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Self-Dithered Digital Delta-Sigma Modulators for Fractional-N PLL Synthesizers

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1. Introduction

Digital Delta Sigma Modulators (DDSMs) are widely used in fractional-N phase locked loops (PLLs) which are indispensable in modern communication systems, such as cell-phones and wireless LANs. In a fractional-N PLL, the DDSM instantly changes the divider's modulo to average out a fractional division ratio so that high-resolution frequencies are available at the PLL's output [1].

DDSMs are generally classified into two types – MASH and single-loop. The MASH posses advantages of stability and considerable noise shaping, while single-loop modulators are conditionally stable but enable a flexibly optimized noise transfer function (NTF). Unfortunately, both of them suffer from spurious tones which finally appear at the PLL's output spectrum, known as "fractional spurs", degrading the fractional-N PLL's spectral purity [2]. To solve this problem, several solutions have been proposed which will be discussed in the following sections.

In this paper, we propose an effective alternative, called self-dithering, featuring extremely simple implementation and no hardware overhead.

2. Previous Solutions

The origin of fractional spurs is attributed to the limited sequence length of modulator's output; thus more power converges onto some certain spectral tones. Solutions are classified into two types – deterministic [3][4] and stochastic [1][2]. Deterministic approaches modify the DDSM's structure or set up an irrational condition to disrupt the modulator's internal states. The advantages of this type of solutions are the controllable sequence length and no low-frequency noise floor incurred, yet so far they are mainly used for MASH. On the other hand, the stochastic solution, also called dithering, is used for both types of modulators. It exerts a 1-bit pseudorandom (PN) sequence to scramble the DDSM's input. Since dithering introduces an elevated noise floor at low frequencies, shaped dithering has been proposed to shape the noise floor into a high-pass characteristic [1].

An unwanted task to implement the dithering is that the PN generator has to be specifically designed with extra circuits. It is commonly realized with linear-feedback-shift-registers (LFSR) [4], while a recently published method employs another accumulator together with an 11-stage LFSR to dither the DDSM's coefficients [2]. Indeed, such extra endeavor can be avoided by applying the method proposed in the following section.

3. Proposed Self-Dithering Method

The proposed method circumvents the design of the PN generator; instead, utilizes the DDSM's own quantization noise which is generally approximated to be white, thus suitable as a dithering source. For a MASH DDSM, the quantization noise of interest is generated at its last-stage accumulator's output, while for a single-loop modulator, it lies at the n LSBs of the data before the quantizer, where n is the DDSM's input bit width. Fig. 1 and Fig.2 illustrate the implementation of 3^{rd}-order self-dithered DDSMs of MASH and single-loop, respectively, where the single-loop modulator holds the NTF the same as that of MASH: $(1-z^{-1})^3$.

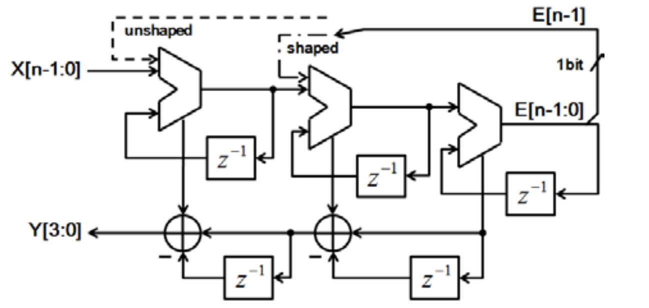

Fig. 1 Proposed self-dithering for a MASH DDSM

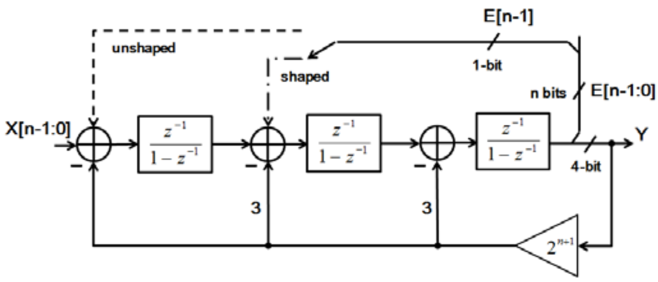

Fig. 2 Proposed self-dithering for a single-loop DDSM

As shown in Fig.1 and Fig. 2, the quantization noise's most significant bit (MSB) is extracted and fed back to the input of DDSMs. For unshaped-dithering, this MSB is added to the modulator's input, while for shaped-dithering, it is added to the first-stage accumulator's output. Note that shaped dithering is effective only if the modulator's stages are no less than three [1]. Once applied with such self-dithering, even for those spur-containing quantization noises, they are whitened by this feedback scheme.

Not any extra circuits but only one bit wire is required. Therefore, the proposed method lessens hardware overhead and the design effort.

4. Simulations

MASH and single-loop modulators with proposed self-dithering are simulated with MATALB and Simulink.

