Analysis of an alternative approach to digital domain volume control claiming high perceptual audio quality

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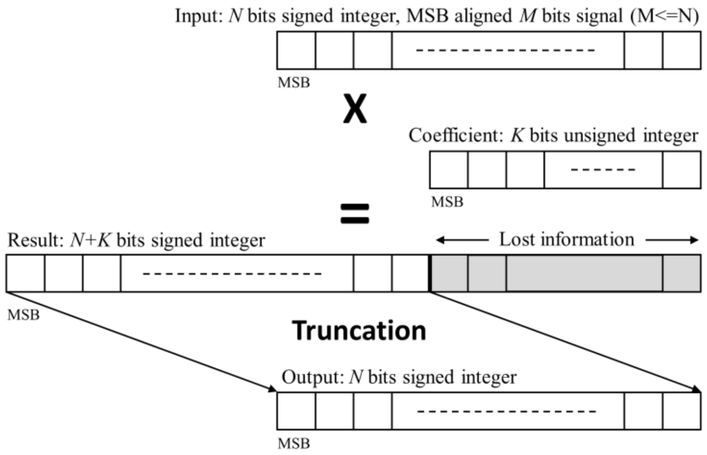
Overview of digital domain volume control

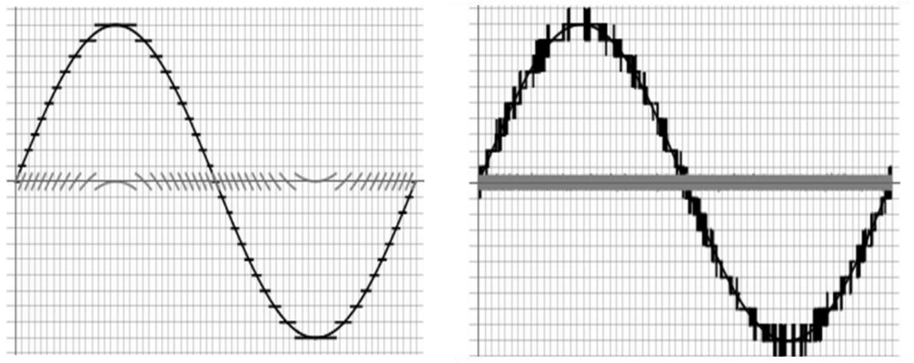


Digital domain volume control is simply implemented by multiplying sample values by a volume control coefficient and truncating the result to the desired number of bits.

The figure on the left shows this operation on an *M* bits integer input signal (formatted in an *N* bits word) with a *K* bits unsigned volume control coefficient, resulting in an *N* bits output.

The **final truncation** introduces signal dependent quantization noise. It is widely known that addition of TPDF dither spanning +/- 1 LSB will **decorrelate quantization noise from signal content** as illustrated by the figure on the right.

However, many audiophiles still report that digital domain volume controls are inferior compared to their analog siblings.



Alternative approach to digital domain volume control

The **alternative approach to digital domain volume control** has been proposed by Mr. Milot from French company Acoustical Beauty.

The key principle is to minimise the number of bits *K* used to quantize volume control coefficients so that information loss is minimized at truncation stage. In other words, **it trades volume control coefficients precision against information loss minimization**.

As an illustration, consider a volume control using 1dB steps. The table on the right shows the volume control coefficients used by the alternative approach for the top 6dB range (-1dB to -6dB). The full coefficients table is then built by shifting these values by 1 bit to the right (i.e. increasing *K* by 1) for each 6dB slice.

For *N* = 24, the example allows for **truncation free volume control** of 16 bits signal up to about -30dB.

Nominal attenuation	K	Coefficient value	Effective attenuation
-1 dB	3	7	-1.16… dB
-2 dB	4	13	-1.80… dB
-3 dB	4	11	-3.25… dB
-4 dB	3	5	-4.08… dB
-5 dB	4	9	-5.00… dB
-6 dB	1	1	-6.02… dB

Frequency domain analysis

We consider an input signal consisting in an un-dithered 16 bits (M = 16), 0dBFS, 1.5kHz sine wave sampled at 48kHz, MSB aligned in a 24 bits word (N = 24). This results in a repeating sequence of 32 samples and a power of two length FFT **clearly shows the harmonics due to 16 bits truncation**.

