A General Method for Passband Quantization Noise Suppression in Pulsed Transmitter Architectures

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***Abstract*— In this paper we describe a novel method for selective bandpass cancellation of the quantization-noise that occurs in pulsed transmitter architectures, where the signal is partially or completely quantized. A carrier bursting transmitter architecture, where the amplitude part is quantized and then recombined with a phase-modulated RF carrier, is used as a general example to demonstrate the principles of the method proposed. Measurements on a high efficiency 10 W LDMOS PA working at 1 GHz are used to verify the theoretical results.**

***Index Terms*— Carrier bursting, bandpass filter, power amplifier, quantization noise, $\Sigma\Delta$-modulator, noise-shaping.**

I. Introduction

One of the many methods for improving the efficiency in microwave power amplifier systems is to apply 1-bit quantization of different forms on the signal, thus using the power amplifier only in its most efficient regions, i.e. in deep compression or in 'pinch-off' mode. A summary of some of the most common types of pulsed transmitter architectures is provided in [1].

However, a well known artifact of these coarse 1-bit quantization schemes is the large amount of quantization noise produced. In order to comply with the spectral demands put on the system, one then has to take certain measures to ensure that this noise is properly terminated. The two methods presently used to address this problem is based on using very narrow band bandpass filters, as described in Fig. 1, or use extremely high pulse rates. In any of the cases, the efficiency will suffer either due to large insertion losses of the filter due to its narrow band nature, or due to switching-losses caused by the extreme pulse rates needed.

Recently, a number of promising realizations of pulsed transmitter architectures have been presented where either the PA input [2] or supply voltage [3] are quantized for high efficiency operation. In both cases, a narrowband filter is needed to cancel the quantization noise near the carrier. In [4] it is suggested to use a feed forward method, a otherwise quite common method used to perform linearization, to cancel out quantization noise near the carrier.

The feed forward method does however require additional hardware which adds unnecessary cost and complexity to the system in the form of additional hardware which will have a negative impact on the overall system efficiency and complexity.

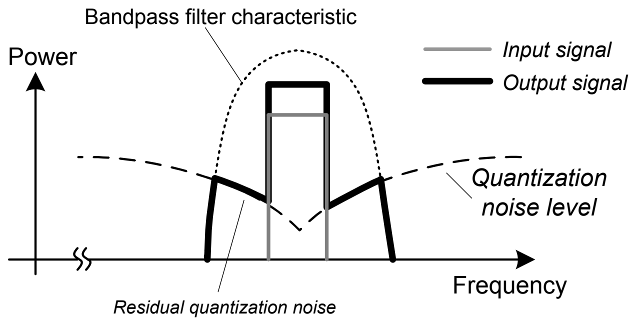

Fig. 1. A principal sketch on how quantization noise needs to be handled by narrow a band filter.

Instead, we suggest a low complexity solution where a trade-off is introduced to deal with quantization noise close to the signal, with no need for additional hardware. A small controlled amplitude component is superimposed on to the quantized signal, canceling out a selected bandpass part of the quantization noise close to the signal, after which one could use a more wideband output filter with less insertion loss, while operating at quite moderate sampling rates, avoiding large switch losses.

II. Theory

The proposed method will be demonstrated by application in a carrier bursting system as described in [1], but can be applied to other pulsed architectures in a similar manner. The overall system architecture is illustrated by a complex baseband model as shown in Fig. 2, which incorporates both the regular carrier bursting mechanisms, as well as the quantization noise cancellation scheme. This model was implemented in MATLAB and simulated using a bandwidth reduced W-CDMA signal in order to verify the theoretical results. The signal has a bandwidth of 1 MHz and a Peak to Average Power Ratio (PAPR) of approx. 6.5 dB. A f_s of 20 MHz was used.

