

Selecting ADCs for digital receiver applications

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How not to select an ADC for a receiver application

- ◆ 4 bits to digitize the noise (that's the way we've always done it)
- ◆ 87 dB to take in the blockers
- ◆ 12 dB (or more) dB for headroom and peak to average

- ◆ Adding it all up
 - 4 bits (for noise)
 - 14.2 bits (for 87 dB)
 - 2 (or more) bits for headroom

 - Total is 20.2 (or more) bits!
- ◆ Is that how you specify your converter?



What will 20.2 bits give you in a digital radio?

- ◆ 20.2 bits is an SNR of 123.4 dB.
- ◆ If fullscale is +4 dBm and the sample rate is 92.16 MSPS...
 - -196.0 dBm/Hz at the ADC input!
 - If noise at the antenna input is -174 dBm/Hz and that gain is 30 dB and NF is 3 dB, it is easy to see that the ADC noise is easily 55 dB (or more) below the front end noise.
 - Conclusion is that there has to be a better way to pick your ADC.



Main guideline for selecting an ADC

- ◆ Don't allow the ADC to limit performance, but don't over spec the ADC and risk an expensive device selection.
- ◆ Common sense suggests that the ADC be allowed a small contribution to the receiver noise budget.
 - ◆ ADC noise equals AFE noise 3 dB
 - ◆ ADC noise 1 dB below AFE 2.54 dB
 - ◆ ADC noise 3 dB below AFE 1.77 dB
 - ◆ ADC noise 5 dB below AFE 1.2 dB
 - ◆ ADC noise 7 dB below AFE 0.8 dB
 - ◆ ADC noise 9 dB below AFE 0.5 dB
 - ◆ ADC noise 10 dB below AFE 0.4 dB
 - ◆ ADC noise 55 dB below AFE 0.00001 dB
- ◆ First step is to determine how much noise the ADC reasonably can be allowed to contribute.



Second Guideline: Understanding the Sources of ADC noise and how they contribute

- ◆ Two main factors to consider
 - Noise
 - ◆ Quantization
 - ◆ Thermal
 - ◆ Jitter
 - ◆ etc.
 - Spurious signals
 - ◆ Harmonic energy
 - ◆ non-harmonic energy

Special considerations for Noise

- ◆ **ADC can be selected such that the noise spectral density contributes at the desired level.**
 - **If the ADC is allowed to contribute 0.8 dB to the overall noise, from our table the ADC noise density must be 7 dB below the AFE noise spectral density.**
 - **AFE noise spectral density:**

$$NSD_{AFE} = -174 + G_{AFE} + NF_{AFE}$$

- **Required ADC SNR**

$$SNR_{ADC} = FS_{ADC} - \left[NSD_{AFE} - guard + 10 \log \left[\frac{sample_rate}{2} \right] \right]$$

Integrate noise over Nyquist band

Noise Spectral Density Example

- ◆ Receiver Conversion gain is 30 dB
- ◆ NF is 3 dB
- ◆ Required ADC sample rate is 92.16 MSPS

$$NSD_{AFE} = -174 + 30 + 3 = -141 \text{ dBm} / \text{Hz}$$

$$SNR_{ADC} = 4 - \left[-141 - 7 + 10 \log \left[\frac{92.16 \text{ MHz}}{2} \right] \right] = 75 \text{ dBFS}$$



Alternate Noise Consideration

- ◆ An alternate method is to simply determine what the NF of the ADC is and utilize standard receiver noise analysis.
- ◆ Normally NF is not associated with ADCs because they are voltage devices, not power devices. However, if the operating conditions are known, NF can be calculated, if the system is impedance matched.
 - fullscale input power
 - ◆ input range in volts and input impedance
 - sample rate
 - SNR
 - ◆ data sheet
 - ◆ lab measurements

ADC Noise Figure

- ◆ A fullscale of 2 volts peak-peak is 0.707 volts rms.
- ◆ with a typical termination of 200 ohms, an input power of +4 dBm is required for fullscale.
- ◆ If SNR is 75 dBFS (from the earlier example) and the sample rate is 92.16 MSPS then the ADC noise figure is:

$$NF = 4dBm - 75dB - 10\log\left(\frac{92.16 \times 10^6}{2}\right) - (-174) = 26.4dB$$



