Steering Broadband Beamforming without Pre-steering

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Abstract: Steering delays are used in broadband beamformers to steer the array in the look direction. Steering delays have to be frequency independent in order to operate for broadband signals. A wide variety of true-time-delay steering techniques are used to achieve this. All of these techniques are subject to power loss, quantization errors and other problems depending upon the particular method used. This paper presents a new approach to steer a broadband beamformer without the need to employ steering delays. The approach is based on a broadband processing using discrete Fourier transform method to obtain time domain weights. This method estimates the weights of the Frost type processor with a specified frequency response in the look direction without using steering delays in front of the broadband processor. The simulation results show the performance of this method for various scenarios.

keywords: Steering delays, Broadband Beamforming, True-Time-Delay.

1 Introduction

In broadband array signal processing signals induced on the array elements are normally delayed using steering delays before being processed by the delay line filter. The weights of the delay line filter are then adjusted by solving a constrained beamforming problem [1]. Steering delays are selected so that the received signals, due to the desired source present in the look direction, are identical after these delays. These signals appear to the TDL section as if the look direction is broadside to a linear array. Hence the beamformer weights are constrained to have a unity response to the broadside of the array when a linear array is used.

Steering delays are also used in other array applications such as scanning arrays. It has been a challenging task to design variable delays to scan a broadband array. Many approaches to achieve a set of perfect delay lines have been the subject of many investigations by several authors [2, 3, 4]. The steering delays need to be frequency independent and be tunable to offer scanning capabilities. Among various issues concerning the design of these delays are loss of power, cost and quantization errors.

This paper introduces a broadband beamformer design which does not require any steering delays between the sensors and the tapped delay section as is presently the case. It has the capability of steering the array in any arbitrary direction with a specified frequency response in the look direction while canceling unwanted uncorrelated interferences. The paper uses the discrete Fourier transform (DFT) method for broadband beamforming reported in [5, 6, 7]. In these studies a pre-steered array was used whereas the present paper assumes no pre-steering and the algorithm has been modified accordingly. The method is described in the next section. A number of examples are presented in Section 3 to show the effectiveness of the method using various scenarios.

2 The Proposed Method

Consider a time domain element space broadband beamformer consisting of L elements and a tap delay line (TDL) section with J taps. Assume that the array is situated in the far field of the broadband uncorrelated directional sources, consisting of a desired source and a number of unwanted interferences. Let x_i, $i = 1, 2, \cdots, L$ be the signal induced on L array elements. These signals are successively delayed and weighted by the tapped delay line filter without using steering delays. Let LJ dimensional vector $\underline{X}(t)$ denote the signals across the filter, that is,

$$\underline{X}^T(t) = [\ \underline{x}^T(t), \quad \cdots, \quad \underline{x}^T(t-(J-1)T)\ ]^T \tag{1}$$

where

$$\underline{x}(t) = [\ x_1(t), \quad x_2(t), \quad \cdots, \quad x_L(t)\ ]^T. \tag{2}$$

Let LJ dimensional vector $\underline{W}$ denote the array weights, that is,

$$\underline{W} = [\ \underline{w}_1^T \quad \underline{w}_2^T \quad \cdots \quad \underline{w}_J^T\ ]^T \tag{3}$$

where $\underline{w}_m$, $m = 1, 2, \cdots, J$ denotes columns of L weights after mth tap.

A block diagram of the proposed method is shown in Figure 1. This method calculates the weights of the TDL

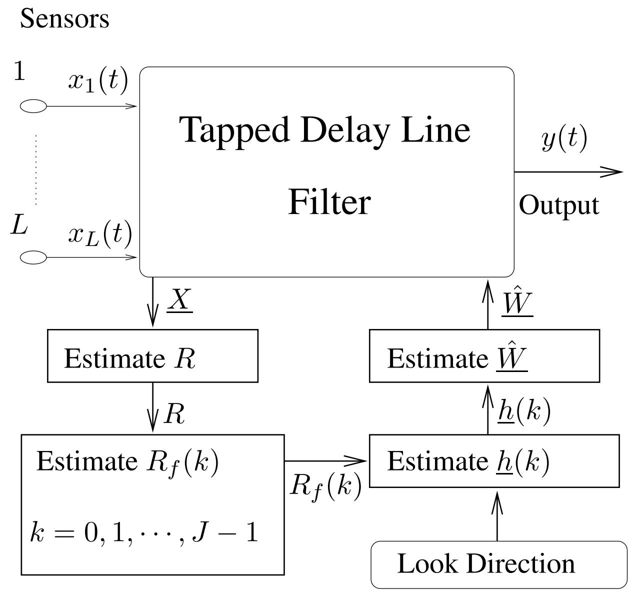

Figure 1: The Steerable DFT based broadband beamformer structure.