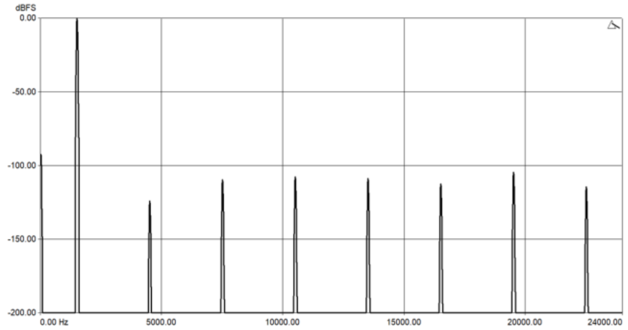


Figure (a)

Let’s apply 20dB of attenuation to this signal:

- Figure (b) uses the alternative approach: the **harmonic structure is clearly preserved, no distortion added**
- Figure (c) uses an un-dithered traditional volume control using 16 bits coefficients (K = 16). **Additional distortion can clearly be seen** due to the final truncation to 24 bits
- Figure (d) uses a TPDF dithered traditional volume control using 16 bits coefficients (K = 16). **The additional distortion is gone**, at the price of **low-level white back-ground noise**

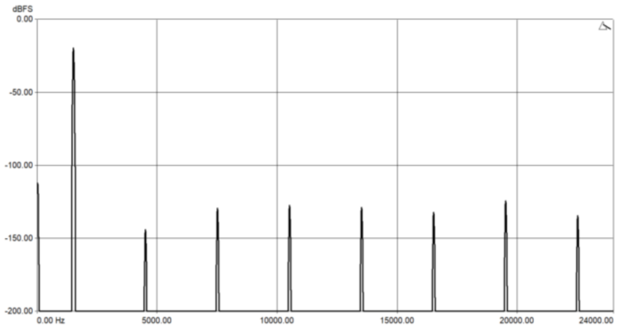


Figure (b)

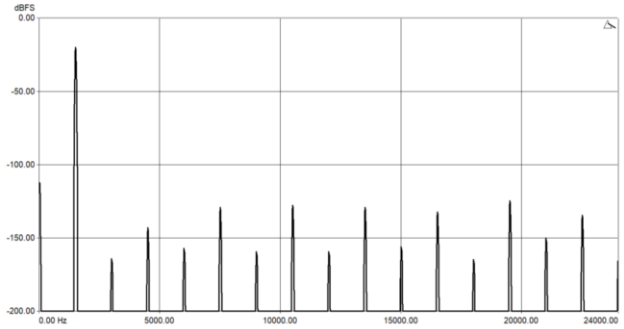


Figure (c)

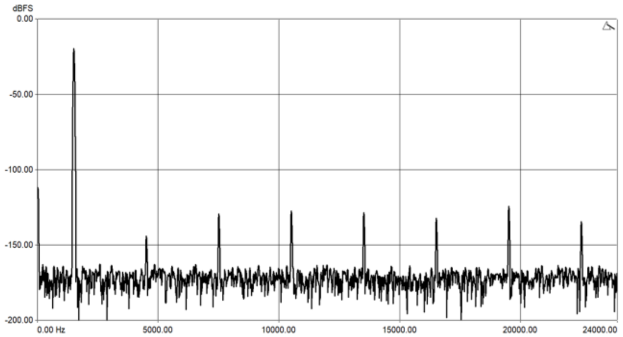
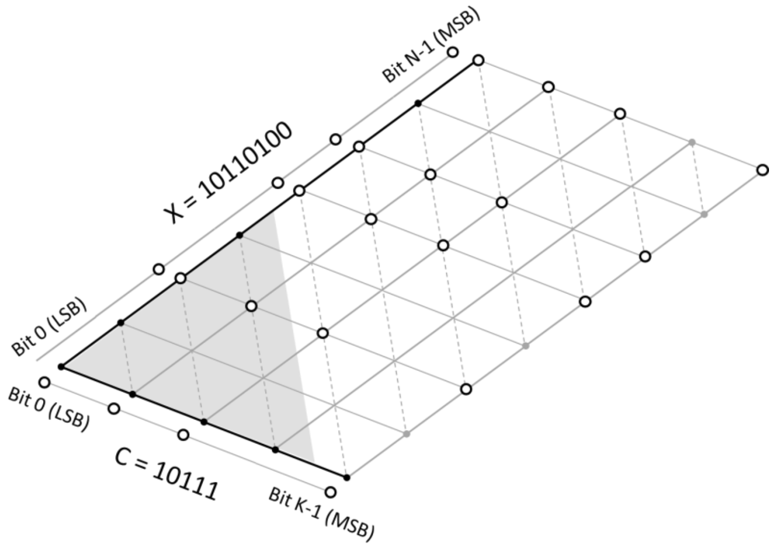