Special considerations for Spurious

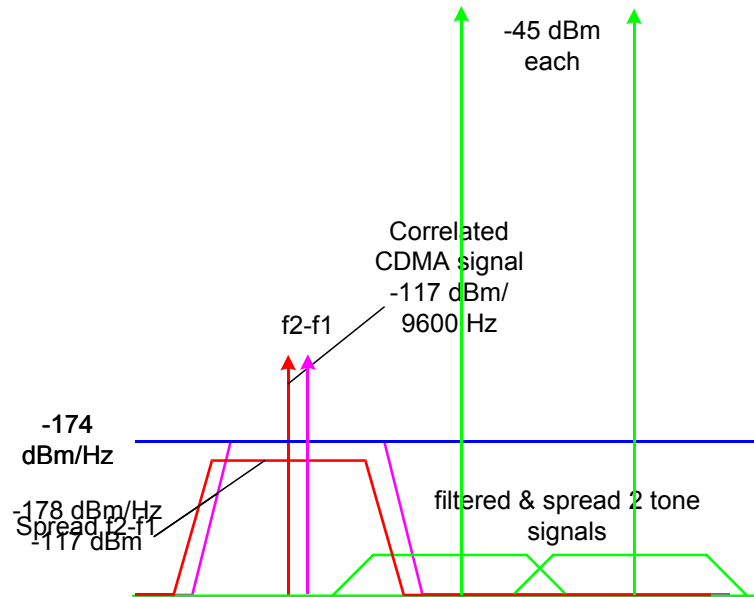
- ◆ **Narrow band receivers are sensitive to narrow (and wideband) blockers.**
 - **Must look at the demodulation scheme to determine how much lower the blocker energy must be to prevent interruption.**
 - ◆ **AM (how much heterodyne/cross talk can you tolerate)**
 - ◆ **FM >0 dB because of capture effect**
 - ◆ **digital standards typically > 9 dB C/I**
- ◆ **Direct Sequence Spread Spectrum receivers will spread the blocker energy over the chipping bandwidth unless the signal correlates with the spreading sequence. This energy then becomes noise added within the channel.**



Narrow band spurious considerations

- ◆ First determine how large the blocker and desired signal are when presented to the ADC.
- ◆ If the spurious generated by the blocker falls within the channel of interest, it must be smaller than the desired signal with the required C/I ratio.
- ◆ If the blocker is near fullscale of the ADC and the desired signal is -81 dB below the blocker and a C/I of 9 dB is required:
 - Worst case inband spurious of the ADC (and total signal chain) must be 90 dB (-81 minus 9 dB).
- ◆ A similar analysis is valid for two tone or IMD requirements.

DSSS band spurious considerations



Single tone and two tone products may fall within the channel of interest causing blocking.

In the receiver (rake) the desired energy is correlated with the PN sequence causing and the energy is 'gathered up'. The spurious energy does not correlate with the PN sequence and is instead spread by the PN sequence.

This causes the spurious signal to appear simply as added thermal noise within the channel.



Wide band spurious considerations

- ◆ **Most spread spectrum standards allow for a 3 dB increase in noise during blocking. This means that the spread energy of the blocker is allowed to equal the effective noise after the ADC.**
- ◆ **From the earlier example, the AFE noise was -141 dBm/Hz. With the ADC, the total noise is -140.2 dBm/Hz. If the noise due to the spurious is allowed to be the same...**
 - **To determine the signal level of the blocker before being spread, the energy can be integrated over the channel. At 1.25 MHz, this is a total spurious energy of -79.2 dBm.**
 - **Although this was caused by a two tone signal, a fullscale single tone signal must still cause the same or less distortion. If the ADC fullscale is +4 dBm, the required single or multi-tone SFDR is 83.2 dBFS.**

An CDMA2000'ish example



Radio tower



Filter



Filter



Filter



Filter



ADC



Rake & Decode

←---Simulation area---→

Compute

Erase

Re-order

ADC Helper



IMD Source

Stages:

- 1.Filter 1 -1 1000
- 2.Agilent HBFP-0450 2 15 29
- 3.Filter 1 -1 1000
- 4.Agilent HBFP-0450 2 15 29
- 5.AD8344 11 3 26
- 6.Filter 2 -2 1000
- 7.HMJx 8 -8 28
- 8.AD8351 IF Amp 7 14 30
- 9.Filter 5 -5 1000
- 10.AD6645 14 bit ADC 28 0 45
- 11.Rake -21 0 1000

NF= 4.34874973792614

Gain = 30

Input IP3=-8.68153763491143

Output IP3= 21.3184623650886

Performing Static simulation.

