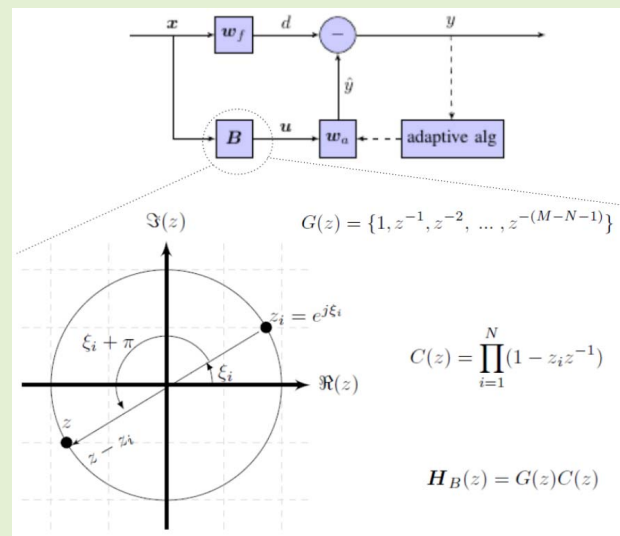


# A Fast Blocking Matrix Generating Algorithm for Generalized Sidelobe Canceller Beamformer in High Speed Rail Like Scenario

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**Abstract**—A fast algorithm to generate the Blocking Matrix for Generalized Sidelobe Canceller (GSC) beamforming is proposed in this paper. The proposed algorithm uses a **Simplified Zero Placement Algorithm (SZPA)** to **directly** generate the column vectors of the Blocking Matrix using the polynomial method. The constrained signal **incoming** angles are converted to spatial frequency and **designated** as zero **locations** in the  **$z$  domain**. Independent vectors that **span** the **whole** left null space of the constraint matrix is then built using a simple shift operation. The algorithm also supports the **derivative** constraints used for robust beamforming. Compared to the **conventional** methods based on **Singular Value Decomposition (SVD)**, the SZPA algorithm can generate Blocking Matrix **more than 9** times faster for scenarios with 15 constraints and will be even more **advantageous** for more constraints. The Blocking Matrix **generated** by the SZPA and SVD methods is then **implemented** in the **same** GSC architecture for performance **evaluation**. The numerical simulation **confirms** that the **same overall** optimum **state** performance and learning speed can be achieved. **By reducing** the calculation time of blocking matrix from 1.541ms of SVD method to 0.168ms, the proposed SZPA algorithm is fast and insensitive to the number of constraints as the required calculation time incremental for each additional constraint with SZPA is only around 1/16 of SVD method. This makes it suitable for scenarios like train to infrastructure communication in High Speed Rail (HSR) where there are multiple constraints and frequent constraints update is required.

**Index Terms**—Blocking matrix, generalized sidelobe canceller, beamforming.



## I. INTRODUCTION

**A**DAPTIVE Beamforming is a widely used technique in wireless communication [1], acoustic sensors array [2], medical imaging [3] and other fields to improve signal quality. It can also be used in the latest tactile internet application when multiple sensors are deployed [4]. The fundamental task of adaptive beamforming is to combine the output from an

array of spatially separated sensors in a way to minimize a predefined cost function adaptively so that a particular performance criteria could be satisfied. 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. In Intelligent Transportation Systems like High Speed Rail (HSR), the high mobility creates unique challenges for the wireless communication [5]. The time varying Direction of Arrival (DOA) [6] is a known issue that adaptive beamformer needs to tackle. The rapid change of DOA in these kinds of scenarios put even high demand on the calculation speed for the adaptive beamformer. This paper introduces a fast Blocking Matrix generating algorithm named Simplified Zero Placement Algorithm (SZPA) for Generalized Sidelobe Canceller (GSC) [7] adaptive beamformer to improve the calculation speed. As a general Blocking Matrix generating algorithm, the SZPA can be used for any GSC application.

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As a widely used beamforming architecture, GSC has the benefit of converting a constrained optimization problem to an unconstrained problem [8] while maintaining the same performance as Linear Constrained Minimum Variance (LCMV) as proved in [9]. Thus many adaptive algorithm like Least Mean Square (LMS), Normalized LMS (NLMS), Recursive Least Square (RLS) etc. could be directly applied in the noise cancellation path. The major components of a GSC beamformer include fixed beamformer, blocking matrix, and adaptive controller. The fixed beamformer in GSC controls the quiescent response. It could be implemented by many radiation pattern synthesis techniques like Sample Matrix Inversion (SMI) and various iterative methods that is based on adaptive beamformer principle which includes Iterative Fourier Transform method [10], [11] and the latest virtual jammer based methods like [12]. The adjustable step size has been investigated in [13] and the included references.

