Bandpass delta sigma optimization using parameter identification

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Abstract— **In this paper, a new method to optimize the noise shape of a bandpass delta sigma (BPDS) modulator for a digital transmitter is presented. The optimal coefficients of BPDS structure are achieved by minimization of a quadratic criterion based on prediction error. To demonstrate the effectiveness of this approach, simulated results for a 6$^{\text{th}}$ order BPDS structure are presented.**

I. INTRODUCTION

Trend in CMOS transceiver is to replace analog blocks by digital ones. Future transmitter could be built based on Sigma Delta modulators (SDM) [1]. One of SDM major properties is its ability to shape the quantization noise [2]. This in turn could create an issue in meeting spurious emission requirements. In current state of the art BPDS modulators, design methods are used to minimize the noise at proximity of the signal frequency, leading to improvement of the Signal to Noise Ratio (SNR) [3]-[4]. The objective of the proposed method is to optimize the shape of quantization noise according to spurious specification defined in particular frequency bandwidths . To demonstrate the interest of the method, it was validated with an usual RF standard, WCDMA FDD: at the top of spurious emission requirements, this standard requires the transmitter to generate a very low noise in the receive channel. Because other elements of the transmitter can modify the Noise Transfer Function (NTF), the frequency response of a generic duplexer is taken in account in the noise shape specification

The proposed method is based on parameter estimation by minimization of quadratic error between an ideal filter and BPDS modulator. Ideal filter will be design using *Digital Filter Design* from MATLAB/SIMULINK according to the noise shape specification achieved from a generic frequency response of duplexers and the standard. Initialization of the parameter estimation is achieved by a Delta Sigma Toolbox[1]. Performances studied are the Adjacent Channel Leakage power Ratio (ACLR) and the margin with standard (spurious).

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[1]Delta Sigma Toolbox can be downloaded from MATWORKS web site http://www.mathworks.com/matlabcentral and the function *RealizeNTF* was use to calculate the initial BPDS coefficients

II. WCDMA AND NOISE SHAPE SPECIFICATION

Among the WCDMA standard bands, Band 1 was selected as it has many spurious specifications defined in different frequency bands, and a gap of 130 MHz between Transmit (TX) and Receive (RX) bands. WCDMA band 1 spurious specifications close to Tx carrier are detailed on Table I.

TABLE I

WCDMA BAND 1 SPECIFICATIONS

Specifications	Values	
Frequency Carrier (Tx band)	1920-1980MHz	
Output Power	24dBm (+1/-3 dBm)	
ACLR	$F_c \pm$ 5MHz	$F_c \pm$ 10MHz
	33dB	43dB
Spurious	1GHz < f < 12.5GHz	-30dBm/1MHz
	1.805GHz < f < 1.88GHz	-71dBm/100kHz
	1.8449GHz < f < 1.8799GHz	-60dBm/3.84MHz
	1.8845GHz < f < 1.9196GHz	-41dBm/300kHz
	2.11GHz < f < 2.17GHz	-60dBm/3.84MkHz

Fig. 1-a displays WCDMA band 1 emission restrictions according to Table I. Resolution bandwidth has been re-calculated in dBm/Hz to achieve a continuity in the specification. Then the overall transfer function depends on frequency response of both amplifier and duplexers.

A BPDS modulators can be used in a transmitter as described in [1]-[5] and shown on Fig. 2.

Commercially available duplexers, implemented for WCDMA band 1, have similar frequency responses. To demonstrate the flexibility and power of the approach, a generic frequency response has been used, as represented in Fig. 1-b.

From the WCDMA standard spurious requirements and generic frequency response, it results a noise shape specification for the BPDS. The resulting curve is shown in Fig. 1-c. The noise rejection must be maximum in two frequency bands (1.8-1.88GHz and 2.1-2.17GHz (Rx band)).

According to the noise rejection, BPDS must have at least three notches. They will be placed in order to maximized the noise rejection especially in the Rx band.
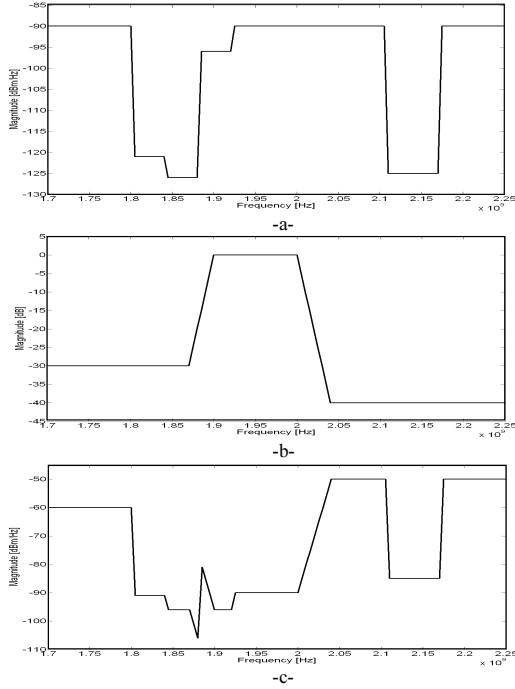
Fig. 1. Noise shape specification : -a- WCDMA band 1; -b- Generic duplexer frequency response for WCDMA band 1; -c- Noise rejection target
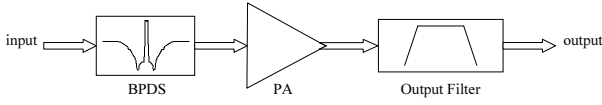

