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A Sensitivity Analysis of Radio Architectures Employing Sample and Hold Techniques

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This letter describes the use of sample and hold devices for frequency conversion within a radio. By assuming a perfect multiplier, a model is developed in order that the noise figure of a sample and hold device can be predicted. The results show that sample and hold devices have higher noise figures than mixers and hence their use can give rise to reduced receiver sensitivity.

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Abstract - This letter describes the use of sample and hold devices for frequency conversion within a radio. By assuming a perfect multiplier, a model is developed in order that the noise figure of a sample and hold device can be predicted. The results show that sample and hold devices have higher noise figures than mixers and hence their use can give rise to reduced receiver sensitivity.

1 Introduction

In a conventional radio architecture mixers and oscillators are used in order to perform frequency conversion. As an alternative, it is possible to simply sample the signal and use the aliasing effect of samplers to re-create the signal either at d.c or some other low frequency [1]. Whilst this technique offers some advantages [1], there are some drawbacks which are described in this letter.

2 Theory: A "Perfect Multiplier"

By using the concept of a perfect multiplier it is straightforward to develop parallels between sampling and mixing devices. An ideal mixer can be described by a perfect multiplier with a signal at the RF input and a sine wave at the LO input. A sampler can be represented in a similar way with an impulse train at the LO input. At the output of an ideal sampler the spectrum shows an infinite number of copies of the input spectrum, each separated by the sampling frequency [2]. The implication of this is that if an ideal sampler is used with a sampling rate which is at least twice that of the bandwidth of the data signal then it will be successfully downconverted close to d.c.(assuming the superposition of images is avoided).

Whilst this approach is very elegant it has the disadvantages in that the impulse train must be very precisely spaced in order to maintain accuracy for the sampling wave's high frequency components. In addition the technique has poorer noise performance. This is because for each spectral line in the impulse train not only is the signal copied but wideband noise also. In the extreme of a "theoretical" impulse train this results in an infinite number of mixed noise signals and hence an infinitely large noise figure. Clearly the degradation arising from this can be reduced by filtering prior to sampling, filtering however will not remove thermal noise.

Noise Model for an Ideal Mixer

Consider an ideal mixer to be made of a perfect multiplier with a sine wave at its LO input. The output of the mixer shows two copies of the spectrum, spaced $2f_{LO}$ (f_{LO} = frequency of the local oscillator), each with a power half that of the input spectrum (assuming LO amplitude $=\sqrt{2}$). If an image reject filter is used the noise figure is equal to the insertion loss of the mixer, which is 3dB.

Noise Model for a Sampler

If the pulse train used to drive the sampler is converted into the frequency domain this can then be convolved with the sampler's input signal. This gives rise to many copies of the input spectrum superimposed on one another. For a non-ideal sampling wave these images will gradually roll off with their peaks following a $(\sin x/x)^2$ curve (see figure 1). Only one harmonic of the sampling wave is used to downconvert the signal to the desired frequency. The amplitude of this harmonic determines the insertion loss and hence the noise figure of the process, and is given by:-

$$\text{amplitude (harmonic)} = \left(\frac{2At}{T}\right)\sin(\pi ft) / (\pi ft)$$

where A=amplitude of pulse (adjusted to ensure unity power)

t=duration of pulse

T=period of sampling wave

f=frequency of harmonic

In addition if no filtering is provided the noise figure is increased by the superposition of additional noise signals. This increase is given by the equation:-

$$Nu = Nf\left(\frac{Pt}{Pu}\right)$$

where Nu= noise factor without filtering

Nf = noise factor with filtering (equal to insertion loss of sampler)

Pt = Power in all the harmonics

Ph = Power in the chosen harmonic

For comparison with the mixer the amplitude of the sampling wave was adjusted so that the power of the sampling pulse train was equal to the sine wave used for mixing (i.e. both have unity power).

The Impact of Holding the Sample

The model described above concentrates on the sampling aspect of a sample and hold device and does not consider the effect of the hold capacitor. It is possible to represent the hold element as a digital low pass filter which has little bearing on the noise performance of the device. Clearly the energy in the signal will increase if the level is held between successive samples. However the signal to noise ratio of the signal will not improve as no extra information has been added.