Blocking matrix is a critical component [7] for GSC beamformer which blocks out the desired signals from being leaked to the cancellation path and thus being canceled as interference. A systematic approach for deriving the blocking matrix has been documented in [14]. As summarized in [15, p. 40], there are two major methods to derive the blocking matrix. When the Signal of Interest (SOI) is from the broadside or the received signal from each sensor has been aligned to be synchronized towards the SOI, the blocking matrix could be implemented as a simple Cascaded Differential Column (CCD) as in the original GSC proposal by Griffiths [7]. But its usage is limited to broadside beamformer or systems that have delay adjustment for each sensor element. To support beamforming towards arbitrary directions without pre-processing, Singular Value Decomposition (SVD) [16] based method is normally used to get the null basis of the constraint matrix. But SVD method is known to be computation intensive.

In scenarios like vehicle to roadside sensor communication where the Direction of Arrival (DOA) changes rapidly, the signal cancellation caused by the DOA mismatch [17] becomes more severe. Various Robust Beamforming Algorithms (RBF) has been investigated in the past decades to address this issue. The RBF based on Diagonal Loading [18] reduces the sensitivity to the SOI mismatch by adding a diagonal matrix to the covariance matrix which is equivalent to putting a quadratic inequality constraint on the weight vector [19, p. 506]. But there is no systematic way for deriving the loading factor. The more recent RBF based on Interference plus Noise Covariance (IPNC) Matrix Reconstruction algorithm address this issue by removing the SOI component from IPNC matrix and make a better estimation of SOI based on Capon spatial spectrum weighted reconstruction [20] or Maximum Entropy Power Spectrum (MEPS) weighted reconstruction [21]. But it requires expensive matrix inversion and integration operation and might not be suitable for the DOA rapid changing scenarios. The RBF based on Derivative Constraint for the weight vector in the direction of SOI is first proposed in [22] and proves to be effective. Later the derivative constraint concept is extended to GSC architecture by [23] which controls the flatness of the null in the blocking matrix. Both methods requires additional degree of freedom in the

blocking matrix for each derivative constraint put in. The other promising way is to increase the speed of DOA estimation or tracking, and at the same time improve the calculation speed of the weight vector. It would require the blocking matrix to be recalculated more frequently to reduce the SOI mismatch.

So clearly there is a need to improve the blocking matrix generation speed in a rapidly changing signal environment since every constraint angle change will trigger a recalculation of the blocking matrix. As predicted in [23], the only requirement for the blocking matrix is that the basis vectors needs to be independent. Orthogonality is not really necessary for the blocking matrix. So by relaxing on the orthogonality requirement, the basis vectors for the blocking matrix could be found by methods other than SVD.

In this paper, a fast algorithm working in the  $\mathbf{Z}$  domain that combines zero placement generated polynomial and a simple linear independent sub-polynomials to derive a set of null space vectors is proposed and simulated. The novelty of this new algorithm is that it finds the null space basis vector directly in the  $\mathbf{Z}$  domain with polynomial methods which eliminates the needs for computation demanding matrix null basis finding methods like SVD with more than 9 times faster speed and the same performance. One additional advantage for this new method is that it makes adding the derivative constraints at the DOA straightforward although it still requires extra degree of freedom as in [23].

The rest of the paper is organized in 4 sections. After the problem and its context is defined in section II, the proposed solution is explained in section III. Then numerical simulation and analysis is presented in section IV. Finally, the section V conclude the proposed solution.

## II. PROBLEM FORMULATION

### A. Vehicle to Roadside Challenge

A major challenge for making beamforming working properly in rapid changing scenarios like railway communication is its reduced coherence time as reported in various channel modeling and experiments. In [26] coherence time of around 5-8 millisecond is reported with a speed of around 60km/h. For explicit beamforming which requires more frequent channel sounding, various methods have been proposed in reducing the overhead for transmitting the Channel State Information (CSI). In [27], an analog channel estimator is proposed to improve the channel sounding speed. But all these will increase the overhead and reduce the bandwidth efficiency.

A typical scenario where a wireless base station deployed along the track side is illustrated in Fig.1. For situations like in High Speed Rail (HSR), where the train travels at speed as high as more than 320km/h [28] and the base station is just 5 meters away as listed in [29], the peak angle change speed could be around  $16^\circ$  per millisecond. So in less than one milli-second, although it is still within the coherence time around 1.4 milli-seconds according to the experiment and investigation in [29], the DOA change could make beamforming degrades very significantly due to the angle mismatch. In this scenario, the explicit channel sounding process becomes too slow and the outdated channel information actually makes the beamforming performance worse. So every time when the



Fig. 1. Base station installed along track side.

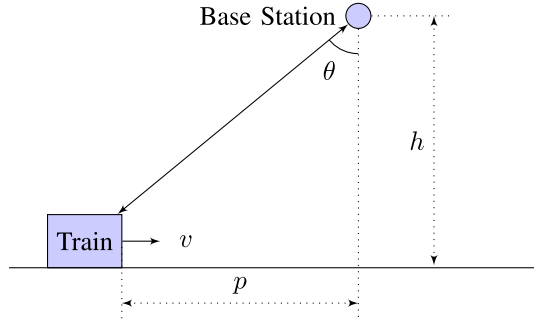


Fig. 2. DOA change effect for vehicle to infrastructure.

train passing by the base station the abrupt increase in DOA changing speed will make the beamforming algorithm break if not handled properly. The smaller cell size adopted in 5G and WiFi deployment makes the situation worse. In the cases where cell size is around 150 meter or less, the performance drop might occur in a frequency of every several milli-seconds.

