How to combat the many causes of radio sensitivity degradation

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Zero-IF (homodyne) receivers are an increasingly popular form of radio receiver, offering several notable advantages over older and more complex architectures. But zero-IF receivers (IF = Intermediate Frequency) suffer from degradation of sensitivity for a wide variety of reasons. Armed with knowledge of the causes of such degradation, design engineers will be well equipped to take counter-measures, and ensure their circuit enjoys reliable radio reception and adequate range.

This article provides a description of the main mechanisms that cause sensitivity degradation in zero-IF receivers, and suggests techniques and components that help the developer to combat their effects.

Zero-IF receivers: a popular choice

The zero-IF receiver has won support among system designers for three main reasons:

- It does not require the transceiver's Local Oscillator (LO) to change frequency when switching between transmit and receive modes. This means that the transition between modes is quick.
- In contrast to the conventional superheterodyne receiver architecture, the homodyne architecture of zero-IF receivers does not give rise to an 'image frequency' – an undesired input frequency equal to the desired frequency plus twice the intermediate frequency. If left untreated, an image frequency interferes with radio reception. Superheterodyne receivers therefore require image rejection, normally accomplished with additional filtering circuitry in the RF front end. Homodyne receivers require no image rejection.
- Most important, signal processing takes place in the digital domain. This contributes to lower system costs. It also supports effective demodulation operation with the use of matched filtering and synchronous detection techniques.

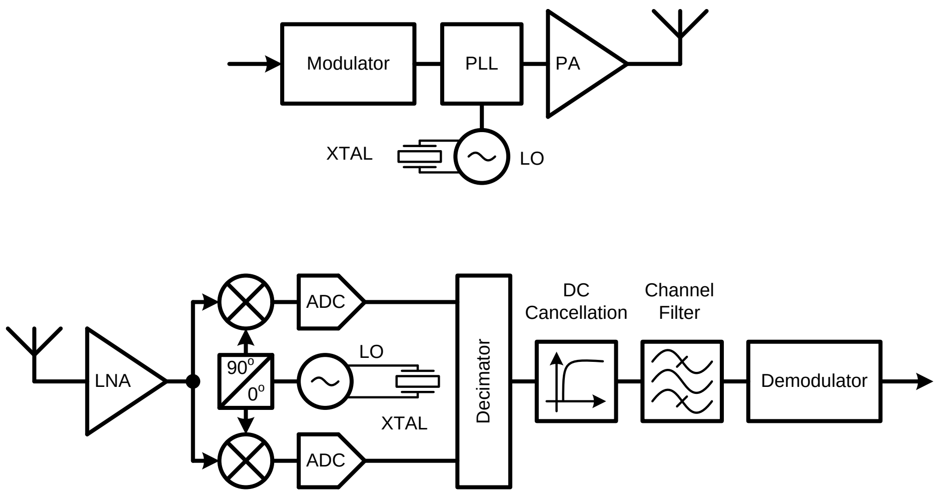

Fig. 1: zero-IF transceivers enjoy many advantages, but also require circuit blocks that other receivers do not. The receiver (bottom) includes post-mixer dc offset cancellation, two ADCs or one shared ADC to digitise the signal, and additional digital circuitry to implement demodulation. At the top is shown the transmitter.

There is a fairly extensive literature on the operation and design of zero-IF radio systems. This article, however, presents for the first time a complete overview of the mechanisms that degrade sensitivity in these circuits (see Figure 2). This shows that there are two root causes of sensitivity degradation in zero-IF transceivers: mismatch of receiver and transmitter, and an increased noise floor at the receiver side.

