Towards Analog Filter-Free All-Digital Transmitters through Hybrid Estimation and Cancellation of Delta-Signma M's Quantization Noise

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TR2018-057 July 10, 2018

Abstract

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International Microwave and Radar Conference

Towards Analog Filter-Free All-Digital Transmitters through Hybrid Estimation and Cancellation of $\Delta\Sigma$M's Quantization Noise

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***Abstract*—This paper discusses one first approach towards the design of analog filter-free All-Digital RF Transmitters suitable for multi-band scenarios. In particular, the implementation of a feedforward technique will be targeted with the overall aim of analog canceling the digitally estimated out-of-band quantization noise. Simulated results are presented and evaluated in terms of Normalized Mean Square Error (NMSE), Adjacent Channel Power Ratio (ACPR) and obtained spectra.**

***Index Terms*—All-Digital Transmitters, Concurrent Multi-band Delta-Sigma Modulators, Inter-band Carrier Aggregation**

I. INTRODUCTION

During the last few years, the concept of All-Digital Transmitters (ADTs) have attracted considerable attention from both the research and the industry community, due to their capability to design integrated, reconfigurable, agile, multi-band and multi-standard transmitters in a highly-efficient way.

Nevertheless, the underlied quantization process is highly non-linear, and thus, a considerable amount of in- and out-of-band distortion is generated and must be considered, in the design of the whole transmitter front-end. One typical way to minimize the out-of-band distortion relies on the use of high-Q bandpass filters, with the inherent drawback of higher insertion losses and/or bulky volume. Moreover, they limit the transmitter to a given carrier frequency and band channel, which constrains the front-end's agility and flexibility. To avoid the inclusion of external Radio-Frequency (RF) filters, novel solutions have been proposed in the literature, such as the combination of multiple ADT's outputs using signal interference and cancellation to design mixed-domain Finite Impulse Response (FIR) filters [1], [2] and the use of iterative optimization methodologies in the synthesis of transmitters with reduced quantization noise [3]. A different approach that will be focused throughout this work, initially proposed in [4], involves the design of an Out-of-band Noise Canceler (NC), with reduced number of levels, to digitally assist the ADT minimizing the amount of quantization noise, as illustrated in Fig. 1. Even though the extra complexity involved in this technique, to the best of author's knowledge, this technique is entirely independent of the number of bands/carriers, and ultimately, it is suitable for relaxing the analog filtering requirements in multi-band digital transmission. Moreover, as pointed out in [4], in an ADT's application-specific design, either by the use of higher sampling rates or higher orders in the modulator, the noise power levels tend to be considerable lower than the in-band ones, leading to the use of low-power linear Power Amplifiers (PAs) in the NC output signal.

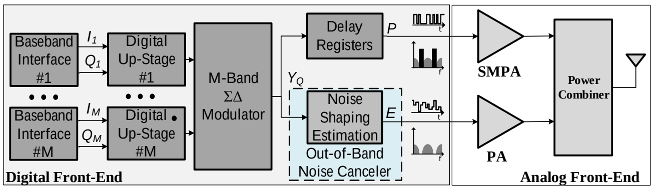

Fig. 1: Block diagram of the reported ADT with external out-of-band NC [4].

Hence, in this paper, a novel optimization of this architecture will be presented with the underlying goal of reducing its overall complexity, leading to an increased integration capability. In particular, it will be shown that the modulator's quantization noise can be digitally estimated in a straightforward way, just by considering the quantizer inputs/outputs.

The remainder of this paper is organized as follows. The reported out-of-band NC will be briefly introduced in Section II a). Then, the digitally estimation of the quantization noise will be addressed in Section II b), and validated with simulated results in Section III. Finally, the conclusions are drawn in Section IV.

II. EXTERNAL OUT-OF-BAND NOISE CANCELER

In this section, the out-of-band NC proposed in [4] is briefly introduced, as well as the new optimization strategy is discussed.

