

Advances in Short-Range RF Transceivers Drive Link Robustness

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In this article, the author examines performance requirements that are often overlooked when designing low-cost, short-range wireless transceivers

Just when it seemed like the market for short-range RF technologies had become synonymous with Bluetooth, Wi-Fi and other products reaching commodity status, there will

soon be another signal to contend with: ZigBee. This pervasive wireless networking environment adds to the challenge that engineers designing these systems have to provide a receiver that delivers valid, uncorrupted data packets.

The recent explosion of RF wireless services in everyday life has made it even more important to remember the factors that make a radio link reliable, immune to interference, robust and bulletproof. Much of the task falls to the radio transceiver chipset. This paper gives the key to a detailed readout of the datasheets, where not only sensitivity, but also spurious response rejection and input third order intercept point (IIP3) are key specifications.

Introduction

The worldwide RF landscape is very crowded. In North America, a large frequency band (ranging from 902 to 928 MHz) is dedicated to short-range devices (SRDs) with few restrictions. Transmitters can reach 1 watt, allowing for applications to reach relatively long distances. In Europe, the g band (ranging from 863 to 870 MHz) is becoming very popular. The allowed power levels are, generally speaking, lower. Across all regions of the world, unlicensed frequency bands are also allocated to non-specific SRDs, anywhere between 300 and 510 MHz. Around those non-

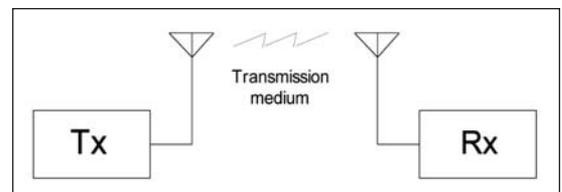


Figure 1 - Basic transmission system.

specific SRD bands, there is a variety of other potential interferers including the UHF bands allocated for analog or digital TV broadcast stations. While their frequency separation to the common SRD bands can be as high as a few MHz or tens of MHz, the allowed field strength emissions are indeed very high as tens or hundreds of kilowatts may be broadcasted. At 2.4 GHz, a large number of SRDs are operating between 2.400 and 2.4835 MHz; including Bluetooth personal area network devices, Wi-Fi 802.11a/b/g/n access points with decent power and large spectral signature, and now Zigbee applications are starting to emerge.

Range, Output Power and Sensitivity

Achieving successful transmission over a long distance depends primarily on the receiver sensitivity, transmitter output power, and antennae used (Figure 1 depicts a simplified RF link). Instinctively one may think that having high power, low sensitivity, and an efficient antenna would guarantee a reliable and long distance link; however, this only holds true in ideal environments with little electromagnetic activity (noise and interference). Practical solutions for non-ideal systems, particularly solutions for receiver response issues, are detailed in this paper.