To apply adaptive beamforming in this kind of scenario, the beamformer needs to adjust its weight fast enough after getting an updated DOA. With deep learning technology applied to DOA estimation [30], the speed and accuracy could be improved significantly. As for the beamformer weight update speed, although GSC is able to automatically adapt to received data and form a null dynamically in the direction of interference which is not specified inside the constraint, it takes many steps to converge. But in many scenarios especially high speed cases, it has limited time window to converge to forming the null in the interference direction. As indicated in [31], when the interference could be detected early, it is often better to put it inside the constraint matrix so that the required attenuation is achieved without an adaptation process. HSR scenario is a very good example for that.

A simplified system model illustrated in Fig. 2 shows the unique problem that requires the beamformer to derive the weight vector fast and frequent when train moving along the track and communicating with the base station.

In Fig. 2, the train moving along the rail with velocity  $v$ . The base station is deployed along the road with a distance of  $h$  to rail. In actual case, there are multiple base station deployed along the road every several hundred meters as indicated in Fig. 1. Here only one is illustrated for clarity. The instantaneous DOA  $\theta(t)$  at time  $t$  is related to the  $v$  and the

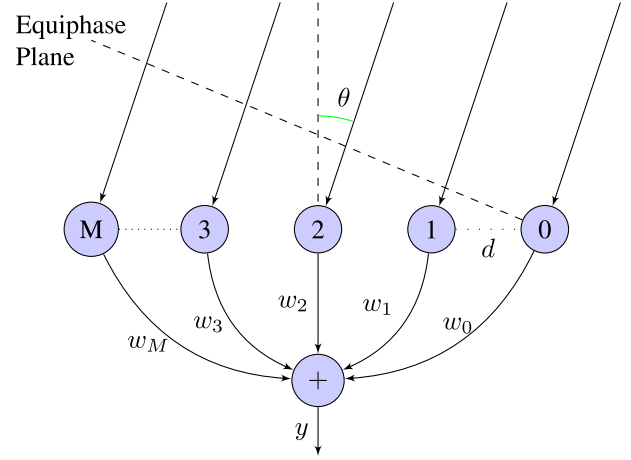


Fig. 3. Beamformer of received signal from multiple element.

relative position in the road  $p(t)$  by the following equation:

$$p(t) = h \tan(\theta(t)) \quad (1)$$

Taking derivative of (1), we can derive the instantaneous  $\theta(t)$  changing speed in (2).

$$\dot{\theta}(t) = \frac{v}{h} \cos^2(\theta(t)) \quad (2)$$

It is clearly shown from (2) that when  $\theta(t)$  is small, the DOA changes fast when train is near base station. And the changing speed is inversely proportional to the distance  $h$ . So the DOA change speed is a unique problem for vehicle to road side scenarios when the distance  $h$  between base station and the route is small. It could be around 1-10 meters which is much shorter than usual 5G base station to vehicle.

### B. Signal Model

For clarity of the discussion without losing generality, a Uniform Linear Array (ULA) is used to illustrate the signal model for a beamformer. Figure 3 shows an example of ULA with antenna elements separated by space  $d$  receives signal from far-field with incident angle  $\theta$ . For signal incident from  $\theta$  with wavelength  $\lambda$ , there is an extra delay of  $2\pi d \frac{\sin(\theta)}{\lambda}$  for each antenna element.

The signal model could be generalized to describe multiple signal sources from different angles. When the plane wavefront of signal  $s_i(t)$  with wavelength  $\lambda_i$  arrives at the antenna from angle  $\theta_i$ , from right to the left, the received signal by each antenna element has traveled progressively longer distance of  $d \sin(\theta_i)$ .

Thus the received signal on  $m^{th}$  antenna element due to the  $N$  incoming signals or interference could be expressed as:

$$x_m(t) = \sum_{i=1}^{i=N} s_i(t) e^{-j2\pi \frac{(m-1)d \sin(\theta_i)}{\lambda_i}} + n(t) \quad (3)$$

where  $m = 1, 2, \dots, M$  is the index of antenna element and  $\lambda_i$  is the wavelength for  $i^{th}$  signal and  $n(t)$  is the additive noise.

