SENSITIVITY ANALYSIS OF RADIO ARCHITECTURES EMPLOYING SAMPLE AND HOLD TECHNIQUES

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1 ABSTRACT

This paper explores the feasibility of developing the “ultimate goal” of a flexible receiver (see figure1), comprised of an analogue to digital converter with an antenna as its input. This is done through some analysis which describes the use of sample and hold devices for frequency conversion within a radio. Through the use of 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. The analysis also demonstrates that their noise figure performance is considerably improved through the use of RF gain and filtering. This demonstrates that the ability to sample at RF can only realistically be achieved with appropriate consideration of the necessary RF gain and selectivity, and thus flexible receivers need programmable filters. Interestingly the paper also concludes that an ideal sampler has an infinite noise figure and is therefore useless.

2 INTRODUCTION

In recent years there has been an emergence of new digital standards in the US, Japan, and Europe. Whilst these digital standards assist the development of communicating appliances, the need to build different radios for each geographic area reduces the economies of scale. The ability to build flexible transceivers capable of operating on different standards is clearly useful. The ultimate goal in this respect is to build an A-D converter with an external antenna connection (see figure 1), Steinbrecher[1]. Through a sensitivity analysis of sampling devices, this paper serves to demonstrate that this goal cannot be realised without prior RF gain and selectivity.

3 DOWN CONVERSION BY SUB-SAMPLING

In a conventional radio architecture (see figure 2) mixers and oscillators are used in order to perform frequency conversion to ultimately extract the information available on the RF (radio frequency) carrier. As an alternative to using mixers and oscillators 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, Greenberg[2]. This technique has the advantages in that it is no longer necessary to generate a high frequency sine wave, instead the sampling device can be clocked with a pulse train at low frequencies. In addition the frequency band of interest can be changed by simply clocking the sampler at a different rate. Unfortunately, for acceptable phase noise performance highly accurate timing is required for the sampling pulse train. In addition it is necessary to avoid the superposition of images and spurious reception. It is also shown in this paper that the noise performance of a sampling device is inferior to that of a mixer.

4 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 one input and a sine wave at the other. In addition a sampler can be represented by a perfect multiplier with the signal as one input and an impulse train as the other. An impulse train is both discrete and periodic and hence its frequency domain representation is both discrete and periodic. The equivalent to multiplying in the time domain is convolution in the frequency domain, therefore 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 (see figure 3), Meade[3]. 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.

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 its high frequency components. In addition the technique has a much 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 an impulse train this results in an infinite number of aliased 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 and therefore some RF gain, prior to filtering, would be advantageous. In this paper it is assumed that device noise is dominant, the filtering is effective,and that the sampler is preceded by RF gain.

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 is a signal whose frequency spectrum is the convolution of the input spectrum and its local oscillator. This gives rise to two copies of the spectrum, spaced $2f_{LO}$ where f_{LO} is the frequency of the local oscillator, each with an power half that of the input spectrum (this assumes that the local oscillator amplitude is $\sqrt{2}$). If an image reject filter is used then it is possible to avoid mixing down two noise signals. For a passive device it can be shown that the noise figure is equal to the insertion loss, Maas[4], therefore the noise figure of the mixer is 3dB.

Noise Model for a Sampler

A similar argument to that of the mixer can be applied to a sampler. If the pulse train used to drive the sampler is converted into the frequency domain this can then be convolved with the input signal. This gives rise to many copies of the spectrum superimposed on one another. For a non-ideal sampling wave these images will gradually roll off with their peak powers following a $(\sin x/x)^2$ curve (see figure 4). Only one particular 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, which is given by:-

$$NF = -20\log\left[\left(\frac{\sqrt{2}At}{T}\right)\left(\frac{\sin(\pi f t)}{(\pi f t)}\right)\right]$$

where NF = Noise figure for a given amplitude

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:-

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

where Nu= noise factor without filtering

Nf = noise factor with filtering

Pt = Power in all the harmonics

Pd = Power in the chosen harmonic

For comparison with the mixer the amplitude of the sampling wave was adjusted in order that the power of the sampling pulse train was equal to the sine wave used for mixing (i.e. both have unity power). This does not reflect the potential efficiency advantage of generating baseband signals, and hence the sub-sampling technique may be able to operate with higher total mixing powers for equal power consumption.

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 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.

5 NOISE RESULTS

The concepts described in section 4 have been collected in a C program which calculates the noise figure of a sample and hold device. The inputs it requires are:-

- Pulse repetition frequency
- Pulse width or acquisition time
- Frequency of RF carrier

Figure 5 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. For all pulses the first harmonic is used to perform the downconversion of a signal placed nominally at 120 MHz.

These results show that as the width of the pulse is reduced the power becomes more evenly spread across a large band and hence the first order fundamental becomes smaller. This has the added effect of the increasing potential noise power introduced by the images and hence should the device be used without appropriate filtering the noise figure can exceed 40 dB.