filter such that the processor has a specified frequency response in the look direction and cancels the directional interferences by minimizing the mean output power at each frequency bin by using the following algorithm:

1. Estimate $LJ \times LJ$ dimensional array correlation matrix R using the array signals, that is,

$$R = E\left[\underline{X}(t)\ \underline{X}^T(t)\right]. \tag{4}$$

2. Calculate $L \times L$ dimensional matrices $R_f(k)$, $k = 0, \cdots, (J-1)$ using the relationship

$$\left(R_f(k)\right)_{\ell i} = \underline{e}^H(k)\ (R_{\ell i})\ \underline{e}(k) \quad \ell, i = 1, 2, \cdots, L \quad k = 0, 1, \cdots, J-1 \tag{5}$$

where
$$\underline{e}(k) = \left[\ 1 \quad e^{-j\frac{2\pi}{J}k} \quad \cdots \quad e^{-j\frac{2\pi}{J}(J-1)k}\ \right]^T \tag{6}$$

and $(R_{\ell i})$ is a $J \times J$ matrix denoting the correlation between signals following elements ℓ and i.

3. Estimate J vectors of dimension L using

$$\underline{h}(k) = \begin{cases} \frac{R_f^{-1}(k)\underline{S}_0(k)\tilde{f}_k^*}{\underline{S}_0^H(k)R_f^{-1}(k)\underline{S}_0(k)} & k=0,\cdots,\frac{J-1}{2} \\ \underline{h}^*(J-k) & k=\frac{J+1}{2},\cdots,J-1 \end{cases} \tag{7}$$

where
$$\tilde{f}_k = DFT\left\{f_m\right\} \quad k = 0, 1, \cdots, J-1 \quad m = 1, \cdots, J \tag{8}$$

with f_m, $m = 1, \cdots, J$ selected to specify the frequency response of the processor in the look direction, and $\underline{S}_0(k)$ is the look direction steering vector at the kth bin given by

$$\left(\underline{S}_0(k)\right)_\ell = e^{j2\pi f_k \tau_\ell(\theta)} \qquad \ell = 1, 2, \cdots, L \tag{9}$$

with f_k denoting the center frequency of the kth bin and $\tau_\ell(\theta)$ denoting the time taken by a plane wave arriving from direction θ and measured from element ℓ to the reference point. For the linear array, $\tau_\ell(\theta)$ is given by

$$\tau_\ell(\theta) = \frac{d(\ell-1)\cos\theta}{\upsilon} \qquad \ell = 1, 2 \cdots L \tag{10}$$

where d is the inter element spacing, υ is the speed of propagation of the wavefront and θ is the look direction. It should be noted that in writing (7) it is assumed that J is an odd integer.

4. Calculate LJ weights of the tapped delay line filter using

$$\underline{\hat{w}}_m = IDFT\left\{\underline{h}^*(k)\right\} \quad m = 1, 2, \cdots, J \quad k = 1, 2, \cdots, J-1. \tag{11}$$

3 Examples

Some examples are presented below to illustrate that the processor is able to steer in any direction without the need to use steering delays and is also able to cancel unwanted interferences. For these examples a 10 element linear array with an inter element spacing of half wavelength at the highest desired frequency is taken. The bandwidth of the directional signal ranges from the normalized frequency of 0.22 to 0.42 and the normalization is carried out with the sampling frequency $f_s = \frac{1}{T}$. A TDL filter of 125 taps with a tap spacing of T is used. Figures 2 and 3 show the power patterns when the array is steered in direction $40°$ and $80°$ respectively relative to the line of the array. For these two cases no directional interference is present. These figures illustrate that the processor is capable of steering the array in the desired direction successfully. Figure 4 shows the power pattern when

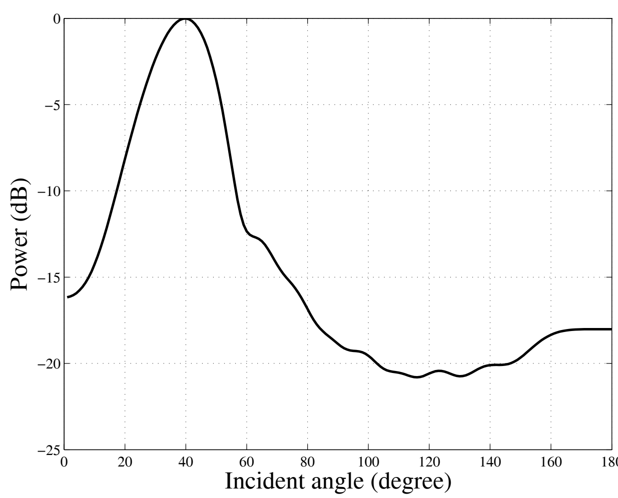

Figure 2: Power pattern of the beamformer steered to $40°$.