Fig. 2. Diagram of simulated architecture

III. BPDS MODEL

A. structure

A discrete time BPDS design requires to choose different elements like discrete resonator cell (z^{-1} or z^{-2}), structure (*Butterworth* or *Chebyshev*) and form (*Cascade-of-Integrators, FeedBack/FeedForward* (CIFB/F) or *Cascade-of-Resonators, FeedBack/FeedForward* (CRFB/F)) [2]. For the proposed study, z^{-1} delay cell combined with *Chebyshev* structure under CRFB form has been chosen to allow a frequency asymmetric repartition of the notches in the noise shape. Finally, a $6^{t}h$ order BPDS is choosen to achieve the required three notches, as illustrated in Fig. 3.

Input signal is modulated at frequency carrier (F_c) and BPDS is sampled at four times $F_s = 4.F_c$.

B. State space representation

BPDS is defined by two transfer functions, the Signal Transfer Function (STF) and the Noise Transfer Function (NTF). In our case, the NTF function is used in optimization to extract the BPDS feedback parameters noted a_i and notches coefficients noted g_i as referenced on Fig. 3. The CRFB structure is described in state space model. This representation based on transition matrix allows to describe easily the STF

and the NTF function. For a 6th order BPDS[2], the state space model is defined by the following equations :

$$\begin{cases} \underline{x}_{n+1} = A\,\underline{x}_n + B\,\underline{e}_n \\ y_n = C^T \cdot \underline{x}_n \end{cases} \qquad (1)$$

where

$$A = \begin{bmatrix} 1 & -g_1 & 0 & 0 & 0 & 0 \\ 1 & 1-g_1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & -g_2 & 0 & 0 \\ 0 & 1 & 1 & 1-g_2 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -g_3 \\ 0 & 0 & 0 & 1 & 1 & 1-g_3 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 & -a_1 \\ 1 & -a_1-a_2 \\ 0 & -a_3 \\ 0 & -a_3-a_4 \\ 0 & -a_1 \\ 0 & -a_1-a_1 \end{bmatrix}, C = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$\underline{x}_n^T = [x_1\ x_2\ \cdots\ x_6]$: transposed state space vector

$\underline{e}_n = \begin{bmatrix} u_n \\ v_n \end{bmatrix}$: input vector

The state space diagram is represented in Fig. 4. Using this representation, the discrete STF and NTF functions can be achieved according to:

$$[STF\ NTF] = C^T\,(z\,I - A')^{-1}\,B + D \qquad (2)$$

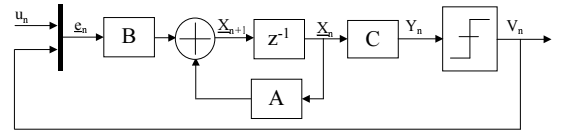where $A' = A + B \cdot [\,0\ \cdots\ 1\,]$ and $D = [0\ 1]$

Fig. 4. Block diagram of corresponding state space representation

IV. PARAMETER IDENTIFICATION ALGORITHM

Parameter estimation is the procedure which allows the determination of the mathematical representation of a real system from experimental data [6]. The block diagram of parameter identification with Output Error technique is shown in Fig. 5. This technique is based on minimization of quadratic error in time domain between desired discrete filter and NTF function of BPDS.