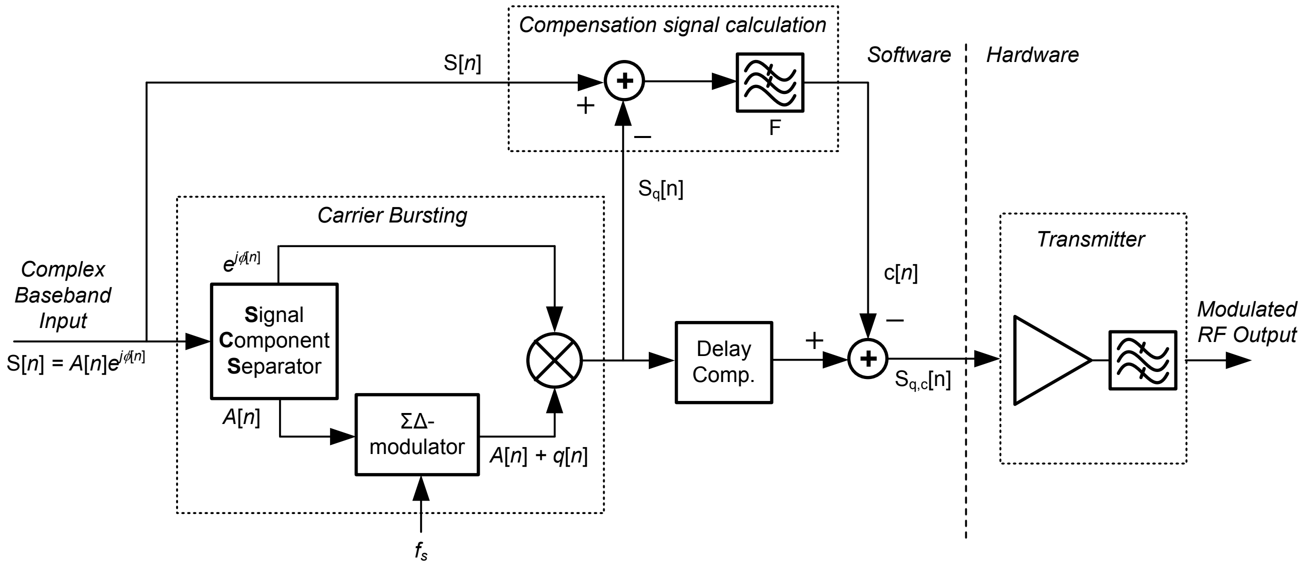

Fig. 2. Complex baseband model illustrating the components of the proposed quantization noise cancellation scheme, applied with a carrier bursting transmitter.

A. Envelope quantization using the $\Sigma\Delta$-modulator

First, the complex baseband signal $S[n] = A[n]e^{i\varphi[n]}$ is separated into amplitude and phase components, where the amplitude component is passed through the $\Sigma\Delta$-modulator for quantization and then recombined again with the phase part. The amplitude signal, after quantization, is denoted A_q, and is defined as

$$A_q[n] \triangleq A[n] + q[n] \tag{1}$$

where $A[n]$ is the original amplitude component and $q[n]$ is the quantization error. The spectral characteristics of $q[n]$, which will be of importance later, is in the case of a $\Sigma\Delta$-modulator determined by both the input signal distribution, as well as the loop-filters. These loop-filters provide an extra degree of freedom via their noise shaping properties, whose vital impact of the system performance will be shown.

B. The compensation signal

As the complex baseband model in Fig. 2 suggests, the frequency range over which we aim to cancel out the quantization noise is given by the frequency response of the linear phase low pass filter F. For a given cancellation filter with impulse response $\{f[k]\}_{k=1}^{M}$ of length M, we can calculate the cancellation signal as

$$c[n] = \sum_{k=0}^{M} f[k](q[n-k]e^{i\varphi[n-k]}) \tag{2}$$

The new complex baseband signal that contains the compensation signal $c[n]$, is now denoted as $S_{q,c}$ and can be written as

$$S_{q,c}[n] = A[n]e^{i\varphi[n]} + \left(q[n]e^{i\varphi[n]} - c[n]\right) \tag{3}$$

