain of 63)
Operating voltage:	V_{suppl} = 5.0 V typ., 5.5 V limit value
Current consumption:	I_{suppl} = 40 mA typ.
Operating temperature:	-40 to +85 °C

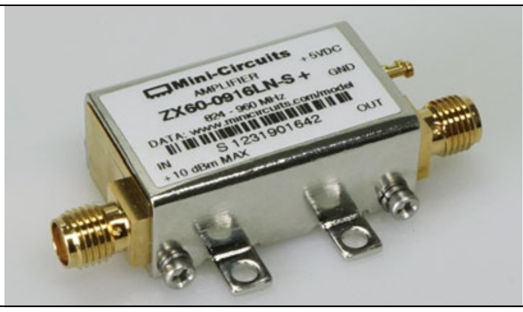


Fig. 2-1 Low-noise preamplifier ZX60-0916LN-S+ by Mini Circuits

Power splitter/combiner

In some applications, multiple antennas are connected to one receiver or multiple receivers are connected to one antenna. In these cases, it must be ensured that all modules with a system impedance of 50 Ω are terminated. For this purpose, JUMO recommends the power splitter/combiner **ZAPD-1-S+** by Mini-Circuits for cases where two cables are due to be connected to one input or output, or the **ZB4PD1-930-S+** where four cables are due to be connected to one input or output.

As the name suggests, power splitters/combiners are reciprocal elements, which means they are able to split a signal between two inputs and also to combine two signals.

The **ZAPD-1-S+** has a sum port S, which is located on one side of the housing, as well as two identical connections on the opposite side, which are marked with "1" and "2".

Fig. 2-2 Connections on the power splitter ZAPD-1-S+

When a signal is fed into the sum port S, it is split evenly between the two connections 1 and 2. In a frequency range of around 868 MHz, the insertion loss is normally 3.35 dB. The same insertion loss is achieved when a signal is fed into connection 1 or 2 and collected at the sum port. A unique scenario occurs when signals with the same amplitude, frequency, and phase are connected to connections 1 and 2: the insertion loss at the sum port is then just 0.35 dB.

Connections 1 and 2 are isolated from one another: the attenuation between these two connections is over 30 dB.

All of these specifications are valid provided that all of the power splitter/combiner's connections with 50 Ω are terminated.

Here is a summary of the most important specifications:

Insertion loss S ↔ 1 or S ↔ 2:	3.35 dB
Isolation 1 ↔ 2:	>30 dB
Insertion loss 1+2 → S:	0.35 dB for the same frequency, amplitude and phase

The **ZB4PD1-930-S+** is used if four cables are due to be connected to one input or output. The most important specifications for this power splitter/combiner are as follows:

Insertion loss S ↔ 1 to 4:	6.3 dB
Isolation 1 to 4:	>30 dB
Insertion loss 1+2+3+4 → S:	0.3 dB for the same frequency, amplitude and phase at all inputs

The final scenario (frequency, amplitude, and phase are identical at all four inputs) rarely occurs in practice.

Bias tee

The final additional module to be described is something known as a bias tee. A bias tee is used to supply modules with direct current via a high-frequency cable. Figure Fig. 2-3 shows a typical electrical circuit:

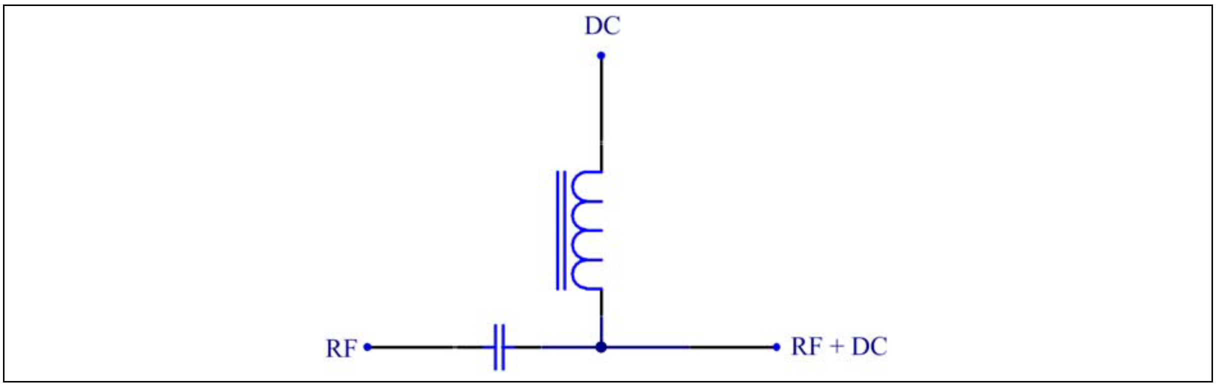


Fig. 2-3 General circuit with a bias tee

Bias tees have been optimized to ensure good isolation between the high-frequency path and the direct current path using a broad frequency range. A suitable bias tee is the **ZFBT-4R2G-FT+** by Mini-Circuits. The following specifications are useful for the frequency range of 869 MHz:

Insertion loss of the HF path:	0.33 dB typ.
Isolation between direct current and HF path:	40 dB typ.
Maximum admissible HF output:	+30 dBm
Maximum admissible direct voltage:	30 V
Maximum admissible direct current:	500 mA

JUMO supplies the RG174 coaxial cables in lengths of 3 m, 5 m, and 10 m for connecting offset antenna. This cable is specified for ambient temperatures of up to 85°C. JUMO can provide the coaxial cable RG316 in a length of 10 m for higher temperatures up to 125°C. The attenuation for these cables is around 0.95 dB/m for the RG174 and 0.9 dB/m for the RG316; in general, a cable attenuation of 1 dB/m is assumed.

The following section examines various combinations of the receiver JUMO Wtrans T01.ECl with the additional modules described above.

2.2 Antenna – Cable – Receiver

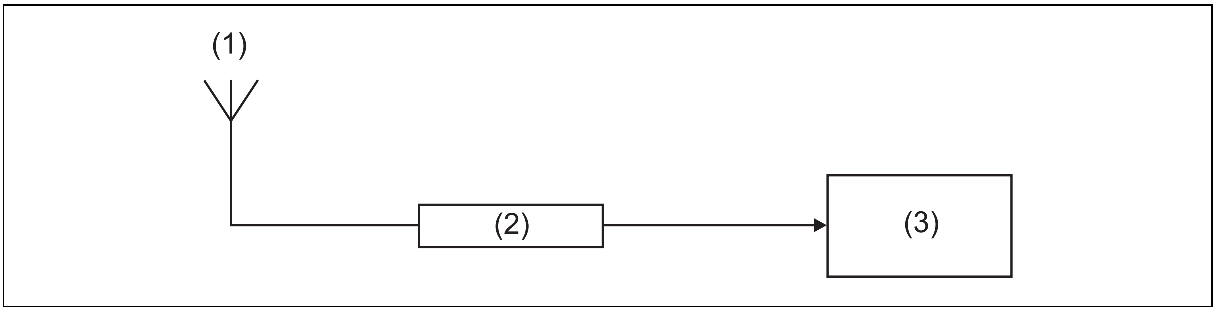


Fig. 2-4 Antenna – Cable – Receiver

(1) Antenna
(2) Cable
(3) Receiver

The first element in the signal path is an attenuator; the attenuation of the cable is added straight to the noise figure and, as a result, to the sensitivity as well. A 10-metre cable therefore reduces the sensitivity from -95 dBm to -85 dBm, for example.

The following table contains the total noise figures and receiver sensitivity for the three cable lengths available from JUMO, as well as for cable lengths of 20 m and 30 m.

Cable length	**NF_{tot}**	**Receiver sensitivity**
3 m	16 db	-95 dBm - 13 db + 16 dB = **-92 dBm**
5 m	18 db	-95 dBm - 13 db + 18 dB = **-90 dBm**
10 m	23 db	-95 dBm - 13 db + 23 dB = **-85 dBm**
20 m	33 db	-95 dBm - 13 db + 33 dB = **-75 dBm**
30 m	43 db	-95 dBm - 13 db + 43 dB = **-65 dBm**

Tab. 2-1 Receiver sensitivity figures for the arrangement: Antenna – Cable – Receiver

These results show that the sensitivity is significantly impaired for long cable lengths in particular.

