# Lab 6 Solution

## Requirements

Many receiver design requirements could be derived from the specification but only four requirements were marked and are described below: input frequency, maximum and minimum gain, cascade noise figure, and cascade IIP3. Other important specifications that might be considered include gain vs input level (based on analysis of IIP3 and NF for various input levels) and LO phase noise (based on the adjacent channel rejection).

The design below is for the 2450 MHz radio specification as specified during the lab.

### Carrier Frequency

The carrier frequency is specified in section 6.1.2.1:

$$F_c = 2405 + 5(k–11)$$

in megahertz, for $k = 11, 12, ..., 26$.

### Maximum and Minimum Gain

The maximum gain will be required for the minimum input signal level. The minimum input signal level is the receiver sensitivity as specified in section 6.1.7 and 6.5.3.3 (-85 dBm). The peak-to-peak voltage of the ADC was specified as 1 V during the lab. For a sinusoidal input signal this corresponds to an amplitude of $\frac{1}{2}$V, an RMS voltage of $\frac{1}{2\sqrt{2}}$ and a (50-ohm referenced) power of $\frac{1}{50\times(2\sqrt{2})^2} = 2.5\times10^{-3}$ W or 4 dBm. The minimum gain required is thus $4 - (-85) = 89$ dB.

The maximum input signal level is -20 dBm which is 65 dB higher than the sensitivity. The minimum gain should thus be 65 dB lower or $89 - 65 = 24$ dB.

Improving gain and gain control range is relatively inexpensive so these requirements would probably be revised after the first design iteration to see if higher minimum and lower maximum gains could improve the performance of the receiver without much additional cost.

### Noise Figure

The sensitivity is specified for a PER of $< 1\%$ for a PSDU (PHY payload) length of 20 bytes ("octets"). The PHY adds a header which is used for synchronization. For a well-designed protocol and receiver the probability of incorrectly decoding the PHY header is much less than the PER and can be ignored.

We can convert PER to BER assuming independent errors:

$$\text{PER} = 0.01 = 1 - (1-\text{BER})^{8\times20}$$

which gives a BER of $1-(1-0.01)^{1/160} = 6\times10^{-5}$.

The BER vs SNR performance of an ideal 802.15.4 receiver is given in the coexistence study in Appendix E.4.1.8. The bandwidth (noise, presumably) used in these calculations is specified as 2 MHz which is equal to the symbol rate and so is the minimum (Nyquist no-ISI) bandwidth and would require a "brick wall" filter. A practical receiver would likely have a different filter and a larger noise bandwidth. However, using the BER curve for 802.15.4 in Figure E.2 we find the required SNR is about 1dB.

The noise figure can be derived from the required SNR, the signal level at the sensitivity limit (-85 dBm) and the noise bandwidth (somewhere between 2 and 4 MHz) as SNR = Signal (dB) - Noise (dB) where the noise is computed as $kTBF$ where $kT = -174$ dBm/Hz, B is the noise bandwidth (63 dB-Hz for 2 MHz) and the noise figure F, which we need to determine:

$$\text{SNR} = 1 = -85 - (-174 + 63 + F)$$

$$F = 174 - 63 - 1 - 85 = 25\text{dB}$$

It is common to add a margin to the requirement to take into account the non-ideal performance of the receiver. Section E.3.2.1 states that "a typical low-cost detector implementation is expected to meet the 1% packet error rate (PER) requirement at SNR values of 5 to 6dB". This would imply a typical implementation margin of 4 to 5 dB. The implementation margin would reduce the noise figure requirement by that amount. For example, if the implementation margin were 5 dB the noise figure requirement would be reduced to 20 dB.

### IIP3

Don't believe everything you read on the Internet! Many students used a solution from a similar assignment from Texas A&M University. Unfortunately, the author of this lab confused the definitions of alternate and adjacent channel.

The adjacent channel's third-order intermod products fall within the desired signal's channel (this is how we measured amplifier IP3 in lab 5). Thus we should be computing the power of the IM3 products using the adjacent channel power, not the alternate channel power as in the above solution.

The third-order intermodulation (IM3) power should be significantly (say 3dB) lower than the desired signal power so as not to limit the performance of the receiver. The adjacent channel level is specified in section 6.5.3.4 as 0 dB relative to the the desired signal level. The IIP3 should therefore be $3/2 = 1.5$ dB above the desired signal level (the adjacent channel signal's IM3 drops 3 dB for each 1 dB it is below the IIP3).

We would want to specify the IIP3 for the *maximum* input signal level of -20 dBm. In this case the IIP3 would be -18.5 dBm, the adjacent channel power is -20 dBm and the IM3 power in the desired channel is -17 dBm.

A margin larger than 3dB could have been chosen. For example, if the margin had been 6dB the IIP3 requirement would have been -17 dBm.

Section 6.5.3.4 of the specification only requires that the adjacent channel "jamming resistance" be measured at an input level of -82 dBm. So an acceptable answer would also be $-82+3 = -79$ dBm for a margin of 6 dB. Although this would meet the test criteria, such a low IIP3 would result in poor performance in actual use.

Note that the IIP3 requirement typically only needs to be met by the stages before channel selection filtering. The channel-select filter (low-pass filters in a zero-IF architecture) will attenuate the adjacent channel signal and reduce the IIP3 requirements by an amount equal to the attenuation of the adjacent channel signal.

## Design

There are many options for completing the design. For a cost-sensitive market like ZigBee the design would likely be fully integrated into a single IC. Connectorized components such as those sold by Mini-Circuits are convenient for prototyping or for setting up test fixtures.