By defining spatial frequency as

$$\xi_i = \frac{d \sin(\theta_i)}{\lambda_i} \quad (4)$$

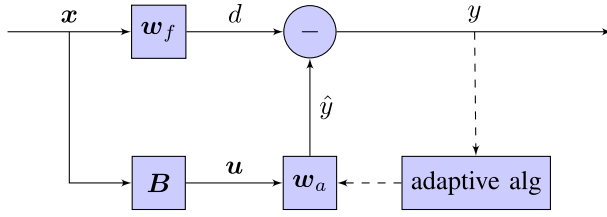


Fig. 4. Beamformer implementation with GSC structure.

the received signal on  $m^{th}$  antenna element could be simplified as:

$$x_m(t) = \sum_{i=1}^{i=N} s_i(t) e^{-j2\pi(m-1)\xi_i} + n(t) \quad (5)$$

and the steering vector for incoming signal  $s_i(t)$  could be arranged as

$$\alpha_i = [1, e^{-j2\pi\xi_i}, \dots, e^{-j2\pi(M-1)\xi_i}]^T. \quad (6)$$

where  $[\cdot]^T$  indicates the transpose of the vector.

Thus the received signal vector could be expressed as:

$$\mathbf{x} = \mathbf{A}\mathbf{s} + \mathbf{n}. \quad (7)$$

where  $\mathbf{x} = [x_1(t), x_2(t), \dots, x_M(t)]^T$  is the received signal vector for the antenna elements,  $\mathbf{A} = [\alpha_1, \alpha_2, \dots, \alpha_N]$  is the array's manifold,  $\mathbf{s} = [s_1(t), s_2(t), \dots, s_N(t)]^T$  is the input signal vector,  $\mathbf{n}$  is the additive noise vector and usually it is assumed to be Additive White Gaussian Noise (AWGN).

The beamformed output  $y$  would be expressed as:

$$y = \mathbf{w}^H \mathbf{x} \quad (8)$$

where  $\mathbf{w}$  is the weight vector and  $[\cdot]^H$  indicates the conjugate transpose of the vector. Although the beamformer model in Fig. 3 is illustrated for narrow band signals, due to the widely applied Orthogonal Frequency Division Multiplexing (OFDM) techniques in various wireless standards, it is still valid for each subcarrier. And the algorithms proposed in this paper is applicable to those wide-band wireless system with easy extension.

### C. GSC Architecture

A typical GSC beamformer is illustrated in Fig. 4. It consists of a fixed beamformer  $\mathbf{w}_f$  which controls the quiescent response for input vector  $\mathbf{x}$  from  $M$  receivers, a blocking matrix  $\mathbf{B}$  which projects the input vector  $\mathbf{x}$  to the null space of the constraint matrix as vector  $\mathbf{u}$  that is further adaptively combined to produce the estimated interference  $\hat{y}$  for cancellation and an unconstrained beamformer  $\mathbf{w}_a$  which is adaptively controlled through an adaptive algorithm block.

The required responses for signals from a set of  $N$  angles are regulated through a linear equation:

$$\mathbf{C}^H \mathbf{w} = \mathbf{f}^* \quad (9)$$

where  $\mathbf{C}$  is the  $M$  by  $N$  constraint matrix with each column specified as a steering vector from a corresponding incoming angle,  $\mathbf{w}$  is the overall equivalent weight for the GSC beamformer,  $\mathbf{f}$  is the column vector with each element being

the required response from the beamformer and  $[\cdot]^*$  is the conjugate operator and  $[\cdot]^H$  is the hermitian operator.

The fixed beamformer  $\mathbf{w}_f$  works in the column space of constraint matrix  $\mathbf{C}$  to make sure that after processing the received input vector  $\mathbf{x}$ , the signals from a specified direction follow the desired response. It could be calculated as [32]:

$$\mathbf{w}_f = \mathbf{C}(\mathbf{C}^H \mathbf{C})^{-1} \mathbf{f}^* \quad (10)$$

The blocking matrix  $\mathbf{B}$  is in the left null space of the constraint matrix  $\mathbf{C}$  so that any signal coming from the regulated angle would be blocked by blocking matrix. Thus an unconstrained adaptive algorithm like LMS could be used to adjust  $\mathbf{w}_a$ . In this way, any interference not from the regulated angle would be adaptively reduced or eliminated. The conventional way of computing the blocking matrix using SVD is denoted as Normal GSC in this paper for comparison. The beamformer in its unconstrained format could then be expressed as [32]:

$$\underset{\mathbf{w}_a}{\operatorname{argmin}} E\{|\mathbf{y}|^2\} = (\mathbf{w}_f - \mathbf{B}\mathbf{w}_a)^H \mathbf{R}_{xx} (\mathbf{w}_f - \mathbf{B}\mathbf{w}_a) \quad (11)$$

where  $\mathbf{R}_{xx}$  is the covariance matrix of the input signal  $\mathbf{x}$ .

