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Improve Tracking Speed of Beamformer With Simplified Zero Placement Algorithm

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***Abstract*—This paper presents a new structure and algorithm to improve the tracking speed of a Generalized Sidelobe Canceler (GSC) based adaptive beamformer. Iterative methods like Conjugate Gradient algorithm to calculate the beamformer weight vector eliminates the complexity of Matrix reversing. But the reduced complexity comes with time cost which requires iterations of calculation before converge to the desired direction. To combat the problem, a Simplified Zero Placement algorithm is proposed to set the initial weight vector to make the starting value near the optimum location of weight vector. Numerical simulation and analysis confirms the effectiveness of the proposed solution.**

***Index Terms*—smart antenna, beamformer, tracking speed.**

I. INTRODUCTION

Adaptive Beamforming is widely used in wireless communication and other fields like medical ultra sound to improve signal quality. Working as a spatial filter, it can be used to enhance signal from an interested look direction and reject noise or interference from other direction. Various algorithms like Minimum Variance Distortionless Response (MVDR) and its generalized version Linearly Constrained Minimum Variance (LCMV) [8, p.672] has been investigated extensively in the past decades. To avoid the complexity of matrix inversion, iterative algorithms such as Least Means Square (LMS) [2, p.33] or Recursive Least Square (RLS) [2, p.98] has been used to reduce the hardware complexity in the industry.

One of the popular architecture to implement adaptive beamforming is Generalized Sidelobe Canceler (GSC) [2, p.108]. The constraints could be expressed as:

$$\boldsymbol{C}^{\boldsymbol{H}}\boldsymbol{w} = \boldsymbol{f}^* \tag{1}$$

where $\boldsymbol{C}$ is the contraint matrix which contains the steervec from all angles to be regulated, $\boldsymbol{w}$ is the expected weight vector and $\boldsymbol{f}$ indicates the required response. The linear constraints $\boldsymbol{C}$ are analyzed and the weight vector $\boldsymbol{w}$ is then decomposed into two orthogonal portion: $\boldsymbol{w}_f$ and $\boldsymbol{B}$ as indicated in figure 1.

The fixed beamformer $\boldsymbol{w}_f$ works in the column space of constraint matrix $\boldsymbol{C}$ to make sure that after processing the received input vector $\boldsymbol{x}$, the signals from specified direction follow the desired response. It could be calculated as [9]:

$$\boldsymbol{w_f} = \boldsymbol{C}(\boldsymbol{C}^{\boldsymbol{H}}\boldsymbol{C})^{-1}\boldsymbol{f}^* \tag{2}$$

The blocking matrix $\boldsymbol{B}$ works in the null space of constraint matrix $\boldsymbol{C}$ so that an unconstrained adaptive algorithm like LMS could be used to adjust $\boldsymbol{w}_a$.

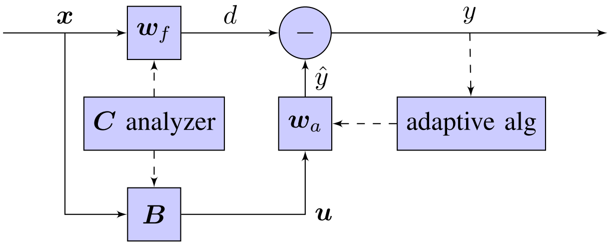


Fig. 1: Beamformer implementation with GSC structure

A. Motivation

When the look direction is static or vary slowly, the constraint matrix remains almost static, the fixed beamformer $\boldsymbol{w}_f$ and null basis matrix $\boldsymbol{B}$ then can be updated slowly. The current solution of GSC can adaptively cancel any interference by adjusting the $\boldsymbol{w}_a$ to minimize the output power. Clearly, this model works well for fixed wireless or slowly moving scenario.

But when the look direction is rapidly changing as in the transportation industry where the train pass by the road side Access Point (AP), both $\boldsymbol{w}_f$ and $\boldsymbol{B}$ needs to be recalculated continuously in a real time manner. The overhead of matrix inversion and multiplication operation as indicated in equation 2 by $\boldsymbol{C}$ analyzer then becomes a bottle neck.

B. Current Solution

Currently, there are different ways to do the matrix inversion to derive the fixed beamformer $\boldsymbol{w}_f$ and blocking matrix $\boldsymbol{B}$.

Factorization methods like Singular Valude Decomposition (SVD), QR decomposition etc can be used for the calculation. These are well known methods to identify the eigenvalues of the contraint matrix. And the eignvectors corresponds to the smallest set of eigenvalue makes the basis of the null space. The disadvantage of these mature algorithm is its high demand on the computation cost.

