Direct Digital-to-RF Conversion for Mobile-Phone Basestation Applications using Bandpass Sigma Delta Modulation

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Abstract: *Sigma-delta modulator based digital-to-analog converters (DAC) have offered low-frequency designers a highly linear, high resolution data converter architecture that is highly amenable to integration with complex digital systems. Increasingly these data converters have been used to deliver all the power needed. In wireless applications, it is increasingly desirable to apply low-frequency sigma-delta techniques to RF signals and try to achieve similar benefits. In this paper we discuss the unique challenges that DACs in mobile phone basestations must satisfy and we present a flexible bandpass sigma-delta modulator architecture that can satisfy these criteria.*

I. INTRODUCTION

Digital-to-analog converters (DAC) key technology in any radio transmitter, enabling complex waveforms to be developed digitally and then subsequently converted to an analog signal for transmission. In mobile phone basestations traditional high resolution high-bandwidth architectures have been used. This has resulted in a simplified transmitter architecture, as shown in Figure 1. However this architecture still requires many analog components, each of which introduces distortion, noise and cost to the system. A desirable solution would be for the DAC to be capable of producing an analog output at the RF frequencies of interest, for example either 850, 900, 1800 or 1900 MHz. If such a DAC were available, the transmitter architecture could be significantly simplified to just a DAC and a power amplifier (Figure 2). In such a system, the digital processing unit, perhaps an FPGA or a microprocessor, constructs the final signal for transmission, with the advantages of ideal linearity and no added noise.

One promising architecture for direct-to-RF conversion is that of sigma-delta bandpass modulator based data converter, first proposed in 1991 [1]. Sigma-delta modulators have been used extensively in low frequency applications, providing designers with an architecture highly amenable to integration and yet delivery superior linearity and noise performance. As a sigma-delta modulator converts a high resolution digital data to a high speed stream of binary data, which can be used for driving a digital switch, this switch can also be used to deliver power. It has been proposed that a particular form of sigma-delta modulator that delivers a bandpass transfer function could be used for RF data conversion and also to deliver power to the antennas [2-5]. If achieved, radio transmitters could be reduced to some digital logic, a pair of switches and a filter, with few of the challenging RF design problems commonly experienced today (Figure 3).