A. Conventional Architecture

Th out-of-band NC, proposed in [4] and depicted in the Figs. 1 and 2, samples the Delta-Sigma Modulator ($\Delta\Sigma$M)'s pulsed waveform ($Y_q(z)$), and down-converts it to subtract each input baseband signal, with the overall aim of solely preserve the out-of-band quantization noise ($E(z)$). Afterwards, the resultant signal's phase is inverted and combined using an extra N-bit $\Delta\Sigma$M. After amplifying the delayed pulsed waveform ($P(z)$) and $E(z)$, they can be combined in an (a)symmetric power combiner, enabling the reduction of the out-of-band noise, with no external filtering mechanism. The extra delay logic is required to take into account the out-of-band noise canceler's internal delay.

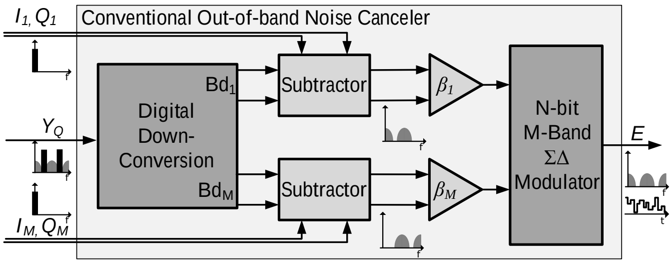

Fig. 2: Block diagram of the Out-of-band NC presented in [4], herein referred to as "Conventional".

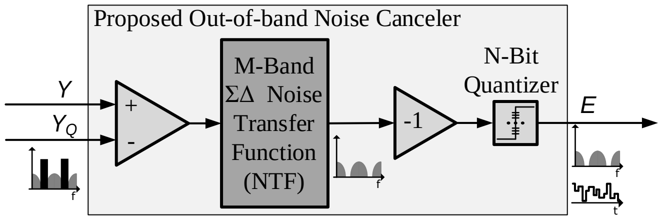

Fig. 3: Block diagram of the proposed Out-of-band NC, herein referred to as "Proposed".

B. Proposed Architecture

It is widely known that to transform an envelope-varying signal into a low-resolution equivalent, ΔΣM employs signal oversampling, quantization and a feedback loop for shaping the quantization errors. In particular, the quantizer reduces the number of output levels (which inherently adds quantization noise), the oversampler spreads the quantization noise for all the spectrum, while the feedback loop shapes the error in order to minimize the in-band noise. To accomplish this, the noise's transfer function applied to the quantization noise ($NTF(z)$) must maintain the in-band integrity. The formal way to model this kind of modulators is based on the modeling of the non-linear quantizer by a noise source ($E_q(z)$):

$$Y_q(z) = STF(z)X(z) + NTF(z)E_q(z) \tag{1}$$

where $X(z)$ is the envelope-varying incoming signal and $STF(z)$ is the transfer function applied to the input signal.

Hence, based on this general equation, it is possible to define a second signal ($E(z)$), which represents the quantization noise presented in the ΔΣM's output waveform:

$$E(z) = -NTF(z)E_q(z) \tag{2}$$

Taking into account that $E_q(z)$ is introduced in the ΔΣM's quantizer, thus, one can compute this variable just by digital filtering the comparison between the quantizer's input ($Y(z)$) and output ($Y_q(z)$), as illutrated in Fig. 3, leading to:

$$E(z) = -NTF(z)(Y(z) - Y_q(z)) \tag{3}$$

After estimation, the same reported ADT (Fig. 1) can be used: a coarse N-bit quantizer reduces the number of levels, a linear amplifier increases the signal power level before being combined with the amplified pulsed waveform. Afterwards, the out-of-band noise shall be considerably reduced and thus, no fixed filtering mechanism was required. Several advantages of this technique shall be pointed out. Firstly, the complexity of this proposed technique is considerably reduced as compared to the conventional one (Fig. 2). Secondly, it is a scalable technique, in the sense that moving from 1- to M-bands just affects the complexity of the digital FIR/Infinite Impulse Response (IIR) filter. Thirdly, it has no negative impact into the modulator's sampling rate. In other words, pipeline registers can be included in the digital filter to speed up the logic, provided that the pulsed waveform signal is digitally delayed to ensure a proper synchronism between the two branches. Finally, no extra ΔΣM is required, which is a major advantage because no extra quantization noise is created, leading to an inaccurate prediction of the spectrum's out-of-band noise.

