ADAPTIVE SUBARRAY DESIGN FOR INTERFERENCE CANCELLATION

Ho Yang and Mary Ann Ingram

School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0250

ABSTRACT

A method for designing near-optimal, tapered subarrays for adaptive interference cancellation is proposed. The limited aperture or limited element feature of these subarrays enables a low-complexity hardware implementation of a partially adaptive array. This approach optimizes canceller performance for a given number of beams and a given number of elements per beams.

1. INTRODUCTION

We consider the problem of designing a partially adaptive array such that the fixed beamformer (non-adaptive part) has a low-complexity RF implementation. Such a design is appropriate in applications such as forward-looking radar in which adaptive arrays must be implemented under extreme size and weight constraints. In particular, we consider the architecture shown in Figure 1, where all elements are weighted and summed to form the main channel, but some of the elements are also weighted differently and summed to form auxiliary channels. These weights are fixed and can be implemented in hardware. Steering is assumed to be performed by conventional RF phase shifters on each element. The outputs of the auxiliary channels are then adaptively weighted and summed to estimate the interference in the main channel. Our design goals are to minimize the number of adaptive weights, which enhances adaptive algorithm performance and reduces receiver hardware, and minimize the number of elements used in each auxiliary channel or subarray, which reduces the size and complexity of the RF manifold. To achieve these goals, we take a fundamentally new approach, as described below.

Several authors have considered the design of subarrays that each use a limited number of elements. Nickel considered quantizing a low-sidelobe tapering function for the entire aperture, and grouped elements into a subarray when they corresponded to the same quantization level [1]. The elements in a subarray were
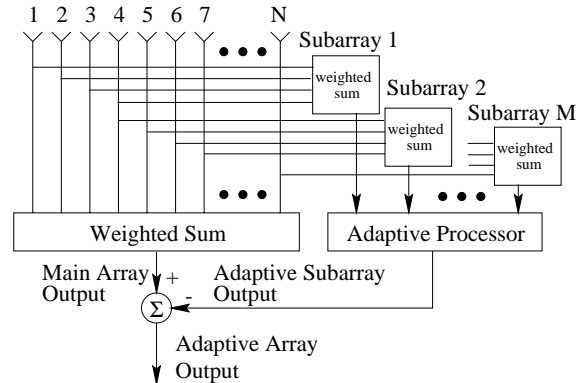
Figure 1: Adaptive Subarrays

weighted and combined using the full-aperture taper. The procedure leads to non-overlapping, irregularly shaped, and tapered subarrays. Xu et al. [2] discussed a similar "equal subarray-weight" method based on quantization of the integrated tapering function. Abraham and Owsley [3] considered minimum variance distortionless response (MVDR) using several different subarray configurations, including overlapping subapertures. They did not address the design of the auxiliary channels other than to note that the spatial windows and phase centers of the subarrays were selected to avoid spatial aliasing when the subarrays were adaptively combined. Other authors [4, 5] have chosen individual elements for adaptive weighting, either randomly or by exhaustive search, or considered simple equal partitions or row-column combinations.

Other authors [6] have proposed auxiliary beams that are designed to optimize cancellation performance using as few beams as possible. However, each beam in these designs uses all the elements, and are therefore too complex and costly to implement as RF beamformers.

In this paper, we derive tapered, overlapping subarrays from the optimal full-aperture beams proposed by Yang and Ingram [6]. These beams require a small fraction of the total elements (22 % for an example rectangular array) and only a small number of beams

are required to approximate the performance of the full apertured fully adaptive array. The design procedure produces a full set of beams that is ordered in the sense that the designer can use the first M beams if M adaptive weights are desired. We compare our design with quantization-based, regular partition, and irregular partition designs and show significant improvement in signal-to-interference-plus-noise ratio (SINR), in particular 3 to 9 dB average improvement and 14 to 34 dB worst case improvement for a set of 500 randomly generated point jammer scenarios. It is also interesting that the highest priority beams for our example confirm the experience of others [5, 7] that "edge clustered" elements make good subarrays.

2. DESIGN PROCEDURE

To begin, we assume the generalized sidelobe canceller (GSC) structure [8] with a non-square matrix $\mathbf{T}$ inserted for rank reduction. Here, $\mathbf{x}$ is the N-dimensional input snapshot vector taken at N sensor elements. The quiescent weight vector $\mathbf{w}_c$ defines the main channel and may be designed to satisfy constraints of look direction, beam shape, and sidelobe level. The columns of the signal blocking matrix, $\mathbf{W}_s$, are orthogonal to those of the constraint matrix, $\mathbf{C}$. Adaptive algorithms control the adaptive weight vector, $\mathbf{w}_o$, so as to minimize the average output power of the GSC output.

