# ACHIEVING EFFECTIVE DITHER IN THE SUPER AUDIO CD FORMAT

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## 1. INTRODUCTION

Many analogue-to-digital (A/D) and digital-to-analogue (D/A) converters use an intermediate sigma-delta modulating stage to convert signal inputs and outputs into a simple digital form for high quality conversion. In the case of A/D converters, a multibit representation of the signal is achieved with a decimating filter and, similarly, D/A converters employ interpolators to increase the sampling rate and to remove images of the baseband audio signal that are created by oversampling. The well-documented sigma-delta modulating technique [1-4], employing Nth order noise shaping, is then used to create a highly quantised two level signal. This one bit signal is a perfectly valid representation because it contains all of the audio band information and is used as the information carrier in the new "Super Audio CD" format. Direct processing of the one bit signal has also been proposed as an alternative approach to audio signal processing these signals and removes the decimating or interpolating requirements in an analogue interface. Because the signal is heavily oversampled, the system characteristics can approach those of high quality analogue processors in terms of phase response and distortion effects, while retaining the advantages of digital processing techniques.

Recently the efficacy of dither in such systems has been called into question and there has been confusion over which system, PCM or Sigma-Delta Modulation, is most appropriate [5].

A difference between the two systems is that PCM systems are essentially memoryless whereas Sigma-Delta Modulation relies on memory for its operation. This makes it difficult to compare the two systems as regards the effectiveness of dither.

This paper proposes a method by which the two systems can be compared. It first considers the difference between the two systems and then presents a novel comparison technique that allows a direct comparison between the two systems. It then goes on to examine the effect of various dither strategies in the two systems and shows that dither can be effective in both systems.

## 2. THEORY

In order to understand the differences between the two systems it is helpful to review the principles behind the two systems.

### 2.1 Multi-bit Quantisation

Quantisation is defined as the conversion of a signal of continuous amplitude to one with a certain number of discrete amplitude levels. The number of levels to which a signal is quantised is very often an integral power of two and this power represents the number of bits

Whereas the sampling process is reversible, the quantisation process is not. Once a continuous analogue signal has been quantised, the exact original of the analogue signal cannot be reconstructed. The amplitude data stored at a particular sampling instant is only accurate to the nearest quantisation level, and thus it is reasonable to assume that the greater the number of levels (and hence bits) the better. However there will always be a difference between the output of the quantiser and its input and this is known as the quantisation error. As the number of levels increase, the amplitude of the error is reduced and the error becomes less correlated to the input signal.

## 2.2 Delta Modulation

Delta (Δ) modulation [12,13] was devised in the 1940s as an alternative to PCM coding. It is a one-bit version of differential PCM (DPCM) in which the output signal represents the difference between the previous and current samples, thus reducing the dynamic range of the signal. This in turn requires fewer bits for encoding purposes and so is more efficient.

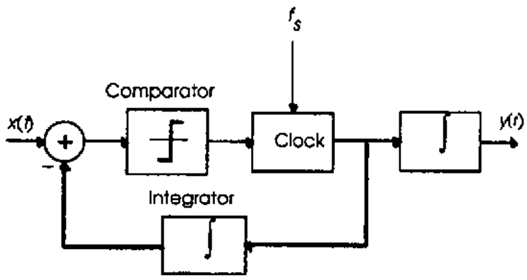


Figure 1 Block diagram of a Δ modulator.

Delta modulation works by providing a staircase approximation of the input signal. A block diagram of the system is given in figure 1. At each sampling instant, the sign between the input sample and the previous staircase approximation is calculated and the staircase signal is updated. The process occurs at a greatly oversampled rate, and thus is able to represent the analogue input signal reasonably accurately. This is demonstrated in figure 3 which shows the output to the Δ modulator tracking the analogue input.

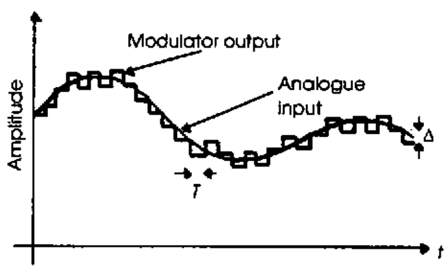


Figure 2 The output of the Δ modulator tracks the input

However, if the step size chosen for the Δ modulator is either too large or too small, two different types of quantisation error will occur. For too small a step size, slope overload distortion will occur which is illustrated in figure 4. For too large a step size, granular noise will be present (see figure 5). Even if the optimum step size is chosen, the amount of slope overload distortion and granular noise will to some extent depend on the input waveform. For example, a slowly varying waveform will result in excessive granular noise, and a rapidly changing one will result in slope overload distortion.