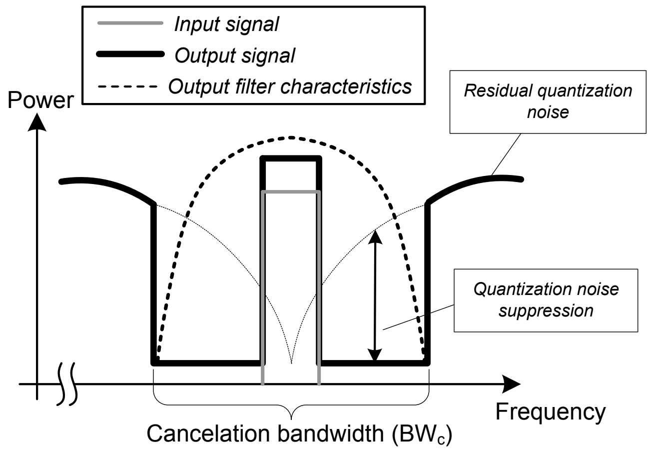

Fig. 3. A view of the quantization-noise free region due to the cancellation method.

for which $\sum_{n}^{N} |S[n] - S_{q,c}[n]|^2 \longrightarrow 0$ within the cancellation bandwidth, BW_c, as illustrated in Fig. 3. The compensation signal $c[n]$ will manifest itself as an amplitude limited ripple superimposed on to the pulsed RF carrier, which becomes obvious when studying the signal in the IQ-plane as illustrated in Fig. 4, where the case of regular carrier bursting have been added for comparison. It is also interesting to note that when $BW_c \rightarrow f_s$, then $S_{q,c}[n] \rightarrow S[n]$, i.e the case of a normal linear drive signal, while if $BW_c \rightarrow 0$ then $S_{q,c}[n] \rightarrow S_q[n]$, which is simply a regular Carrier Bursting signal.

As input parameters to the proposed architecture, the signal envelope probability density function (PDF) is given in advance, but the noise-shaping filters in the $\Sigma\Delta$-modulator and the sample rate f_s can be adapted to minimize the variance of

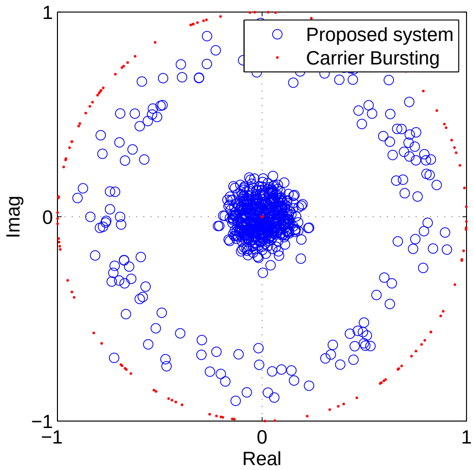

Fig. 4. Calculated IQ-data, with and without quantization noise cancellation.

the error within the cancellation region BW_c. For a given set of parameters, σ_c^2 can then be calculated as

$$\sigma_c^2 = \mathbb{E}\left[|c|^2\right] = \frac{1}{N}\sum_{n=0}^{N}\left\|\sum_{k=0}^{M} f[k]\left(q[n-k]e^{i\varphi[n-k]}\right)\right\|^2 \quad (4)$$

from which its quite obvious that σ_c^2 is directly proportional to the power of the phase modulated quantization noise within the passband of F. This means that σ_c^2 can be minimized by optimizing the loop filter coefficients in the $\Sigma\Delta$-modulator with the objective of minimizing the term $q[n]e^{i\varphi[n]}$ within BW_c.

In order to illustrate the effects of the $\Sigma\Delta$-modulators noise shaping in this architecture, it is enough to study the histogram of $|c[n]|$ for two cases. First, a standard 2^{nd} order low pass $\Sigma\Delta$-modulator that has high Signal to Quantization Noise Ratio (SQNR) within the signal bandwidth, implemented with integrators. Secondly, a $\Sigma\Delta$-modulator where the impulse response of the loop filters have been selected to minimize the amount of quantization noise within BW_c is shown. The result is presented in Fig. 5.