The power-space (PS) method [6] finds a prototype $\mathbf{T}$ matrix, $\mathbf{T}_{ps}$, that approximately minimizes the average GSC output power, when further averaged over a large collection of randomly generated interference scenarios. It produces a square $\tilde{\mathbf{T}}_{ps}$ matrix with ordered columns such that the left most M columns form a $\mathbf{T}_{ps}$ matrix that is best for M adaptive weights. The columns of $\mathbf{W}_s \mathbf{T}_{ps}$ form the weights of auxiliary channels, and each column generally has no zero elements. However, there is significant fluctuation in weight magnitudes, as shown in the following example.

For the 64 element uniform rectangular array (URA), Figure 2 illustrates the magnitude of fixed weights for the first 9 significant beams from a PS design. In other words, if only 3 adaptive weights are desired, then only the top three blocks would be used in a partially adaptive design. And each point in each block corresponds to the magnitude of each element in $\mathbf{W}_i = \mathbf{W}_s \mathbf{t}_i$, normalized by maximum value in the block, where $\mathbf{t}_i$ is the ith column of $\mathbf{T}_{pa}$.

Next, we disconnect the weights with the smallest magnitude. Option 1 is to remove the elements below a certain threshold level thus resulting in subarrays with different numbers of elements. Option 2 is to remove a ce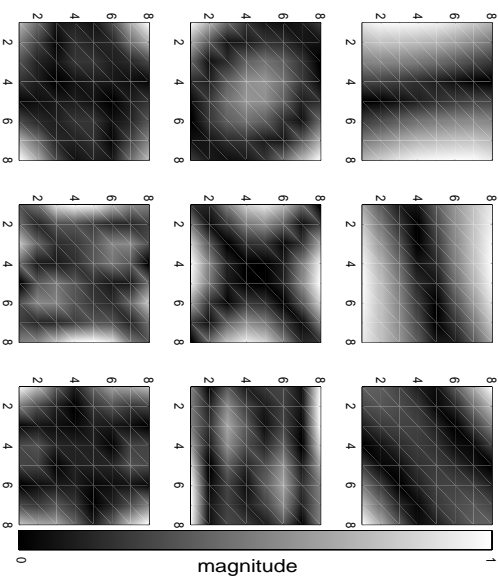rtain percentage of insignificant elements to produce subarrays with same number of elements. Element removal breaks the orthogonality of the signal subspaces in the GSC, and thus causes a signal cancellation. To remedy this problem, we iteratively project the subspace of the fixed weights into the null space of the desired signal while keeping the same elements removed. More specifically, we use an orthogonal projection matrix, $\mathbf{P}_n = \mathbf{I} - \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H$ for the constraints matrix $\mathbf{C}$, to modify the fixed weights of the subarrays. The design of the subarray is summarized as follows:

1. Design $\mathbf{T}_{pa}$ using the PS method for the partially adaptive GSC.

2. Calculate the magnitude of $\mathbf{w}_i = \mathbf{W}_s \mathbf{t}_i$, where $\mathbf{t}_i$ is the ith column of $\mathbf{T}_{pa}$.

3. Remove the jth element from the group of auxiliary beams by substituting a zero into $\mathbf{w}_i$, either if $w_j < \gamma_t$ or if $w_j \in K$th percentage of elements having the smallest magnitude of $\mathbf{w}_i$, where w_j is the magnitude of $\mathbf{w}_i$'s element corresponding to the jth sensor. γ_t is the threshold level in Option 1 and K is the desired percentage in Option 2. This procedure introduces $\mathbf{T}_{sa} = [\mathbf{t}_1, \mathbf{t}_2, \cdots, \mathbf{t}_M]$ with $\mathbf{t}_i = \text{NULLING}(\mathbf{w}_i)$. M is the maximum number of beams considered for the design and NULLING denotes the element nulling operation according to either Option 1 or Option 2.

4. Apply the projection, $\mathbf{P}_n = \mathbf{I} - \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H$, to the $\mathbf{T}_{sa}$ with element nulling.