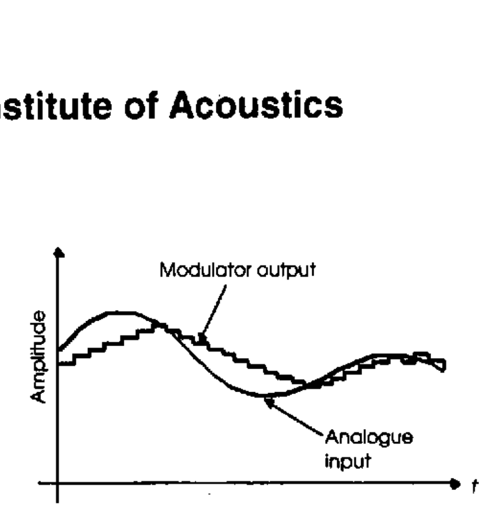


Figure 3: Too small a step size results in slope overload distortion.

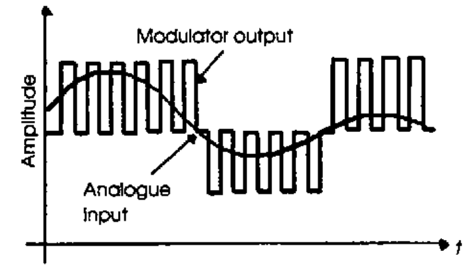


Figure 4 Too large a step size results in excessive granular noise.

Besides the problems with inappropriate step size, there are other problems with Δ modulation. If there is a single channel error, which causes a +1 to be output instead of a -1 or vice versa, the decoded signal will permanently be in error by at least two steps. Furthermore, encoding a DC input signal is very difficult. Another undesirable feature of Δ modulation is that whereas the noise transfer function (NTF) is flat the maximum signal transfer function (STF) is dependent on the frequency of the input signal. This is due to the location of the integrator in the Δ modulator circuit. A plot of the STF and the NTF for a Δ modulator is shown in figure 5.

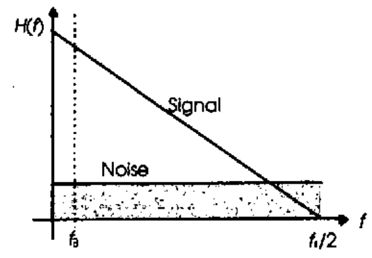


Figure 5. General shape of the STF and NTF for a Δ modulator.

All of the problems described above for the Δ modulator can be remedied by placing an integrator at the input of the circuit. This forms the basic structure of the sigma-delta (Σ-Δ) modulator [14].

## 2.3 Sigma-Delta Modulation

The general structure of the Σ-Δ modulator is shown in figure 6, and can be seen as a combination of two integrators, a comparator and a latch clocked at the oversampled rate.

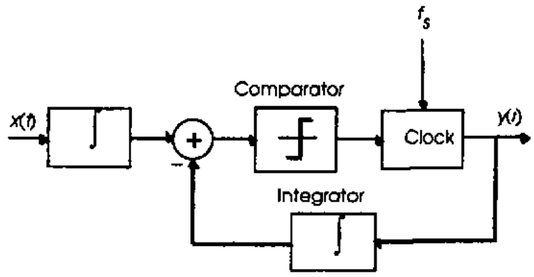


Figure 6 Block diagram of a sampling Σ-Δ modulator.

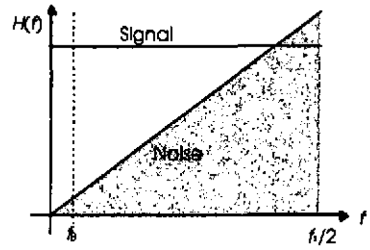


Figure 7 General shape of the STF and NTF for a Σ-Δ modulator.

The main feature of the Σ-Δ modulator analogue-to-digital converter is that its NTF is shaped so that the majority of the noise power can be made to fall outside of the audio band. The STF is flat, and therefore unlike the Δ modulator, does not depend on the frequency of the input signal. The plots in figure 7 show this.