Figure 6 shows results taken using the same sampling waveform, (which has been chosen to be high speed, but realistic, Burr[5]) but altering the RF carrier so that different harmonics are used for the mixing. The sampling wave has a period of 20ns and is “high” for 10ns. This curve clearly shows that if the RF carrier is increased beyond 500MHz (harmonic =11) the noise performance of the sample and hold device begins to deteriorate significantly. Once again the two curves are shown in order to demonstrate the need for appropriate filtering.

6 MEASURED RESULTS

No measurements have been performed by the author, however measurements of a downsampling mixer have been carried out by Chan [6]. In his paper he describes a downsampling mixer which is used to downconvert a signal at 900 MHz to around 50 MHz with an LO of less than 120 MHz. Chan [6] reports a noise figure of 14 dB which he attributes to aliasing wideband noise.

7 CASCADED EFFECTS FOR A CONVENTIONAL RADIO ARCHITECTURE

It is useful to take these results and study the impact of using sample and hold devices within a complete radio. The architecture shown in figure 2 has a cascaded noise figure of 5 dB, Erst [7]. If the first stage mixer is replaced by a sample and hold device with characteristics similar to those shown in figure 6 then its noise figure will be higher. Figure 7 shows a graph of the cascaded noise figure vs the noise figure of the sample and hold device. 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 7 also shows the effect on the overall noise figure of using the sample and hold device in replacement for the second stage mixer. This curve shows that the gain in the receiver prior to the second stage mixer is dominant in determining the noise performance and hence the noise figure degrades only slightly when using a sample and hold device with a high noise figure.

8 CONCLUSIONS

An analysis of the noise performance of a sample and hold device has been performed. This has shown that sample and hold techniques can be used for frequency conversion but they suffer from a significantly larger noise figure (assuming equal signal powers for mixing).

The effect of the noise figure, on the sensitivity of the radio, has been studied and the results indicate that sample and hold techniques cannot be used for frequency conversion at the front end of the receiver without desensitising the receiver. However in heterodyne architectures it is acceptable, and in some circumstances preferable, to use a sample and hold device to perform the second mixing process. In addition the paper has highlighted the importance of RF gain and selectivity and demonstrated that sampling at RF requires prior gain and filtering.

9 ACKNOWLEDGEMENTS

I would like to gratefully acknowledge my colleague Dr Bill McFarland for his contribution to this work.

10 REFERENCES

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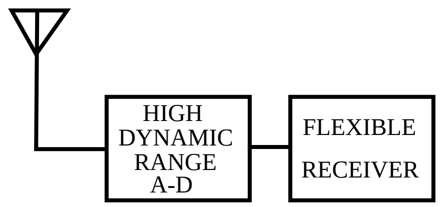

