Design of Pipelined Signal Adaptive Architectures for Processing and Filtering of 2D Signals

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***Abstract*— Signal adaptive multiple-clock-cycle hardware design of the space/spatial-frequency optimal (Wiener) filter with all implementation and verification details, as well as the extensive comparative analysis has been already developed, [1]. The design allows the implemented filter to take variable (signal adaptive) number of clock cycles per a space/spatial-frequency point during the execution, resulting in the optimization of the complexity of the implemented system and in minimization of its execution time. But, completely pipelined solution could additionally improve the execution time (for a clock cycle per each space/spatial-frequency point performed within the execution). Development of the completely pipelined filtering 1D and 2D systems represents our topic in progress.**

Keywords—Overlaping in execution, Pipelining, Execution time

I. Introduction

Space/spatial-frequency (S/SF) filter that avoids distortion of an estimated nonstationary 2D FM signal is defined as [1]

$$(Hx)(\vec{n}) = \sum_{\vec{k}=-N/2+1}^{N/2} L_H(\vec{n},\vec{k}) STFT_x(\vec{n},\vec{k}) \qquad (1)$$

where $STFT_x(\vec{n},\vec{k}) = FT_{\vec{m}}[w(\vec{m})x(\vec{n}+\vec{m})]$ is the linear 2D short-time Fourier transform (2D STFT) which contains information about the estimated q-component noisy 2D signal $x(\vec{n}) = \text{sum}_{i=1,..,q}(f_i(\vec{n})) + \varepsilon(\vec{n})$, $L_H(\vec{n},\vec{k})$ is the filter's region of support (FRS), $N\times N$ is the duration of the windowed signal $w(\vec{m})x(\vec{n}+\vec{m})$, and $\vec{n} = (n_1, n_2)$. In the case of 2D FM signals $f_i(n_1,n_2)$, $i=1,...,q$, highly concentrated (in the S/SF space) around their local frequencies (LFs), and of a widely spread white noise, FRS of the optimal filter corresponds to the combination of LFs of signals $f_i(n_1,n_2)$, [1]. Then, in a single realization of noisy signal and the optimal filter case, as well as the S/SF framework, the FRS can be estimated by determining frequency-frequency (FF) points $(k_1,k_2)_i$, $i=1,...,q$, where S/SF distribution of the noisy signal has local maximum, [1, 2],

$$LF_i(\vec{n}) = \arg[\max_{\vec{k}\in Q_{\vec{k}_i}} CTFWD_x(\vec{n},\vec{k})]. \qquad (2)$$

$Q_{\vec{k}_i}$ is the basic FF region around $f_i(n_1,n_2)$, the LF of which is $LF_i(\vec{n})$, whereas the 2D cross-terms-free Wigner distribution (2D CTFWD), used in (2), has the best LF estimation characteristics among all S/SF tools [2] and is defined based on the same 2D STFTs used in (1), [3].

II. Signal Adaptive Design

The LF estimation-based optimal S/SF filter, completely developed in [1], is given in Figs. 1, 2, for a predefined maximum convolution window width L_m (used in the 2D CTFWD definition [3]) and the sliding matrix size L (determined by the LF estimation procedure [1]). Input memory is used to enable the design to import the 2D STFT input data owing to each double clock cycle (CLK), but to propagate them through the system by the signal adaptive *STFTLoad/CTFWDStore* cycle. Convolution window register block determines address order of the STFT-to-CTFWD gateway's inputs, necessary for the 2D CTFWD calculation [3] in the S/SF point corresponding to the central register block element. Convolution window operation file provides sliding over input 2D STFTs to enable calculation in different S/SF points. Sliding matrix register block creates basic FF region from (2), whereas the sliding matrix operation file provides sliding of this region over the calculated 2D CTFWDs. Implementing the LF estimation procedure [1], the COMP block (set of comparators combined with the basic logic gates) tests an LF existence in the S/SF point corresponding to the central sliding matrix register block element lying outside bordering positions, inv(*Left_Border_2*+*Bottom_Border_2*)=1. Based on (1) and the LF existence, it allows the corresponding 2D STFT element to participate in the $(Hx)(\vec{n})$ creation.

To respectively provide the 2D CTFWD calculation [3] and the LF estimation (in the last–Estimation–CLK), the design takes multiple, but variable (signal adaptive) number of CLKs in different S/SF points within the execution. In each S/SF point, only the first execution and Estimation CLKs have to be performed to provide the LF estimation-based S/SF filtering