Combining the two separate integrators and placing the single resulting integrator directly before the comparator can simplify the circuit of the Σ–Δ modulator in figure 6. This gives the more conventional Σ-Δ modulator circuit, as shown in figure 7. It is important to note that this transformation applies to any filter order. That is, a higher order Σ-Δ modulator could be implemented, in theory, as a high order prefilter to a high order Δ modulator, as shown in figure 8b. This alternative view is vital for comparing Σ-Δ modulation with linear PCM.

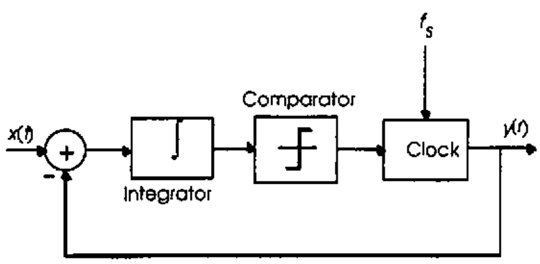


Figure 8a A 1st order Σ-Δ modulator.

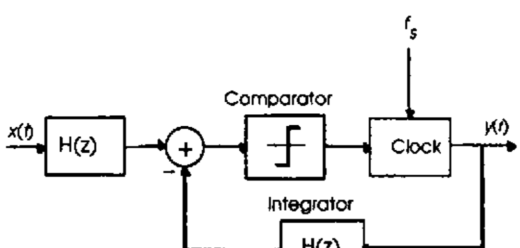


Figure 8b An alternative $N^{th}$ order Σ-Δ modulator implementation.

# 3 PCM/SIGMA-DELTA MODULATION COMPARISON

A difference between the two systems is that PCM systems are essentially memoryless whereas Sigma-Delta Modulation relies on memory for its operation.

One of the vital concepts to hold in mind is that we are only concerned with the low frequency performance of Σ-Δ Modulation, whereas for linear PCM we are interested in its full bandwidth performance. This makes it difficult to compare the two systems as regards their effective quantisation levels. However by considering the structure in figure 8 a basis for comparison can be found.

Figure 8b shows that $N^{th}$ order Σ-Δ modulation is essentially $N^{th}$ order Δ modulation with a matching $N^{th}$ order prefilter. This means that we can use Δ modulation to examine the quantisation characteristics of Σ-Δ Modulation.

Consider first order Δ modulation, at each clock pulse the output of the integrator can move ±Δ, as shown in fig 2. Thus the output of a delta modulator is a quantised version of the input with quantisation levels spaced Δ apart. In fact this technique was used for linear PCM conversion in the past. An up/down counter replaced the integrator and clock and the output of the counter used to drive a multibit D/A converter whose output was used as the basis of comparison with the input signal. This arrangement is shown in figure 9, and its transfer function in figure 10.

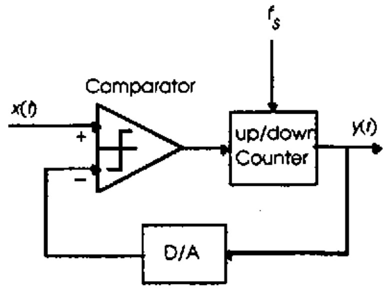


Figure 9 Block diagram of a Δ modulation A/D converter.

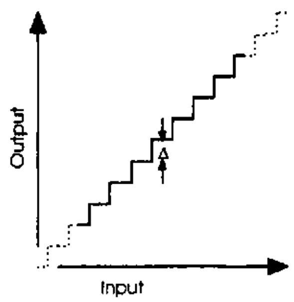


Figure 10 Transfer function of a Δ modulation A/D converter.

Clearly such a PCM converter's stepsize will depend on how high the clock frequency is with respect to the bandwidth of the signal, that is, the oversampling ratio. In the limit the step size will approach zero as the OSR approaches infinity, as does normal PCM with respect to the number of levels.

In the same way as normal PCM, the Δ modulation A/D converter will have the non-linear problems associated with quantisation. The remedy is also the same, dither [15-17], which should be applied at the quantiser input, as shown in figure 11.

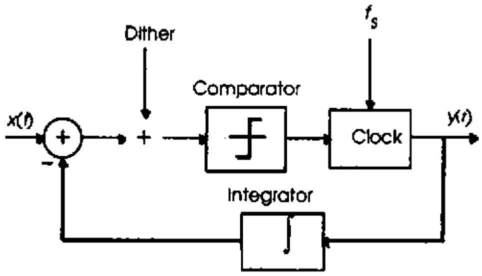


Fig. 11 A dithered Δ modulation A/D converter.

