New Ideas to Improve the Performance of Frequency Invariant Wideband Antenna Array Beamforming

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ABSTRACT:
Nowadays, it is very important to receive high quality wideband signal in the presence of interference and unwanted environmental effects. To achieve this goal, one way is to improve the quality of signal and decrease the undesired phenomena by antenna array beamforming. In this paper, first we investigate the problem of wideband beamforming in frequency domain considering the effect of interference signals. Then, we present a new low-complex efficient idea to jointly decrease the effect of interference signal and increase the Signal to Interference plus Noise Ratio (SINR). Afterwards, another idea is proposed which increases the value of SINR using some changes in the main beampattern generator. Finally, the performance of new proposed method is compared with previous work by simulations in MATLAB software. Simulation results show that the proposed wideband frequency invariant beamforming approach offers faster convergence and higher gain for main signal with respect to previous work.

KEYWORDS: Antenna Array, Frequency Invariant Beamforming, Multipath signals, SINR, Wideband.

1. INTRODUCTION

In today applications, requests for wireless systems are increased so we need more bandwidth to transmit high rate information. Wideband systems can transmit or receive electromagnetic signals in wide range of frequency which in that range, the amount of frequency bandwidth respect to central frequency is more than 25 percent [1]. Wideband systems have some advantages in comparison with narrowband systems such as, higher information and various services. But, the adverse effects of multipath signal propagation in these systems are more effective than narrowband systems. So, wideband array beamforming techniques are used to decrease interference [2].

Wideband beamformers have been studied extensively due to their wide applications to sonar, radar and communications [3-4]. Amongst them is a class of arrays with frequency invariant beampatterns, which aim to overcome the fact that for fixed aperture, the spatial resolution is proportional to the frequency of signal. Up to now, many solutions are presented for this problem in time, space and frequency domains. Spatial delay line (SDL) and tapped delay line (TDL) filters are two solutions in space and time domains, respectively [5,6]. Reference [7] has presented a complete comparison between SDL and TDL beamformers. Wideband beamforming can be implemented in time domain if desired response can be calculated using short length filters. In some applications, in order to achieve good performance, hundreds of weights are needed. In other hand, by increasing the length of filters in time domain beamforming, computational complexity will be increased which equals to low speed of convergence and inability in tracking.

Frequency domain beamforming equipped with least mean square (LMS) algorithm which needs lower complexity is proposed in [8-11] to solve above mentioned problem. Another advantage of frequency domain beamforming is that the sampling frequency does not affect the beam steering resolution. The beam steering directions can be of any magnitude, unlike time domain beamformers where it is quantized. Moreover, the discrete Fourier transform (DFT) can be computed efficiently using the fast Fourier transform (FFT) [12-16].

One of the important criteria in antenna beamforming is signal to interference plus noise ratio (SINR). Higher SINR means that the interference signal is removed better and the main detected signal has higher quality. Reference [17] has presented an algorithm for removing interference using frequency invariant beamformers. Beamforming method of reference [17] assumes that direction of arrival (DOA) of signal is calculated, exactly. But, in practice, this estimation is not accurate and has some errors. In this paper, we present some ideas to form the beampattern insensitive to DOA estimation error which is applicable for wideband signals.

The rest of this paper is organized as follows. Section 2 explains designing process of frequency invariant beamforming in frequency domain. Section 3 presents our first idea for improving the algorithm of reference [17] to increase SINR. By using the first idea, despite SINR is high but it is so sensitive to DOA estimation error. So, in section 4, second idea is proposed to solve this problem. Simulation results in MATLAB software are presented in section 5. Finally, section 6 concludes this investigation.

2. FREQUENCY INVARIANT BEAMFORMER

Wideband beamforming can be achieved by employing the traditional TDL structure as shown in Fig. 1. The received signal by the *m*th sensor is sampled with a sampling period of T and then processed by a digital filter with coefficients $W(M,J)$. The response of the array is given by

$$P(\omega,\theta)=\sum_{M=-\infty}^{+\infty}\sum_{J=-\infty}^{+\infty}W(\mathrm{M},\mathrm{J})\,\mathrm{e}^{-jM\frac{\omega\sin\theta}{c}dx}\,e^{-j\omega TJ} \tag{1}$$