2.3 Antenna – Cable – Preamplifier – Receiver

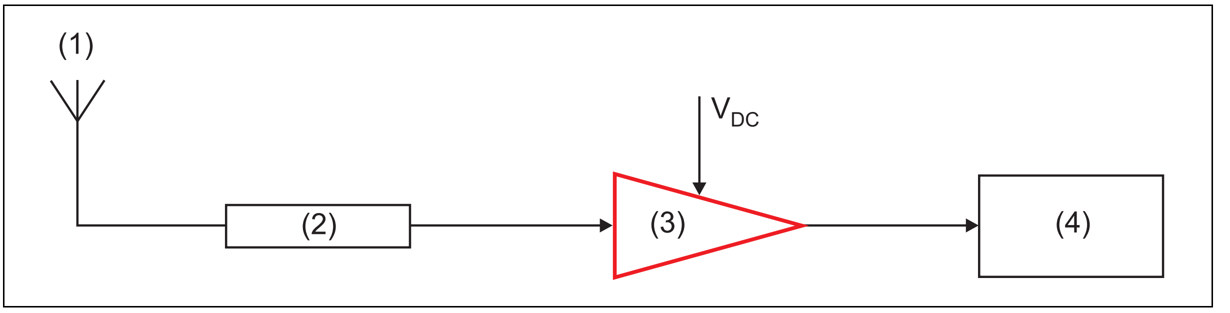


Fig. 2-5 Antenna – Cable – Preamplifier – Receiver

(1) Antenna
(2) Cable
(3) Preamplifier ZS60-0916LN-S+
(4) Receiver

In this arrangement, the preamplifier helps to suppress the additional noise from the receiver; however, the cable attenuation is still added to the total noise figure.

According to the Friis formula, the receiver's noise figure plus the preamplifier (without cable) is:

$$F_{RX + VV} = 1.15 + \frac{20 - 1}{63} = 1.45 \quad (10)$$

This corresponds to the logarithmic noise factor:

$$NF_{RX + VV} = 10 \bullet \lg 1.45 = 1.62\ \text{dB} \quad (11)$$

The cable attenuation in dB is then added to this. This results in the noise factor NF_{tot} for the receiver with the antenna cable. The sensitivity of the receiver with an original noise factor of 13 dB improves by 13 dB - NF_{tot} to -95 dBm - 13 dB + NF_{tot}.

For the cable lengths examined here, this means:

Cable length	NF_{tot}	Receiver sensitivity
3 m	4.62 dB ≈ 4.6 dB	-95 dBm - 13 db + 4.6 dB = **-103.4 dBm**
5 m	6.62 dB ≈ 6.6 dB	-95 dBm - 13 db + 6.6 dB = **-101.4 dBm**
10 m	11.62 dB ≈ 11.6 dB	-95 dBm - 13 db + 11.6 dB = **-96.4 dBm**
20 m	21.62 dB ≈ 21.6 dB	-95 dBm - 13 db + 21.6 dB = **-86.4 dBm**
30 m	31.62 dB ≈ 31.6 dB	-95 dBm - 13 db + 31.6 dB = **-76.4 dBm**

Tab. 2-2 Receiver sensitivity figures for the arrangement: Antenna – Cable – Preamplifier – Receiver