The optimum dither for such a PCM converter has already been derived by Vanderkooy and Lipshitz [15,16] and is triangularly weighted pdf random noise with a range of 2Δ. Of course there is the expected SQNR penalty of 4.8 dB. However such a system clearly satisfies Lipshitz's concept [5] of a "perfectible" converter.

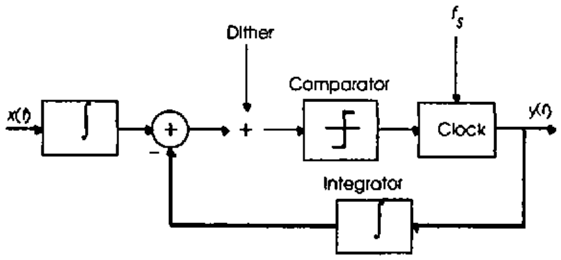


Figure 12 A dithered Σ-Δ modulation A/D converter.

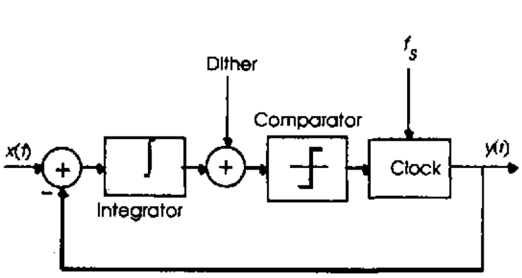


Figure 13 A more conventional dithered Σ-Δ modulation A/D converter.

So how does this apply to Σ-Δ modulation? The answer is very simple because, as we have already seen, Σ-Δ modulation is merely a form of Δ modulation with some matched prefiltering of the input signal. As this is a linear process, the dither requirements are identical, as shown in figure 12. That is, triangularly weighted pdf random noise with a range of 2Δ, where Δ is determined by the effective step size of the modulator. Note that this will be a function of both the OSR, and the noise-shaping filter, but will be considerably less than the values suggested in [5]. The same merging of the two filters that was done for figure 8 can also be done in the dithered structure and this is shown in figure 13. This structure also has identical dither requirements to the previous structures. The only effect of the prefilter is to reduce the SQNR at higher frequencies because the input signal is attenuated by it. This gives one the typical rise in noise with frequency that one expects from noise shaped encoders. However it also allows a flat overload response and better immunity from errors. As with Δ modulation, the dithered Σ-Δ modulation system also satisfy Lipshitz's concept of "perfectible" encoding.

## 4 COMPARING Σ-Δ MODULATION WITH PCM

One of the problems in comparing Σ-Δ modulation systems with their equivalent PCM counterpart is the extreme difference in sample rates. A further problem is that, unlike the PCM system, the upper part of the Nyquist band contains noise that is broadly uncorrelated with the audio signal. In some senses this is similar to the presence of the alias sidebands of a PCM signal when one considers the same bandwidth, as shown in figure 14. Clearly we are only interested in the baseband signal in both cases. For PCM systems this is naturally assumed but for Σ-Δ modulation systems often the whole bandwidth is considered. In order to provide a fair comparison it is important to consider the performance, in all aspects, over the same bandwidth.

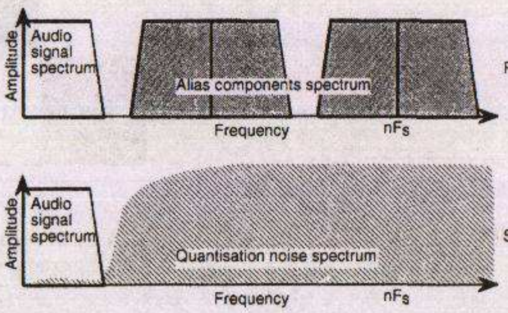


Figure 14 PCM versus DSM spectra over the same bandwidth.

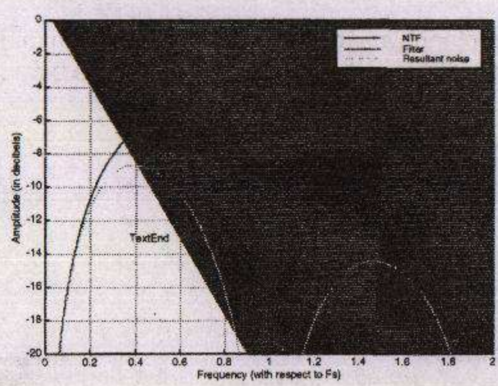


Figure 15 Frequency response of the filter for an OSR of 4.