Taking the derivative of (11) with respect to  $\mathbf{w}_a$  and force it to 0, we could find the optimum value of  $\mathbf{w}_a$ .

$$(\mathbf{w}_f - \mathbf{B}\mathbf{w}_a)^H \mathbf{R}_{xx} \mathbf{B} = 0 \quad (12)$$

So that the optimum value of  $\mathbf{w}_a$ , denoted as  $\mathbf{w}_{aopt}$ , would be [32]:

$$\mathbf{w}_{aopt} = (\mathbf{B}^H \mathbf{R}_{xx} \mathbf{B})^{-1} \mathbf{B}^H \mathbf{R}_{xx} \mathbf{w}_f \quad (13)$$

To block desired signal from leaking to the cancellation path, the  $i^{th}$  column vector of the blocking matrix  $\mathbf{B}$  denoted as  $\mathbf{b}_i$  needs to satisfy:

$$\mathbf{C}^H \mathbf{b}_i = \mathbf{0} \quad (14)$$

where  $i = 1, 2, \dots, M - N$  stands for the  $M - N$  degree of freedom for an  $M$  element array with  $N$  constraints.

## III. PROPOSED SOLUTION

### A. Simplified Zero Placement Algorithm (SZPA)

Since any  $M - N$  independent vectors in the null space of  $\mathbf{C}^H$  span the whole null space, it might be simpler to just find  $M - N$  vectors that satisfy equation (14). It turns out to be straightforward when looking from this perspective. For weight vectors  $\mathbf{b}_i$  that satisfies (14), their  $\mathbf{Z}$  transform  $\mathbf{H}_B(z)$  could be separated into two parts. The first one contains the zeros for all the constraints.

$$\mathbf{C}(z) = \prod_{i=1}^N (1 - z_i z^{-1}) \quad (15)$$

where  $N$  is the total number of constraints,  $z_i$  represents the zero location of the spatial frequency corresponding to the directions of interference and signals in the constraint matrix. The full  $\mathbf{H}_B(z)$  then could be represented as

$$\mathbf{H}_B(z) = \mathbf{G}(z) \mathbf{C}(z) \quad (16)$$

where  $\mathbf{G}(z)$  represents the leftover  $M - N - 1$  degree of polynomial. Since the signals from the  $N$  constrained direction



corresponds to the  $N$  embedded  $z_i$  in (16), any signal from those directions will result in 0 output. So any valid  $G(z)$  would make  $H_B(z)$  a valid transform for vectors in null space of constraint matrix. So the task is simplified to just choose  $M - N$  linearly independent polynomials to make up the null basis vectors. And we can choose the simplest ones which is easy for hardware implementation and guaranteed to be independent.

$$G(z) = \{1, z^{-1}, z^{-2}, \dots, z^{-(M-N-1)}\} \quad (17)$$

Since the  $z^{-1}$  is just a delay operator, the  $M - N$  vectors that form the null basis is just the  $M - N$  shifted version of the core vector that produces the zero response for all the constraints. The algorithm is described as follows.

**Algorithm 1** SZPA: Calculate Zero Location for  $B$  Based on Constraint Matrix  $C_{MN}$

**Require:**  $M \geq N$   
1: **for**  $i$  in 1 to  $N$  **do**  
2:  $\xi_i \leftarrow \frac{d \sin(\theta_i)}{\lambda_i}$  //Convert to spatial frequency  
3:  $z_i \leftarrow e^{j2\pi \xi_i}$   
4: **end for**  
5:  $C(z) \leftarrow \prod_{i=1}^N (1 - z_i z^{-1})$   
6: **for**  $i$  in 1 to  $N$  **do**  
7:  $h(i) \leftarrow$  coefficient of  $z^{-i}$   
8: **end for**  
9: **for**  $i$  in 1 to  $M-N$  **do**  
10:  $B(:, i) = [\text{zeros}(i-1, 1); h; \text{zeros}(M-1-N-i, 1)]$   
11: **end for**

The shifting operation is equivalent to add additional zeros in the origin for the  $Z$  transform. So effectively in step 10 we are getting all the required independent vectors in null space by a simple shifting operation. It is a very efficient and light operation. To our best knowledge, it has not been reported in the literature before.

### B. Derivative Constraint Based Robust Beamforming

By constraint the first, second or even higher derivative of the beam pattern with respect to the DOA to zero, the beamformer can cater for larger signal DOA mismatch [2], [22]. In the framework of GSC, the derivative constraint is enforced in the noise cancellation path. By control the flatness of the null direction in the blocking matrix, the signal cancellation could be made less sensitive to the angle change in the vicinity of the SOI. This section looks the problem of derivative constraint in the  $Z$  domain and gives the way to implement the derivative constraint in the proposed SZPA algorithm.

The norm of  $G(z)$  is constant by choosing (17) as the left over polynomial. This gives an additional advantage when investigating the beampattern of blocking matrix. Combine (16) and (17), it is apparent that the beam pattern is totally controlled by  $C(z)$  which in turn is determined by the zero placement location.

$$P_B(z) = C(z)C^*(z) \quad (18)$$

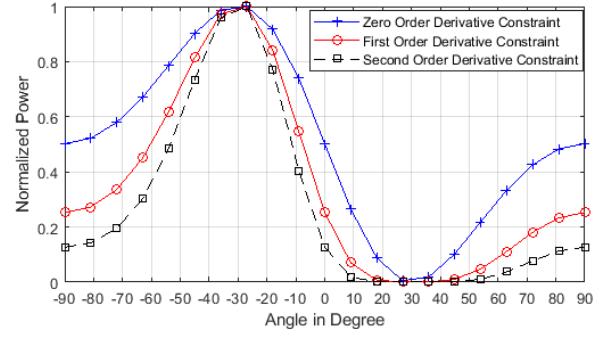


Fig. 5. Derivative constraint and number of zeros effect.

