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Improving the Performance in Delta Sigma Modulator Transmitter

N. Erfani Majd[1,*]

[1] Department of Electrical Engineering, Shohadaye Hoveizeh Campus of Technology, Shahid Chamran University of Ahvaz, Susangerd, Khouzestan, Iran

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ABSTRACT

One significant limitation associated with delta-sigma modulator (DSM)-based transmitters is the substantial quantization noise generated at the output of the DSM, which negatively impacts the overall efficiency of the transmitter. This quantization noise arises due to the finite resolution of the digital-to-analog conversion process, leading to unwanted distortion and signal degradation. As a result, the performance of DSM-based transmitters is often limited by the trade-off between quantization noise and signal quality, specifically the signal-to-noise and distortion ratio (SNDR). This paper addresses the challenge of improving the efficiency of DSM-based transmitters by proposing a novel technique aimed at reducing quantization noise while maintaining a high SNDR. The focus of this approach is on enhancing the overall performance of DSM systems, without compromising the quality of the transmitted signal. The proposed technique involves advanced signal processing methods that selectively mitigate the effects of quantization noise, thereby improving the efficiency of the transmission process. Simulation results demonstrate the effectiveness of the proposed method, particularly in the context of a 1.92 MHz Long Term Evolution (LTE) input signal, which is commonly used in modern wireless communication systems. For an oversampling ratio (OSR) of 16, the coding efficiency (CE) of the DSM-based transmitter is significantly improved, rising from 9.7% to 23%. At the same time, the SNDR remains high, measuring approximately 41 dB, indicating that the quality of the transmitted signal is preserved. These results suggest that the proposed technique offers a promising solution to enhance the performance of DSM-based transmitters, making them more efficient without sacrificing signal quality.

1. INTRODUCTION

The Delta Sigma Modulator (DSM)-transmitter is a transmitter architecture designed to generate signals capable of efficiently driving power amplifiers (PAs) and switch-mode power amplifiers (SMPAs) [1-6]. In the DSM-transmitter context, a non-constant envelope input signal is converted into a constant envelope signal [7, 8]. This

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[*] Corresponding Author: n.erfanimajd@scu.ac.ir
Department of Electrical Engineering, Shohadaye Hoveizeh Campus of Technology, Shahid Chamran University of Ahvaz, Dasht-e Azadegan, Khuzestan, Iran

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transformation allows the PA to operate without power back-off, thus maximizing its efficiency. Additionally, the constant envelope signal effectively drives high-efficiency switched-mode power amplifiers (SMPAs) [9]. Due to their high reconfigurability, DSMs are ideal for software-defined radio (SDR) applications [10-12, 6].

Several architectures have been proposed for DSM-transmitters. In [13-15], a band-pass DSM is used to quantize the RF signal for driving the SMPA. However, this quantization is performed at a high carrier frequency, which presents significant challenges in RF applications operating at gigahertz frequencies. Alternatively, in [10, 16, 17], a low-pass DSM is utilized to quantize the baseband signal. The main issue with this approach is the substantial quantization noise at the DSM output, which results in low coding efficiency (CE) and, consequently, poor power efficiency in the DSM-transmitter [17].

Efforts have been made in [18, 19] to reduce quantization noise at the DSM output by using a multi-bit low-pass DSM. However, in these cases, the DSM output signal does not maintain a constant envelope, making it unsuitable for driving PAs or SMPAs.

To address this, a polar transmitter configuration featuring a low-pass envelope DSM (LPEDSM) in an envelope elimination and restoration (EER) setup is proposed in [20-22]. In this design, the quantized envelope of the signal, produced by the DSM, controls the drain voltage supply of the SMPA. Nonetheless, switching a large DC-supply current on and off remains challenging, particularly when high output power is required [14].