Simulation Results:

- Input Signal=-117 dBm.
 Available Noise=-113.008129026918 dBm.
- 1.Filter output -118 dBm.
 - 2.Agilent HBFP-0450 output -103 dBm.
 - 3.Filter output -104 dBm.
 - 4.Agilent HBFP-0450 output -89 dBm.
 - 5.AD8344 output -86 dBm.
 - 6.Filter output -88 dBm.
 - 7.HMJx output -96 dBm.
 - 8.AD8351 IF Amp output -82 dBm.
 - 9.Filter output -87 dBm.
 - 10.AD6645 14 bit ADC output -87 dBm.
 - 11.Rake output -87 dBm.
- Cumulative Noise output -99.6593792889914 dBm.
 Resulting SNR 12.6593792889914 dB.

Rx Analysis – Key specifications

- ◆ Required minimum sensitivity: -117 dBm (-178 dBm/Hz) or better
- ◆ Two tone intermodulation: 2 CW signals at -45 dBm
- ◆ Single tone desensitization: $+87$ dBc (-30 dBm)

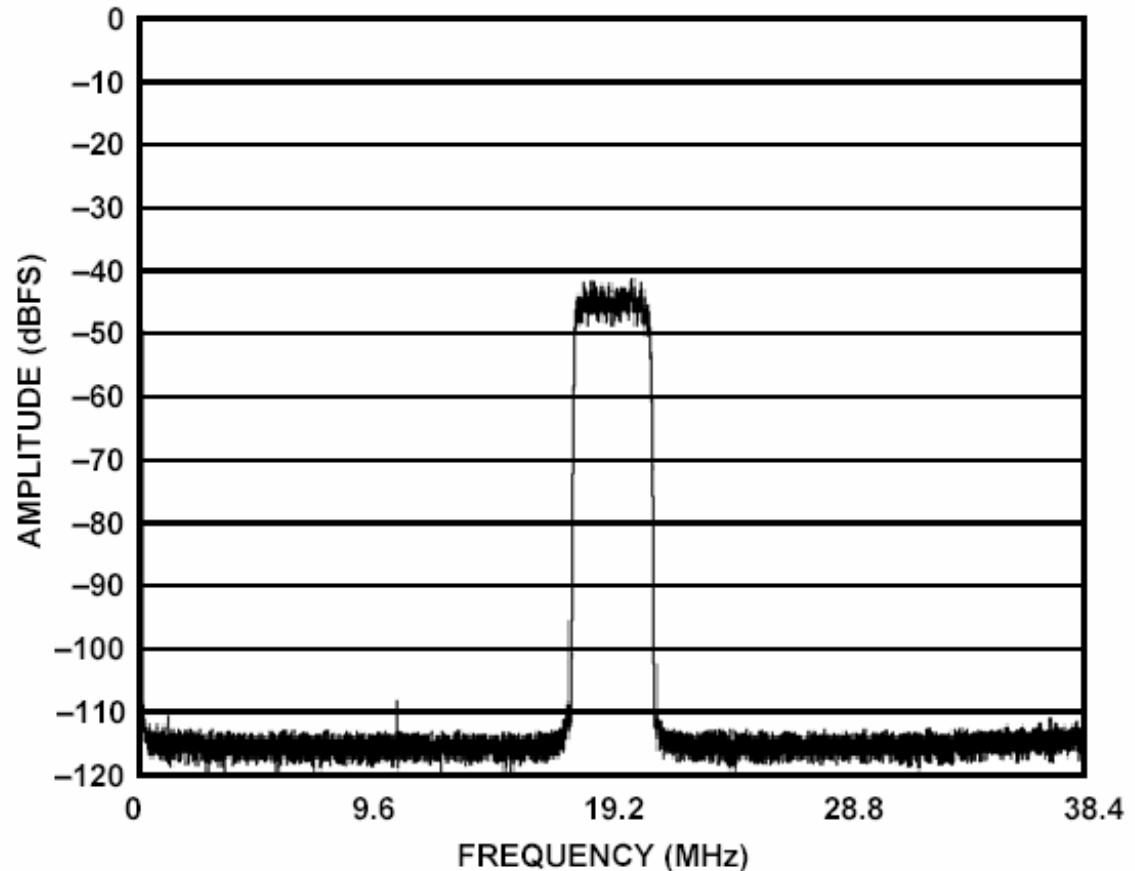
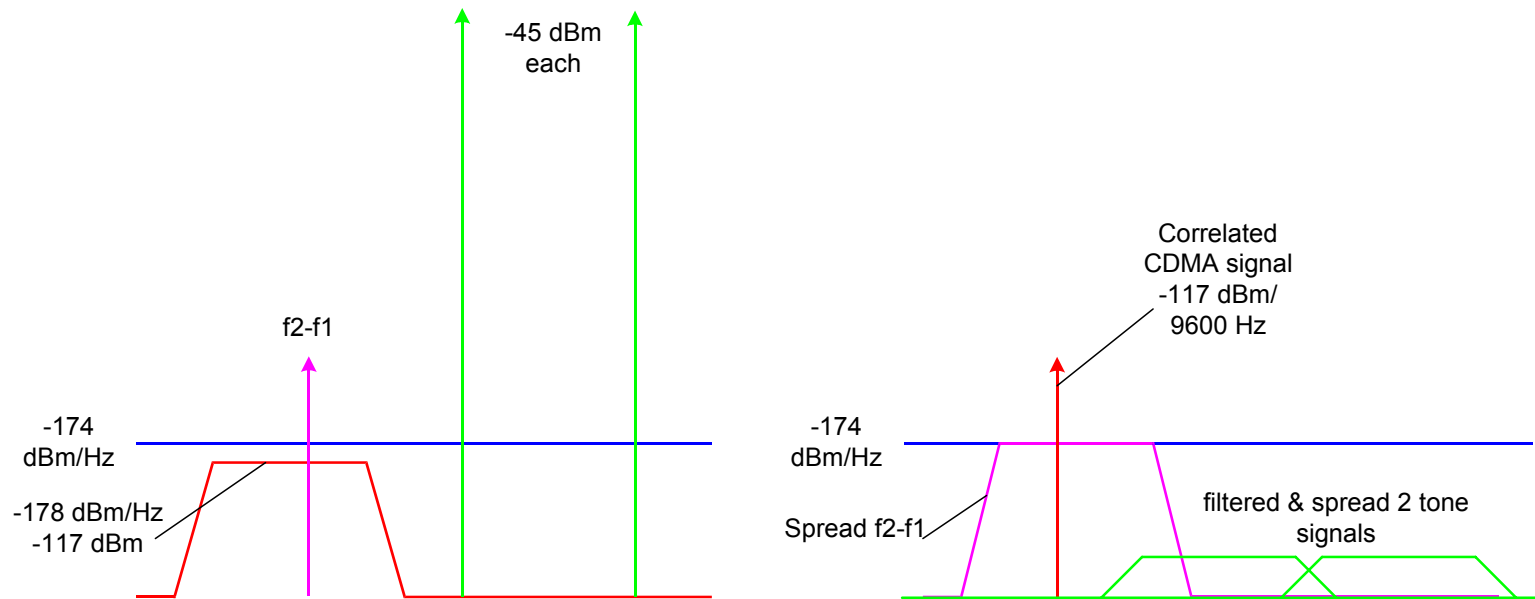


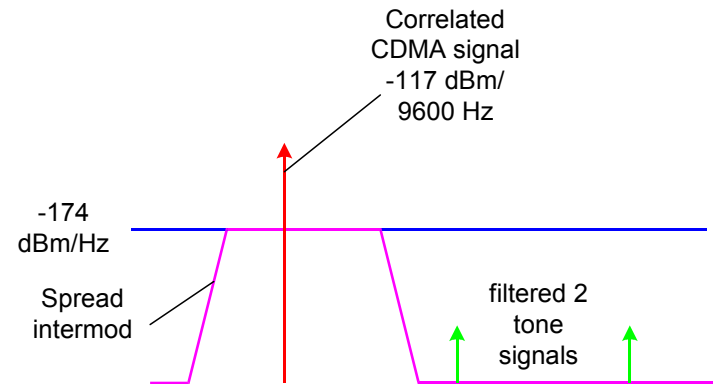
Figure 24. Two 32K FFT CDMA2K Carriers @
 $F_{IN} = 46.08$ MHz; Sample Rate = 61.44 MSPS