To find the beam pattern over the DOA, (18) can be evaluated over the unit circle:

$$P_B(z)|_{z=e^{j\zeta}} = \prod_{i=1}^N (z - z_i)(z - z_i)^* \quad (19)$$

$$= 2^N \prod_{i=1}^N (1 - \cos(\zeta - \xi_i)) \quad (20)$$

By taking the derivative with respect to  $\zeta$ , we have:

$$\frac{dP_B}{d\zeta} = 2^N \sum_{i=1}^N (\sin(\zeta - \xi_i) \prod_{j \neq i} (1 - \cos(\zeta - \xi_j))) \quad (21)$$

It is clear from (21) that for the first order derivative at  $\xi_i$  to be 0, at least one of  $\xi_j$  needs to equal to  $\xi_i$ . This means that by putting two zeros at the specified location, we can enforce their first derivative to be 0. And this will consume one more degree of freedom as expected. Keep taking derivative over (21), it can be found that for higher order of derivatives, we can just put more zeros to the specified location.

A simple simulation could illustrate the idea better. Different number of zero is placed at a specific incoming angle  $30^\circ$  for a half wavelength spaced array, the power transfer function is then calculated and illustrated in Fig.5.

In Fig. 5, it is clear that the pattern curve is flattened in the vicinity of degree  $30^\circ$  when derivative constraint is put on  $30^\circ$ . The higher the derivative order, the flatter the curve at the constrained angle. A side effect can be noticed in Fig. 5 is that the derivative constraint put on angle  $30^\circ$  would create a steeper peak at angle  $-30^\circ$ . This is an expected behavior according to (20). It becomes more obvious when viewed from the  $Z$  plane as in Fig. 6 where the  $\Re(\cdot)$  and  $\Im(\cdot)$  indicates the real and imaginary part of  $z$  respectively. When  $z$  moves around the unit circle, the norm  $|z - \xi_i|$  experience the minimum of 0 at the zero location  $z_i = e^{j\xi_i}$  and maximum at  $e^{j(\xi_i + \pi)}$ . For each zero placement of  $\xi_i$ , there is a corresponding peak at  $\xi_i + \pi$ . So for DOA of  $30^\circ$ , the corresponding  $\xi_i$  is  $\frac{\pi}{2}$ . The peak would appear at  $\arcsin(-\frac{1}{2})$  which corresponds to  $-30^\circ$ .

The side effect of peak doesn't affect blocking capability since only the zero location has the blocking capability. This makes adding the derivative constraint in SZPA a straightforward step. The flatness of the nulls in the blocking matrix is controlled by the duplication number of zeros. For making the beamformer robust against SOI mismatch, we can just

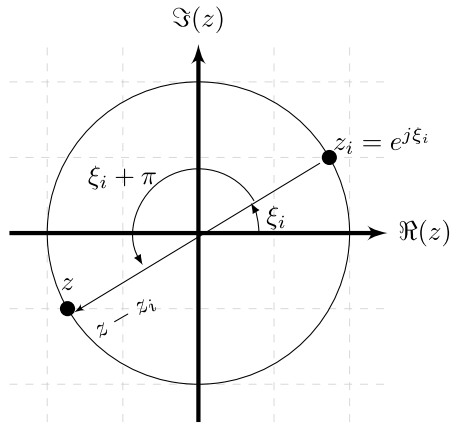


Fig. 6. Each zero located at  $\xi_i$  has a corresponding peak at  $\xi_i + \pi$  for the norm  $|z - \xi_i|$ .

duplicate the required number of zeros when calculate the blocking matrix in step 5 of SZPA.

#### IV. NUMERICAL SIMULATION AND ANALYSIS

The main advantage of this new blocking matrix calculation algorithm SZPA is its fast computational speed for multiple constraints with no requirement on the pre-steering of sensors. Simpler blocking matrix that acting as a high pass filter like CCD and its variant [6], [33] requires pre-steering delay thus limited its usage. For scenarios require multiple constraint angles like in HSR scenario, no pre-steering GSC [34] should be used where the Blocking Matrix is in the left null space of constraint matrix. So the comparison is conducted with the SVD method denoted as normal GSC [15, p. 60]. Since the simulation is designed to show performance of Blocking Matrix generation, any GSC algorithm like LMS GSC, NLMS GSC, Conjugate Gradient GSC [35] can serve the purpose and the angles used in constraints matrix are assumed to be derived by tracking or estimation through location aided scheme [24], [25] or other fast schemes like deep learning algorithm [30] etc. In this simulation we choose NLMS as it makes the selection of step size normalized and easy for comparison. With NLMS GSC chosen, the performance comparison can be done just by swapping the generated Blocking Matrix. Several simulations have been setup to demonstrate its effectiveness. The results are obtained from three simulations. The first simulation is to show that the calculation performance is substantially faster and insensitive to the number of constraints. The second simulation is to show that the optimum state performance is unaffected. The third simulation is to show that the learning speed is also not affected.