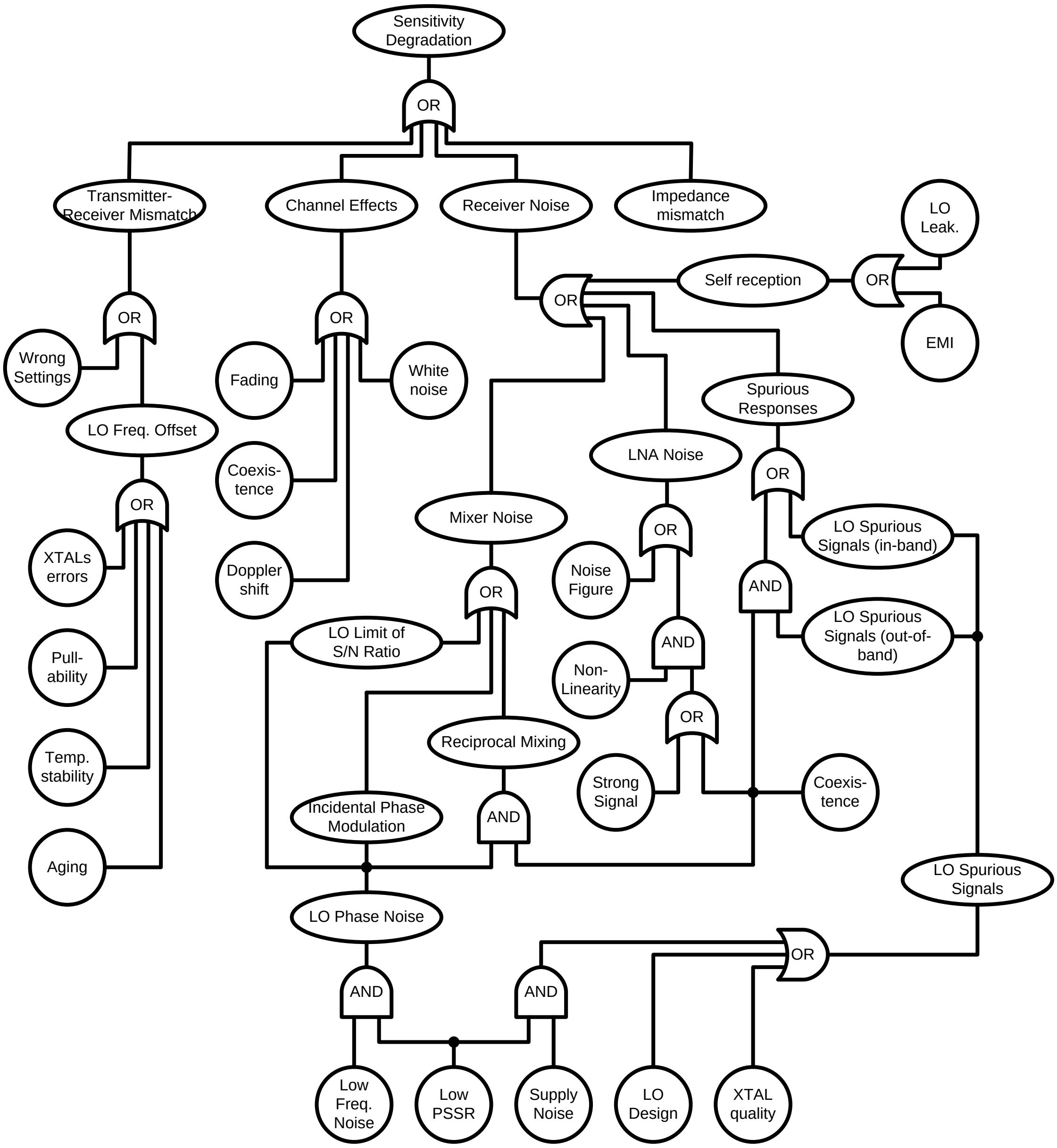

Fig. 2: fault tree diagram showing the causes of sensitivity degradation in zero-IF receivers

Transmitter-receiver mismatch

A mismatch between the transmitted signal spectrum and the receiver's bandwidth causes a decrease in sensitivity because some fraction of the transmitted energy fails to enter the receiver's pass band. This occurs most commonly in the early stages of system prototyping, and is quickly fixed by an analysis of the influence of the chosen modulation parameters and schemes on the carrier's frequency spectrum. Also it is normal to find that, in narrow-band channels, wider receiver bandwidth is used for the transmitter and receiver LO frequency offset compensation, at the cost of slightly decreased sensitivity.

Frequency drift in crystal-stabilised oscillators, widely used as reference frequency sources, is another common cause of transceiver-receiver mismatch. The initial frequency tolerance and temperature stability are usually clearly specified in the datasheet. But ageing can degrade the frequency output. Some manufacturers claim that the biggest change in frequency occurs during the first 45 days of operation; others provide data showing frequency drift over one year and ten years [1]. In practice, however, the rate of ageing can vary with use, and can be affected by factors such as drive current, internal contamination, changes to the surface of the crystal, ambient temperature, wire fatigue and frictional wear.