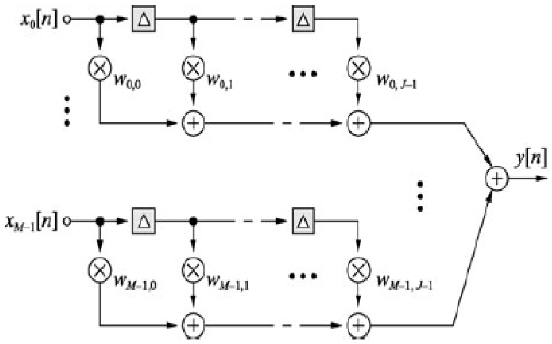

Fig. 1. A wideband beamforming structure based on TDL

It is assumed that this specific case is alias-free sampling, so d_x and T can be estimated using Eq. (2) and (3), respectively.

$$d_x=\frac{\lambda_{\max}}{2}=cT \tag{2}$$

$$\omega_{\max}T=\pi \tag{3}$$

Otherwise, in the presence of aliasing phenomenon, T should be less than half of the period of the maximum frequency ($\omega_{\max}$) of interest and (d_x) should be less than half of the maximum wavelength ($\lambda_{\max}$) corresponding to ($\omega_{\max}$).

Now, we suppose that normalized angular frequency is $\Omega=\omega T$. Then, Eq. 1 can be rewritten using Eq. (4)

$$P(\Omega,\theta)=\sum_{M=-\infty}^{+\infty}\sum_{J=-\infty}^{+\infty}W(\mathrm{M},\mathrm{J})\,\mathrm{e}^{-jM\Omega\sin\theta dx}\,e^{-j\Omega J} \tag{4}$$

So, by substituting $\Omega_1=\Omega\sin\theta$ and $\Omega_2=\Omega$, Eq. 5 is obtained [17].

$$P(\Omega_1,\Omega_2)=\sum_{M=-\infty}^{+\infty}\sum_{J=-\infty}^{+\infty}W(\mathrm{M},\mathrm{J})\,\mathrm{e}^{-jM\Omega_1}\,e^{-j\Omega_2 J} \tag{5}$$

$P(\Omega_1,\Omega_2)$ as beampattern is obtained by applying a 2-D FFT to $W(\mathrm{M},\mathrm{J})$. It is frequency invariant, if $P(\Omega_1,\Omega_2)$ is a function of only θ In order to achieve this, $P(\Omega_1,\Omega_2)$ must depend on Ω_1 and Ω_2 such that it can be written as $P(\frac{\Omega_1}{\Omega_2})$. Therefore, $(\frac{\Omega_1}{\Omega_2})$ can be written using Eq. 6. It means, eliminating any dependency on Ω .

$$\frac{\Omega_1}{\Omega_2}=\frac{\Omega\sin\theta}{\Omega}=\sin\theta \tag{6}$$

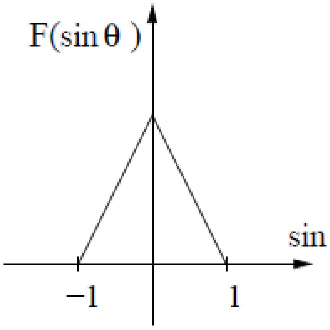

Fig. 2. An example for a frequency invariant beampattern

For this purpose, a desired frequency invariant beampattern $F(\sin\theta)$ is considered as shown in Fig. 2. The 2-D response is obtained as

$$P(\Omega_1,\Omega_2)=F(\frac{\Omega_1}{\Omega_2})=\mathrm{F}(\sin\theta) \tag{7}$$

Applying a 2-D inverse Fourier transform to $P(\Omega_1,\Omega_2)$ results in an infinite support of $W(\mathrm{M},\mathrm{J})$. For more details, please refer to [17].

Fig. 3 shows a design result with $M = 7$ sensors and a tapped delay-line length of $J = 50$.