##### A. Calculation Performance Simulation

The blocking matrix  $\mathbf{B}$  calculation time comparison is shown in Fig. 7. An Uniform Linear Array (ULA) with 20 antenna elements spaced at half carrier wavelength is simulated in a MATLAB running on a Dell laptop with Intel i7 CPU. The angle of constraints increased from 1 to 15 for this antenna array which could happen in multiple user

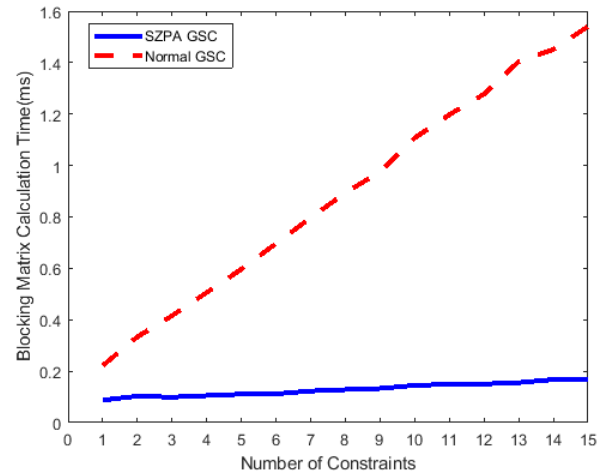


Fig. 7. Blocking matrix calculation time comparison with respect to number of constraints.

scenarios. The calculation time is averaged over 20 times of running.

It clearly shows that the proposed algorithm has very stable performance over the different sizes of constraints. In comparison, the calculation time for the SVD in normal GSC increases linearly with the increased number of constraints. There are two factors that limit the calculation speed for the normal GSC and give the SZPA the calculation advantage. Firstly, the normal GSC requires to build the constraint matrix from each of the specified angles and SZPA just needs to convert each specified angles to spatial frequency. Secondly, the matrix inversion and SVD operation used to find the null space basis is known to be expensive and SZPA replaces those expensive operation with simple polynomial operation. While required time for SZPA increase from 0.087ms to 0.168ms when constraints increased from 1 to 15, the SVD method used in normal GSC increase from 0.22ms to 1.541ms. So it is obvious that SZPA calculation time is faster and insensitive to number of constraints. For 15 constraints, the speed to calculate the blocking matrix using SZPA is more than 9 times faster than Normal GSC. The required calculation time incremental for each additional constraint with SZPA is only around  $\frac{1}{16}$  of SVD method.

##### B. Optimum Beam Pattern Performance Simulation

The beam pattern performance comparison is illustrated in Fig. 8. For clarity, the scenario with two angles constraints is depicted for an 8 element ULA where the desired signal is from  $20^\circ$ , a constrained interference is from  $40^\circ$  and an unconstrained interference is from  $50^\circ$ .

The blocking matrix prevents the constrained signal from being leaked to the cancellation path thus there are nulls formed at  $20^\circ$  and  $40^\circ$ . The overall converged beam patterns confirm that the main beam is untouched and nulls are formed at the constrained interference direction  $40^\circ$  and unconstrained direction  $50^\circ$ . The green dotted lines show patterns for each vector of the normal blocking matrix. But vectors of the SZPA blocking matrix are just shifted versions of each other,

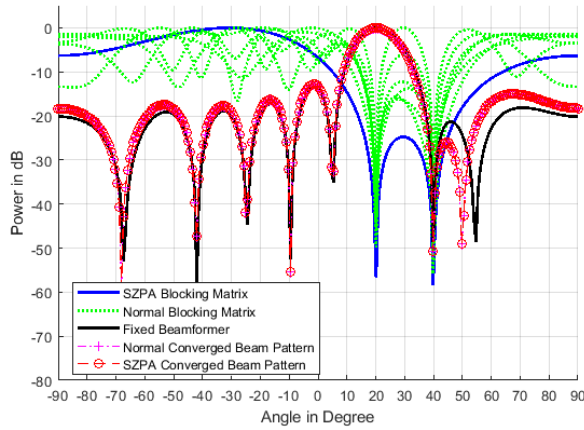


Fig. 8. Converged beam pattern performance comparison.