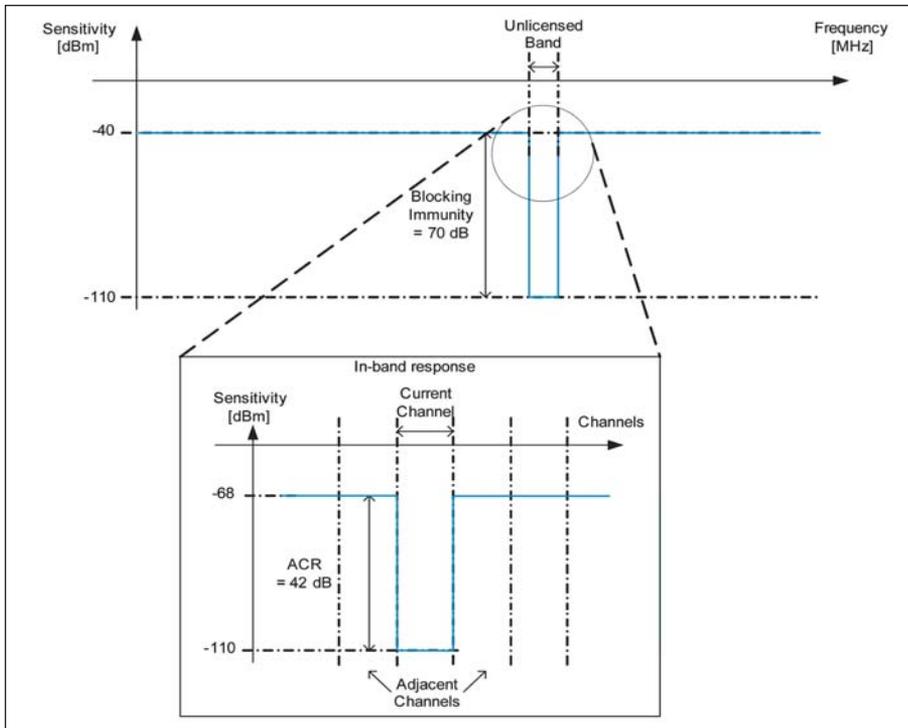


Figure 2 · Blocking immunity and ACR.

Receiver Response

Receiver sensitivity corresponds to a receiver’s ability to effectively collect valid bits of information. Although raw receiver sensitivity is of significant importance, a receiver must also be as immune to its electromagnetic environment as possible. A receiver sensitive to any frequency would not be able to reconcile multiple users sharing the spectrum.

A given receiver is sensitive to a specific frequency, defined as the “channel.” By extension, a good receiver must be as insensitive as possible to all other frequencies. Potential interferers are numerous and reside anywhere in the electromagnetic spectrum including, but not limited to, cell phone users, TV broadcasting stations, and nodes sharing the 2.45 GHz band (Wi-Fi, Bluetooth, Zigbee).

The frequency response of an ideal receiver is shown in Figure 2.

As with any receiver architecture, the first order parameters describing the receiver’s immunity to interferers

are its adjacent channel rejection (ACR) and its blocking immunity (BI). Both figures are specified at a certain offset of the channel, and their value is stated in dB. A receiver with an ACR of 42 dB at a ±25 kHz offset and BI = 70 dB at a ±10 MHz offset would still have successful reception with its companion transmitter 1,000 meters (1,100 yards) away and an interferer 1 meter away (assuming a 915 MHz link, Free Space Path Loss model).

It is important to select RF transceivers that maximize ACR and BI, though this proves to be a trade-off exercise as optimization of ACR and BI increases current consumption and the bill of materials. Furthermore, optimization can make transceiver integration more difficult. The best-in-class commercially available low-power RF receivers with a high level of integration, such as Semtech’s SX1231 [1], exhibit an ACR in the range of 40-45 dB, and their BI exceeds 70 dB (at all offsets larger than 1 MHz).

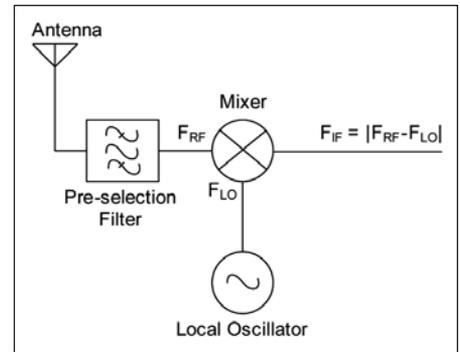


Figure 3 · Mixing concept.

Receiver Spurious Response Frequencies vs. Architecture

The ideal receiver response shown in Figure 2 is a crude simplification of real-life receivers. More realistic architectures that are well adapted for low-cost/high-integration/low-power implementation include superheterodyne, Low-IF, and Direct Conversion (or Zero-IF) receivers.

Superheterodyne

Practical superhet implementations employ an Intermediate Frequency (IF) ranging from 10 to 100 MHz. With mixers performing frequency additions or subtractions, the incoming RF signal is down-converted to its first IF as shown in Figure 3, then to a second very low IF through a second mixer. The selection of the IF is driven by multiple concerns, including commercial availability of filters at the desired frequency, Local Oscillator sideband noise performance impacting reciprocal mixing [2], and importantly, Image Frequency.