Therefore to compare Σ-Δ modulation with PCM we must first filter the Σ-Δ modulation. The million-dollar question is, what form of filtering is appropriate? Clearly, by applying excessive amounts of filtering one can achieve any result one wants. However, it seemed to the author that the fairest form of filtering was to average the Σ-Δ modulation signal over the same time range as a sample period in the PCM system that it was being compared to. For a first order Σ-Δ modulation system this corresponds to a sum of N adjacent samples, where N is the oversampling ratio. Thus for an oversampling ratio of 4, the filter correspond to the sum of 4 Σ-Δ □□□□□□□. The frequency response of such a filter is shown in figure 15. Using this type of filter a fair comparison between the two systems, as regards dither may be effected.

## 5 RESULTS

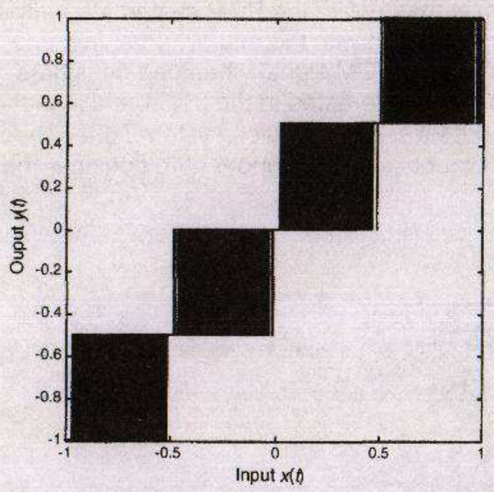


Figure 16 Rectangularly dithered 5 level PCM.

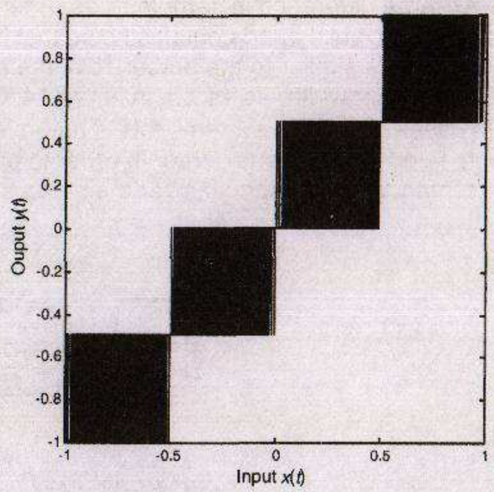


Figure 17 First order Σ-Δ modulation, OSR=4, no dither.

Sigma-delta modulators using a variety of dither strategies were implemented using SIMULINK. In order to make the results readable a low OSR of 4 was used. The transfer functions of these modulator were compared with 5 level (4 step) PCM with rectangular and triangular dither. The results are shown in figs. 16 to 20.

Figures. 16 and 17 compare rectangularly dithered 5 level PCM with undithered first order Σ-Δ modulation. From these we can see that the transfer functions are broadly comparable.

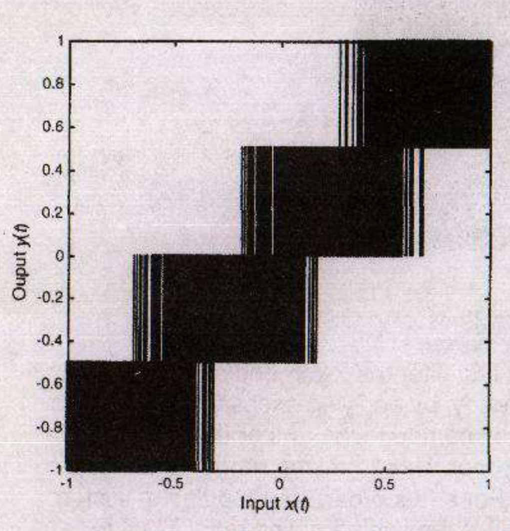


Fig. 18 Triangularly dithered 5 level PCM.