Separately, a crystal should be rated for its 'pullability' – a measure of frequency change as a function of load capacitance (see Figure 3). Sometimes the circuit designer can generate a particular operating frequency range by changing or varying the load capacitance of the crystal. But more often the effect is parasitic, which means that it needs careful consideration when selecting a crystal for zero-IF radio applications.

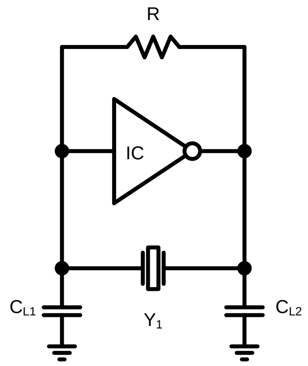

Fig. 3: parallel resonant crystals are intended for use in circuits which contain reactive components (usually capacitors) in the oscillator feedback loop

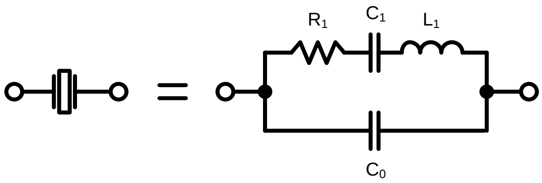

Fig. 4: the equivalent circuit of the quartz crystal unit when operating near the frequency of natural resonance

The average frequency pull (in ppm) per pF about the known load capacitance C_L is found through the calculation:

$$P_L = 10^6 \cdot \frac{C_1}{2 \cdot (C_0 + C_L)^2}, \quad (1)$$

where C_0 is the shunt capacitance, which represents the capacitance of the crystal electrodes plus the capacitance of the holder and leads; the motional inductance L_1 represents the vibrating mass of the crystal; motional capacitance C_1 represents the elasticity of the quartz; and the resistance R_1 represents bulk losses occurring within the quartz (see Figures 3 and 4). A quartz with low motional capacitance will provide a more stable frequency.

Frequency or bandwidth mismatch problems have a greater impact on narrowband than on wideband systems. But in any radio design, the problems described above can be greatly mitigated by proper circuit design which allows for stable operating temperatures, minimum drive levels and, if necessary, static pre-ageing.

Raised noise floor

An increase in the noise floor on the receiver side may be caused by several different mechanisms. For instance, noise from switching digital circuits can leak in to the receiver's input in unshielded circuits, an effect that can be mitigated through the use of good board layout practices. A white paper [2] from Intel, studying the impact of USB RF interference on nearby 2.4GHz wireless devices, indicates that the use of high-quality shielded connectors and noise-source shielding both greatly improve system performance.

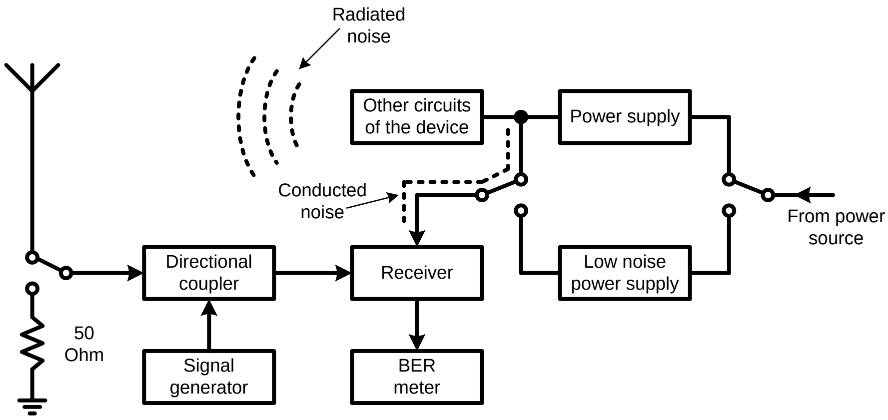

Fig. 5: measurement set-up for detecting the effect of self-radiated and conducted high-frequency noise

These techniques could be supplemented by efforts to manage the frequency spectrum of noise, distancing the frequencies at which noise occurs from the frequency of the carrier signal.

Other useful techniques include filtering, through the implementation of decoupling and bypassing circuits in the power supply [3], and mitigation of self-polluting interference [4]. The measurement set-up shown in Figure 5 can uncover noise sources by monitoring variations in bit error rate (BER) and Received Signal Strength Indicator (RSSI) levels.