Superheterodyne receivers are not only sensitive at their tuned channel frequency $F_{channel}$, they are also equally sensitive at their image frequency, which is defined as:

$$F_{Image} = F_{channel} - 2 \times F_{IF}$$

for low-side injection, and

$$F_{Image} = F_{channel} + 2 \times F_{IF}$$

for high-side injection. This image

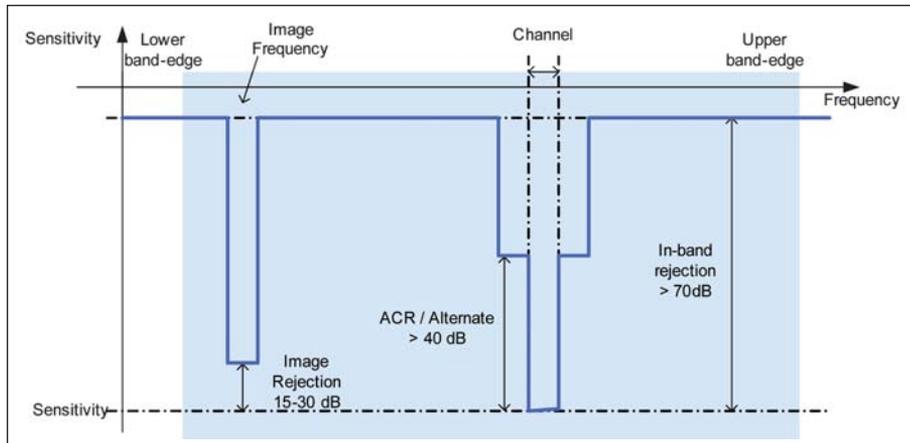


Figure 4 · Typical low-IF in-band response.

frequency response can be mitigated by the use of a front-end pre-selection filter. Since the IF is usually high (>10 MHz), the image response of the receiver will be out-of-band, where high power interferers may exist. Fortunately, high-Q filter technologies such as Surface Acoustic Wave (SAW) filters, offer a good rejection (40 to 50 dB) at the image frequency, and they are widely used as pre-selection filters, to remedy the image frequency pitfall.

Low-IF

Low-IF receivers also employ the heterodyning method, but they convert the incoming RF signal to a lower IF frequency (typical range is 100 kHz to a few MHz). Low-IF frequency architectures lend themselves better to higher integration, where sharp channel filtering can be implemented on-chip at an acceptable silicon size and cost. Also, current digital technologies allow for signal processing at a few hundreds of kilohertz, making the low-IF approach a good candidate for high integration. However, low-IF receivers also suffer from the Image Frequency phenomenon described for detailed in the superheterodyne section. The major difference is that, the IF frequency being lower, the image frequency actually lies in-band, very close to the channel, literally a few hundred of kilohertz off-channel. With

such a small frequency offset, the pre-selection filter proves inefficient.

The alternative method in modern low-IF receivers is the Image Rejection Mixer (IRM). IRM employs a combination of in-phase and quadrature (I&Q) mixing, with complex poly-phase filtering. Its image rejection performance is intimately linked to the ability to “match” the I&Q signals in phase and amplitude. Without any calibration, the best achievable matching between two elements on an integrated circuit is limited to approximately 0.5% in amplitude and 1° in phase. In turn, the IRM will “only” provide about 30 dB of image rejection. Practical implementations in commercially available sub-GHz transceivers offer a typical Image Rejection in the range of 17 to 30 dB. There is often no minimum guaranteed Image Rejection, and one could estimate it to be as low as 15 dB in worst cases.

The in-band response of the typical low-IF receiver will show an isolation ranging from around 40 dB (ACR) in the adjacent and alternate channels, and increasing to 60 or 70 dB (BI) at 1 MHz offset, with a “hole” located $2 \times \text{IF}$ away from the channel, jeopardizing the chances of the device to receive messages in a real environment where multiple users are sharing the frequency band. This is illustrated in Figure 4.