Figure (d)

Information propagation analysis (1)



We will now analyse how signal information is propagated through the volume control.

The multiplication process of an *N* bits integer by a *K* bits unsigned integer can be visualized on a 2D representation as shown on the figure to the right. The grey zone on the left represents truncation of the output to *N* bits.

Let's consider an input signal *x* and a volume coefficient *c* defined by

$$x = \sum_{i=0 \ldots N-1} 2^i x_i \qquad c = \sum_{j=0 \ldots K-1} 2^j c_j$$

The product of *x* by *c* consists in the sum of all inner product terms which are non-zero. For each of these non-zero inner product terms, we define the *Signal Information Relative Contribution* (*SIRC*) as:

$$SIRC(i, j) = \frac{(i+1)}{N} \times \frac{(i+j+1)}{N+K}$$

Information propagation analysis (2)

Plotting the *SIRC* at each basic product inner term node of the 2D representation of an *N* x *K* bits multiplication, results in the *Signal Information Propagation Map* (*SIPM*) of the product of *x* by *c*.
The figure below show the *SIPM* for a *N* x *K* bits multiplication (*N* = 8, *K* = 5), once with *c* spanning the full 5 bits to illustrate a standard volume control (figure (a)) and once with *c* spanning only 2 bits to illustrate the alternative volume control (figure (b)).

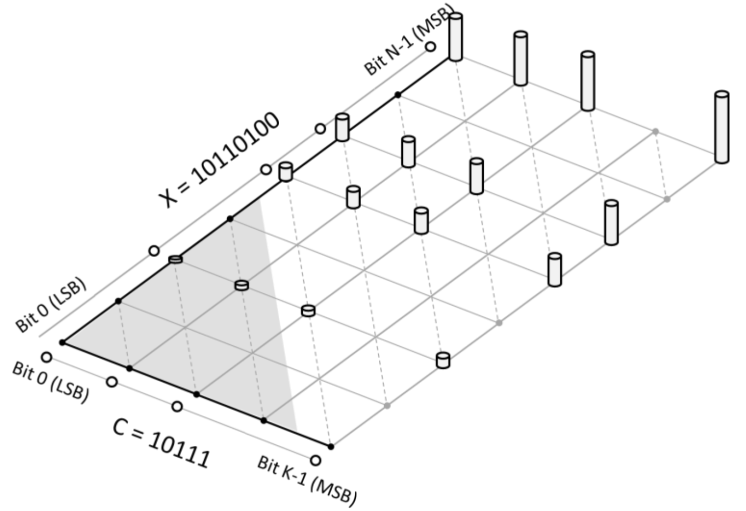


Figure (a)

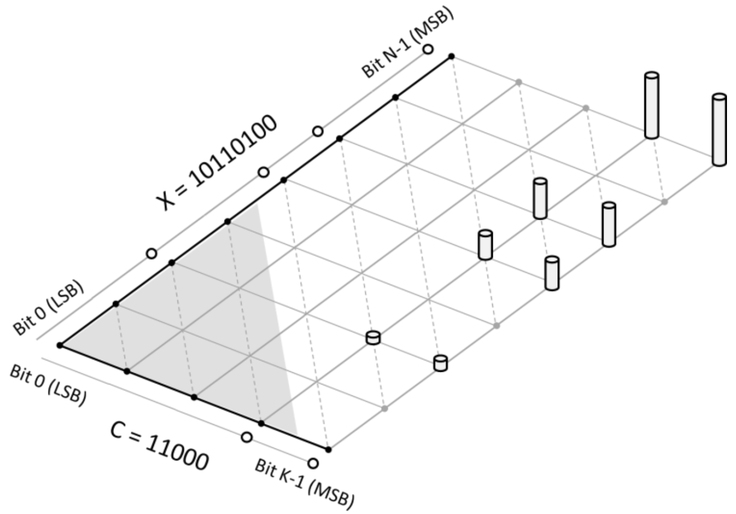


Figure (b)