Rx Analysis – Two Tone effects



- ◆ The two tones create $f_2 - f_1$ which falls near the channel center.
- ◆ After the rake receiver, the desired signal is correlated while $f_2 - f_1$ and the intermodulation terms are de-correlated.
- ◆ The rake receiver makes $f_2 - f_1$ look like additional noise.

Rx Analysis – Two Tone effects



- ◆ The mobile is allowed to increase power by 3 dB, the noise floor can effectively double.
- ◆ Therefore, the noise caused by spreading the intermodulation product can equal the thermal noise.
- ◆ If the spread intermodulation is integrated over 1.25 MHz (at a density of -174 dBm/Hz), this will give the total power of the intermodulation.
 - $-174 \text{ dBm/Hz} + 10\log(1.25 \text{ MHz}) = -113.0 \text{ dBm}$ at the antenna.
- ◆ If the NF of the receiver is assumed to be 4 dB, then the f_2-f_1 term is allowed to be -109 dBm before disrupting performance.



Rx Analysis – Two Tone effects

- ◆ **The receiver doesn't care about the source of the spurious. Therefore spurious generated by single tones must also be no higher than -109 dBm referenced to the antenna.**
- ◆ **Therefore, a single tone at -30 dBm on the antenna must not generate spurious any larger than -109 dBm and SFDR must be better than -79 dBc.**



Rx Analysis – Conversion Gain

- ◆ **If the largest signal is -30 dBm and the ADC fullscale is $+5$ dBm then**
 - **Maximum gain during blocking conditions is 35 dB.**
 - **Gain higher than 35 dB is possible in non-blocking environments providing increased sensitivity.**
 - **Nominal gain with 5 dB of headroom is 30 dB.**



Rx Analysis - Sensitivity

- ◆ With 30 dB of gain and 3 dB of NF, the anticipated sensitivity is:
 - Signal = $-117 \text{ dBm}/1.25 \text{ MHz} + 30 \text{ dB} = -87 \text{ dBm}/1.25 \text{ MHz}$
 - Noise = $-174 \text{ dBm}/\text{Hz} + 61 \text{ dB} + 30 + 3 = -80 \text{ dBm}/1.25 \text{ MHz}$
- ◆ The SNR before de-spreading is -7 dB .
- ◆ Ideally, de-spreading will ‘increase’ the SNR by up to 21 dB $10\log(1.2288 \text{ MHz} / 9.6 \text{ kHz})$.
- ◆ The SNR after de-spreading is 14 dB. Since this is more than needed, in many practical test modes, better sensitivity can be achieved.



Rx Analysis – Required ADC performance

- ◆ The ADC can not dominate the noise floor. From the gain and NF above, the noise density at the ADC input is:
 - $-174 \text{ dBm/Hz} + 30 \text{ dB} + 3 \text{ dB} = -141 \text{ dBm/Hz}$
- ◆ The ADC noise should be 7 dB better or -148 dBm/Hz :
 - When sampled at 61.44 MHz: SNR = 78 dBFS or better
 - When sampled at 78.6432 MHz: SNR = 77 dBFS or better
 - When sampled at 92.16 MHz: SNR = 76 dBFS or better
 - ◆ with the an analog input -5 dBFS.
- ◆ ADC SFDR, Harmonics and other spurious:
 - $-79 \text{ dBc} + 5 \text{ dB headroom} = 84 \text{ dBFS}$ or better



Conclusion

- ◆ **Be reasonable and allow an appropriate noise contribution from the ADC.**
- ◆ **Stop and take an engineering look at the problem. Don't just do what you've always done, especially if you don't have a clue why you've done it that way.**
- ◆ **Analyze your converter needs both from a noise point of view and a spurious point of view.**
- ◆ **Do the numbers to see if you are correct.**
- ◆ **If you do, you'll end up with exactly what you needed. Even more important, you'll end up without more converter than you needed.**



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