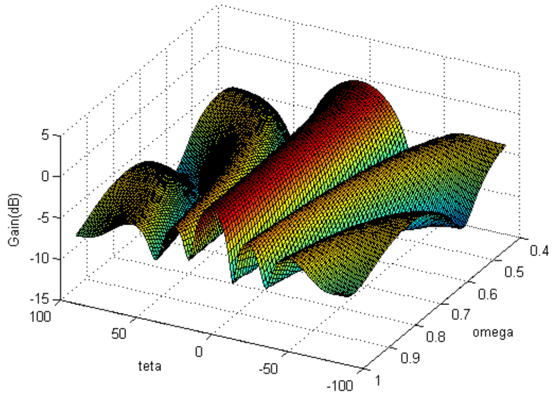

Fig. 3. Frequency invariant beampattern on frequency domain

3. FIB-BASED SCHEME

Assuming the main direction θ_0 of the signal of interest is known, a solution can be obtained based on the traditional beamforming idea by employing the FIB technique. The proposed structure is shown in Fig. 4, where $x[n]$ is the signal vector at time n and each block labeled as FIB$_i$, $i = 0,1,\ldots,N-1$ represents a frequency invariant beamformer with a response $P_i(\theta)$ The output of block FIB$_i$ is denoted by $b_i[n]$. FIB$_0$ is the main beam pointing to θ_0 and the remaining $N-1$ beams are auxiliary beams pointing to the remaining directions. The final beamformer output is given by $e[n]$, a weighted sum of the FIB network outputs (error):

$$e[\mathrm{n}] = \mathrm{b}_0[n] - \omega^T b[n] \tag{8}$$

A classical adaptive algorithm such as LMS algorithm can be employed to update the weight vector iteratively as:

$$w[n+1] = w[n] + \mu e[n] b[n] \tag{9}$$

$$b[n] = [\mathrm{b}_1[\mathrm{n}]\mathrm{b}_2[\mathrm{n}]\ldots\mathrm{b}_{N-1}[\mathrm{n}]]^T \tag{10}$$

$$w = [w_1 w_2 \ldots w_{N-1}]^T \tag{11}$$

Where μ is the step size.

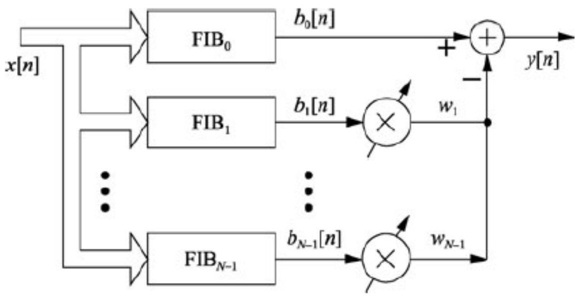

Fig. 4. The FIT-based beamforming structure employing a narrowband beamforming scheme [16]

Note that the responses $P_i(\theta)$ $i = 0,1,\ldots,N-1$ of the frequency invariant beamformers are independent of frequency. Then, each of their outputs can be expressed as a weighted sum of the impinging signals

$$b_i[n] = P_i . s[n] \tag{12}$$

$$\mathrm{s[n]} = [\mathrm{s}_1[\mathrm{n}]\ldots\mathrm{s}_{\mathrm{L}-1}[\mathrm{n}]]^T \tag{13}$$

$$Pi = [\mathrm{P_i}(\theta_0)\,\mathrm{P_i}(\theta_1)\ldots\mathrm{P_i}(\theta_{L-1})] \tag{14}$$

According to the above equations, the purpose of Eq. 6 is obtaining optimum weights which they can reduce the explained error in Eq. 9 to zero. It is noteworthy that the error of Eq. 9 represents the difference between the main block and the sum of the other blocks related to interfering signals.

The main block is designed to set the main lobe in the direction of desired signal whereas the other blocks are needed to suppress the effect of interference.

The output signal contains two components. Desired signal as y_0 and interference signal as y_1.

$$y_0 = P_0(\theta_0).s_0(nT) \tag{15}$$

$$y_1 = (P_0(\theta_1) - \sum_{i=1}^{N-1} P_i(\theta_1)\omega_i)s_1[n] \tag{16}$$

Final output which contains main and interference signals can be given by Eq. 17.

$$s = y_0 + y_1 = P_0(\theta_0)s_0(nT) + (P_0(\theta_1) - \sum_{i=1}^{N-1} P_i(\theta_1)\omega_i)s_1[n] \tag{17}$$

4. PROPOSED METHOD

In order to convert $F(\sin\theta)$ to a function of Ω_2, Ω_2 high number of samples is needed. For instance, the beampattern will be as Figure 5, if low number of samples is used. It shows that the beampattern is not acceptable and desired and interference signals may not be separable