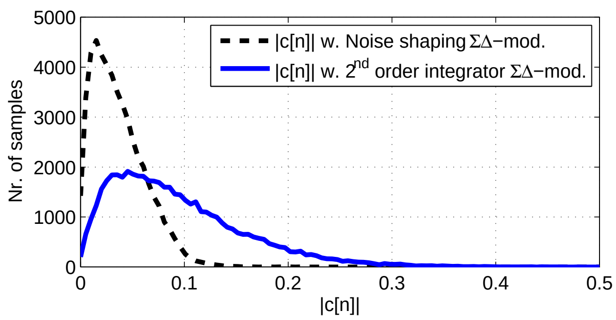

Fig. 5. Histogram of $|c[n]|$, with both a 2^{nd} order $\Sigma\Delta$-modulator and a $\Sigma\Delta$-modulator using noise-shaping filters.

The power spectral density, PSD, of the output signal in the two cases mentioned above is performed using the complex baseband model and the results are shown in Fig. 6, along with one example using the described method of quantization noise cancellation.

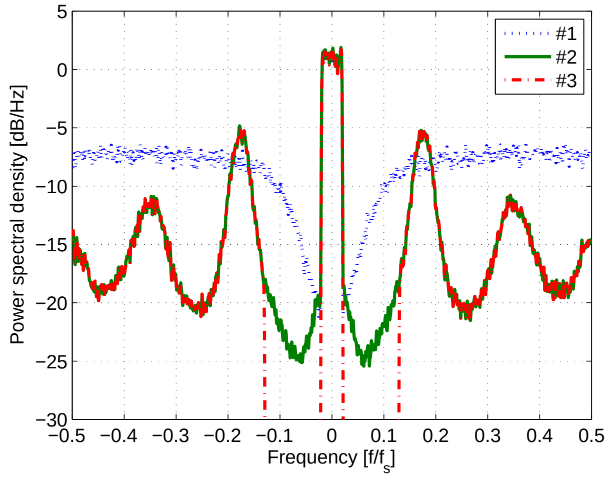

Fig. 6. Simulated power spectral density of three cases. # 1: $A_q[n]$ quantized with a regular 2^{nd} order $\Sigma\Delta$-modulator. # 2: $A_q[n]$ quantized with a $\Sigma\Delta$-modulator comprising noise shaping loop-filters. # 3: Case # 2 with quantization noise cancellation.

As σ_c^2 is kept small we will run the amplifier only in its most efficient regions. However, as opposed to a traditional carrier bursting transmitter, the characteristics of the compensation signal added need to be presented at the power amplifier output. Therefore, since the regions $c[n]$ operates in are highly nonlinear, keeping σ_c^2 as small as possible will reduce the need of complex pre-distortion algorithms. Also, keeping σ_c^2 minimized will reduce the backoff needed for pre-distortion, therefore also maximizing the efficiency obtained.

III. Experimental Results

In order to practically demonstrate the proposed architecture, measurements were performed on a wideband 10 W LDMOS PA operating at 1 GHz with 80% peak drain efficiency. The amplifier and its characteristics are described in detail in [5]. The measurement setup is shown in Fig. 7.

The bursted RF-carrier was generated via simulated IQ-data, and uploaded to a vector signal generator (Agilent 4438C) thus providing an input signal to the power amplifier. The input power was adjusted to drive the signal peaks into compression of the amplifier. The following parameters were used to generate the data used for the measurements:

- Burst-rate (f_s) = 20 MHz
- Signal BW = 1 MHz
- BW_c = 5 MHz

The input signal used during the measurements is the same bandwidth-reduced W-CDMA signal as used in the simulations. The signal was further upsampled a factor of 5

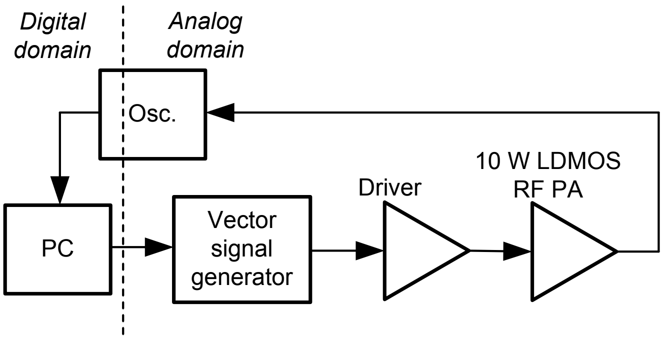

Fig. 7. The measurement setup.

to provide sufficiently accurate burst flanks at the generator output.