Direct Conversion

Direct conversion is also a popular architecture for short-range radios. In this specific case of down-conversion, the IF frequency is set to zero, showing significant advantages: processing is done at the baseband, reducing the power consumption required to process incoming data. A high level of integration is possible with the design of sharp channel filters on a smaller silicon area. The most important advantage however is the absence of image frequency. High-Q pre-selection filters and image rejection mixers, with their inherent limitations, are therefore not required.

Indeed, the direct conversion receiver is the closest approach to a spurious-response-free receiver. It is however noticeable that both the low-IF and the direct conversion architectures are subject to amplitude modulation (AM) detection. This is a critical factor [3], since burst radios can be seen as high power AM interferers. Such is the case of the FCC’s 902-928 MHz band in North America, where Frequency Hopping Spread Spectrum (FHSS) is a proposed technique to spread energy and use up to 1 watt of peak power. An FHSS system will turn its power amplifiers on and off rapidly (400 ms maximum). To receivers lying in-band, the resulting spectrum will look like an AM signal, potentially causing low-IF and direct conversion receivers to desensitize. Careful mixer design techniques solve this issue, and modern processes allow for mixers with a high enough input 2nd order intercept point (IIP2) to completely eradicate the AM detection. When selecting a low-IF or direct conversion receiver, the RF system designer should ensure that the AM rejection matches the blocking immunity of the receiver. Doing so guarantees a bulletproof front-end, capable of rejecting both constant wave (CW) and AM or pulse modulated interferers located in-band and out-of-band.

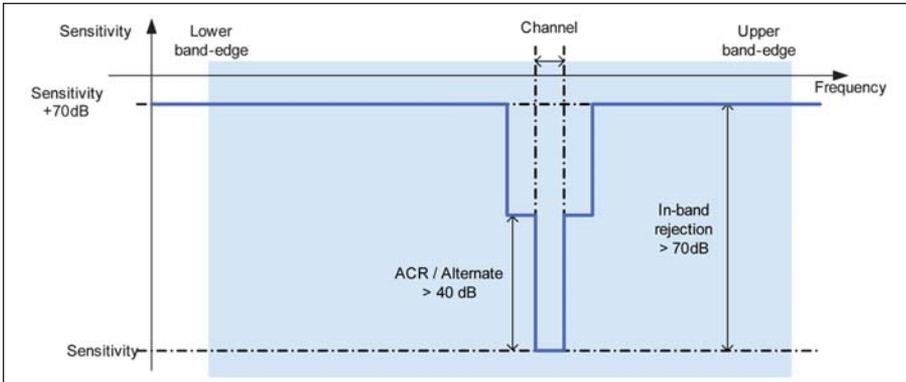


Figure 5 · Typical zero-IF in-band response, CW or AM interferer.

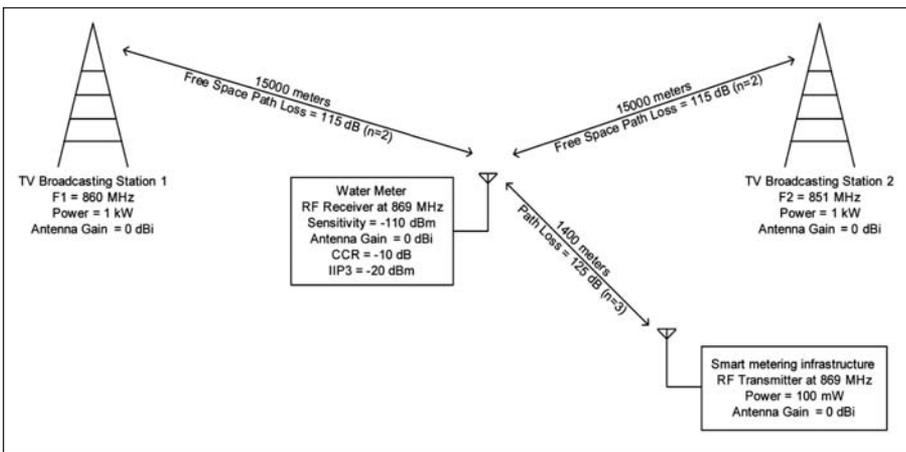


Figure 6 · IIP3 scenario.