For the case of 6th BPDS optimization, the previous state space model is considered (1) and the following parameter vector is defined :

$$\underline{\theta} = [a_1\ a_2\ \cdots\ a_6\ g_1\ g_2\ g_3]^T \qquad (3)$$

The identification problem is to estimate the values of the parameters $\underline{\theta}$ using K samples of the desired filter output (y_n) which is excited by K samples of a white noise uniformly distributed over $[-1, 1]$ (v_n) [8]. Thus, the output prediction error is defined as follow:

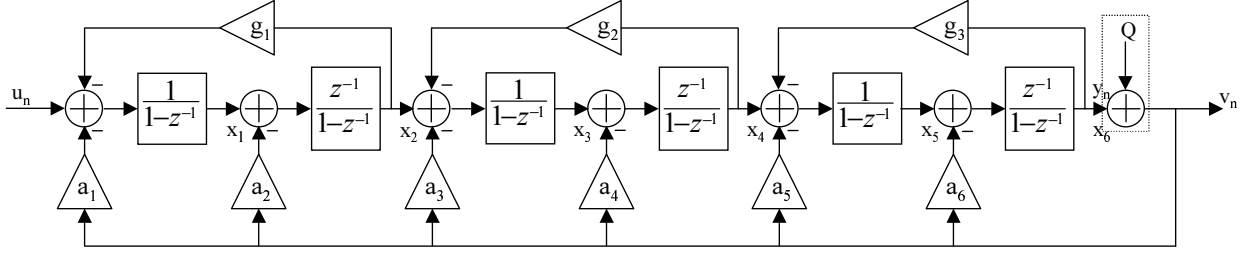[2]The proposed state space model can be generalized to an nth order

Fig. 3. The 6th order BPDS modulator with CRFB structure

$$\varepsilon_n = y_n - \hat{y}_n(\hat{\underline{\theta}}, v) \tag{4}$$

where the estimated NTF output $\hat{y}_n$ is obtained by simulations of the NTF (2) and $\hat{\underline{\theta}}$ is an estimation of optimal parameter vector $\underline{\theta}$ (best a_i and g_i).

As a general rule, parameter estimation with Output Error technique is based on minimization of a quadratic criterion defined as:

$$J = \sum_{n=1}^{K} \varepsilon_n^2 = \sum_{n=1}^{K} (y_n - \hat{y}_n)^2 \tag{5}$$

Optimal values of $\underline{\theta}$ are achieved by Non Linear Programming (NLP) methods. Practically, Marquardt's algorithm [7] is used for off-line estimation:

$$\hat{\underline{\theta}}_{i+1} = \hat{\underline{\theta}}_i - \{[J''_{\theta\theta} + \lambda \cdot I]^{-1} . J'_\theta\}_{\hat{\underline{\theta}} = \underline{\theta}_i} \tag{6}$$

with

$J'_\theta = -2 \cdot \sum_{n=1}^{K} \underline{\varepsilon}_n^T \cdot \underline{\sigma}_{n,\theta}$: gradient.

$J''_{\theta\theta} \approx 2 \cdot \sum_{n=1}^{K} \underline{\sigma}_{n,\theta} \cdot \underline{\sigma}_{n,\theta}^T$: hessian.

λ : monitoring parameter.

$\underline{\sigma}_{n,\theta} = \frac{\partial \hat{y}}{\partial \underline{\theta}}$: output sensitivity function.
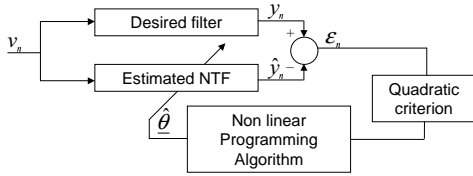

Fig. 5. BPDS optimization scheme

V. SIMULATION RESULTS

A. Digital filter design

First, a discrete Chebyshev StopBand filter (NTF form) is designed according to the noise shape specification shown in Fig. 1-c. Filter coefficients are tuned in order to have an important noise rejection in frequency ranges defined in section II.

Notches positions are defined by poles placement in the unit disk to satisfy the stability condition. However, the noise rejection form of the desired NTF is obtained with the zeros placement. During simulation, the filter is excited by the white noise previously defined in section IV. The coefficients of this digital filter and its simulation results in time-domain will be used in optimization procedure.

B. Estimation results

The proposed parameter identification method is used to adjust the BPDS coefficients. Appropriated initial values, noted $\underline{\theta}_{init}$, are required to assure convergence of the identification procedure. For example, $\underline{\theta}_{init}$ can be achieved using Delta Sigma Toolbox. Initial coefficients are listed in Table II and the resulting NTF is presented on Fig. 7, noted $Initial NTF$. In this case the NTF correspond to a important reduction of noise around the carrier frequency.

At the end of the proposed identification procedure, a new set of coefficients ($\hat{\underline{\theta}}$) is achieved. Table II shows $\hat{\underline{\theta}}$. The resulting BPDS parameters allow closed performances between NTF and ideal filter, as illustrated by time or frequency domain simulations.