Further on, a $BW_c = \frac{1}{4} f_s$ is chosen in order to provide a fairly good region ($\frac{3}{4} f_s$) over which to noise shape. Using a regular static polynomial-based pre-distortion, a noise free dynamic range of approx. 50 dB was obtained within specified BW_c.

The measured AM/AM characteristics with and without pre-distortion is shown in Fig. 8 and the measured PSD for the same cases is shown in Fig. 9.

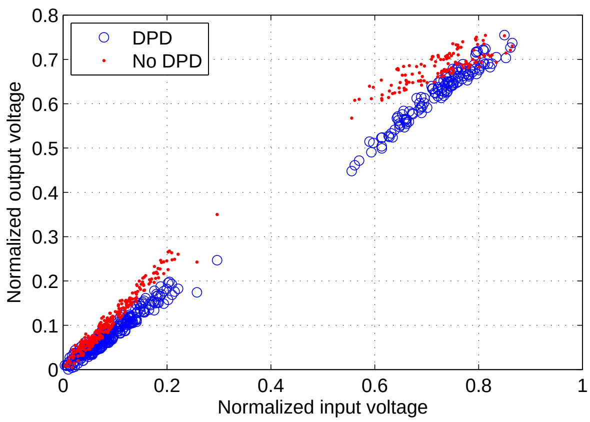

Fig. 8. Measured AM/AM, with and without pre-distortion.

The measurements show that pre-distortion increases the amplitude variations slightly, since the signal expands in order to compensate for the amplifiers behavior in compression. This will in turn reduce the efficiency and it is therefore very important to apply proper noise-shaping.

The overall efficiency of the transmitter, excluding filtering at the power amplifier output, was measured by relating the total power delivered by the PA in relation to the power from the bias supply. Without pre-distortion, the efficiency was measured to be 55%, while it decreased to 45% when the pre-distortion was applied. These results are very promising considering the very large suppression of quantization noise obtained close to the carrier and the relatively low switching frequency used.

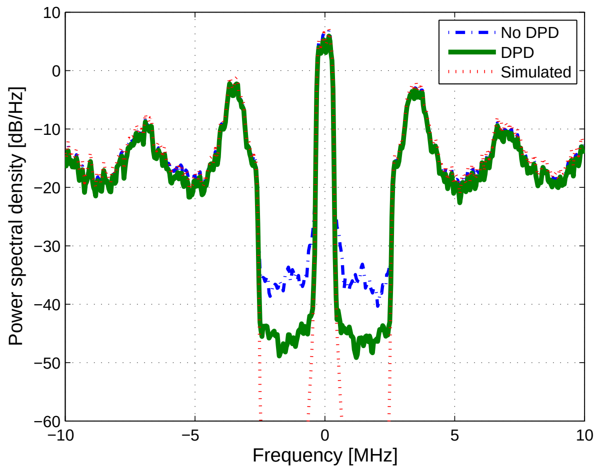

Fig. 9. Measured normalized power spectral density, with and without pre-distortion applied.

IV. Conclusion

A general method for cancellation of quantization noise in pulsed transmitter architectures has been suggested. The concept has been illustrated with simulations as well as demonstrated with measurements on a power amplifier.

Two important design parameters have been identified to be the noise-shaping of the $\Sigma\Delta$-modulator and the ratio of BW_c/f_s. The experimental results have also shown the possibility of implementing the method using a regular wideband quadrature modulator.

Measurements shows good potential for high efficiency operation without the need for using exceedingly high pulse rates, while still providing a good noise free dynamic range over a fairly large bandwidth.

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