The Semtech SX1231 receiver features an outstanding IIP2 of at least +35 dBm, allowing for the AM suppression to meet or exceed the blocking immunity at any offset.

The Puzzling Question of Linearity

Receiver linearity, usually specified as the input third order intercept point (IIP3), is sometimes overlooked by RF system designers; it is rarely documented in the datasheets of consumer-grade RF transceivers. However, selecting a receiver with poor linearity can be the Achilles' heel of a reliable radio frequency system.

Multiple references are easily found in the literature to theoretically understand the intermodulation mechanism [4]. In this article, two hypothetical receivers with comparable sensitivities will be compared.

Their impact of their intrinsic linearity on the actual distance this RF link will also be discussed.

The example shown in Figure 6 describes a typical smart metering system. A water meter, located in a water pit, operates at 869 MHz (ISM license-free band in Europe). For simplification, all antenna gains are set to 0 dBi. We will assume the following performance for this receiver:

- Sensitivity = -110 dBm in the conditions of this transmission
- Co-channel rejection, CCR = -10 dB
- IIP3 = -20 dB (for example, Semtech's SX1231 [1])

The data collection unit in this fixed infrastructure network is located on a utility pole, 1.4 kilometers

away, and its output power is 100 mW.

For path loss calculations, the following simplified model can be used:

$$\text{Path Loss} = 20 \log(4\pi/\lambda) + 10n \log(d)$$

where λ is the wavelength at 869 MHz, i.e. 0.35 m, and n is an experimentally defined constant. For the transmission between the utility pole and the water pit radio, $n = 3$; this is a realistic approximation of the path loss in a suburban environment. For the transmission of the TV broadcast stations, we will assume $n = 2$, which corresponds to a line-of-sight situation, closer to reality when the elevation of the broadcast station antenna is high.

Exploiting this equation, the path loss from the meter reader to the meter itself will approach 125 dB. In turn, the power collected by the meter's antenna will equate -105 dBm. This is well over its sensitivity level. In the absence of interferers, this link will be reliable at a 1.4-kilometer distance.

Now let's assume two TV stations, each being located at a distance of 15 kilometers, several tens of meters above ground, whose output power of 1 kilowatt translates into two tones hitting the water meter antenna:

- One tone at F1 = 851 MHz, with -55 dBm power level, defined as P_{in}
- The second tone at F2 = 860 MHz, same power level

Following the theory of intermodulation products generated in the radio front-end, a parasitic intermodulation tone will appear at:

$$F_{intermod} = 2 \times F2 - F1 = 869 \text{ MHz}$$

Its level is calculated as follows:

$$P_{intermod} = 3 \times P_{in} - 2 \times \text{IIP3}$$

Table 1 summarizes the performance for two different radios, claiming the same sensitivity.

	Radio A*	Radio B	Comment
Sensitivity	-110 dBm	-10 dB	Same signal conditions
CCR	-20 dBm	-30 dBm	
IIP3	-105 dBm	-55 dBm	Signal at 869 MHz
Pwanted	-125 dBm	-105 dBm	Unwanted tones hitting the Receiver antenna
Pintermod	-115 dBm	-115 dBm	Intermodulation product at 869 MHz
Maximum bearable co-channel signal level	10 dB	-10 dB	
Margin			

Reception is guaranteed

Reception is impossible, despite the high sensitivity of the RF

Table 1 · Receiver's IIP3 performance report.

Conclusion

In optimal conditions, when there is no interferer, the Short Range Device embedding the receiver with the best sensitivity will achieve the longest-range coverage. In the deployment of networks, longer distance means fewer nodes, lower cost, lower latency, less redundancy, or in a word, superior system. But, as described, this is an impractical assumption to make in real world applications as architectural choices have a signifi-

cant impact on the ability of the receiver to receive packets in an increasingly busy RF spectrum. Any wireless system designer should not only consider chip cost, power consumption, transmitter output power and receiver sensitivity, but should also look at the receiver architecture to make an informed choice.