TABLE I  
ADAPTIVE SPEED IMPACT SIMULATION SETUP

Parameters	Value
Modulation Scheme	QPSK
Number of Sensors	8
Desired Signal Angle of Arrival	30°
Interference Angle of Arrival	60°
Interference to Signal Ratio	35dB
Signal to Noise Ratio	20dB
Monte Carlo Simulation Runs	20
Adaptive Algorithm Used in GSC	NLMS
Number of Samples Simulated	10000
Step Size used	0.001, 0.01, 0.1

their amplitude response is the same thus the blue pattern appears as only one track. The overall converged state beam pattern shows that both algorithms achieve exactly the same optimum performance. This behavior is expected from (13). The difference in  $\mathbf{B}$  will result in different input for the unconstrained adaptive filter in the cancellation path. But the adaptive process will reach different optimum value for the  $\mathbf{w}_a$  and finally the combined effect for the cancellation path  $\mathbf{B}\mathbf{w}_a$  will be the same.

### C. Learning Curve and SNR Performance Comparison

The Blocking Matrix generated by SZPA is not guaranteed to be orthogonal as compared to SVD based normal GSC Blocking Matrix generation algorithm. To evaluate the impact of the orthogonality in the adaptive speed of the noise cancellation path, different step size for the Normalized Least Mean Square (NLMS) with 0.001, 0.01, 0.1 is used for the simulation. Quadrature Phase-Shift Keying (QPSK) is used for the modulation scheme since it is the most basic Quadrature Amplitude Modulation (QAM) scheme which is widely used in many wireless standards. The results are average of 20 times of run. The simulation setup parameter is detailed in Table I.

The learning curve and Signal to Noise Ratio (SNR) for the same GSC beamformer with Normal Blocking Matrix and SZPA Blocking Matrix is illustrated in Fig. 9 and Fig. 10.

Fig. 9 shows clearly that the learning curve is a typical NLMS algorithm based learning curve. For different step size,

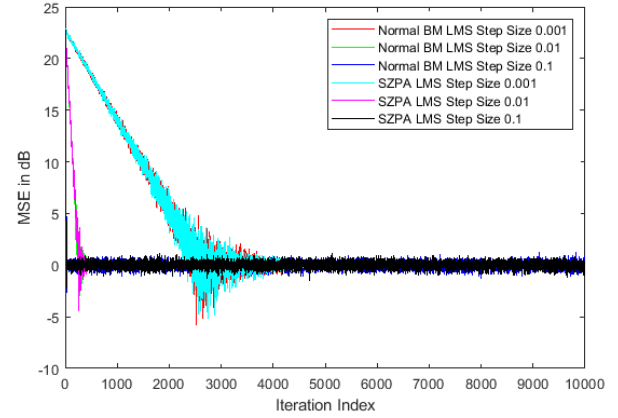


Fig. 9. Learning curve performance comparison with different step size.

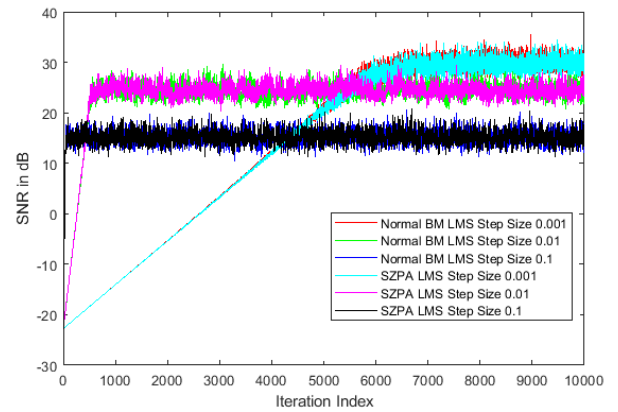


Fig. 10. SNR performance comparison.

the learning speed is the same for both algorithm generated Blocking Matrix.

From Fig. 10, it is clear that the SNR performance is also the same for both algorithms under different step sizes. The step size is well known have great impact on the adaptive speed and steady state SNR performance. As investigated in [36], variable step size could achieve both fast speed and low steady state MSE. A variety of Variable Step Size algorithm [13] could be employed to improve both performance. Since the main objective for this paper is on the blocking matrix generation algorithm, the investigation on variable step size to achieve high learning speed and good performance will not be in the scope of this paper.

## V. CONCLUSION

A simplified zero placement algorithm (SZPA) to generate the blocking matrix is proposed and simulated. Working in the Z domain, the proposed SZPA is fast and also straightforward to support derivative based robust beamformer algorithms. The novelty of this new algorithm is that it finds the null space basis vector directly in the Z domain with polynomial methods and simple shift operations. The simulation results confirm the effectiveness of the proposed method. It could be more than 9 times faster than the conventional SVD based Normal GSC method for scenarios with 15 constraints and even more

advantageous for more constraints. The optimum beam pattern performance of the whole GSC using the Blocking Matrix generated by the SZPA and SVD methods are the same. And from the simulation, the learning speed characteristics is also not compromised. In conclusion, this fast blocking matrix generation algorithm is suitable for any scenario that requires multiple constraints and frequent update like HSR train to infrastructure communication. It makes the real time update for Blocking Matrix possible for HSR scenario so that the signal loss due to DOA mismatch could be reduced.

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