2.4 Antenna – Preamplifier – Cable – Receiver

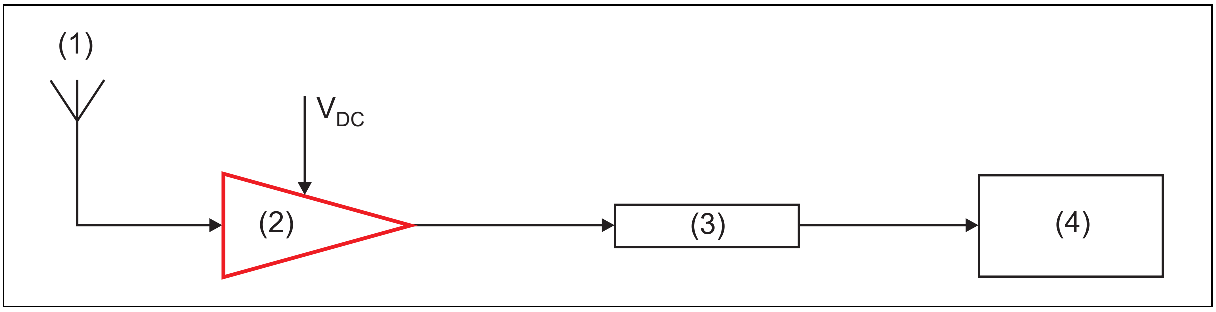


Fig. 2-6 Antenna – Preamplifier – Cable – Receiver

(1) Antenna
(2) Preamplifier ZS60-0916LN-S+
(3) Cable
(4) Receiver

In the configurations examined so far, the logarithmic cable attenuation is added directly to the total noise factor and, thus, to the receiver sensitivity. This can have a significant effect on longer cable lengths.

The best sensitivity is achieved when the preamplifier is connected directly to the antenna, i.e., in front of the cable. Because the cable's attenuation can be added directly to the 13 dB noise factor of the Wtrans T01.ECI, this has the following effect on the total noise figure:

$$F_{total} = 1.15 + \frac{10^{\frac{13 + a_{Cable}}{10}} - 1}{63} \quad (12)$$

This results in the following values for the total noise figure and sensitivity:

Cable length	F_{tot}	NF_{tot}	**Receiver sensitivity**
3 m	1.77	2.47 dB	-95 dBm - 13 db + 2.5 dB = **-105.5 dBm**
5 m	2.14	3.30 dB	-95 dBm - 13 db + 3.3 dB = **-104.7 dBm**
10 m	4.30	6.34 dB	-95 dBm - 13 db + 6.3 dB = **-101.7 dBm**
20 m	32.8	15.15 dB	-95 dBm - 13 db + 15.2 dB = **-92.8 dBm**
30 m	317.8	25.02 dB	-95 dBm - 13 db + 25.0 dB = **-83.0 dBm**

Tab. 2-3 Receiver sensitivity figures for the arrangement: Antenna – Preamplifier – Cable – Receiver

A comparison with table 2 shows that this configuration significantly improves the sensitivity compared to the arrangement in Fig. 2-4, particularly for long cable lengths.

2.5 Antenna – Preamplifier – Bias tee – Cable – Bias tee – Receiver

In many cases, the scenario may require the operating voltage to be supplied directly to the preamplifier via the HF cable. In this case, one bias tee is required at each end of the cable:

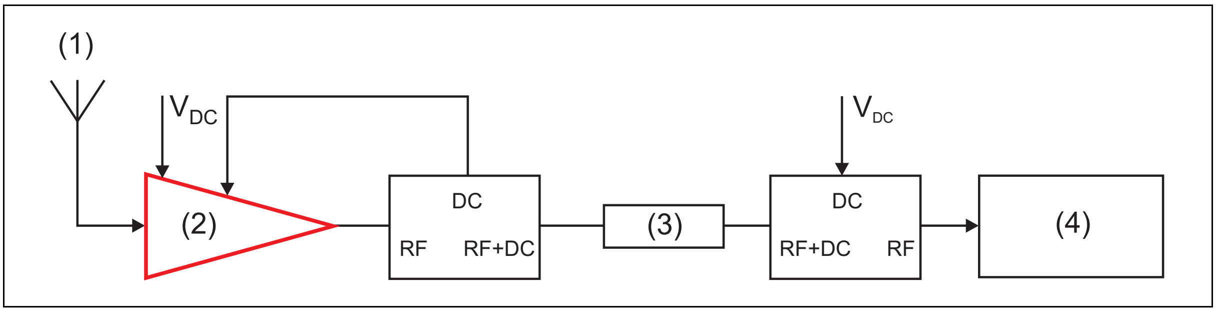


Fig. 2-7 Antenna – Preamplifier – Cable – Receiver, remote supply via bias tees

(1) Antenna
(2) Preamplifier ZS60-0916LN-S+
(3) Cable
(4) Receiver

For the sensitivity calculation, this means that the insertion loss of 2 × a_{iBT} from the two bias tees must be added to the cable attenuation. The total noise figure is then:

$$F_{total} = 1.15 + \frac{10^{\frac{13 + a_{Cable} + 2 \bullet a_{iBT}}{10}} - 1}{63} \qquad (13)$$