3 Simulation Results

Using the ideas above a computer program has been written to calculate the noise figure of a sample and hold device.

Figure 2 shows the noise figure of a sample and hold device which takes samples every 10ns with a varying pulse width. Curves are shown for both with and without prior filtering to avoid image noise (the effect of aliased thermal noise is neglected). For all pulses the first harmonic is used to perform the downconversion of a signal. These results show that as the width of the pulse is reduced the power in the fundamental reduces, thus increasing the noise figure[2]. This has the added effect of the increasing potential noise power introduced by the images if no filtering is employed.

Figure 3 shows results which were taken using the same sampling waveform (chosen to be realistic [4]) but altering the RF carrier and using different harmonics for the mixing. The sampling signal has a period of 20ns and is "high" for 10ns (to ensure acquisition). This curve shows that downconverting with high harmonics increases the noise figure of the sampler.

4 Cascaded Effects for Conventional Radio Architecture

Consider a conventional RF receiver (noise figure = 5dB) with the first stage mixer replaced by a sample and hold device, similar to those shown in figure 3. Figure 4 shows the receiver noise figure [3] vs the sampler's noise figure. This shows that the overall noise figure could become as high as 18 dB with a sample and hold device having a noise figure of 30 dB.

Figure 4 also shows the effect on the overall noise figure of using the sample and hold device in replacement for the second stage mixer, here the noise performance degrades only slightly.

5 Conclusions

This letter has shown that sample and hold techniques can be used for frequency conversion but they have poor noise performance.

The effect of the noise figure, on the sensitivity of the radio, indicates that sampling devices may not be desirable at the front end of a receiver. However, in heterodyne receivers, it may be preferable, to use a sample and hold device to perform the second mixing process.

6 References

[1] "Undersampling Techniques Simplify Digital Radio," R. Groshong and S. Ruscak, Electronic Design May 23 1991.

[2] "Signals and Systems: Models and Behaviour", M.L. Meade and C.R. Dillon, Van Nostrand Reinhold (UK) Co. Ltd, 1986.

[3] "Receiving Systems Design", S.J. Erst, Artech House Inc., 1984.

[4] "Burr-Brown Integrated Circuits Data Book, Vol 33", Burr-Brown Corporation, 1989.

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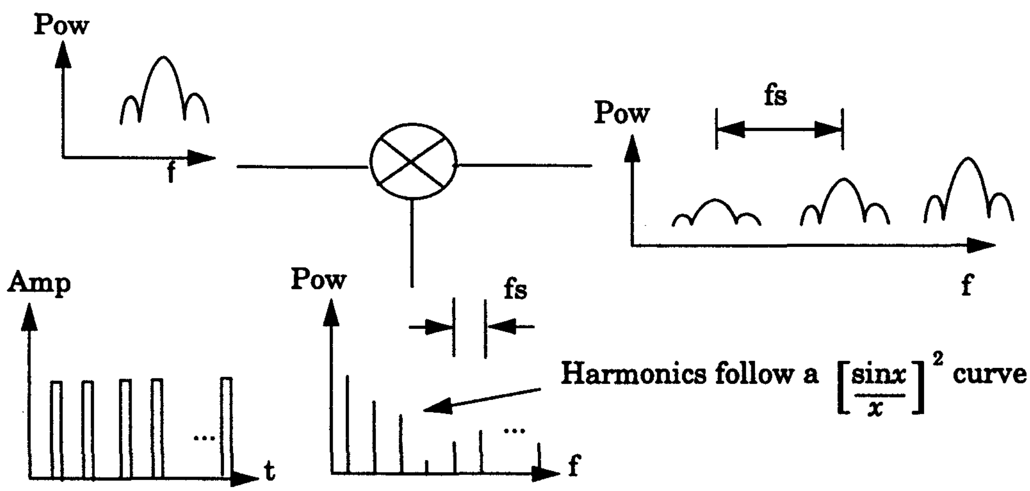