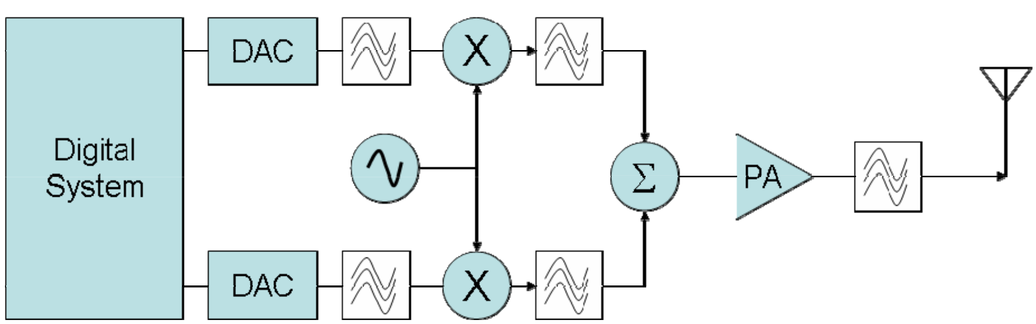

Figure 1: Conventional RF Transmitter

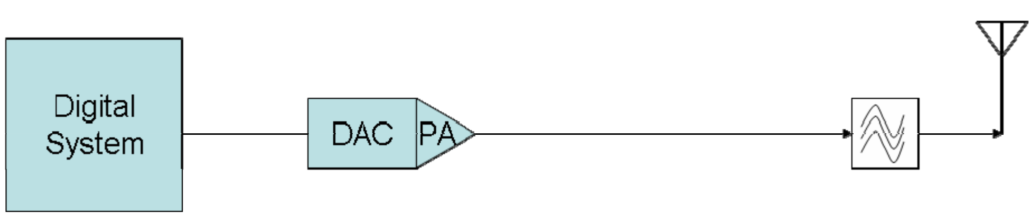

Figure 2: Direct-to-RF Transmitter

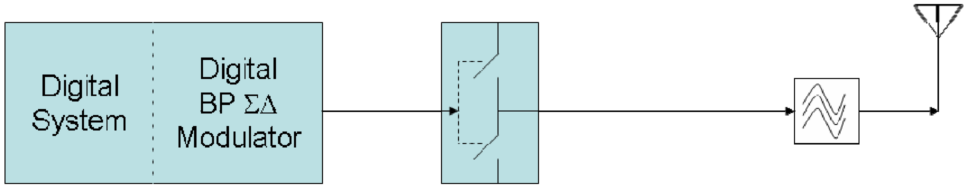

Figure 3: Direct-to-RF Transmitter using a Bandpass ΣΔ Modulator

II. THE MOBILE PHONE BASESTATION

The trend in modern mobile phone basestations is towards ever increasing signal complexity and wider bandwidths. This is being driven by the need to send increasing quantities of information, whether voice or data, to the users. At this time, a basestation transmitter has a digital-to-analog converter requirement of at least a 35 MHz signal bandwidth with a requirement that the SNR of the signal is approximately 70 prior to the final filtering stage. With additional analog elements following the existing DACs, this corresponds to a 12, or 13, bit DAC. The second challenging aspect of designing the transmitter chain for a basestation is the proximity of the receiver, both spectrally and physical. Through the use of a duplexor, the antenna in the basestation will be shared, providing a path, though highly attenuated, between the transmitter and the receiver. As the transmitter typically operates at approximately 100 W (50 dBm) average power, and the receiver must be sensitive to signal strengths of only 63 nW (-102 dBm), and basestations have tended to exceed these sensitivities as the technology has matured. The duplexor attempts to isolate the receive and transmit paths, however with a 150 dB difference in signal strengths transmit signal noise at the receiver frequency needs to be avoided as far as possible.

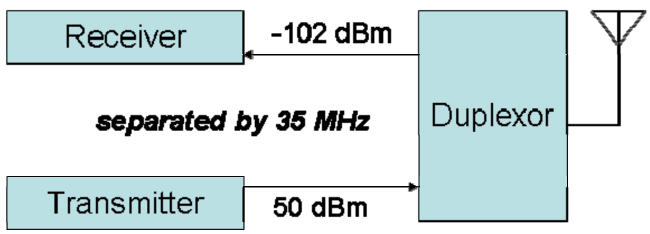

Figure 4: Transmitter and Receiver share a single antennas, separated spectrally by up to 35 MHz

III. SIGMA-DELTA DATA CONVERTERS

Sigma-delta modulation (ΣΔM) has been used in many applications and is well understood [6]. A brief explanation is that a ΣΔM takes a high resolution, low speed signal and generates a pulse-density modulated bit-stream which is high speed but low-resolution. The characteristics of this transformation is due to the use of feedback, the signal content of the output is maintained equal to that of the input. An important advantage of ΣΔ modulation is that the noise transfer function can be designed such that there is a noise null coincident with the signal passband. The degree and nature of this noise-shaping is defined by the loop filter transfer function H(z). Due to the importance of the loop filter, sigma-delta modulators are typically defined by the order of the loop filter transfer function.

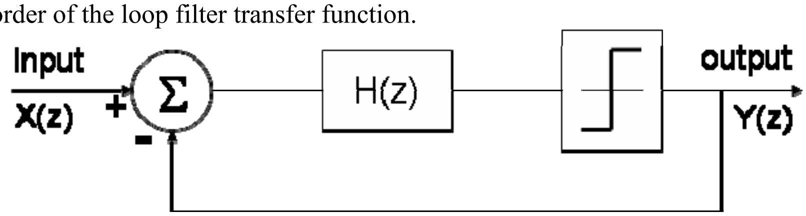

Figure 5: Generic sigma-delta modulator

This noise-shaping feature has been commonly used in lower 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 data converter (shown in Figure 6), and mathematically expressed below assuming a linear additive noise model.

$$NTF(z) = \frac{1}{1 + H(z)} = 1 - z^{-1} \qquad STF(Z) = \frac{H(z)}{1 + H(z)} = z^{-1} \qquad (1)$$