This paper enhances DSM-transmitter efficiency by employing a signal processing technique that reduces quantization noise at the DSM output. The proposed technique improves coding efficiency (CE) while preserving the signal-to-noise and distortion ratio (SNDR) of the DSM-transmitter.

The structure of the paper is as follows: Section 2 introduces the DSM-transmitter architecture. In Section 3, we explain how the efficiency of the DSM-transmitter is improved by mitigating quantization noise. Section 4 presents the simulation results for the proposed quantization noise reduction method. Finally, Section 5 concludes the paper.

2. ARTICHECTURE OF DSM-TRANSMITTER

The architecture of the DSM-Transmitter is depicted in Figure 1. Initially, the quadrature components of the baseband input signal (I, Q) undergo quantization through the utilization of 1-bit DSMs. The quantized quadrature components exhibit two distinct levels, namely -1 and 1. The envelope and phase of the quantized signal at the output of DSMs can be expressed as follows [23]:

$$|S_q| = \sqrt{{I_q}^2 + {Q_q}^2} = \sqrt{2} \tag{1}$$

And

$$\angle S_q = tan^{-1}\left(\frac{I_q}{Q_q}\right) = \frac{\pi}{4}.\frac{3\pi}{4}.\frac{5\pi}{4}.\frac{7\pi}{4} \tag{2}$$

Here, Iq and Qq are quantized quadrature components and Sq is the quantized signal at the output of DSMs. as can be seen in (1) this quantized signal has constant envelope with the magnitude of $\sqrt{2}$. Therefore, this signal is an ideal signal for PA and SMPA in order to have a good linearity and efficiency. Then this quantized signal is up converted to desire frequency in order to drive SMPA and at last a bandpass filter is used to remove the quantization noise. Two metrics are used in order to evaluate the quantization noise effect on DSM-transmitter performance: CE and SNDR. CE is the ratio of the signal power to the total power at the output of DSM (Figure 2). Since the quantization noise has a significant role in a transmitter's efficiency, this parameter is used to evaluate the effect of the DSM quantization noise on the transmitter's efficiency. CE can be defined as [17, 23]:

Two metrics are employed to assess the impact of quantization noise on DSM-transmitter performance: Coding Efficiency (CE) and Signal-to-Noise and Distortion Ratio (SNDR). CE represents the ratio of signal power to the total power at the output of DSM (Figure 2). Given the significant role of quantization noise in a transmitter's efficiency, CE serves as a crucial parameter for evaluating the effect of DSM quantization noise on the transmitter's efficiency. CE is defined as follows [17, 23]:

$$CE = \frac{SignalPower}{TotalPower(SignalPower + QuantizarionNoisePower)} \tag{3}$$

In fact, the CE shows how much of the quantized signal power at the output of the DSM belongs to desired signal. SNDR is another metric to study the linearity performance of the delta – sigma-based transmitter and can be defined as [11, 23]:

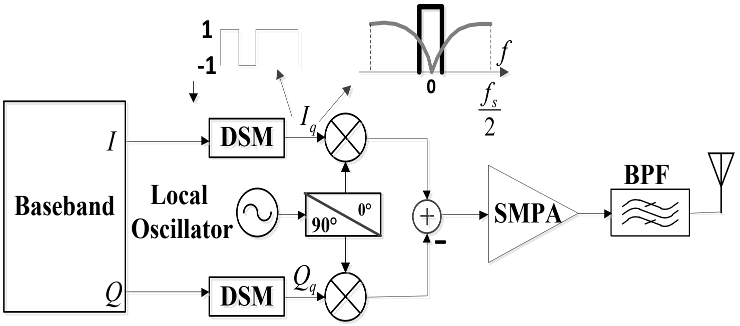


Fig. 1. Architecture of DSM-transmitter.

