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Time Efficient Structure for DFT Filter Bank

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ABSTRACT
Conventional filter bank based spectrum sensing methods employ uniform Discrete Fourier Transform Filter Bank (DFTFB). But the complexity with this is very high and the structure is inefficient since it remains idle for most of the time. This paper proposes a time efficient DFTFB employing Polyphase decomposition for each of filters in the DFT filter bank. Proposed structure also provides a tight control over per-channel frequency response which is critical for many of applications to achieve the specified level of performance.
Keywords—*DFT filter bank, polyphase, DFTFB, DFT, polyphase filter bank.*

INTRODUCTION

Filter banks are used as a tool for spectrum sensing wherein they separate frequency components and recombine them to recover the original signal. Process of separating frequency components is done by analysis filter banks and recombination process is done by synthesis filter banks. Analysis and synthesis filters satisfy the perfect reconstruction condition which guarantees the perfect reconstruction of the signal. Filter banks are often implemented based on a prototype filter [2]. The prototype filter is nothing but a low pass filter.

DFTFB finds wide applications like in area of modern acoustic echo cancellation (AEC) [4], sub-band coding and multiple carrier data transmission, spectral detection in TV channels presented in [6] are used to detect 5 continuous TV channels. Multiple-stage coefficient decimation filter bank (MS-CDFB) is proposed in [3]. MS-CDFB offers a complexity reduction of about 30% over the DFTFB giving a superior sensing accuracy.

Spectrum analysis is conventionally done using uniform DFT filter bank. But the structure is computationally complex and is inefficient since the structure will not be active for all the intervals of time. This paper intends to reduce the computational time thereby making structure efficient and faster by employing Polyphase decomposition on transfer function of DFT filter banks, which simplifies theoretical results and leads to computational efficiency [1] [5].

Polyphase filter-bank structure have the ability to reduce spectral image components in each sub-band to very low levels for a given prototype filter response [7]. One more advantage of a Polyphase filter bank is that it provides a control on frequency response of each channel, but when using DFT alone we have limited control over the frequency band covered by each bin. This is sufficient for a lot of applications. Due to these facts polyphase filter-banks are gaining popularity.

DFT FILTER BANK (DFTFB)

Let x(n) be the input sequence and $s_i(n)$ be i-times delayed version of x(n) given as:

$$s_i(n) = x(n-i) \quad (1)$$

where s_i (n) can be obtained passing x(n) through a chain of delay elements.

DFT filter bank can be defined making use of M X M DFT matrix Wk, where $W = e^{-j(2\pi/M)}$ and W* represents conjugate matrix of W, hence x_k (n) can be given as

$$x_k(n) = \sum_{i=0}^{M-1} s_i(n) W^{-ki}, \quad 0 \le k \le M-1 \quad (2a)$$

$$= \sum_{i=0}^{M-1} x(n-i) W^{-ki} \quad (2b)$$

$$= x(n) * h_k(n) \quad (2c)$$

where,

$$h_k(n) = e^{j(2\pi k/M)}, \quad 0 \le k \le M-1 \quad (3)$$

$h_k(n)$ is a M X M matrix of W*

Equation (2c) implies that k^{th} output signal $x_k(n)$ is linear convolution of input signal with the impulse response $h_k(n)$ as shown in Fig. 1. and in frequency domain this can be given as:

$$X_k(z) = X(z)H_k(z) \quad (4)$$

Summarizes that system can be viewed as analysis bank with analysis filter of $H_k(z)$[1]. At the counter side output of synthesis bank can be given as:

$$Y_k(z) = X(z)F_k(z) \quad (5)$$

Where $F_k(z)$ is a synthesis filter bank which can be given as:

$$F_k(z) = W^{-k} H_0(zW^k) \quad (6)$$

Output of synthesis bank gives perfect reconstruction of input sequence x (n) with a scaling factor of M since WW* =MI.

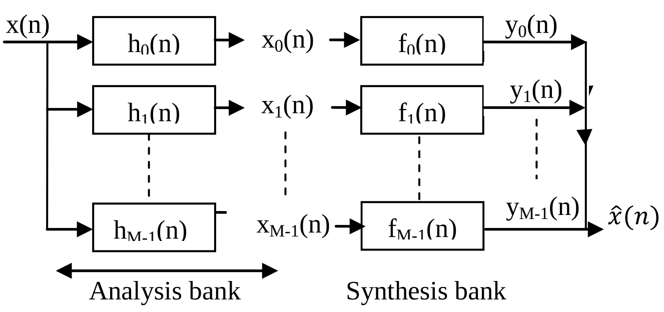

Fig. 1. DFT Filter bank

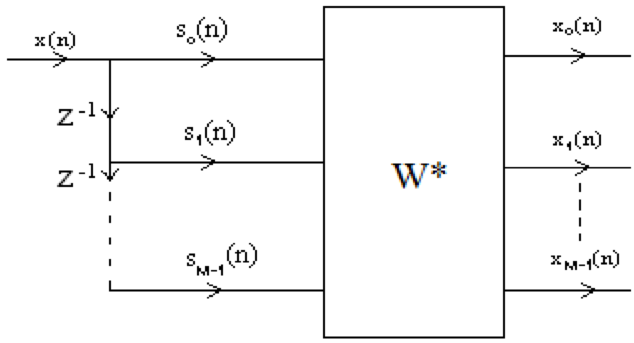

Fig. 2. Other way of representing DFT Filter bank referring to equation (2a)