TABLE II
INITIAL AND OPTIMIZED COEFFICIENTS

index (i)		1	2	3	4	5	6
$\underline{\theta}_{init}$	a_i	0.042811	-0.043716	-0.246777	0.002641	-0.555591	0.555591
	g_i	1.9952	2	2.0047	–	–	–
$\hat{\underline{\theta}}$	a_i	-0.030688	-0.086103	-0.357849	-0.00282	-0.461228	0.602107
	g_i	1.7941	2.2532	1.9524	–	–	–

Fig. 6-a illustrates simulation results in Time-domain of the output desired filter and the estimated NTF. Fig. 6-b shows quadratic error (ε_n) and confirms that the BPDS coefficients calculated are in agreement with the response of the desired filter.

Fig. 7 shows simulated NTF at the BPDS output with initialization coefficients, optimized coefficients and WCDMA constraints. The result clearly shows that the NTF is optimized to satisfy the target standard unlike NTF corresponding to initial values which is optimized for Signal to Noise Ratio (SNR).

For more evaluation, simulations are done with ADVANCED DESIGN SYSTEM (ADS software) using an input signal with a frequency carrier of $F_c = 1.98$GHz and a power of -26dBm, sampling frequency of $F_s = 7.92$GHz and a commercial duplexer. Fig. 8 shows the filtered BPDS output spectrum for different bandwidth resolutions and the corresponding spurious band for WCDMA band 1 standard.
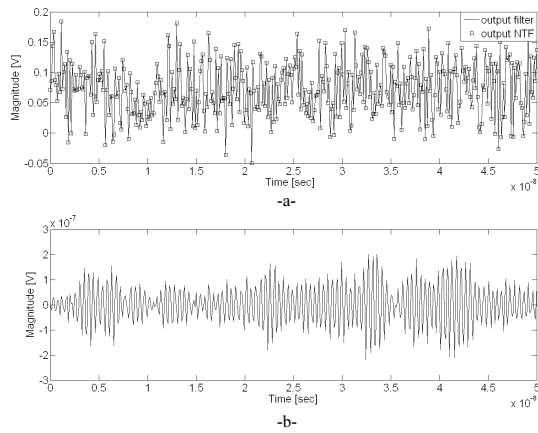
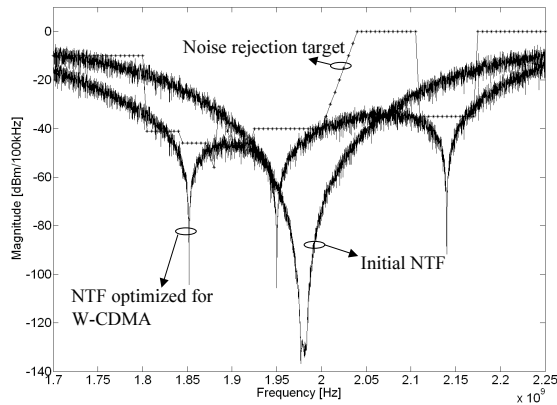Fig. 6. Time-domain simulation
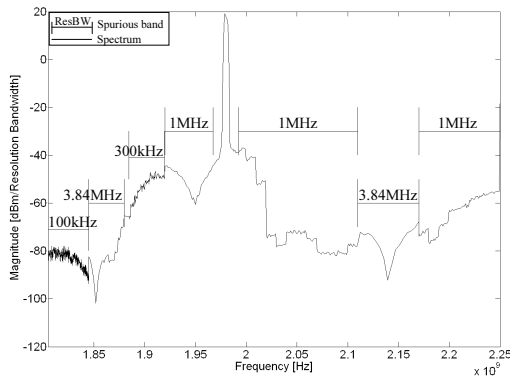

Fig. 7. Frequency-domain simulation

Fig. 8. Output filtered with different resolution bandwidth

As can be seen, the BPDS spectrum has been correctly shaped and would have 10 dB margin with the spurious emission requirements. However we can notice that the simulated structure would still generate significant amount of noise in the receive band. Output power in the channel equal 24dBm. ACLR results given in Table III, demonstrated that the ACLR specifications are achieved while the SNR in the Tx band has been reduced.

TABLE III
ACLR VALUES

Frequency	$F_c - 10\text{MHz}$	$F_c - 5\text{MHz}$	$F_c + 5\text{MHz}$	$F_c + 10\text{MHz}$
ACLR$_{standard}$ (dB)	43	33	33	43
ACLR$_{achieved}$ (dB)	61.34	55.43	53.3	55.43

VI. CONCLUSION

A new method for BPDS modulators optimization has been developed. The procedure is based on output error approach allowing the parameters estimation according to quadratic criterion. The BPDS feedback and notches parameters are iteratively corrected to satisfy the spurious and ACLR of the WCDMA band 1 standard. The proposed optimization method allows to take into account the frequency response of transmitter components, like the output filter. The method can be implemented for analog/digital, Lowpass/Bandpass and generalized to nth modulators order.

ACKNOWLEDGMENT

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