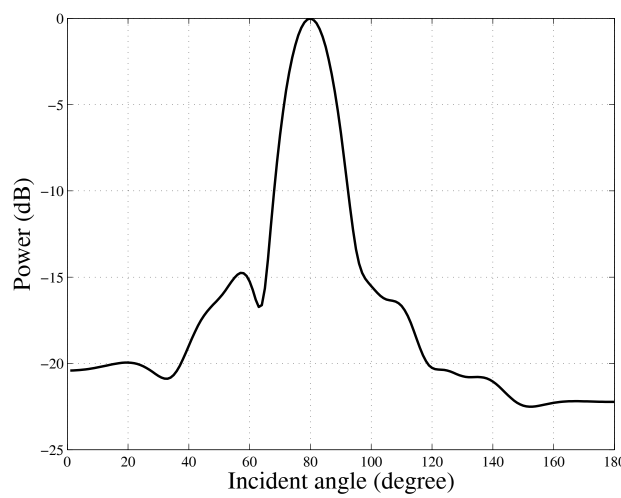

Figure 3: Power pattern of the beamformer steered to $80°$.

four directional interferences of power equal to the power of the desired signal are present. The directions of these interferences are taken to be $40°$, $60°$, $100°$ and $140°$ relative to the line of the array and the direction of the desired signal is $80°$. The background noise power is $10\ dB$ below the power of directional sources. The bandwidth and the filter parameters are the same as that for figures 2 and 3. One observes from Figure 4 that the processor has a unity response ($0\ dB$) in the look direction ($80°$) and has a response in the directions of interferences about $50\ dB$ below the response in the look direction. Figures 5 shows the frequency response of the processor in the look direction ($80°$) with dotted line showing the desired frequency response specified by f_m, $m = 1, \cdots, J$ and the solid line showing the frequency response of the processor designed using the proposed method. One observes from this figure that the actual frequency response of the processor in the look direction over the desired bandwidth is the same as the desired frequency response.

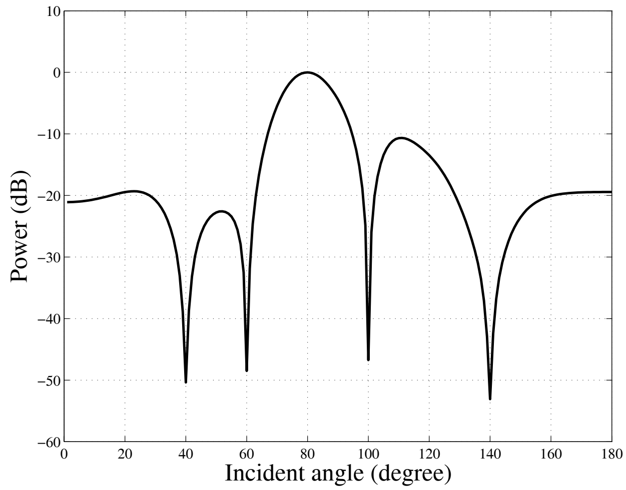

Figure 4: Power pattern of the beamformer.

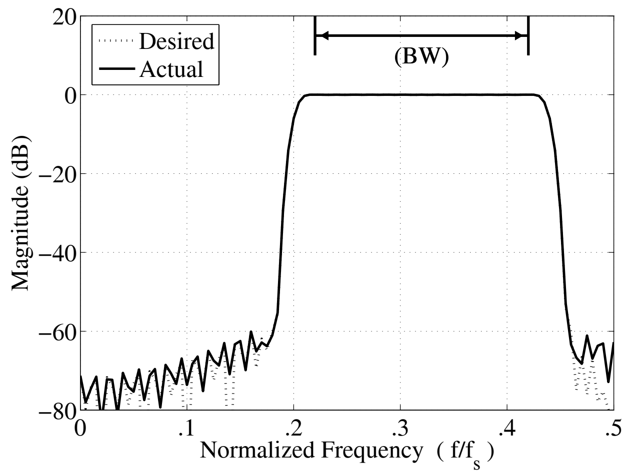

Figure 5: Frequency Response of the beamformer in the look direction.

4 CONCLUSION

The paper has presented a method to design a broadband beamformer with a specified frequency response in the look direction without using steering delays and the capability to cancel broadband directional interferences. The design method uses a DFT approach to broadband beamforming. Examples are presented to show that the processor is able to steer the broadband array in any desired direction without using steering delays and is able to cancel the directional interferences while maintaining the specified frequency response in the look direction.

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