The **traditional volume control suffers from possible information loss** as some *SIPM* elements fall below the output quantization level. In addition, as lowering the volume roughly corresponds to shifting the *SIPM* along the coefficient axis towards the LSB, the **alternative volume control seems to allow for higher attenuation values before signal information gets lost** below the output quantization level.

Information propagation analysis (3)

The *Signal Information Propagation Index* (*SIPI*) for an input sample *x* and a volume control coefficient *c* is the average of *SIRC* values across the corresponding *SIPM* (where *P* is the number of non-zero inner product terms):

$$SIPI(x,c) = \frac{1}{P} \sum_{x_i c_j \neq 0} SIRC(i, j)$$

For a volume control consisting in a set *C* of volume control coefficients, the *Signal Information Propagation Score* (*SIPS*) is defined as the average of *SIPI* across all possible input signal samples and volume control coefficients (where *Q* is the number of *(x, c)* couples*).* **Higher *SIPS* means better information preservation**:

$$SIPS(C) = \frac{1}{Q} \sum_{x,c} SIPI(x,c)$$

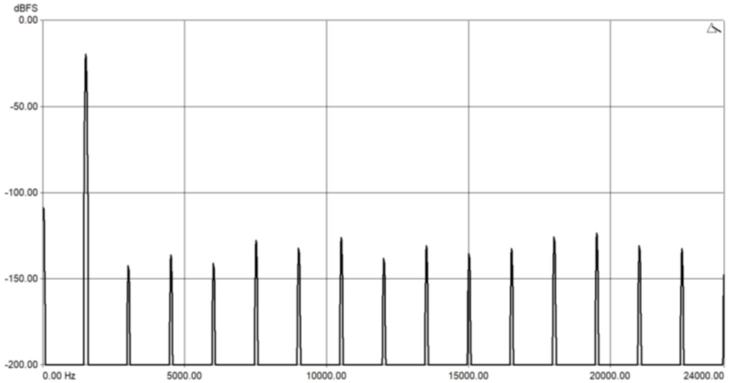
Similarly *SIPS'* is defined as being equal to *SIPS* except that *SIRC(i,j)* is replaced by *0* if *i+j < K*. *SIPS'* removes information contributions that are below the output quantization level. This results in:

	Standard vol.	**Alternative vol.**
SIPS	0.37	**0.42**
SIPS'	0.16	**0.27**

Combined approach

Let's again consider our example from the frequency domain analysis.

But this time, the **output is quantized to 20 bits** (i.e. *N* is changed from 24 to 20). As before, 20dB of attenuation are applied **using the alternative volume control**.



Truncation noise is now present at the output (as for traditional volume controls). This is due to the fact that now $M + K > N$, i.e. there are not enough bits in the output word to allow for exact multiplication.

As an improvement, we therefor propose to **add TPDF dithering** at the *Nth* bit level before final truncation. Apart from **eliminating quantization noise related distortion**, this would provide a **constant noise floor**, which may be of benefit in terms of perceived audio quality

Conclusions

The frequency domain and information propagation analysis presented in the previous slides has shown that the alternative approach to digital domain volume control:

- can provide **distortion-free attenuation** (up to a certain level)
- seems to present **advantages in terms of signal information propagation**

More precisely, if signal information preservation is considered to prevail over exact target attenuation value, the alternative seems to be at advantage**.** However, we **cannot conclude that this correlates with superior subjective audio quality** as no data resulting from a significant study is available.

Finally, we have proposed a **combined approach** where TPDF dithering is added to the alternative volume control to avoid truncation distortion that can appear at higher attenuation settings.

Thank you for your attention!