Another technique, active noise cancellation, is especially effective with closely spaced antenna radiation, internal processor noise, video camera and display noise (see Figure 6). This can be implemented through the use of a device such as the QHx220 interference canceller from Intersil.

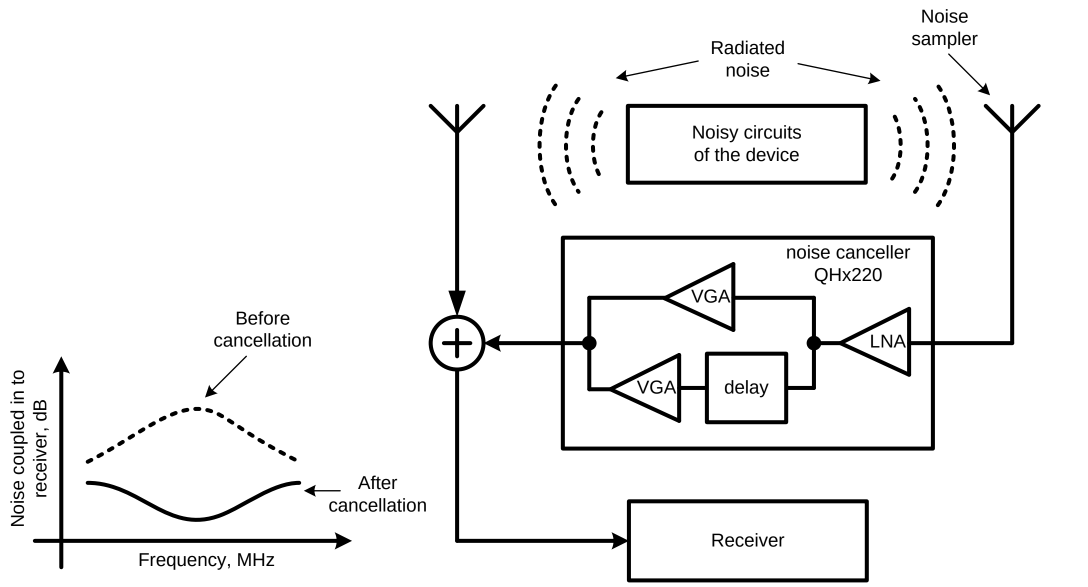

Fig. 6: Intersil's QHx220 cancels up to 20dB of noise in the frequency range 300MHz - 3GHz

Low-frequency noise in the power supply is as dangerous as high-frequency noise (see Figure 7). For instance, if a circuit is handicapped by a low Power Supply Rejection Ratio (PSRR), LO phase noise will rise, impairing the performance of the receiver. To be more specific, LO phase noise either lowers the Signal-to-Noise Ratio (SNR) below the level that could be achieved with the ideal mixer, or it causes parasitic incidental phase modulation (when a phase-modulated carrier is used). Both effects reduce receiver sensitivity [5].