Another type of solution uses iterative methods to solve the classical $\boldsymbol{A}\boldsymbol{x} = \boldsymbol{b}$ algebra problem. It converts the matrix inversion problem to an iterative process to approach the optimum solution of $\boldsymbol{x}$. In the context of beamforming, the optimum solution is the fixed beamformer $\boldsymbol{w}_f$.

The second type of methods includes Jacobi [3] method, Gauss-Seidel method and other line search methods like Steepest Descent and Conjugate Gradient method [5]. They have minimum hardware requirement on the computation power.

But it requires longer time to converge to the optimum solution due to its iterative nature.

C. Novelty, Originality and Contribution

In this paper, a new structure and algorithm to reduce the complexity of matrix inversion for the beamformer weight vector calculation that works for both high speed and low speed direction tracking with simple hardware is proposed.

The novelty of the new structure is that it combines the fast speed characteristic of Schelkunoff polynomial method with the iterative method which produces accurate result after convergence. To utilize this structure in the GSC architecture, a Simplified Zero Placement algorithm based on the Schelkunoff polynomial [1] method is used to set the initial value. An iterator is then used to refine and update the result of Simplified Zero Placement algorithm.

D. Paper Organization

The paper is organized into 4 sections. After discussed the background, motivation and problem of existing solution in the first section, The second section details the proposed solution. The third section gives numerical simulation results and analysis. The final section concludes the paper.

II. PROPOSED SOLUTION

The proposed solution is targeted for a simple hardware based beamformer that works in high speed direction change scenario like in vechicle to road side communication. It assumes that Direction of Arrival (DoA) is already obtained either by those widely available high resolution subspace based algorithm like Multiple Signal Classification (MUSIC) [6], [7] or manually determined as in fixed wireless outdoor application. It uses iterative method yet able to track the look direction fast enough. There are two factors that affect the iterative solutions converge speed which is the initial position and matrix condition number.

The key new concept is to combine Schelkunoff polynomial method [1] to set the initial value of the fixed beamformer and blocking matrix so that the initial position is close to the optimum value. Thus in the worst scenario that the iterator takes long to converge, the approximate initial value still can do the beamforming. In this way, the beamformer can start from a near optimum position and slowly adjust to the optimum location eventually.

Figure 2 illustrates the design for the improved contraint matrix $\boldsymbol{C}$ analyzer. The Simplified Zero Placement Algorithm (SZPA) takes input from DoA or manually specified contratint information $\boldsymbol{C}$ and $\boldsymbol{f}$.

A. $\boldsymbol{Z}$ transform of angular spatial frequency

For signal incident from θ, there is an extra delay for each antenna element. Figure 3 shows an example of Uniform Linear Array (ULA) with 5 antenna elements separated by space d receives signal from far field with incident angle θ.

Each element will receive the signal with phase delay of $e^{j2\pi\frac{d\sin(\theta)}{\lambda}}$ where λ is the wavelength of the incident signal.

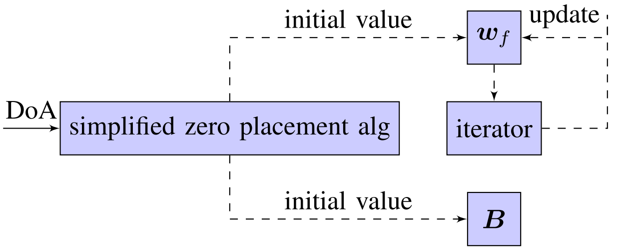


Fig. 2: Simplified Zero Placement Algorithm based $\boldsymbol{C}$ analyzer

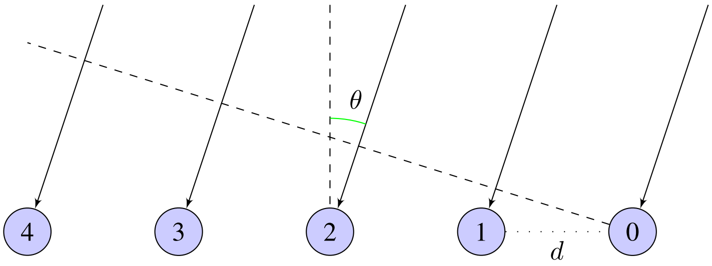


Fig. 3: Incident Signal and Phase Delay

For a M elements antenna array, the received signal could be expressed as

$$x_i(t) = s(t)e^{-j2\pi\xi i} \tag{3}$$

where $s(t)$, ξ, i, x_i is incident signal from direction θ, angular spatial frequency $\frac{d\sin(\theta)}{\lambda}$, antenna element index and received signal from i^{th} antenna element respectively.

