Using High Pass Sigma-Delta Modulation for Class-S Power Amplifiers

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Abstract: Switching power amplifiers offer the potential for superior efficiencies if used at radio frequencies. However many existing bandpass architectures require a switching frequency four times that of the signal, making implementation difficult. In this paper we propose to use a high-pass sigma-delta modulator to reduce the switching rate to only twice of the signal. We will present a solution to the problem of the reflected image and demonstrate it's viability for use in mobile telephony.

I. INTRODUCTION

Switching amplifiers, as depicted in Figure 1, operate by taking a binary digital signal and using this to control a power switch, thus replacing a traditional digital-to-analog converter and amplifier with a single device. As a switched system, these amplifiers theoretically have perfect efficiency and in practice efficiencies of 85-90% [1] have been demonstrated at audio frequencies and over 70% [2] at RF's. These systems have been used for many years in audio applications [3], but there is increasing interest in using this technology in mobile wireless applications where power efficiency is a critical parameter.

Traditionally the switching signal would be pulse-width-modulated, but in recent years has been replaced by sigma-delta modulated bitstreams. These systems have been developed for low frequency applications, such as audio, as the switching frequency has to be many times that of the bandwidth of interest. These low-frequency amplifiers have been called Class-D amplifiers [3]. Recently there has been interest in using bandpass modulated bitstreams for use in RF systems, where they are often called Class-S amplifiers [4,5]. These systems offer the potential for simplified transmitter architectures and increased power efficiency.

While bandpass systems have great potential, they typically require a switching frequency four times that of the signal that they wish to generate. For a modern wireless communication scheme, this could mean a switching frequency of approximately 10 GHz. Implementing a complex system at these frequencies remains impractical for most applications. In this paper we propose the use of a sigma-delta modulator that produces a high-pass transfer characteristic which will enable the power amplifier to operate at only twice the signal frequency [6]. This would enable direct-to-RF conversion with power amplification to be achieved for most wireless communications schemes using the capabilities of existing CMOS technology.

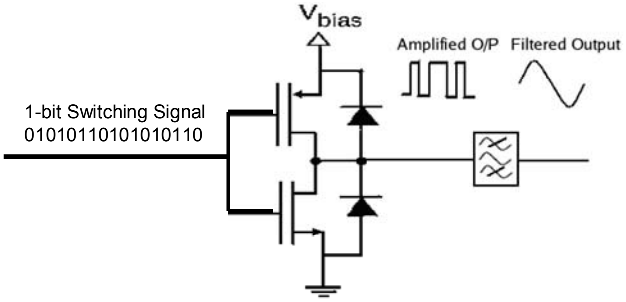

Figure 1: Switching Power Amplifier

II. SIGMA-DELTA DATA CONVERTERS

Sigma-delta (ΣΔ) modulation has been used in many applications and is well understood. The general architecture of a sigma-delta modulator is shown in Figure 2. A high resolution input is provided and through the use of feedback, a high speed, low-resolution output is generated with the characteristic that signal content in the passband of the filter is the same for the lower-speed high resolution input and the high speed, low-resolution output. There are many variants of sigma-delta modulation. These are broadly characterized by the spectral characteristics of this transformation, (lowpass, bandpass, highpass) and the number of poles in the loop filter of the modulator.

The reason for the popularity of sigma-delta modulation is that while a 2-level output stage results in a large amount of quantization noise, this noise can be spectrally shaped such that there is a noise null co-incident with the signal passband. The degree and nature of this noise shaping is defined by the loop filter transfer function H(z). This noise-shaping feature has been widely used in low frequency data converters where the noise is moved away from the lower frequencies to the higher frequencies, leaving the baseband signal noise free. This is demonstrated for a lowpass modulator in Figure 3. Mathematically, the signal and noise transfer functions can be mathematically expressed, assuming a linear additive noise model as

$$NTF(z) = \frac{1}{1 + H(z)} \qquad (1)$$

$$STF(z) = \frac{H(z)}{1 + H(z)} \qquad (2)$$

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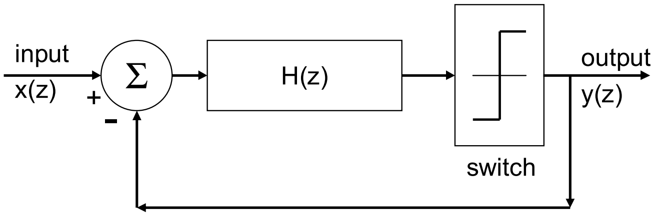