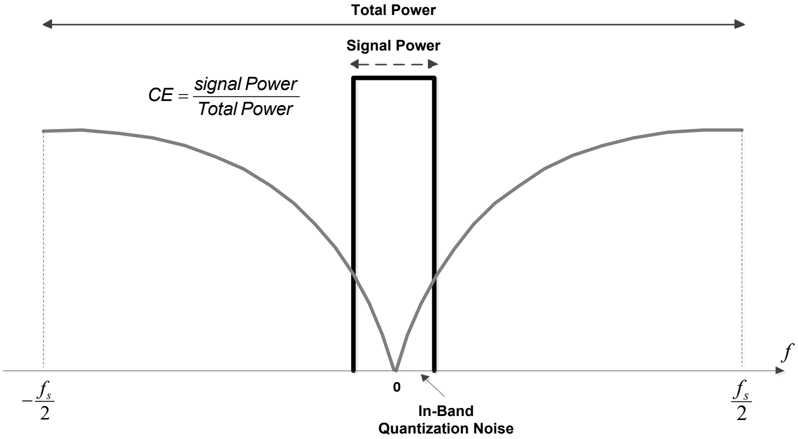


Fig. 2. Definition of CE.

$$SNDR = \frac{SignalPower}{In - Band\ Noise\ and\ Distortion\ Power} \tag{4}$$

Note that, unlike the CE, for calculating SNDR value both DSM quantization noise and PA distortion should be considered.

The overall efficiency of DSM based transmitter is estimated as [21, 23]:

$$\eta_T = CE \times \eta_{PA} \tag{5}$$

Where η_T is the overall transmitter efficiency and η_{PA} is the PA efficiency. By using ideal SMPA with theoretically 100% efficiency [1], (5) can be expressed as:

$$\eta_T = CE \tag{6}$$

We can conclude from (6) CE has the main role in determining the transmitter efficiency. So, improving CE has a significant effect on improving of overall transmitter efficiency.

3. PERFORMANCE IMPROVEMENT IN DSM-TRANSMITTER

The proposed method for reducing quantization noise and improving Coding Efficiency (CE) in DSM-transmitter is illustrated in Figure 3. As depicted, the process initiates with subtracting the input signal from the quantized signal to isolate the quantization noise. Subsequently, a low-pass filter is employed to distinguish the in-band quantization noise from the overall quantization noise. Following this, the in-band quantization noise is subtracted from the quantized signal to obtain a signal devoid of in-band quantization noise, and from the total quantization noise to acquire out-of-band quantization noise. The out-of-band quantization noise is then attenuated by a quantization noise factor, α, and subtracted from the in-band noise-free quantized signal.

In essence, this method achieves complete elimination of in-band quantization noise while reducing out-of-band quantization noise. The elimination of in-band quantization noise has minimal impact on the DSM output signal due to its small magnitude. However, the reduction in out-of-band quantization noise can introduce fluctuations in the DSM's output signal. Therefore, the quantized signal no longer maintains a constant envelope, potentially causing distortion in the Switch-Mode Power Amplifier (SMPA). Nevertheless, by controlling the noise reduction level, the signal variation can be kept sufficiently small to ensure SMPA distortion remains below the DSM quantization noise. Consequently, the overall Signal-to-Noise and Distortion Ratio (SNDR) is preserved, while Coding Efficiency experiences a significant improvement.

The elimination of in-band quantization noise contributes to enhanced SNDR in the DSM-transmitter, allowing for more effective reduction of out-of-band quantization noise and improvement in CE compared to scenarios where only out-of-band quantization noise reduction is applied to the DSM-transmitter. It is crucial to control the quantization noise reduction level to maintain reasonable envelope fluctuation and uphold signal quality, as exceeding a specific threshold can lead to increased envelope variation and substantial degradation in SNDR.

Note that, β in Figure 3 is coding efficiency improvement factor and can be expressed as follow:

$$\beta = \frac{QuantizationNoisePowerbeforeNoiseReduction}{QuantizationNoisePowerafterNoiseReduction} \tag{7}$$

In the next section, the simulation for proposed architecture in Figure 3 will be performed.