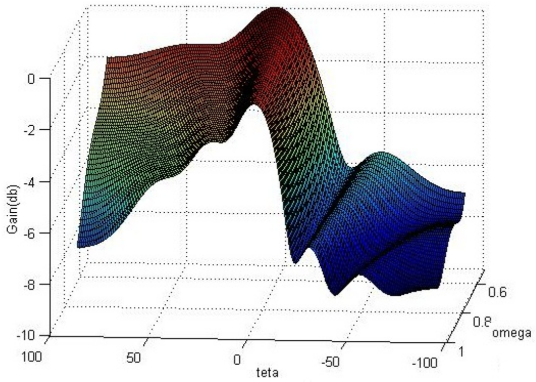

Fig. 5. Beampattern considering low number of samples

In this section, an idea is presented which jointly maximizes the gain of desired signal and minimizes the gain of interference signal. According to this new idea, in order to find the beampattern, the reverse DFT of $P(\Omega_1,\Omega_2)$ will be changed to two-dimensional reverse DFT of $A_1P(\Omega_1,\Omega_2)A_2P(\Omega_1,\Omega_2)...A_nP(\Omega_1,\Omega_2)$, A_i is the coefficient of each response. In addition to find more flexibility, the desired beampattern can be obtained by low number of samples.

To show the effectiveness the new proposed approach, three examples are simulated assuming that. $n=5$ The DOA of the desired signal is zero and a uniform linear array with 7 array elements is used. As example 1, it is assumed that $A_1=1, A_2=A_3=A_4=A_5=0$. In this case, the beampattern is as Figure 6.

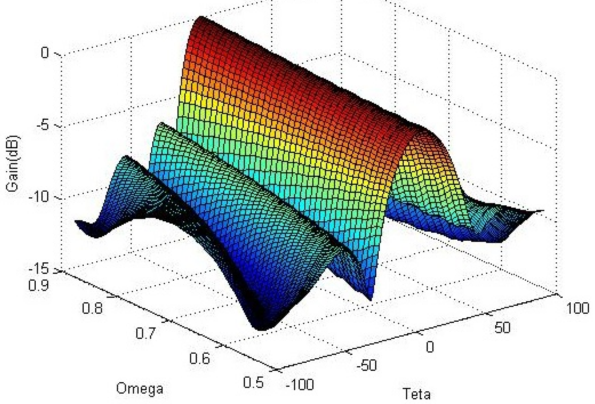

Fig. 6. Beampattern corresponding to $A_1=1, A_2=A_3=A_4=A_5=0$

As expected, to obtain this frequency independent beampattern, much fewer samples are used with respect to the previous state.

In the second example, it is assumed that all coefficients are the same. i.e., $A_1=A_2=A_3=A_4=A_5=1$ As depicted in Figure 7, the gain of side lobes equals to the gain of main lobe but nulls are not as sharp as before.

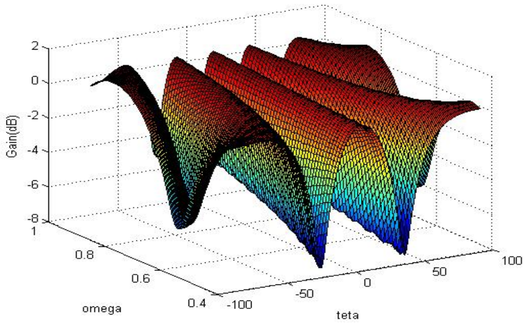

Fig. 7. Beampattern corresponding to $A_1=A_2=A_3=A_4=A_5=1$

As the third example, using $A_1=1$, $A_2=A_3=A_4=A_5=0.25$, the beampattern is as Figure 8. In this case, nulls are sharper than two above mentioned examples.

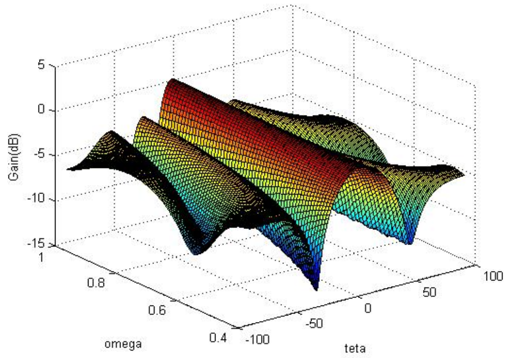

Fig. 8. Beampattern corresponding to $A_1=1, A_2=A_3=A_4=A_5=0.25$

5. SIMULATION RESULTS

In this section, some simulations are run in MATLAB software which show the effectiveness of the proposed ideas. Following assumptions are considered in the simulations:

1. The array spacing is half of the wavelength corresponding to the maximum normalized signal frequency π;
2. The desired signal comes from the broadside direction and interference signal arrives from the direction of $\theta=40$.
3. The step size is set to 0.00009.