Figure 2: Generic Sigma-Delta Modulator

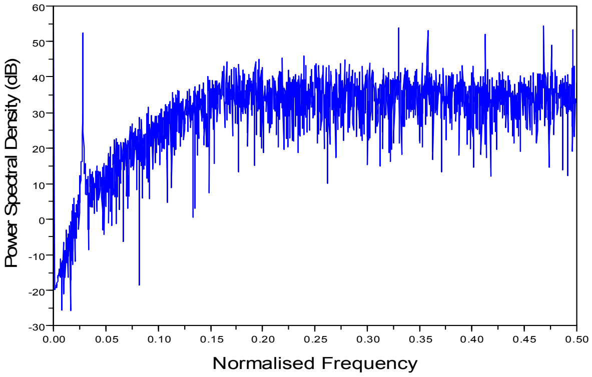


Figure 3: Second Order low-pass sigma-delta modulator

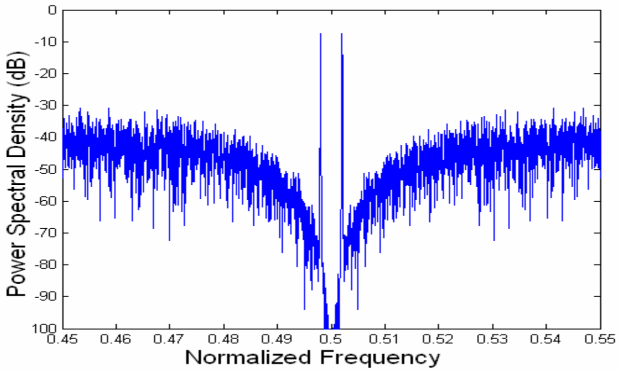


Figure 4: Second Order high-pass sigma-delta modulator with image above half the sampling frequency

By changing the loop filter of the sigma-delta modulator, it is possible to move the signal band, and the co-incident noise notch to other frequencies, generating bandpass or a highpass transfer function (Figure 4).

Designing sigma-delta modulators can be challenging due to their highly non-linear nature. There are a number of methodologies that can be used to design lowpass sigma-delta modulators [7]. Designing bandpass and highpass modulators are more complicated. A common technique that is guaranteed to produce stable modulators is to apply a mapping function to the discrete-time transfer function of a lowpass system. These mapping functions are

Bandpass: $z^{-1} \Rightarrow -z^{-2}$ (3)

Highpass: $z^{-1} \Rightarrow -z^{-1}$ (4)

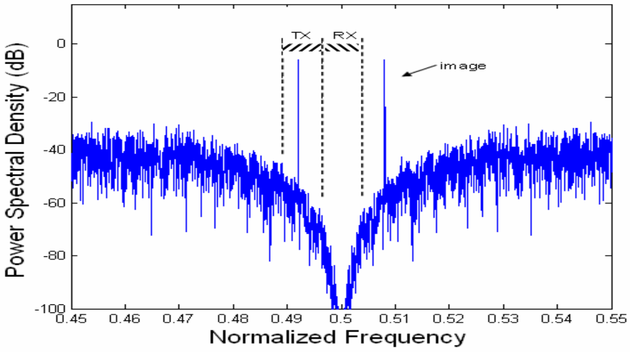
Using this transform, the bandpass modulator's passband is located at ¼ and ¾ the switching frequency (f_s). While it is possible to design arbitrary bandpass modulators, these other architectures require multipliers and are thus expensive to implement in a digital system. It is also worth noting that the loop filter in the bandpass sigma-delta modulator has twice the poles of an equivalent lowpass system, which leads to a more complicated implementation.