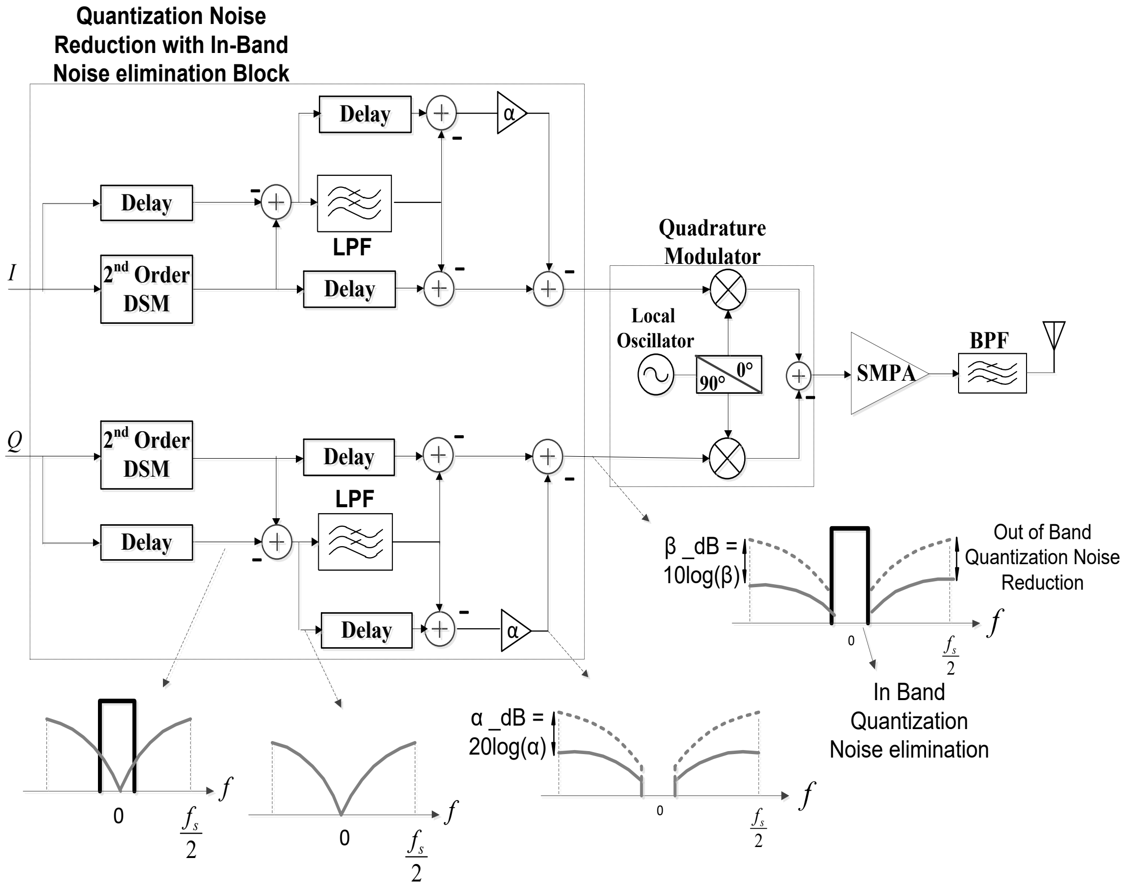


Fig. 3. Quantization noise reduction with in-band noise elimination in DSM- transmitter.

4. SIMULATION RESULTS

To determine the optimal amount of quantization noise reduction that does not compromise signal quality, the quantization noise reduction with in-band noise elimination block in Figure 3 was implemented in MATLAB Simulink. Subsequently, various quantization noise reduction factors (α) were applied to this block, and the resulting outputs were utilized as the input to the Switch-Mode Power Amplifier (SMPA).