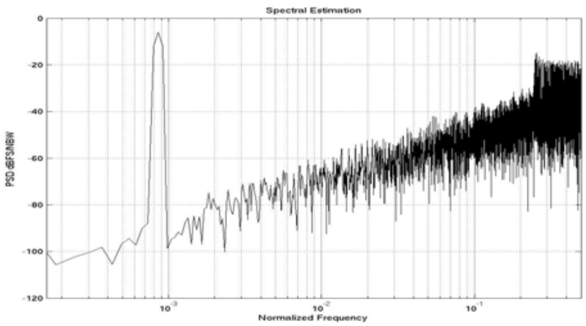

Figure 6: 1st order LPSDM with -6dB Sinusoid Input

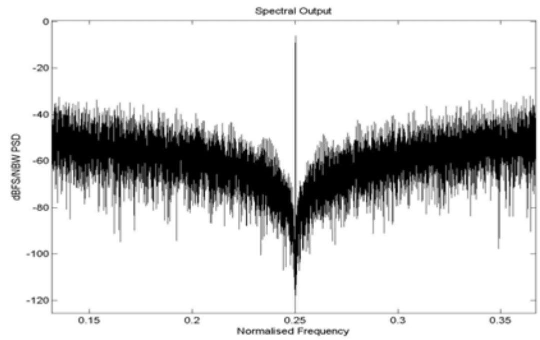

Figure 7: 2nd Order BPSDM with -6dB Sinusoid Input

where
$$H(z) = \frac{z^{-1}}{1 + z^{-1}}$$
The effectiveness of the noise-shaping depends on the degree on the ratio of the output signal frequency to that of the signal, or in other words, the oversampling rate (OSR). When the oversampling rate is large and using higher order modulators, data converters with resolutions up to 24 bits have been achieved.

With a different choice of filter, it is possible to achieve a bandpass signal transfer function with an equivalent noise-notch. In the case of a bandpass sigma-delta modulator (BPSDM), the OSR is defined as the ratio of output sample rate to that of the signal bandwidth that will be used. This means that it possible to create a modulated output where the generated signal experiences very little quantisation noise from the conversion process. The output of a second order bandpass modulator is illustrated in Figure 7

Suitable bandpass transfer functions can be generated by transforming any lowpass transfer function with the following mapping.
$$z^{-1} \rightarrow -z^{-2} \qquad (2)$$

This transform doubles the number of poles in the loop filter and transfers the zeros of the noise-transfer function from dc to $f_s/4$ and $3f_s/4$, as illustrated in Figure 8. This transform is popular as it results in stable, easy to implement transfer functions. However it is possible to design other transfer functions with the zeros located differently.

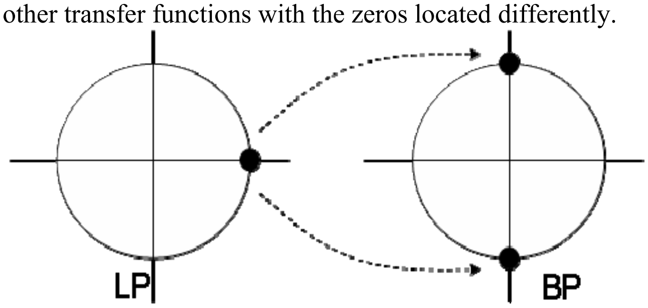

Figure 8: LP → BP Zero Transformation

IV. Architecture for use in Basestation

If a bandpass modulator is to be use to generate an RF signal for mobile communications, it will need to locate the signal frequency at one of the communications, either 850, 900, 1800, 1900 MHz. As the signal frequency is typically at $f_s/4$, this means that the digital modulator must operate at 4 times the signal bandwidth. It is possible to utilise the image at $3f_s/4$ but this incurs degraded SNR performance due to the sinc function roll-off. With the digital modulator operating at such high frequencies, it is important that multipliers within the implementation must be avoided. will have to be capable of operating at GHz frequencies because of the need to over sample. This can be achieved by selecting coefficients that are powers of two. However this results in a certain level of quantisation of the poles of the more complex transfer functions, resulting in a spreading of the noise zeros around fs/4, degrading performance. We propose to take advantage of an architecture that was proposed by Roberts [7, 8] in 1995 that is relatively insensitive to quantization of the coefficients and is computationally efficient. The authors used a slightly different implementation of a sigma-delta modulator where the loop filter is in the feedback path.