In the highpass modulator, the noise notch is located at half the sampling frequency ($f_s/2$) as shown in Figure 4. It also retains the same number of filter poles as for the lowpass modulator. These are desirable features however as the signal must now be located close to half the switching frequency, an image is seen immediately above the $f_s/2$ point. This prevents the use of frequencies close to the $f_s/2$ point.

III. USING HIGHPASS ΣΔ MODULATION FOR WIRELESS APPLICATIONS

In 3G mobile telephony, there are separate receive and transmit bands, each 30 MHz wide, comprising a total of 60 MHz of bandwidth. Individual operators are allocated sub-bands (say 5 MHz) within the transmit and receive bands. As mobile phones, and basestations may change from operator to operator, it is necessary for the transmitter to be able to range over the full 30 MHz transmit band while not impacting on the receive band. In a Class-S application this implies that the noise notch must extend for 60 MHz even though the transmitted signal bandwidth will rarely exceed 5 MHz. For a signal frequency of approximately 1900 MHz, this corresponds to a fractional signal bandwidth of approximately 6%, which is relatively wide. It is also important to note that it is more critical to achieve a low-noise floor in the receive band than the transmit band. Receivers are highly sensitive and can receive signals over 100 dB lower than the transmitted signal. While filters exist after the amplifier to reduce interference, any additional noise produced makes this task more difficult.

To overcome the issues of the noise floor and the unwanted image, we propose that it is possible to offset the signal to be generated from the $f_s/2$ mark by increasing the switching frequency slightly. This has two advantages: first the image is now further away and thus easier to filter out; and secondly it is possible to place the region of the spectrum with the lowest quantisation noise in the frequency band that corresponds to the receivers, as illustrated in Figure 5.



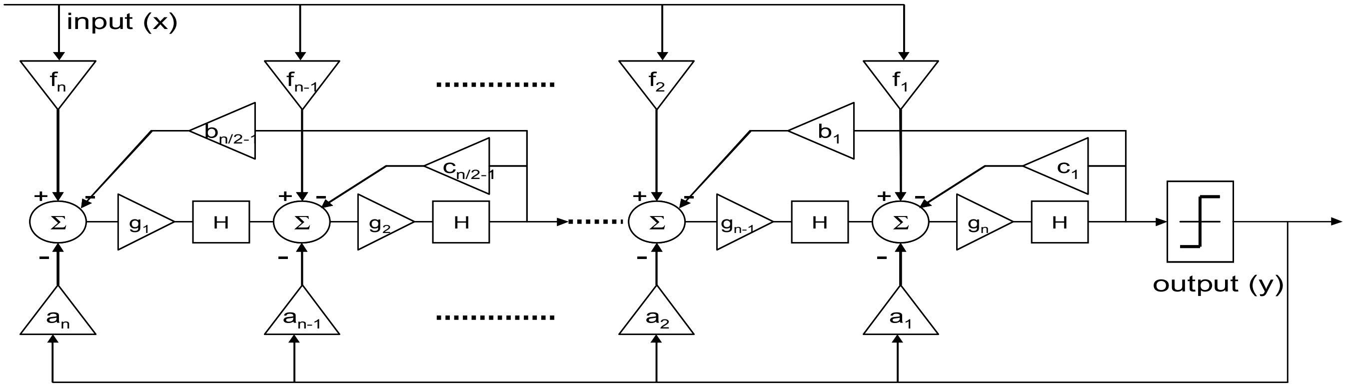


Figure 6: Architecture for a Sigma-Delta Modulator with a CRFB Structure [8]

Figure 5: The offset signal generation and receive noise floor minimisation

However placing the generated signal away from the $f_s/2$ mark implies that the signal generated will be moving up the noise curve shown in Figure 4. The further we place the generated signal away from the $f_s/2$ mark, the simpler it is to remove the unwanted image but at the expense of increased in-band noise. Given that the signal bandwidth is a relatively large percentage of the switching frequency, this is a particularly concern.