Author Information

Sebastien Lebreton is an RF Application Support Engineer for

Semtech Corp., and works with customers on ISM-band radio frequency applications. Prior to Semtech, he worked on RF applications at Atmel. Lebreton has a BSEE from Ecole nationale supérieure d'Electronique, Informatique et de Radiocommunications de Bordeaux in France.

Information about Semtech products and applications can be found at: www.semtech.com

References

1. Semtech SX1231 data sheet: www.semtech.com/wireless-rf/rf-transceivers/sx1231/.
2. E. Ngompe, "Computing LO Phase Noise Requirements in a GSM Receiver," *Applied Microwave & Wireless*, 11(7), 54-58, 1999.
3. ETSI GTS GSM 05.05-v5.2.0-1996-07, AM Suppression.
4. Peter Vizmuller, *RF Design Guide Systems, Circuits and Equations*, Artech House 1995, see Ch. 1.1.6.

Ready-made RF transceivers like this saves the hobbyist from designing RF circuits and PCBs which can get quite complex and expensive. All you have to do is configure the required registers, put it in a microcontroller, and you're done. Creating a two way wireless link is fun and exciting. Recently I ordered some RF modules based on NRF 24L01+ transceiver from sparkfun (link here or here). Ready-made RF transceivers like this saves the hobbyist from designing RF circuits and PCBs which can get quite complex and expensive. RF Cafe began life in 1996 as "RF Tools" in an AOL screen name web space totaling 2 MB. Its primary purpose was to provide me with ready access to commonly needed formulas and reference material while performing my work as an RF system and circuit design engineer. The World Wide Web (Internet) was largely an unknown entity at the time and bandwidth was a scarce commodity.

Advances in Short-Range RF Transceivers Drive Link Robustness Sebastien Lebreton. Simulations and Measurements of a Circular Waveguide Septum Feed Jeffrey Pawlan and Rastislav Galuška. Design Method for the Fastest Settling Type 2 Phase Lock Loop: Part 2 Akmarul Ariffin Bin Salleh. 4 RF Transceiver System Optimization 4.1 Transceiver Power Consumption . . . 4.1.1 Power Consumption of Short-Range Transceivers . . .

Advances have been significant in this area. The power consumption of integrated Bluetooth transceivers have been brought down from 100's of milli-Watts to 10's of milli-Watts [11]. Transceivers designed for Zigbee, which is a new standard optimized for ad-hoc networks, have also been reported with power consumption figures in the same range [12]. For these reasons, more and more short-range transceivers are implemented in the 2GHz and 5GHz unlicensed bands. This work focuses on the design of short-range transceivers in the UNII band, which occupies 300MHz unlicensed spectrum at 5GHz [26]. The ADF7023 short-range RF transceiver is a low-power, low-IF transceiver designed for operation in the license-free ISM bands at 433MHz, 868MHz and 915MHz. The ADF7023 includes enhanced baseband features and offers a low transmit-and-receive current, as well as data rates in 2FSK/GFSK up to 250 kbps. It offers industry-leading blocking resistance and receive sensitivity with very low receive and transmit currents, allowing the radio to operate in environments where interfering signals are greater than four times stronger and more than double the operating range. It operates with a power supply range of 1.8 V to 3.6 V and has lower power consumption in both transmit and receive modes, enabling longer battery life.

Advances in Short-Range RF Transceivers Drive Link Robustness. Sebastien Lebreton. Just when it seemed like the market for short-range RF technologies had become synonymous with Blue-tooth, Wi-Fi and other products reaching commodity status, there will soon be another signal to contend with: ZigBee. This pervasive wireless networking environment adds to the challenge that engineers designing these systems have to provide a receiver that delivers valid, uncorrupted data . . . Much of the task falls to the radio transceiver chipset. This paper gives the key to a detailed readout of the datasheets, where not only sensitivity, but also spurious response rejection and input third order inter-cept point (IIP3) are key specifications. Read more.