The process involved importing the output signals of the quantization noise reduction block with different noise reduction factors, obtained from MATLAB, into the Advanced Design System (ADS). The RF modulator block in ADS was then employed for frequency up conversion and signal amplification to feed the SMPA. The SMPA chosen for this study was the inverse class F (F-1), designed based on the methodology outlined in [24]. The GaN transistor (CGH40010 from Cree Inc.), nonlinear model provided by the manufacturer, biased at VDS=28 V and VGS=-3 V, was utilized for the SMPA design. This inverse class F SMPA exhibited a maximum output power of 39.6 dBm, a power-added efficiency of 78%, and a power gain of 13.5 dB at 850 MHz.

The output signal from the inverse class F SMPA was then re-imported into MATLAB to calculate the Signal-to-Noise and Distortion Ratio (SNDR). This iterative process allowed for the assessment of different quantization noise reduction levels and their impact on the SMPA output signal quality.

The results of the quantization noise reduction with in-band noise elimination technique for an Uplink Long-Term Evolution (LTE) signal with a 1.92 MHz bandwidth and an oversampling ratio (OSR) of 16, for different quantization noise reduction factors, are presented in Figure 4 and Table 1. It is evident that utilizing quantization noise reduction with in-band quantization noise elimination for the Uplink LTE signal with 16 OSR improves Coding Efficiency (CE) from 9.7% to 23% (for α=0.38), while maintaining a signal quality of around 41 dB. Furthermore,

Figure 4 and Table 1 indicate that this CE improvement ranges from 9.7% to 20% (for α=0.34) when only quantization noise reduction technique (without in-band quantization noise elimination) is employed. Therefore, by incorporating in-band quantization noise elimination along with quantization noise reduction technique, we can further enhance CE while maintaining the same Signal-to-Noise and Distortion Ratio (SNDR) (41 dB).

The magnitude of the Delta Sigma Modulator (DSM) output signal before and after quantization noise reduction with in-band quantization noise elimination for α=0.38 is displayed in Figure 5. The plot illustrates that quantization noise reduction introduces fluctuations in the signal magnitude. However, as long as the value of α remains below 0.38, this signal variation does not adversely impact signal quality, and the SNDR remains above 41 dB.

Additionally, Figure 6 depicts the spectrum of the Switch-Mode Power Amplifier (SMPA) output signal for the Uplink LTE signal with a 1.92 MHz bandwidth and OSR of 16 under various conditions, including without quantization noise reduction (α=0), and using quantization noise reduction with in-band noise elimination for α=0.3.

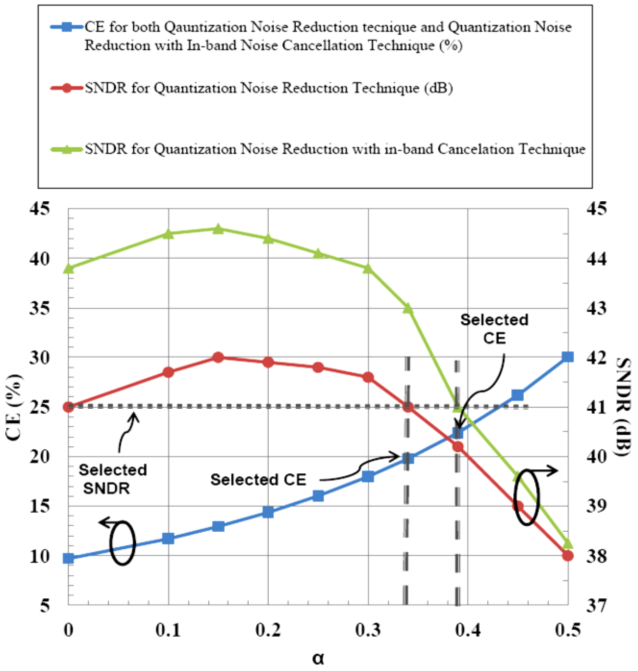
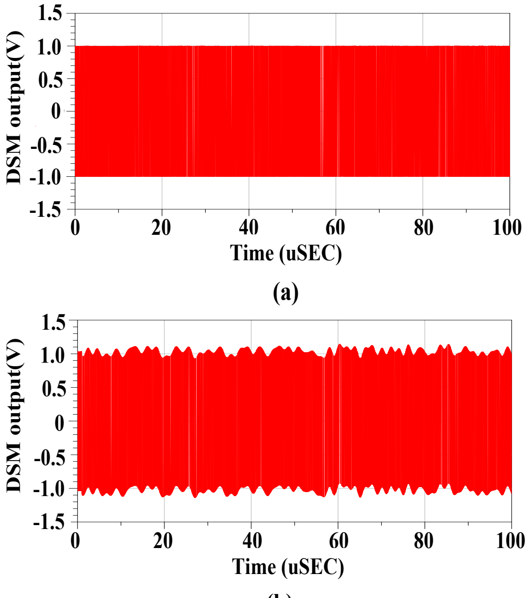