III. SIMULATED RESULTS

A. Proposed Implementation

To validate the proposed technique in a multi-band scenario, the ΔΣM's architecture proposed in [5] and utilized in [4] (Fig. 4) was used as starting point. This architecture was chosen due its capability to independently place each one of the bands. By modeling the quantization noise by a random noise signal ($E_q(z)$), the following transfer function can be derived:

$$Y_q(z) = \left(\sum_{i=1}^{N} STF_i(z)X_i(z)\right) - NTF(z)E_q(z) \tag{4}$$

where $STF_i(z) = \frac{1+L_i(z)}{1+\sum_{i=1}^{N} L_i(z)}$, $NTF(z) = \frac{1}{1+\sum_{i=1}^{N} L_i(z)}$, $L_i(z) = \frac{1}{NTF_i(z)} - 1$ and $N = 2$, for a dual-band modulator. However, contrarily to [5] and [4], the loop transfer functions ($L_i(z)$) did not fall in the well-known Cascade of Resonators Feedback Form (CRFB) due to the huge inherent critical path that compromises the future integration in online-based ADTs. Thus, in order to speed up the modulator's sampling rate, a low-complex loop filter was designed with 2 complex zeros to define the notch frequency, together with 2 complex poles to control the Noise-Transfer Function (NTF)'s maximum gain. Hence, the NTF per band can be easily derived:

$$NTF_0(z) = \frac{1 + \alpha z^{-1} + z^{-2}}{1 + r\alpha z^{-1} + r^2 z^{-2}} \tag{5}$$

$$NTF_1(z) = \frac{1 + \beta z^{-1} + z^{-2}}{1 + r\beta z^{-1} + r^2 z^{-2}} \tag{6}$$

where $\alpha = -2\cos((2\pi Fc_1)/Fs)$, $\beta = -2\cos((2\pi Fc_2)/Fs)$ and r controls the distance between each zero and its correspondent pole, and ultimately, the NTF's gain. Following the same reasoning, the loop filters can be defined as:

$$L_0(z) = \frac{\alpha(r-1)z^{-1} + (r^2-1)z^{-2}}{1 + \alpha z^{-1} + z^{-2}} \tag{7}$$

$$L_1(z) = \frac{\beta(r-1)z^{-1} + (r^2-1)z^{-2}}{1 + \beta z^{-1} + z^{-2}} \tag{8}$$

At last, the global NTF can also be derived in a straigthforward way:

$$NTF(z) = \frac{1 + Az^{-1} + Bz^{-2} + Cz^{-3} + z^{-4}}{1 + Dz^{-1} + Ez^{-2} + Fz^{-3} + Gz^{-4}} \tag{9}$$

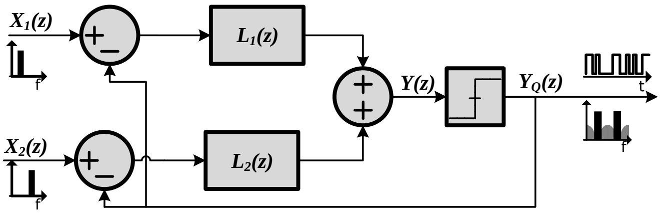

Fig. 4: Block diagram of the dual-band $\Delta\Sigma$M (adapted from [5]).

where $A = (\alpha + \beta)$, $B = (2 + \alpha\beta)$, $C = (\alpha + \beta)$, $D = (r(\alpha+\beta))$, $E = (2r\alpha\beta + 2r^2 - \alpha\beta)$, $F = (r^2(\alpha+\beta) + r(\alpha+\beta) + (\alpha+\beta))$ and $G = (2r^2 - 1)$.

To assess the proposed technique, simulations were carried out in a 40 MHz aggregate bandwidth dual-band transmission at 856 MHz and 1450 MHz, with a sampling rate of 6.25 GHz. Fig. 5 demonstrates that the signal $E(z)$ can faithfully estimate and predict the quantization noise presented in the pulsed waveform ($P(z)$). Moreover, in addition to enable an improvement of the out-of-band spectrum and Figures of Merits (FoMs) (such as ACPR), the in-band ones (NMSE, Signal-to-Noise Ratio (SNR)) can also be slightly improved because $E(z)$ also estimates the residual in-band quantization noise, leading consequently, to higher bandwidth signals.