IV. HIGH ORDER HIGH-PASS ΣΔ MODULATORS

In 3G applications, the transmit chain should have an in-band signal-to-noise ratio in excess of 70 dB prior to the final stage of filtering. To achieve this with the given oversampling ratio, a third order sigma-delta modulator could be used. It has been shown in lowpass systems that it is possible in higher order sigma-delta modulators to shift the noise zeros such that they are offset from dc, thereby allowing for increased control of the spectral characteristics, at the expense of less aggressive noise filtering at dc [8]. This will allow us to selectively widen or deepen the noise notch to match the requirements of your application. Using the transform (4) it is possible to take this approach and apply it to high-pass modulators. This is particularly relevant as highly aggressive filtering at $f_s/2$ is not as valuable as wideband noise suppression.

To demonstrate the viability of this approach, a fifth order high-pass modulator has been designed with offset noise zeros. The filter will be designed with the assumption of a 150 MHz bandwidth, and placing the image 300 MHz away from the original signal. While this is excessive in any practical application, it is useful as a demonstration to show how the noise notch can be widened as necessary.

For this example, the loop filter was implemented using a technique that results in easily implemented filters and is based upon a cascade of resonators with multiple feedback and feedforward paths (CRFB) [9]. The first stage in designing an optimized loop-filter is to consider the lowpass case. In this case the noise transfer function is given by (2) and this can be designed directly. Once the filter has been designed, the coefficients are quantized to a power of two and implemented as binary shifters. The CRFB methodology has been developed to produce robust filters where the parameters have been quantized. For our fifth order system, the Table 1 list the feed-forward and feedback coefficients as per the CRFB structure in figure 6.

TABLE 1: FILTER COEFFICIENTS

a_1	**a_2**	**a_3**	**a_4**	**a_5**	
2^{-11}	2^{-7}	2^{-5}	2^{-2}	2^{-1}	
B_1	**b_2**	**b_3**	**b_4**	**b_5**	**b_6**
2^{-11}	2^{-7}	2^{-5}	2^{-2}	1	1
g_1	**g_2**				
2^{-4}	2^{-3}				
c_1	**c_2**	**c_3**	**c_4**	**c_5**	
1	1	1	1	1	

Figure 7 shows the output spectrum of the resulting lowpass sigma delta modulator, and that of the modulator achieved when the mapping of (4) is used.

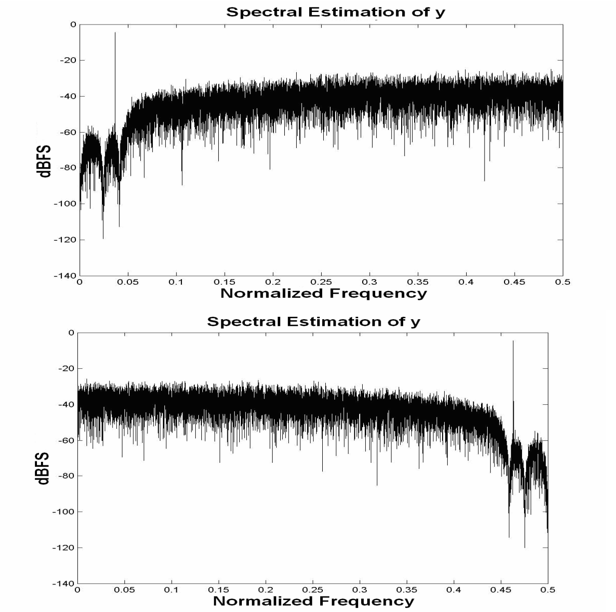


Figure 7: Output Spectrum of the 5th order lowpass modulator, and the equivalent highpass modulator

If we examine more closely the signals around fs/2 (Figure 8) we can see that the image signal is present, but distant from the original. In this simulation it is assumed the signal is located in the 2.4 GHz ISM band. A switching frequency of 4.5 GHz will allow for a 150 MHz offset for the signal frequency, resulting in a 300 MHz separation between the image and the desired signal, facilitating easy removal.