Fig. 4. Results of quantization noise reduction and quantization noise reduction with in-band quantization noise elimination for an Uplink LTE signal with 1.92 MHz bandwidth and an OSR of 16.

Table 1. The SNDR and CE results of quantization noise reduction and quantization noise reduction with in-band noise elimination for an Uplink LTE signal with 1.92 MHz bandwidth and an OSR of 16.

Signal	BW(MHz)	OSR	Method	CE(%)	SNDR(dB)
LTE	1.92	16	Without quantization noise reduction	9.7	41
			Quantization noise reduction (α=0.34)	20	41
			Quantization noise reduction with in-band noise elimination (α=0.38)	23	41



(a)

(b)

Fig. 5. Magnitude of DSM output signal (a) before quantization noise reduction (b)after quantization noise reduction with in-band quantization noise elimination for α=0.38

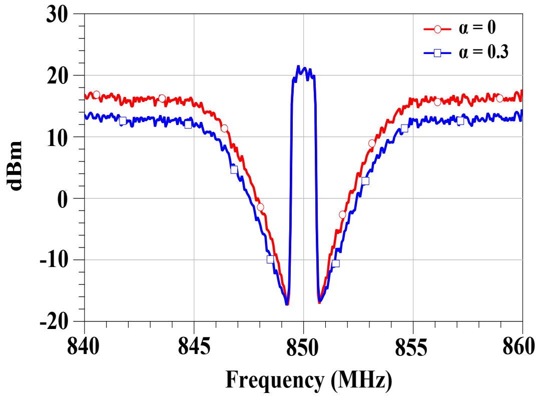


Fig. 6. The spectrum of the SMPA output signal for the Uplink LTE signal with 1.92 MHz bandwidth and OSR of 16 without quantization noise reduction, α=0, and using quantization noise reduction with in-band noise elimination for α = 0.3.

5. CONCLUSION

In this study, the application of quantization noise reduction with in-band quantization noise elimination to the Delta Sigma Modulator (DSM)-transmitter was explored to enhance transmitter efficiency. While this technique introduced fluctuations in the output DSM signal, careful control of the noise reduction level ensured that the signal variation remained sufficiently small to prevent Switch-Mode Power Amplifier (SMPA) distortion from surpassing the DSM quantization noise. As a result, the Signal-to-Noise and Distortion Ratio (SNDR) was successfully maintained.

Simulation results demonstrated that employing this technique for a 1.92 MHz Long-Term Evolution (LTE) input signal with an Oversampling Ratio (OSR) of 16 led to a notable improvement in the Coding Efficiency (CE) of the DSM. The CE increased from 9.7% to 23%, while maintaining an SNDR of around 41 dB. This outcome suggests the effectiveness of the quantization noise reduction with in-band quantization noise elimination approach in optimizing DSM-transmitter performance.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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