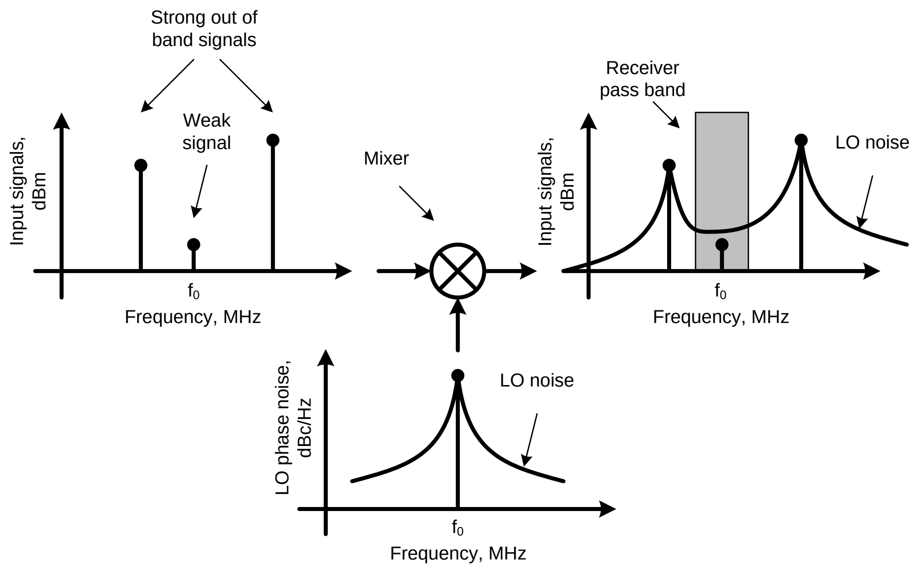

Fig. 7: local oscillator phase noise and the reciprocal mixing model

LO spurs could occur if the power supply noise is periodic rather than random in nature (see Figure 8). In-band spurs have the same effect as the LO phase noise described above; while out-of-band spurs, which occur at unexpected input frequencies, might in turn cause receiver spurs. Any energy in these unexpected input bands is injected as noise into the main receiver band. A common cause of unexpected spurs is the use of a low-quality reference crystal – parasitic vibrations and high drive currents often impair their performance.

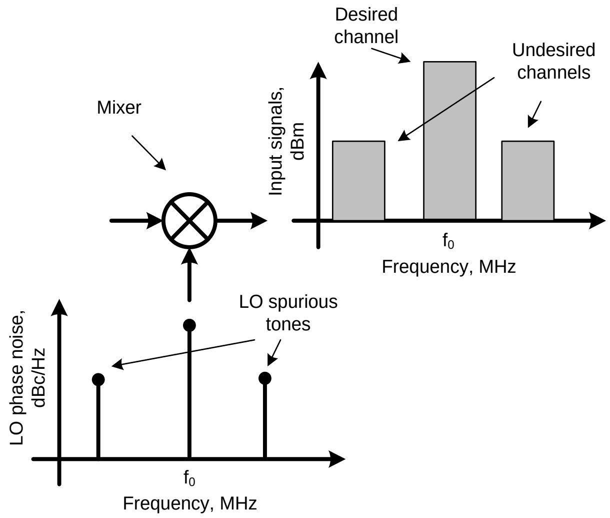

Fig. 8: effect of spurious local oscillator tones and receiver responses

The description of the power-supply noise effects above suggests that the system designer should make a calculation of the maximum noise level that can be accepted. In a recommended method for designing a PLL power supply [5], the VCO pushing figure – the ratio of frequency change to voltage change – may be measured by DC-coupling a low-frequency square wave into the supply, while observing the Frequency Shift Keyed (FSK) modulation peaks on the VCO output spectrum (see Figure 9). The frequency deviation between the peaks divided by the amplitude of the square wave yields the VCO pushing number: this is used to determine the acceptable power-supply noise level, required to keep PLL phase noise at an acceptable level. The method can be adapted for measurement of receiver power supply performance while monitoring the BER.

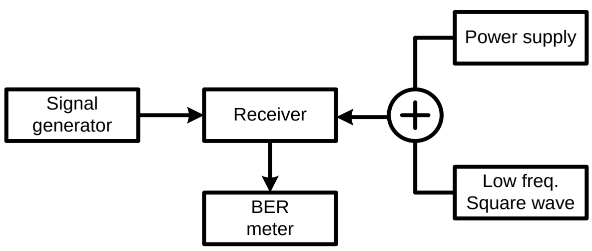

Fig. 9: the VCO pushing figure measurement set-up could be used to measure receiver sensitivity degradation caused by low-frequency power-supply noise

Mitigating the impact of noise on RF circuit performance

Armed with knowledge of the mechanisms of receiver sensitivity degradation, the RF system designer can set to the task of eliminating or mitigating the effects of noise. It is common for high-frequency power-supply noise components to be filtered by a combination of passive RLC networks and shielding.

Low-frequency noise needs a different approach. To start with, high-speed Low Drop-Out regulators (LDOs), which offer high PSRR and low output noise, outperform passive circuits at low frequencies.

The signal received by the antenna is then amplified by an internal or external Low Noise Amplifier (LNA). The performance of these amplifiers has a pronounced impact on the performance of the circuit as a whole. The noise figure and linearity of the LNA, usually specified as the third or second order input intercept points (IIP3 or IIP2), should be studied carefully as the noise and intermodulation products the LNA generates can mask the received signal [6].

According to the Friis equation, the noise figure and the in-band insertion loss or gain of the first stage dominate the noise figure of the receiver chain. This affects the selection of the external pre-filter and LNA. The overall receiver noise factor $F_{receiver}$ is calculated with the equation:

$$F_{receiver} = F_{LNA} + \frac{F_{rest} - 1}{G_{LNA}}$$

where F_{rest} is the overall noise factor of the subsequent stages. According to the equation, the overall noise factor of the LNA

$$F_{LNA} = \frac{SNR_{in}}{SNR_{out}}$$

is dominant if the gain G_{LNA} is sufficiently high. Usually the noise figure is given in datasheets as the noise factor (in dB).