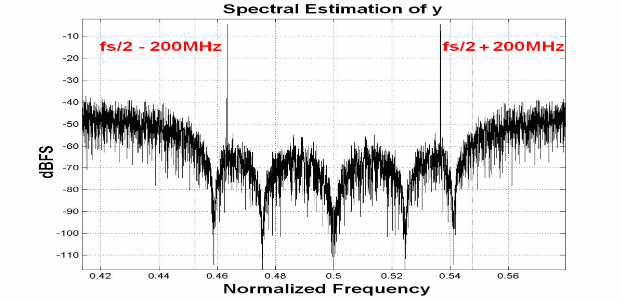


Figure 8: Close-up of 5th Order HPSDM Image Freq

V. EXPERIMENTAL RESULTS

The concept of a high-pass sigma-delta modulator for use in a class-S power amplifier was validated using a Xilinx FPGA and a switching frequency of 50 MHz. The output switch was a standard output pin rather than a power switching stage. While the experimental sampling frequency is significantly lower than that required by the application, implementing the design in a more advanced technology and with better design of the output driving stage, the performance should be equivalent if either frequency or power levels are changed.

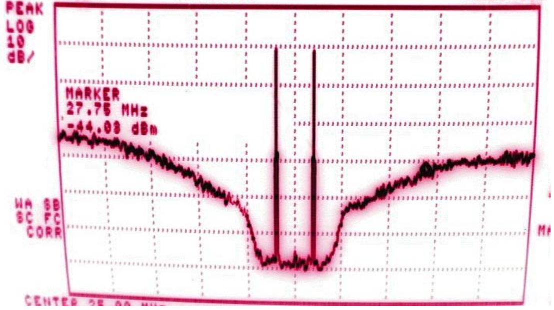


Figure 9: 5th Order high pass sigma-delta modulator with a narrowband noise notch

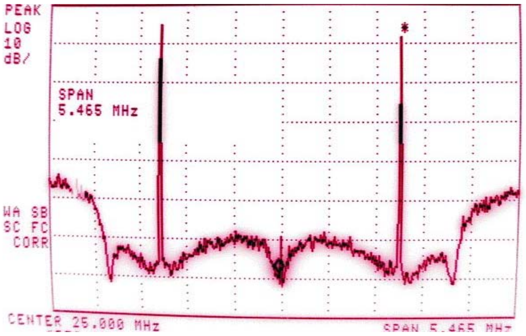


Figure 10: 5th Order high pass sigma-delta modulator with a wideband noise notch

Figure 9 shows a narrowband system with a deep notch and a 1.5% fractional bandwidth, achieving in excess of 70 dB SNR. Figure 10 shows the wideband 5th order system of the previous section with a fractional bandwidth of 8%, it has poorer noise performance but achieves over 60 dB SFDR. In both cases the depth of the noise notches is limited by various noise sources. Two of the most significant noise sources include clock jitter and asymmetric rise and fall times and affect the signal at the discrete-to-continuous interface [10].

VI. CONCLUSION

In this paper a novel highpass sigma-delta modulator has been presented that will enable class-S amplifiers to be used for wireless communications applications. Using a highpass modulator halves the necessary switching frequencies and brings it within the scope of existing technology. In addition the implementation of the modulator is simpler than existing solutions. We have shown that the problems of the reflected image can be overcome and the quantisation noise shaping can be controlled to suit the requirements of the wireless application. Finally these modulators have been demonstrated using a Xilinx FPGA and experimental results match simulations, leading to confidence that viable systems can be constructed for wireless communications systems.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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