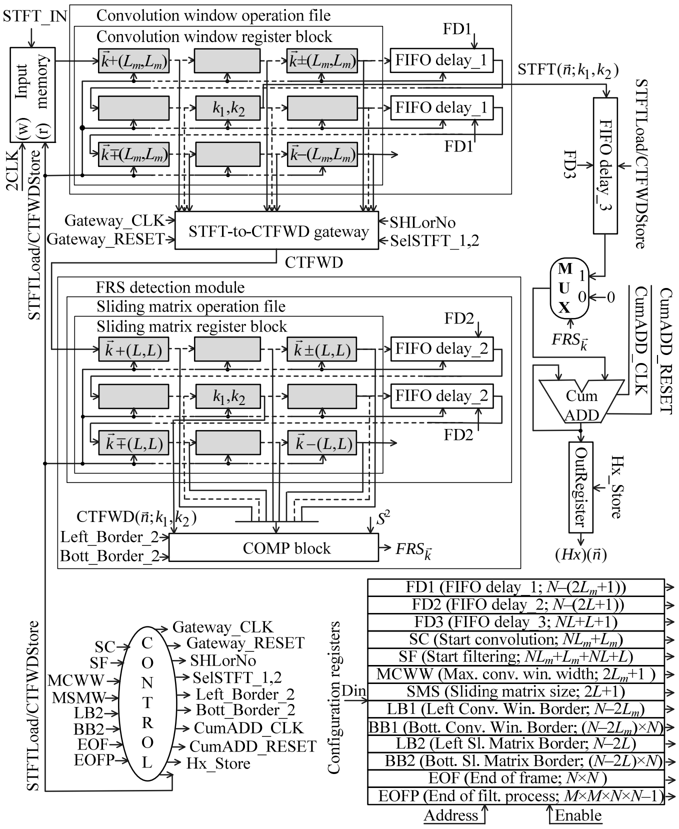

Fig. 1 *Developed design. In configuration registers, the parameters are expressed by the number of STFTLoad cycles (M×M – 2D signal size).*

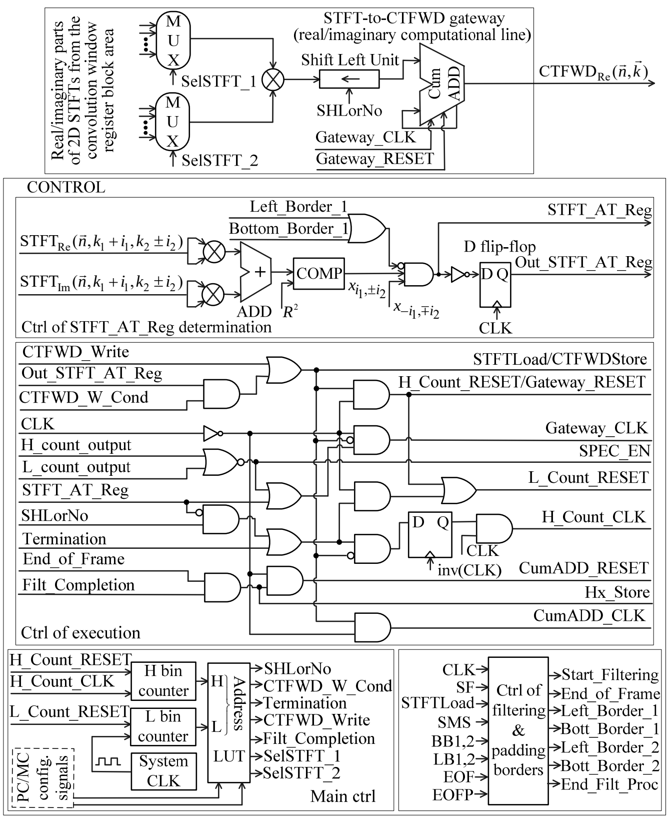

Fig. 2 *STFT-to-CTFWD gateway and CONTROL block from Fig.* 1.

related to the 2D STFT energetic form. Residual CLKs are used in the 2D CTFWD calculation, [3], and to improve quality of the LF estimation-based S/SF filtering up to the 2D CTFWD-based one, but they can be performed only in S/SF points lying inside the 2D STFT auto-terms' domains, Fig. 4. The *CTFWD_Write_Cond* signal (set in the Look-up-Table (LUT) that manages the execution, Table 1) and the *STFT_AT_Reg* one (generated, as a basic signal adaptive control signal, depending on the estimated signal shape and the noise distribution, Fig. 2, [3], to define the 2D STFT auto-terms' domains) control the CLKs execution per an S/SF point.

III. Completely Pipelined Design

To provide participation in the other control signals creation, [1], the *STFT_AT_Reg* signal is generated (through a multiplier, an adder, and a comparator, Fig. 2) in a half of a CLK. Its generation defines both the longest path of the design and the fastest CLK time T_c, $T_c/2=T_m+T_a+T_{comp}$ (T_m, T_a, T_{comp} are multiplication, addition, and comparisson times, resp.). But, operations that participate in execution within the first execution and Estimation CLKs in each S/SF point (storing and propagation through the convolution window and sliding matrix operation files, gateway reset and summation into the output CumADD) require significantly smaller time for their executions, as well as operations that create final–Completion–CLK in a signal point (n_1,n_2) (storing (Hx)(n_1,n_2) into the OutRegister and the output CumADD reset). Following these principles, the further design could provide a completely pipelined execution, making essential improvement in comparison to the signal adaptive design [1]. It would provide overlaping in execution of unconditional–the Estimation and the first execution–CLKs respectively performing in adjacent S/SF points (n_1,n_2,k_1,k_2), (n_1,n_2,k_1,k_2+1), n_1,n_2=–M/2+1,...,M/2, k_1,k_2=–N/2+1,...,N/2, including bordering S/SF points ((n_1,n_2, k_1,N/2), (n_1,n_2,k_1+1,–N/2+1); (n_1,n_2,N/2,N/2), (n_1,n_2+1,–N/2+1, –N/2+1); and (n_1,M/2,N/2,N/2), (n_1+1,–M/2+1,–N/2+1, –N/2+1)). Also, the unconditional Completion CLK of a signal point (n_1,n_2), n_1,n_2=–M/2+1,...,M/2, would be overlapped in execution with the Estimation CLK of the bordering S/SF point (n_1,n_2,N/2,N/2), but also with the first execution CLK of the next bordering S/SF point (n_1,n_2+1,–N/2+1,–N/2+1). Residual CLKs could not be included in overlaping in execution, since they are not neccessarilly performed in each S/SF point.

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