For the cable lengths examined here, this generates the following figures for the total noise figure F_{tot}, the corresponding noise factor NF_{tot}, and the sensitivity for the entire receiver:

Cable length	F_{tot}	NF_{tot}	Receiver sensitivity
3 m	1.87	2.72 dB	-95 dBm - 13 db + 2.7 dB = **-105.3 dBm**
5 m	2.30	3.62 dB	-95 dBm - 13 db + 3.6 dB = **-104.4 dBm**
10 m	4.82	6.83 dB	-95 dBm - 13 db + 6.8 dB = **-101.2 dBm**
20 m	38.0	15.80 dB	-95 dBm - 13 db + 15.8 dB = **-92.2 dBm**
30 m	369.8	25.68 dB	-95 dBm - 13 db + 25.7 dB = **-82.3 dBm**

Tab. 2-4 Receiver sensitivity figures for the arrangement: Antenna – Preamplifier – Cable – Receiver in the event of a remote preamplifier supply via bias tees

Compared with the configuration in Fig. 2-5, the sensitivity only deteriorates slightly in this arrangement.

2.6 Antenna – Splitter/combiner – Cable – Preamplifier – Receiver

Splitters/combiners can be used to connect multiple antennas to one common receiver. In terms of the sensitivity calculation, this scenario is very easy to deal with: ignoring the unlikely scenario that both of the splitter/combiner's inputs are supplied with a signal from transmitters with exactly the same amplitude and phasing, the splitter/combiner is represented by its insertion loss of 3.35 dB or 6.3 dB.

However, if the signal from a single transmitter is sent to two antenna and is then sent from there to the two inputs in the splitter/combiner, the phase relations between the two signals have to be taken into account: if the phase difference is zero or an integer multiple of 360°, the two signals are added together; this results in a 3 dB increase to the signal level. If the phase difference is 180° or an odd multiple of 180°, the phases cancel each other out. This results in a directionality that deviates significantly from that of the individual antennas: in some directions, the sensitivity improves slightly, while in others, reception is lost altogether.

As a result of multipath propagation caused by reflections off walls, floors, buildings, etc., the electric field strength at the point of reception can vary significantly. Moving a single antenna by just a few centimeters can cause the received signal level to increase or decrease by up to 40 dB.

To combat this effect, which is known as fading, you can use multiple antenna, achieving something known as antenna diversity. The basic idea behind antenna diversity is that the likelihood of all antenna being located in an area with a very low field strength is lower than the likelihood of this being the case for just one antenna.

However, in the case of antenna diversity, the signals from the individual antenna cannot simply be added together. This is because antenna diversity could result in the signals from two antenna canceling each other out due to an unfavorable phase difference, if the two signal strengths received by the antenna are identical. Adding the signals from multiple antenna together always leads to the change in directionality described above.

If antenna diversity is going to be used to reduce the fading effect, either an HF toggle switch is needed to alternately connect the two antenna to the receiver input, or each antenna must have its own receiver. Another option is to apply in-phase addition to the signals from both antenna. However, this requires a great deal of work, which is why this variant will not be examined further here.

The use of two or more antenna in conjunction with one splitter/combiner is therefore only recommended if the individual antenna are going to receive signals from different sensors and the sensors are in different rooms, for example, or the sensors are moving and there is a risk that they will move outside of one antenna's reception range. In all cases, the effect of the change in directionality must be taken into account. The most favorable locations for the antenna must be determined in tests.

The JUMO Wtrans T01.ECI receiver was designed for use with a λ/4 antenna on a wall-mounted antenna bracket. In electrical terms, this combination is a monopole antenna with a ground plane. If the antenna is mounted directly on the receiver instead of on the wall bracket, a range decrease of up to 40 % must be expected due to the lack of ground plane. When used in combination with the holder for wall mounting and a 3-metre antenna cable, the receiver's sensitivity is typically -92 dBm. In a clear space, data transmission can be achieved over a distance of around 300 m.