For the proposed schemes, we consider the number of frequency invariant blocks in Fig. 3 equals to 5 which the main beam of FIB_0 is pointed to zero degree and the main beam of other blocks are pointed to the ± 50 and ± 30, respectively. Using Eq. 9, in order to obtain the weights of Fig. 3, LMS algorithm is run. In Fig. 9, desired (y_0) and interference (y_1) signals are shown. It is clear that the interference signal is eliminated.

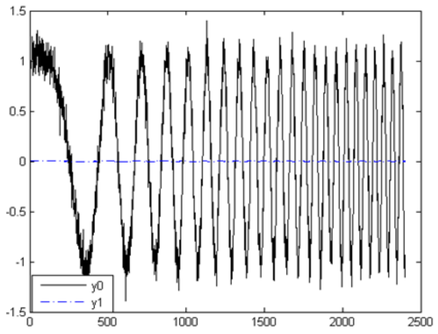

Fig. 9. Desired (y_0) and interference (y_1) signals

Mean square error (MSE) of LMS algorithm for different iterations is shown in Fig. 10. It shows that error tends to zero after 15 iterations.

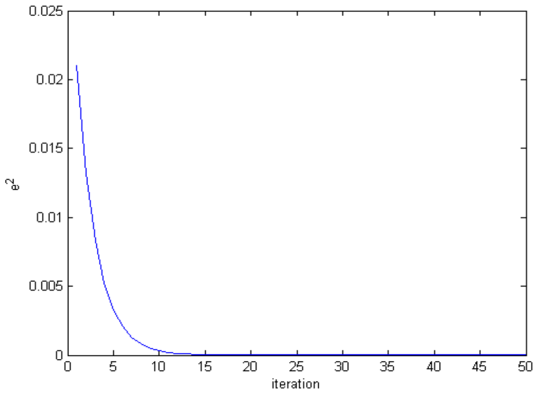

Fig. 10. Error changes based on number of iterations

Output of the first FIB and final output are shown in Fig. 11. As expected, final output offers lower null for interference in 40 degree with respect to the output of the first FIB.

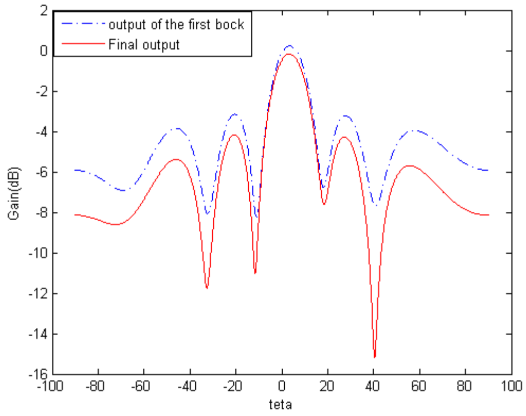

Fig. 11. Beampattern of signal

Determining the incoming angle is not always accurate and it has some errors. Here, it is assumed that the exact DOA of interference signal is 40 degree. Fig. 12 shows the SINR changes versus the estimation error of DOA of the interference signal. As depicted in this Figure, despite SINR experiences a reduction between 0-2dB for a ± 2 degrees interval but its SINR is higher than the output of the first FIB.

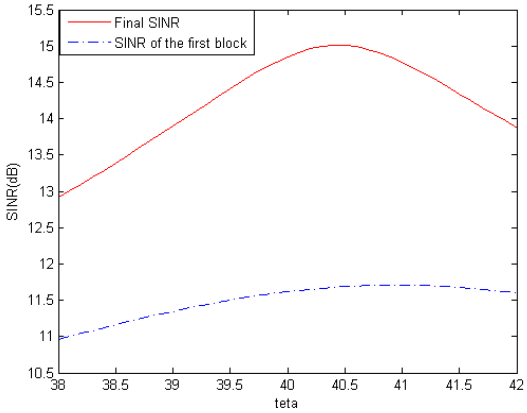

Fig. 12. SINR changes versus the estimation error of DOA of the interference signal

6. CONCLUSION

In this paper, a novel beamforming approach for multipath wideband signals based on the frequency invariant beamforming technique was proposed. Considering the new approach, the received signal is first processed by an FIB network and then the proposed algorithm is applied to its output to find optimal weights.

In the next step, we improved SINR paying more attention on DOA of signal and applying some changes in the initial beampattern. Simulation results show an improvement on output SINR which has been achieved by the proposed scheme compared to the traditional beamforming method.

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