Figure 1 A non-ideal sampler

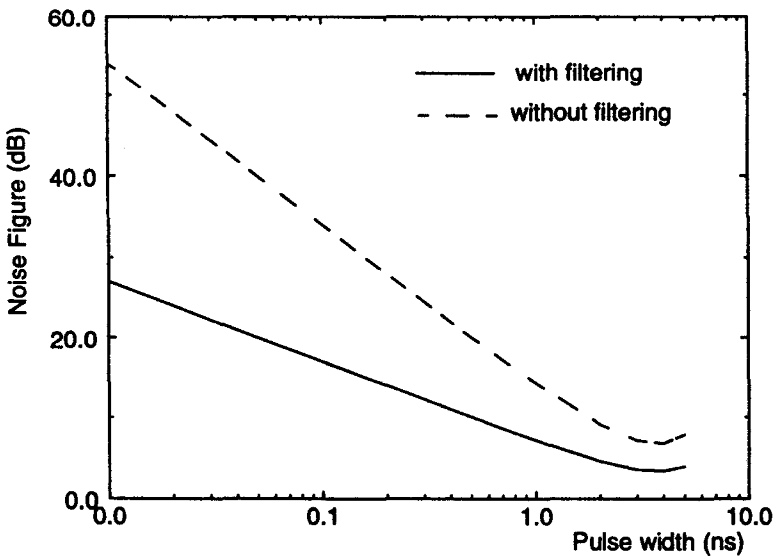

Figure 2 Noise figure vs pulse width (pulse period 10ns)

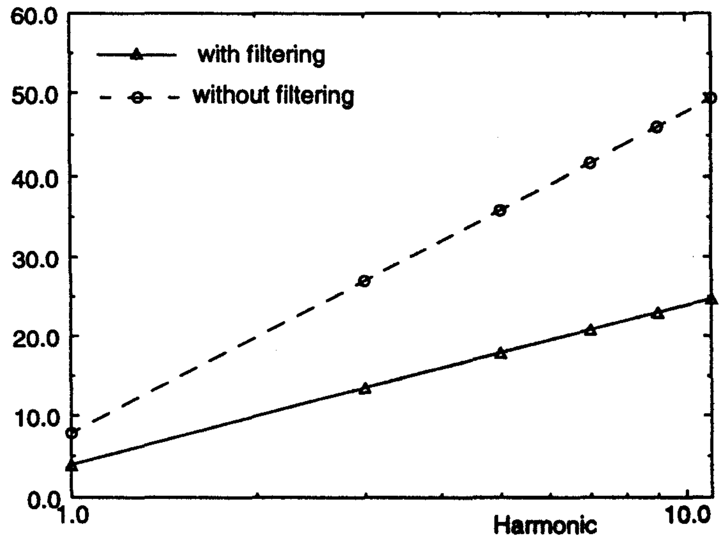

Figure 3 Noise figure vs harmonic used to downconvert, for a square wave

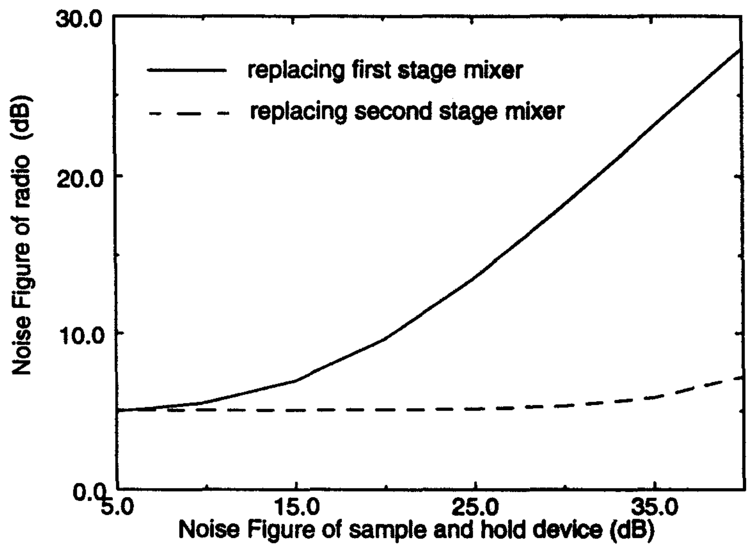

Figure 4 Cascaded noise figure of radio vs noise figure of sample and hold device