When using an antenna wall bracket, the antenna cable should be as short as possible. In this case, the following rule applies: the longer the cable = the higher the attenuation, the lower the sensitivity, and the lower the range. The antenna cables used by JUMO exhibit attenuation of around 1 dB/m.

Preamplifiers

A preamplifier can be used to increase the sensitivity of the receiver. If the distance is doubled in a clear space, this increases attenuation by approx. 6 dB. Vice versa, increasing the transmission power by 6 dB almost doubles the range. Because data is not normally transmitted in a clear space but inside a building, for example, a general rule of thumb is usually applied in practice: increasing the transmission power by 10 dB (or improving sensitivity by 10 dB) causes the range to double.

Cable length [m]	**Receiver sensitivity [dBm]**		
	Combination A Antenna – Cable – Receiver (Fig. 2-4)	**Combination B** Antenna – Cable – Preamplifier – Receiver (Fig. 2-5)	**Combination C** Antenna – Preamplifier – Cable – Receiver (Fig. 2-6)
3	-92	-103.4	-105.5
5	-90	-101.4	-104.7
10	-85	-96.4	-101.7
20	-75	-84.4	-92.8
30	-65	-76.4	-83.0

Tab. 3-1 Receiver sensitivity in relation to cable lengths and receiver hardware arrangement

Example:

1) When using a 3-m antenna wire, integration of a preamplifier (combination A to B) can increase the sensitivity from -92 dBm to -103.4 dBm. Inside a building, the rule of thumb states that this would more than double the range.
2) If, in combination A, the cable length is changed from 3 m to 30 m and a preamplifier is connected (combination B), the sensitivity will drop from -92 dBm to -83 dBm due to the significant increase in the cable attenuation. In practice, this arrangement would only achieve half the range.

The second example demonstrates the significant impact achieved by cable length. Despite using a preamplifier, it is impossible to balance out the attenuation of the 27-m longer cable, which causes the range to fall.

Bias tees

If the preamplifier is on the antenna, the voltage supply for the preamplifier can be fed by the antenna cable with the help of two bias tees. The bias tee only causes the sensitivity to decrease slightly.

Power splitters/combiners

A splitter/combiner can be used to connect multiple antennas to one common receiver or to connect multiple receivers to just one antenna. When using a power splitter/combiner, the power is divided between the number of connections. The insertion loss is 3.35 dB (two connections) or 6.3 dB (four connections).

3 Summary and use in practice

When two antennas are connected to the receiver's antenna input, there is a risk that the signal received from one transmitter will be overlaid by the two antenna, meaning it will be canceled out. Arrangements with two antenna are therefore only recommended if the individual antennas are positioned so that they receive signals from different sensors (for instance, if the sensors/antennas are in different rooms). The correct locations for the antennas must be determined in tests.

Devices tested

Preamplifier:	ZX60-0916LN-S+
Bias tee:	ZFBT-4R2G-FT+
Power splitter/combiner:	ZAPD1-S+ and ZB4PD1-930-S+

JUMO GmbH & Co. KG
Street address:
Moritz-Juchheim-Straße 1
36039 Fulda, Germany
Delivery address:
Mackenrodtstraße 14
36039 Fulda, Germany
Postal address:
36035 Fulda, Germany
Phone: +49 661 6003-0
Fax: +49 661 6003-607
Email: mail@jumo.net
Internet: www.jumo.net

JUMO Instrument Co. Ltd.
JUMO House
Temple Bank, Riverway
Harlow, Essex, CM20 2DY, UK
Phone: +44 1279 63 55 33
Fax: +44 1279 62 50 29
Email: sales@jumo.co.uk
Internet: www.jumo.co.uk

JUMO Process Control, Inc.
6733 Myers Road
East Syracuse, NY 13057, USA
Phone: +1 315 437 5866
Fax: +1 315 437 5860
Email: info.us@jumo.net
Internet: www.jumousa.com