Fig. 6 demonstrates that the out-of-band noise can be successfully eliminated after combination of the different outputs. Moreover, as can be seen in the zoomed figure, the number of levels in the error signal defines the noise floor of the system, and, ultimately, the higher the number of levels, the better will be the overall FoM.

Table I summarizes the obtained NMSE and ACPR FoMs for different quantization levels. As expected, the performance of the system is significantly improved. Even though in the 5-bit NC the NMSE is slightly inferior to the scenario without NC (due to the higher noise floor imposed by the coarse quantization), the output spectrum is almost clean, which leads to a significant reduction of filtering requirements, interference issues as well as to a possible accommodation of higher bandwidths.

TABLE I

Simulated in-band and out-of-band FoMs of the proposed technique with and without NC for a 16-Quadrature Amplitude Modulation (QAM), 21.5 MHz per band.

	Fcarrier 1		Fcarrier 2	
	NMSE (dB)	ACPR T (dBc)	NMSE (dB)	ACPR T (dBc)
w/o NC	-36.55	31.68	-35.69	32.33
w/ 5 bit NC	-35.83	34.30	-34.68	34.35
w/ 6 bit NC	-38.64	39.97	-37.01	39.85
w/ 7 bit NC	-39.77	44.27	-37.81	44.29

IV. CONCLUSIONS

In this paper, a new optimization approach was proposed towards the aim of reducing the complexity of out-of-band NC through digitally estimation of the $\Delta\Sigma$M's quantization noise. Simulations carried out demonstrate that this low-complex technique can significantly improve the major FoMs, at the same time that may lead to analog-filter-free ADT, regardless of the number of bands. Work in the laboratorial validation of this concept is on the way, together with new techniques that are under investigation to reduce even more the quantization levels of the error signal with no considerable reduction of the performance of the system.

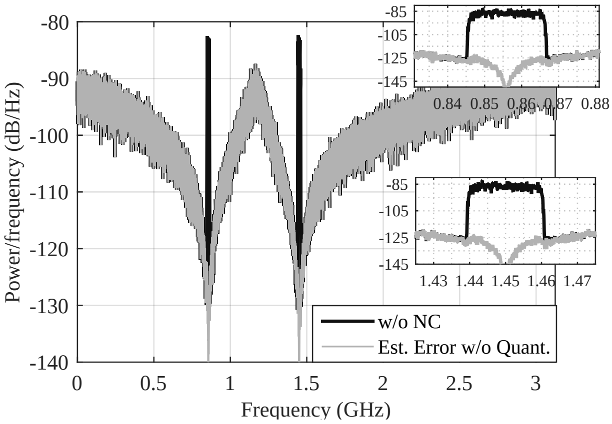

Fig. 5: Comparison between the resultant simulated output spectrum with and without NC for a 16-QAM, 21.5 MHz per band.

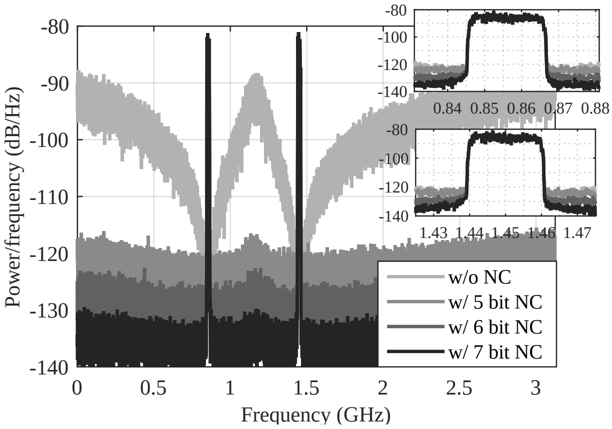

Fig. 6: Comparison between the resultant simulated output spectrum for different levels of quantizated error signals $E(z)$.

ACKNOWLEDGMENT

This work is supported by Mitsubishi Electric Research Laboratories. With additional support for Daniel C. Dinis, Arnaldo S. R. Oliveira and José Vieira by FCT/MEC through national funds and when applicable co-funded by FEDER PT2020 partnership agreement under the project UID/EEA/50008/2013, and by FCT - Fundação para a Ciência e a Tecnologia - under the PhD (PD/BD/105857/2014) grant given to the first author.

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