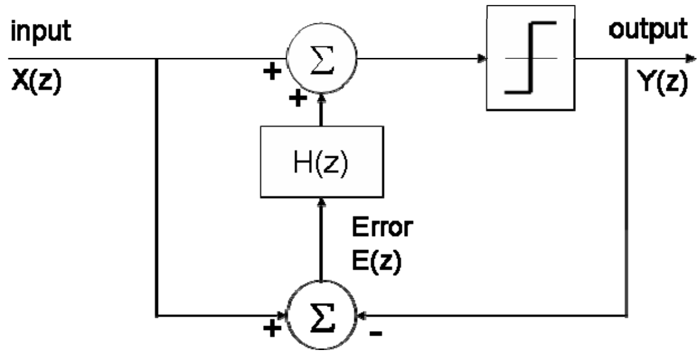

Figure 9: Error Feedback Structure

The authors developed a 2-stage complex filter structure (figures 10 and 11) whose zeros remain on the unit circle and only slightly move from there optimum position after quantization. This means near optimum noise suppression is achieved. While the poles tend to move quite a lot it is possible to choose the coefficients that ensure stable operation. The transfer function for each filter stage is

$$\frac{Y(z)}{E(z)} = \frac{a_{i+1}z^{-2} + (a_{i+1}.(1-m^{i}) + a_{i}).z^{-4}}{1+(2-m_{i}).z^{-2} + z^{-4}} \tag{3}$$

This architecture has two primary benefits for basestation bandpass applications. The architecture is computational efficient as the maximum number of adders in the signal path is two, and is unrelated to the modulator order and is restricted to two. Secondly the poles of the transfer function can be independently controlled by changing the parameters of (4) on a stage by stage basis. This provides flexibility in the selection of the noise transfer function that is valuable in the context of the basestation application.

In most cases where bandpass sigma-delta modulators have been used, the signal bandwidth has been sufficiently narrow that the effective oversampling rate has ensured good noise rejection. In a basestation application where a bandwidth in excess of 35 MHz will be required, the rising noise floor begins to impact on performance. More seriously, the noise floor at the receiver frequency, another 35 MHz offset again will experience substantial noise power, making the challenge of the duplexor more difficult. As this implementation of a sigma-delta modulator is computational efficient, high order sigma-delta modulators may be used. The increased noise floor can be controlled by high-order SAW filters with little insertion loss. It can also be noted that as there is no subsequent analog stage, an equivalent SFDR of 70 dB and an SNR of approximately 60 dB will be sufficient. For a high order BPSDM, this can be easily exceeded when the noise-transfer zeros are superimposed, though the bandwidth available is limited.

We propose that with a sufficiently high order BPSDM, we can use the additional noise zeros to deliberately manipulate the noise transfer function to address some of the specific basestation challenges, specifically to support a wider bandwidth or to suppress noise leakage into the receive band. It is possible to spread the noise zeros out so as to smoothly widen the available noise notch and thus provide additional bandwidth (protecting the receive bands), or to generate an additional notch in the noise floor at both the receive and transmit bands, thereby ensuring minimal noise escapes the DAC at either frequency.

V. Results

To demonstrate the viability of these techniques, a 10th order bandpass modulator was implemented on a Virtex II development board. While the Virtex II board cannot achieve the necessary frequencies, as it is a digital system the behaviour will scale accordingly. For this demonstration, we used a 50 MHz clocked digital I/O resulting in a signal band centered on 12.5 MHz. The input signal is a sinusoidal signal of magnitude 75% of full scale. The vertical axis on the graphs is 10 dB/decade