POLYPHASE REPRESENTATION

Consider a filter H(z) given as:

$$H(z) = \sum_{n=-\infty}^{\infty} h(n) z^{-n} \quad (7)$$

Separating even and odd numbered co-efficient of h(n) we get [1],

$$H(z) = \sum_{n=-\infty}^{\infty} h(2n) z^{-2n} + z^{-1} \sum_{n=-\infty}^{\infty} h(2n+1) z^{-2n} \quad (8)$$

Let,

$$E_0(z) = \sum_{n=-\infty}^{\infty} h(2n) z^{-n}, \quad (9)$$

$$E_1(z) = \sum_{n=-\infty}^{\infty} h(2n+1) z^{-n} \quad (10)$$

Therefore H(z) can be given as:

$$H(z) = E_0(z^2) + z^{-1} E_1(z^2) \quad (11)$$

Extending above equation for M-fold decimation, we get

$$H(z) = \sum_{n=-\infty}^{\infty} h(nM) z^{-nM} + z^{-1} \sum_{n=-\infty}^{\infty} h(nM+1) z^{-nM} + \cdots + z^{-(M-1)} \sum_{n=-\infty}^{\infty} h(nM+M-1) z^{-nM} \quad (12)$$

In general we can therefore write as:

$$H(z) = \sum_{l=0}^{M-1} z^{-l} \sum_{n=-\infty}^{\infty} h(nM+l) z^{-n}, 0 \le l \le M-1 \quad (13)$$

Defining

$$e_l(n) \triangleq h(Mn+l), \quad (14)$$

$$E_l(z) = \sum_{n=-\infty}^{\infty} e_l(n) z^{-n} \quad (15)$$

Therefore H(z) can be given as:

$$H(z) = \sum_{l=0}^{M-1} E_l(z^M) z^{-l} \quad (16)$$

Above equation is a Type 1 polyphase representation with $E_l(z)$ as polyphase component of H(z).

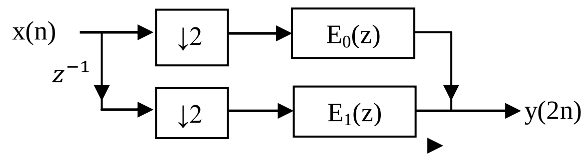

Fig. 3. Polyphase representation for M=2

PROPOSED STRUCTURE

This paper intends to present a time efficient DFTFB employing Polyphase decomposition for each of filters in the DFT filter bank.

Therefore applying Type 1 Polyphase decomposition on each DFT filter bank i.e. using equation (8) into $H_k(z)$ of equation (4), we get

$$H_k(z) = H_{k0}(z^2) + z^{-1}H_{k1}(z^2) \qquad (17)$$

where,

$$H_{k0}(z) = \sum_{n=-\infty}^{\infty} h(2n)\, z^{-n}, \qquad (18)$$

$$H_{k1}(z) = \sum_{n=-\infty}^{\infty} h(2n+1)\, z^{-n} \qquad (19)$$

Extending the same for M-fold decomposition, we get

$$X_k(z) = X(z)\left[\sum_{l=0}^{M-1} z^{-l} \sum_{n=-\infty}^{\infty} h(nM+l)\, z^{-n}\right] \qquad (20)$$

From equation (20) and Fig. 2 the structure for DFT filter bank with Type 1 Polyphase decomposition can be given as shown in Fig. 4.

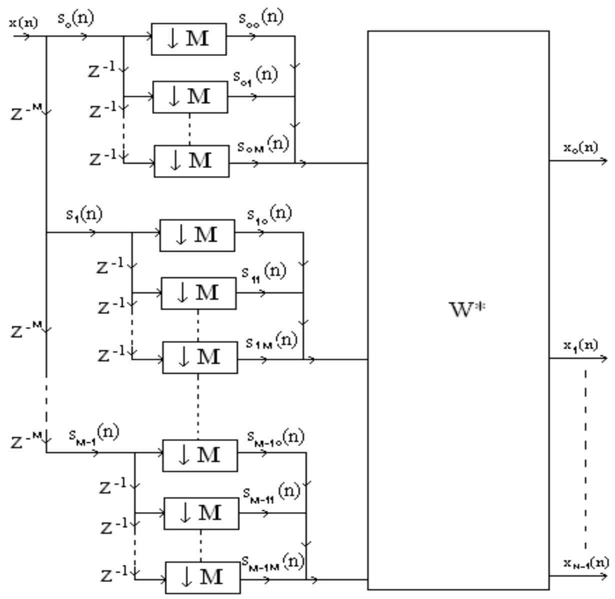

Fig. 4. Proposed DFT Filter bank with Type 1 Polyphase decomposition

COMPUTATIONAL COST

For Type 1 M-fold decomposition of filter H(z) of length N:

Proposed structure requires N multipliers and $(N-1)$ adders which is same as that for DFT Filter bank alone.

Considering multiplications per input unit time (MPU) and additions per input unit time (APU), only N/M MPU and $(N-1)/M$ APU are required for proposed structure where as DFTFB takes N MPU and $(N-1)$ APU at every M instant of time and structure stays idle at other instants. In other words proposed structure performs computations M-times faster than conventional DFTFB.

CONCLUSION

In the proposed DFT Filter bank with polyphase decomposition, frequency response of each channel can be controlled to obtain desired resolution. Hence proposed structure can be used to implement whatever filter is needed to achieve the specified level of performance. And proposed structure performs computations M-times faster than conventional DFTFB, where as hardware requirement remains same as that for DFTFB since same number of adders and multipliers are required.

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