Avago Technologies provides an interesting perspective on the mitigation of noise figure degradation when the LNA is overloaded by a strong out-of-band interferer signal [7]. Avago shows that a pre-filter to block a strong interferer signal from leaking into the receiver path gives better results than any other mitigation method (see Figure 10) in GPS systems. The results may be extended to all other bands, as the degradation mechanisms of the LNA remain the same.

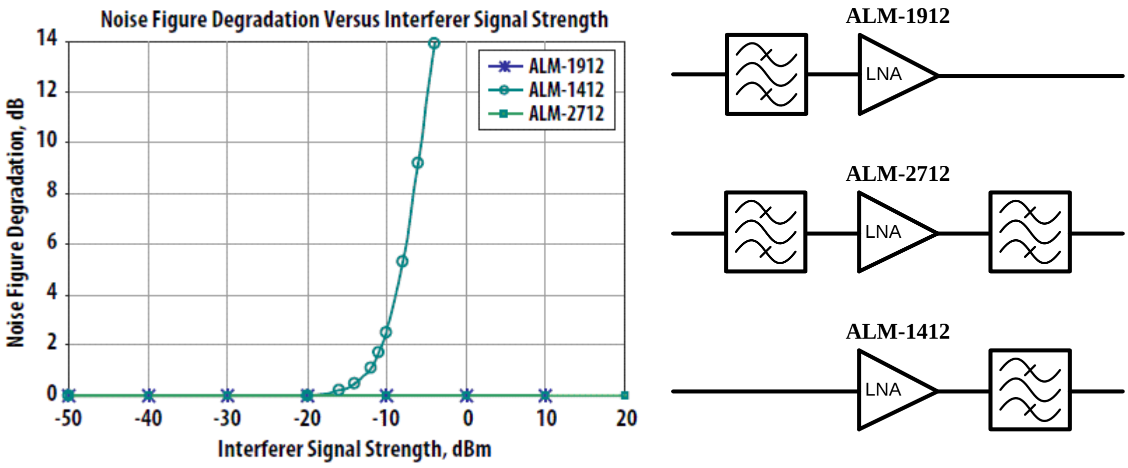

Fig. 10: various pre- and post-filter configurations of the LNA stage

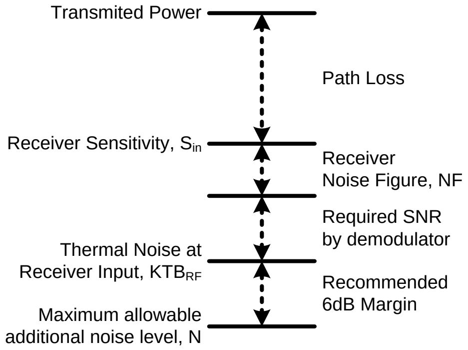

Fig. 11: RF link budget and noise floor components

Another good practice to follow is to specify the receiver noise floor at a level 6dB below the calculated thermal noise floor at the receiver's input bandwidth (see Figure 11). If this is not done, the increased noise floor will start to dominate in the receiver sensitivity equation:

$$S_{in} = K \cdot T \cdot B_{RF} + N + NF + SNR$$

where S_{in} is the available input signal power (dBm); $N_{in} = K \cdot T \cdot B_{RF}$ is the available input thermal noise power (K = Boltzmann's constant, T is room temperature and B_{RF} is the RF carrier bandwidth in Hz); NF is the noise figure in dB; SNR (in dB) is the ratio required by the receiver in normal operation (to produce a specified output signal); N is the additional noise level (dBm) in a real application.

Lastly, new products and technologies developed by semiconductor manufacturers can provide a marked improvement in receiver sensitivity, quite independently of the mitigation techniques described above. The new LoRa™ modulation scheme deployed in the SX1272 and SX1273 products from Semtech is an example of this. LoRa provides 10dB better sensitivity than an FSK modulation scheme can achieve when used with a low-cost, low-tolerance crystal reference. The enhanced performance of LoRa devices is due to a proprietary spread-spectrum modulation technique developed by Semtech. It also offers another benefit: each spreading factor is orthogonal, allowing multiple transmitted signals to reside on the same channel without interfering.

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