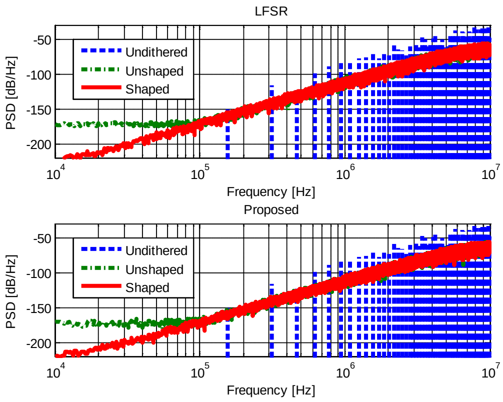

Fig. 3 PSDs of 3rd-order single-loop DDSM

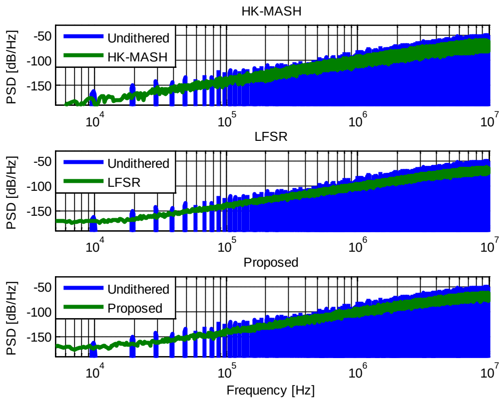

Fig. 4 PSDs of 2nd-order MASH DDSM

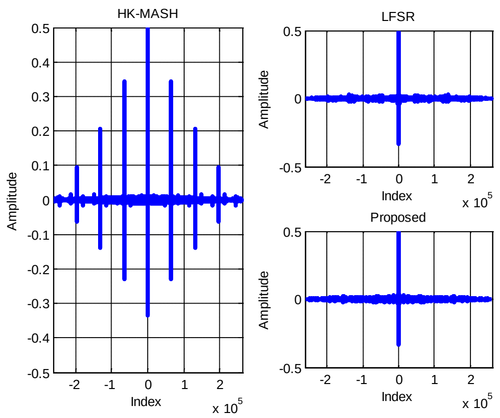

Fig. 5 Auto-correlations of 2nd-order MASH DDSM

The DDSM's input bit width is 16 bits, i.e. input values range from 0 to 65536. The number of stages of LFSR is 16. The power spectral density (PSD) of DDSM's output is calculated using FFT of Welch method with 65536-point hanning window and 50% overlapping [4].

Fig. 3 shows the PSDs of a 3rd-order single-loop DDSM with the input equal to 1024. Unshaped and shaped ditherings are applied, and the results are compared with using LFSR. It can be observed from the figure that 1) the noise shaping is corrupted by tones if no dithering is applied on the modulator; 2) both LFSR and proposed self-dithering effectively randomize the output and eliminate the spurs, and their PSDs are almost the same; 3) the proposed shaped self-dithering can successfully transfer the low-frequency noise floor into a high-pass characteristic.

Fig. 4 illustrates the PSDs of a 2nd-order MASH DDSM with the input equal to 64. Since there is no guaranteed shaped dithering scheme for 2nd-order DDSMs, unshaped dithering is applied. The results are compared with using LFSR and HK (Hosseini and Kennedy)-MASH, a MASH DDSM with deterministic spur reduction [3]. We do not consider initial-condition method since it is ineffective for 2nd-order MASH according to [4]. Seen from Fig. 4, three methods all effectively suppress the spurs. It is interesting to mention that HK-MASH's spectrum is "thicker" meaning that the noise floor is less whitened than the other two; in other words, its output sequence length is shorter. For the edge inputs such as 64 or 65500, 2nd-order HK-MASH holds this characteristic. Other drawbacks of 2nd-order HK-MASH in this case are its limited input range (1 to 65521) and its output mean value deviates up to $15/2^{16}$, which leads to the central frequency deviation at PLL's output. In contrast for dithering methods including our proposal, such deviation is only $0.5/2^{16}$.

Fig. 5 shows the autocorrelation of 2nd-order MASH DDSM output under the same condition as in Fig. 4. Autocorrelation is an indicator to estimate the repetive pattern and the sequence length of DDSM's output. Except for the spikes at the center, if the amplitude is close to 0, the quantization noise is whitened, while if spikes exist, its x-index represents the sequence length. In Fig. 5, no spikes are observed for dithering methods so that their sequence lengths are longer than the number of simulation samples (2^{18} in this case), while for HK-MASH we obtain the sequence length as 65521, long to "burry" the spurs but short to whiten the noise floor.

Finally, Table I summarizes characteristics of the 16-bit 2nd-order MASH DDSM with various spur solutions.

TABLE I Summary of 16-bit 2nd-order MASH DDSM

	Proposed	LFSR	HK-MASH
Input Range	1~65535	1~65535	1~65521
Mean Value Deviation	$0.5/2^{16}$	$0.5/2^{16}$	$15/2^{16}$
Hardware Overhead	None	16 flip-flops + some logic gates	1 multiplexer + 1 multibit adder

Reference

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