Figure 1 The “ultimate” flexible receiver

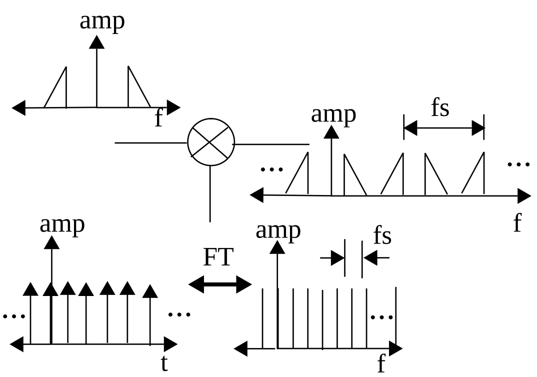

Figure 3 An ideal sampler

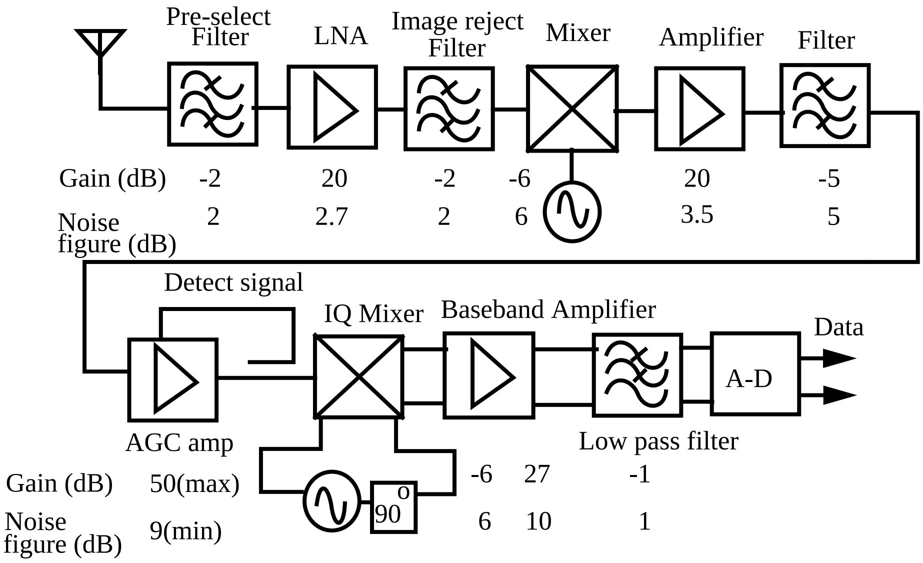

Figure 2 Conventional radio architecture

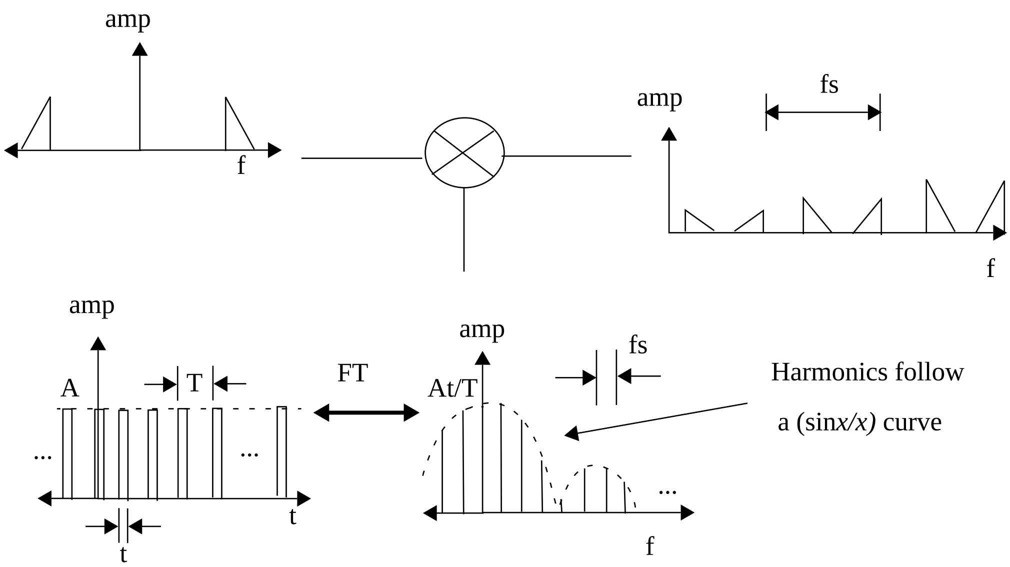

Figure 4 A non-ideal sampler

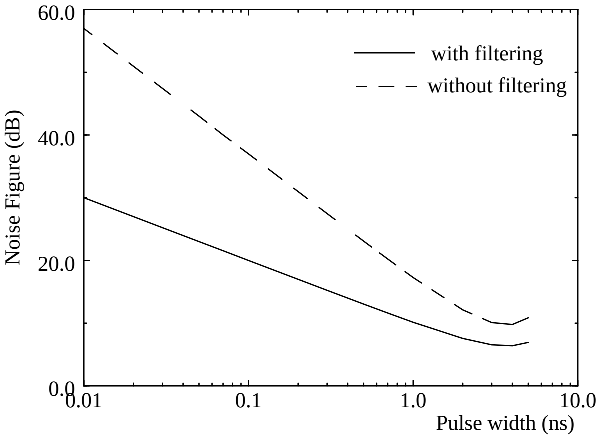

Figure 5 Noise figure vs pulse width (pulse period 10ns)

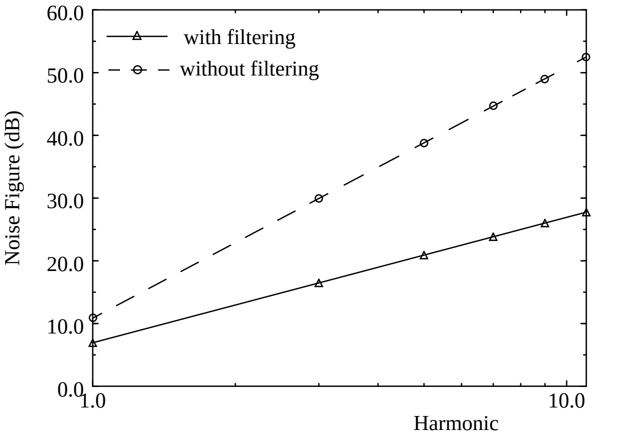

Figure 6 Noise figure vs harmonic used to downconvert, for a square wave

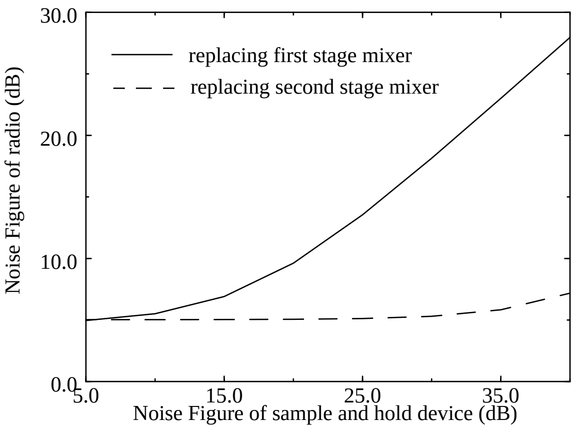

Figure 7 Cascaded noise figure of radio vs noise figure of sample and hold device