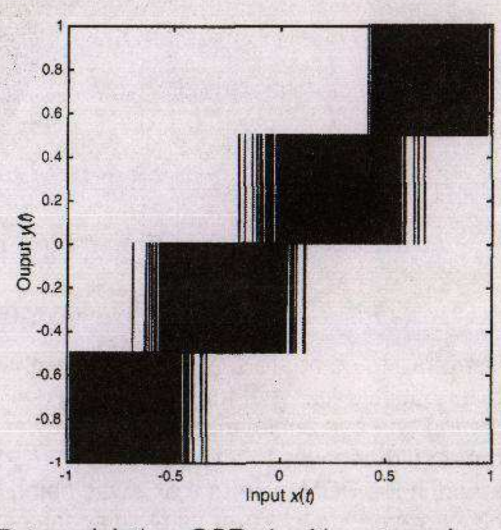


Fig 19 Σ-Δ modulation, OSR=4, with rectangular dither.

Figures. 18 and 19 compare triangularly dithered 5 level PCM with rectangularly dithered first order $\Sigma$-$\Delta$ modulation. From these we can see that the transfer function of rectangularly dithered first order $\Sigma$-$\Delta$ modulation is between that of triangularly dithered and rectangularly dithered PCM

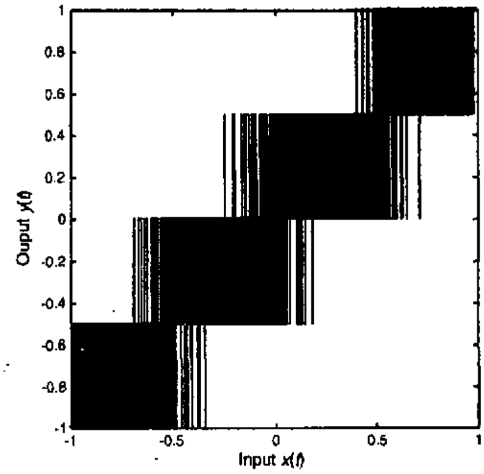


Figure 20 First order $\Sigma$-$\Delta$ modulation, OSR=4, with triangular dither.

Finally figures. 18 and 20 compare triangularly dithered 5 level PCM with triangularly dithered first order $\Sigma$-$\Delta$ modulation and shows that the transfer function of triangularly dithered first order $\Sigma$-$\Delta$ modulation is similar to that of triangularly dithered PCM

# 6 DISCUSSION

PCM and $\Sigma$-$\Delta$ modulation have very different sample rates and apparently different modes of operation. The analysis has shown that over the same frequency range of operation, they are similar. This has some important consequences.

## 6.1 Low amplitude dither is effective.

A major difference between a linear PCM quantiser and a sigma-delta quantiser is that in the sigma-delta quantiser the quantisation error is fedback. Because of this feedback it is not necessary to have as high a level of dither at the quantiser as that required by linear PCM systems. In fact an amount of *in-band* dither that corresponds to the apparent *in-band* step size is effective. A variety of researchers [18-21] have shown that a much lower level of dither than that proposed by Lipshitz can be effective in removing the "birdies" and noise modulation that he discusses. The fedback quantisation noise can also act as a form of "dither". In fact it is well known that in higher order one-bit sigma-delta modulators the input to the quantiser becomes more noise like.

## 6.2 $\Sigma$-$\Delta$ audio delivery has less processing steps.

If one uses linear PCM directly in a recording system then the analogue signal will have passed through several steps of decimation and interpolation before it arrives at the listener's ear. The minimum will be two, one at the A/D and one at the D/A. However in practice there will be more because interpolation and decimation steps occur in mixing desks and sample rate converters. With a sigma-delta signal format it is possible to have no interpolation or decimation stages between the original sound and the listener's ear. This "direct coupled" signal processing does not suffer the degradation caused by rounding, aliasing and frequency/time response errors that can occur in decimators and interpolators.

# 7 CONCLUSION

This paper has presented a comparison of the effect of dither in PCM and Σ-Δ modulation and has shown that dither can be effective in both systems. In fact both systems benefit from dither with triangular probability density function whose range is equal to twice the effective quantiser step size. In the case of Σ-Δ modulation the effective step size is much smaller than the physical step size over the frequency range of interest due to the error feedback and the dither is restricted to the bandwidth of the signal.

Both PCM and Σ-Δ modulation are "infinitely perfectible" however real audio systems are finite. Given real world parameters a Σ-Δ modulation based audio delivery system offers many opportunities for preserving the sound quality all the way to the listener.

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