5. Repeat 4 until the orthogonality is recovered, i.e., $\mathbf{T}_{sa}^{(k)} = \text{NULLING}\{\mathbf{P}_n \mathbf{T}_{sa}^{(k-1)}\}$, for $k = 1, 2, \cdots, K$, where K is given such that $\mathbf{T}_{sa}^{(K)H} \mathbf{w}_c \approx \mathbf{0}$.

Figure 2: Weights for beams of partially adaptive URA

3. DESIGN EXAMPLE

We consider a 64 element URA with $\lambda/2$ spacing and a single look-direction mainbeam constraint for a desired signal of $(\theta, \phi) = (30^o, 50^o)$ and 0 dB signal-to-noise-ratio (SNR), where θ and ϕ denote the elevation and azimuth, respectively. For the design of $\mathbf{T}_{\mathrm{pa}}$ and the evaluation of designed adaptive subarrays, 500 random jamming scenarios in which jammer angles were uniformly distributed over an annulus of 5° inner radius and 65° outer radius, centered on the desired signal. The magnitude of fixed weights corresponding to the designed $\mathbf{T}_{\mathrm{pa}}$ is shown in Figure 2. Based on this magnitude plot, we remove part of the elements using Option 1 and Option 2. Figure 3 shows the cosine angles between $\mathbf{w}_c$ and the 63 columns of nulling matrix $\mathbf{T}_{\mathrm{sa}}^{(k)}$ with the number of iteration k. Option 1 using $\gamma = 0.8$ requires about 200 iterations for near zero value of cosine angle, while Option 2 using 80 % element nulling requires about 40 iterations for near zero value. The 80 % removal in Option 2 specifies 14 elements for each subarray out of 64 elements. It is clear that the iteration is effective in both options to recover the orthogonality between mainbeam and auxiliary beams. We note that Option 2 is more efficient that Option 1 because of its fast convergence to zero cosine angle.

Figure 4 and 5 show the SINR performance of the adaptive subarrays. We use 250 and 100 iterations for the both Option 1 and Option 2, respectively. To account for potential signal cancellation, we use the SINR index instead of the mean-squared error (MSE). For the SINR of the adaptive subarray, termed as SINR_{sa}, and the SINR of the full apertured and fully adaptive array, termed as SINR_{fa}, we define the SINR loss as

$$\mathrm{SINR\ loss\ (dB)} = 10 \log_{10}\{\mathrm{SINR}_{sa}/\mathrm{SINR}_{fa}\}.$$

For Option 1 shown in Figure 4, we calculate average SINR loss in (a) and the worst case SINR loss in (b) for 500 random scenarios. In the figure, the smaller value of threshold level means the smaller number of elements for a subarray. The performance becomes worse as fewer beams and fewer elements/beam are used. How-
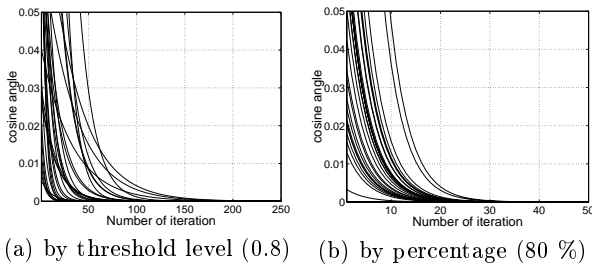

(a) by threshold level (0.8)   (b) by percentage (80 %)

Figure 3: Iterative projection with element removal

(a) Average penalties   (b) Worst case penalties
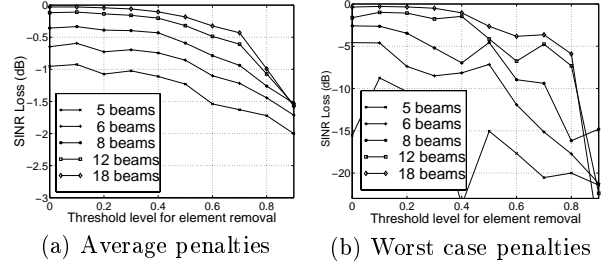
Figure 4: Element removal based on the threshold level
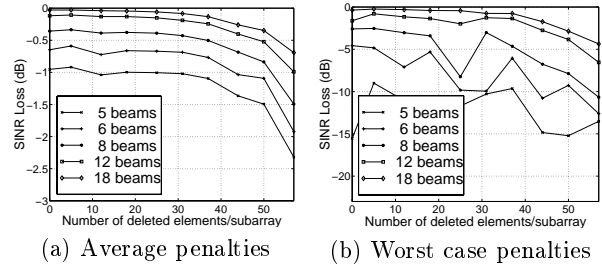

(a) Average penalties   (b) Worst case penalties

Figure 5: Element removal based on the percentage

ever, if 4 dB SINR loss is tolerable, the 18 beams with 0.7 threshold level can be used. The next results in Figure 5 use Option 2, where the subarrays were obtained by deleting a percentage of insignificant elements. For the same tolerance of 4 dB SINR loss, 12 beams with 14 elements/beam can be used for the adaptive subarrays. Figure 6 shows the element locations for 12 beams designed by Option 2. It is interesting to note the edge clustering, which has been observed to perform well by previous authors [5, 7].