Equation 3 is similar to a Finite Impulse Response (FIR) filter. As described in [1], $\boldsymbol{Z}$ transform could be used to find out the relationship between weight vector $\boldsymbol{w}$ and its angular spatial frequency response. For a beamformer with weight vector $\boldsymbol{w}$, the corresponding $\boldsymbol{Z}$ transform would be:

$$\boldsymbol{H}(z) = \sum_{i=0}^{i=M-1} w_i z^{-i} \tag{4}$$

where w_i, M, i is the combining weight for the i^{th} antenna,total number of antenna elements and element index respectively.

B. Simplified Zero Placement Algorithm

From equation 4 it is clearly shown that the system can only have $M-1$ non-trivial zeros for controlling the frequency response shape. As suggested in [4], it is an effective method for conventional antenna synthesis. By putting zero along the direction of interference, the array beam pattern can be controlled to null out interference. But it seems that this kind of method has not been used for improving the adaptive beamforming due to its fixed constraints of zero placement.

But it seems this method fit well for iterative and adaptive beamforming using GSC structure as illustrated in figure 2. In a LCMV beamformer, most of the desired response for the constraints is set to 0 which corresponds to interference or noise. And only one or a few of them is set to 1 which corresponds to interested look direction.

The Simplified Zero Placement algorithm (SZPA) could then be described as:

- Set maximum number of zeros to be arranged based on antenna elements. For M elements antenna array, $M-1$ zeros could be used to control beam pattern shape;
- Build the final zero list from first $M-1$ elements of the desired response vector. If the desired response is 0, add the zero position corresponding to the incoming direction to the list. Otherwise, add the reverse of the zero position to the list as listed in equation 5

  $$z_i = \begin{cases} e^{j2\pi\xi_i} & f(i) == 0 \\ -e^{j2\pi\xi_i} & f(i)! = 0 \end{cases} \tag{5}$$

  where i, z_i, ξ_i, f_i indicates the constraint index, i^{th} zero, angular spatial frequency and i^{th} desired response.
- Retrieve each element's weight by expanding the factorized $\boldsymbol{Z}$ transform to polynomial form to get the initial value for the fixed beamformer $\boldsymbol{w}_f$ following equation

  $$\boldsymbol{H}(z) = \prod_{i=1}^{M-1} (1 - z_i \boldsymbol{Z}^{-1}) \tag{6}$$
- Build the zero list and expand for the blocking matrix $\boldsymbol{B}$ for all the constraints.

III. NUMERICAL SIMULATION AND ANALYSIS

The algorithm is simulated with antenna element spaced at half carrier wave length using matlab. For easy comparison without loss of generality, we choose to compare with 3 antenna elements.

Following the SZPA, by setting M to 3, the system has two zeros for us to control. The signal is coming from 30° and interference is from 45°. The calculated zeros is illustrated figure 4.

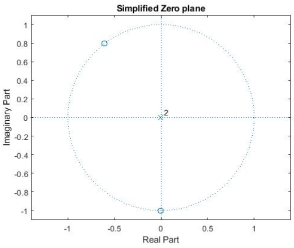
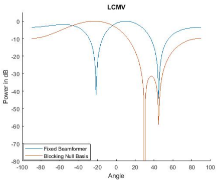


Fig. 4: Zero Position for Simulated Signals

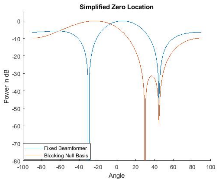
Figure 5a illustrates the beam pattern of $\boldsymbol{w}_f$ and $\boldsymbol{B}$ by directly using LCMV constraints matrix.

As a comparison, the beampattern based on Simplified Zero Plancement is illustrated in figure 5b.

From the comparison, it clearly shows that the Simplified Zero Placement Algorithm has very good performance for interference cancellation which is expected since zero is directly placed at the corresponding direction. When the desired response is not zero, it has some slight deviation. But as a initial value, it is good enough for further refinement through the various iterative method.



(a) Beampattern with LCMV



(b) Beampattern with SZPA

For this simple 3 antenna element array, the difference of required Multiplication and Acculmulate Cycle (MAC) could be compared. While current GSC solution requires around 34 MAC operations to arrive at $\boldsymbol{w}_f$, SZPA based solution needs only 2 MAC to get the similar solution. With this big reduction in the required MAC operation, SZPA can performs many times faster so that it might be able to track the fast direction change in high speed rail scenarios where the train could pass by road side Access Point at speed of around 250km/h.

IV. CONCLUSION AND FUTURE WORK

As polynomial method is a much lighter operation compared to matrix inversion and multiplication, with comparative beamforming performance as compared to direct computation, the proposed Simplified Zero Placement Algorithm can adjust the look direction much faster with less hardware complexity. Future work will need to investigate the impact of the runtime weight change caused by the iterator and more field testing could be conducted to confirm the performance of the proposed solution.

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