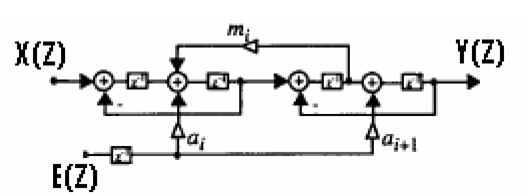

Figure 10: Computational Efficient Filter Structure

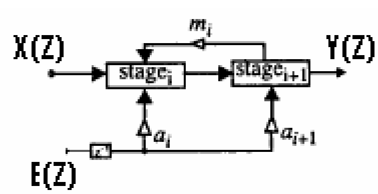

Figure 11: Two-stage complex filter module

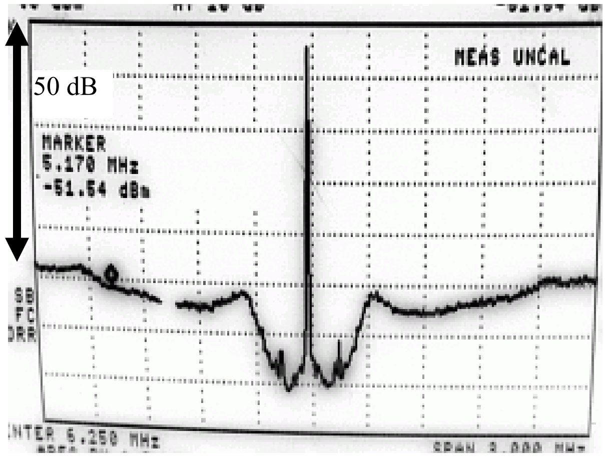

Figure 12: Performance with Zeros Superimposed

Figure 12 shows the performance with the noise zeros superimposed. We get an overall reduced noise in a narrow band but the noise floor rises rapidly. In figure 13, the noise zeros have been spread a small degree agree from fs/4 and we see a gentler increase in the noise floor, effectively provide a wider bandwidth. In this case, the available bandwidth is equivalent to 65 MHz assuming a 900 MHz centre frequency, sufficient for basestation applications.

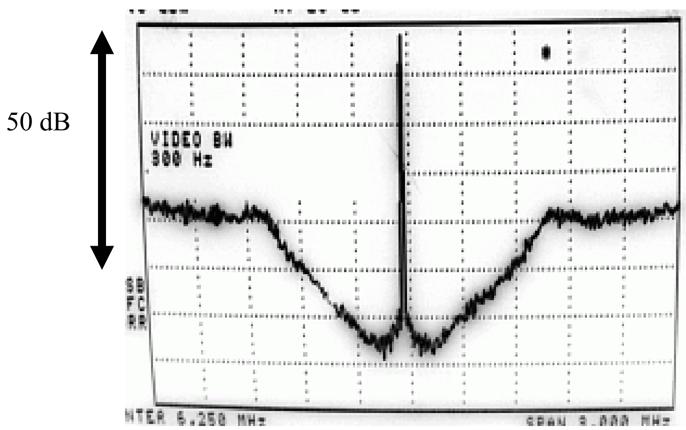

Figure 13: Performance with Uniform Zeros Spreading

The final image shows a transfer function where we have placed superimposed several zeros offset from the centre frequency, producing symmetrical notches. If we operated this converter between the receive and transmit bands, each of these signal notches would ensure minimal noise leakage in the frequencies of interest.

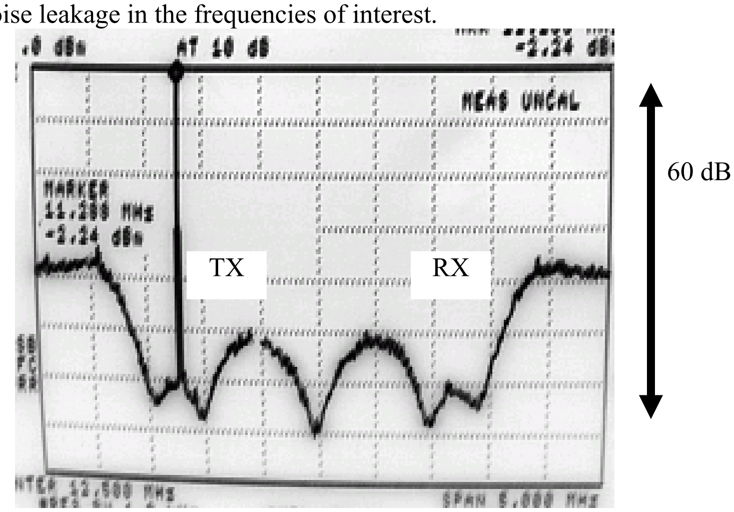

Figure 14: Performance with offset notch

The next stage of this work is to develop this prototype onto the new Virtex 5 FPGAs where the high speed I/Os can switch at 3 GHz, allowing for experimentation in the communications bands.

VI. Conclusion

The trend in electronics is towards ever greater levels of integration, and to minimise the level of analog circuitry in systems. Bandpass sigma-delta modulators provide a powerful means to simplifying radio transmitter architectures. We have presented a modulator architecture with the ability to independently control pole locations without computational overhead. This flexibility will allow future RF frequency converters to support the bandwidths and noise requirements in the highly challenging environment of mobile phone basestations.

Acknowledgements

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