For the comparison with the other design techniques, we considered three other methods: (i) regular subarray without overlapping, (ii) regular subarray with overlapping, and (iii) irregular subarray based on the magnitude of tapers. In particular, (iii) is the method suggested by Nickel [1] with a design requirement of low sidelobe level for the sum and difference beams as well as interference cancellation. For (iii), we apply Taylor and Bayliss tapers with 40 dB sidelobe levels and evenly quantize the relative weights for 14 levels, which results in 12 subarrays. Figure 7 shows the designed elements' location for (i) and (iii). In the figure, the positions having the same number construct a subarray and the number denotes the significance of the subarray in view of interference cancellation. We note that Method (iii) has an irregular structure like our proposed design method. Method (ii) using 16 elements/subarray produces 12 overlapped subarrays with regular shapes.

The performance comparison is given in Table 1. In the table, the second column gives the available
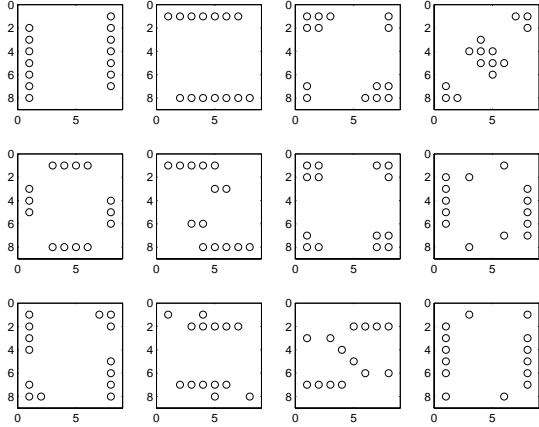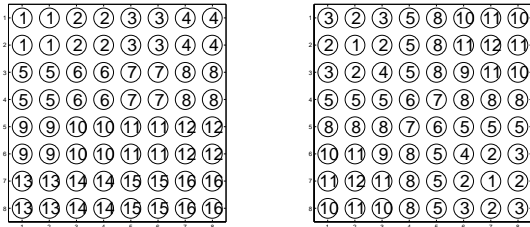
Figure 6: Elements for 12 beams and 14 elements/beam

(a) regular structure   (b) irregular structure

Figure 7: Elements for other subarrays

number of degrees-of-freedom (DOF), i.e., the number of subarrays combined adaptively for interference cancellation. For Option 1 and Method (iii), the number of elements/subarray is not specified due the irregularly sized subarrays. We applied same 500 random interference scenarios to all five different subarrays. The numerical values in the table are SINR losses in dB relative to the averaged optimum SINR of 17.26 dB. Among these methods, our suggested design using Option 2 provides the best performance in maximum SINR loss and average SINR loss. Method (iii), which is designed for lower sidelobe level, shows worse cancellation performance than the proposed designs.

Table 1: Performance comparison

Design method	No. of subarray	No. of elements	Worst case SINR loss	Average SINR loss
Option 1	12	-	-7.31	-1.07
Option 2	12	14	-3.84	-0.52
(i)	16	4	-24.37	-3.38
(ii)	12	16	-18.23	-9.51
(iii)	12	-	-39.19	-7.37

4. CONCLUSION

A new design for adaptive subarrays was suggested for interference cancellation. The proposed method constructs the subarrays by nulling insignificant elements from the full apertured partially adaptive GSC. A rank-reduction matrix designed by the PS method was used as a prototype of element nulling matrix. Two design options were proposed and tested for element nulling. Iterative projection to recover the orthogonality between the mainbeam and auxiliary beams was applied to the non-nulled elements. The option that provides the same number of elements for all subarrays shows the best performance in computer simulations. For the uniform rectangular array with 64 elements, our proposed method (Option 2) shows a significant performance superiority over other subarray structures.

5. REFERENCES

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