Subarray Design for Adaptive Interference Cancellation

Ho Yang and Mary Ann Ingram, *Member, IEEE*

***Abstract*—A method for designing near optimal, tapered subarrays for adaptive interference cancellation is proposed. The design method simultaneously produces a complete ordered set of fixed beam definitions, or nonadaptive weight vectors. The designer may choose to implement the first K of these if he or she wishes to have exactly K adaptive weights. In other words, the digital–adaptive processing is done in beam space, such that the beams are designed using the proposed method. To facilitate a RF implementation of the nonadaptive beamformer, each auxiliary beam uses only a designer-specified number of the elements in the aperture, thereby reducing the number of waveguide connections required. This design approach is fundamentally different from conventional subarray design approaches in that the new designs utilize cost functions related to interference cancellation.**

***Index Terms*—Adaptive arrays, interference, interference suppression, subarrays.**

I. Introduction

WE PROPOSE a new method for designing adaptive subarrays, which is a simple modification of the power space (PS) and weighted-signal-subspace (WSS) methods previously reported by the authors in [1] and [2]. Each of these methods produces an ordered set of fixed beam definitions, such that the lowest-indexed beams provide, on the average, good approximations to the best auxiliary signals for adaptive interference cancellation.[1] However, each beam in these designs is a "full-aperture" beam, which means that it uses all of the elements. Such full-aperture beams may be quite complex and costly to implement as RF beamformers.

In this paper, the low-indexed beams from the PS and WSS designs for a uniform rectangular array are shown to also yield smooth aperture illumination functions. We propose to exploit the smoothness by turning off the elements that have small magnitudes in the aperture illumination function. The elements that remain form a few tight clusters within the aperture and, therefore, might be connected with subarray combining structures that would be simpler and lighter in weight than full-aperture combining structures. A simple iterative projection algorithm modifies the subarray weights to ensure that the auxiliary beams created by the subarrays are orthogonal to the main channel.

Several authors have considered the design of adaptively combined subarrays, exemplified by the illustration in Fig. 1. 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 [3]. The elements in a subarray were weighted and combined using the full-aperture taper. The procedure leads to nonoverlapping, irregularly shaped, and tapered subarrays. Xu *et al.* [4] discussed a similar "equal subarray-weight" method based on quantization of the integrated tapering function. Abraham and Owsley [5] considered minimum variance distortionless response (MVDR) beamforming 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 [6], [7] have chosen individual elements for adaptive weighting, either randomly or by exhaustive search, or considered simple equal partitions or row–column combinations.

In this paper, we derive tapered, overlapping subarrays from the full-aperture beams designed by the PS method [1] and the WSS method [2]. Each beam requires a small fraction of the total elements (22% for an example rectangular array with the PS method) and only a small number of beams are required to approximate the performance of the full-aperture fully-adaptive array. The design procedure produces a full set of beams that is ordered in the sense that the designer can use only 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, the PS-based adaptive subarray achieves 3–9 dB average improvement, and 14–34-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 [7], [8] that "edge clustered" elements make good subarrays.

II. Adaptive Subarray Design

To begin, we design sets of full aperture beams using the PS [1] and WSS [2] design techniques proposed by Yang and Ingram. We assume a partially adaptive version of the generalized sidelobe canceller (GSC) structure [9], as shown in Fig. 2. The vector $\mathbf{x}$ is the N-dimensional input snapshot vector taken at N sensor elements. $\mathbf{w}_c$ is the quiescent weight vector which defines the main channel and may be designed

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H. Yang was with the Nixxo Technologies, Inc., San Jose, CA 95134 USA. He is now with Samsung Advanced Institute of Technology (SAIT), Kiheung, Korea (e-mail: hoyang@samsung.co.kr).

M. A. Ingram is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta GA 30332-0250 USA (e-mail: maryann.ingram@ece.gatech.edu).

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[1]PS approximates the optimum fixed transformation for a partially adaptive array in the minimum mean squared error sense. WSS beam sets are designed to protect only the vulnerable (highest) parts of the quiescent (main beam) pattern.

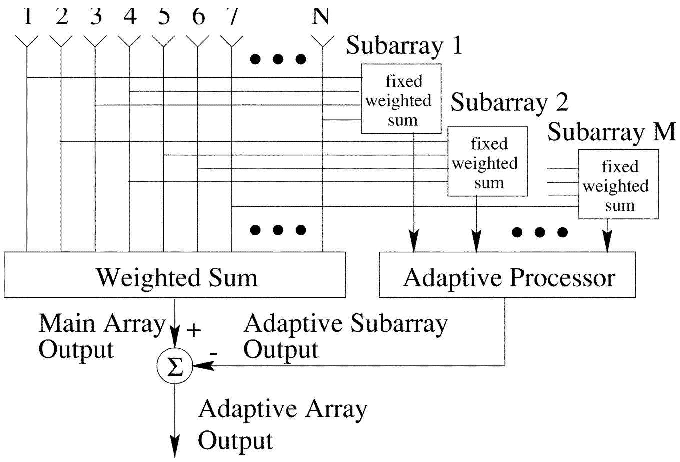


Fig. 1. Adaptively combined subarrays.

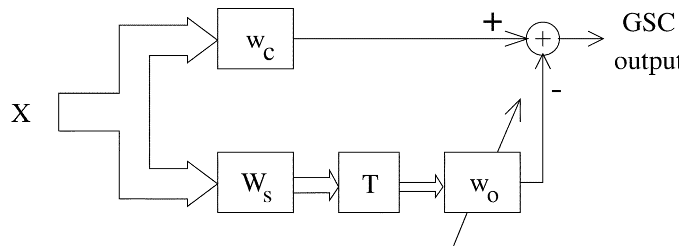


Fig. 2. Partially adaptive GSC.

to satisfy requirements on the look direction, beam shape, and sidelobe level. $\mathbf{W}_s$ is the signal blocking matrix, which allows nonconstrained adaptive algorithms to be used to minimize the output power of the array, subject to the constraint $\mathbf{C}^H\mathbf{w} = \mathbf{f}$, where $\mathbf{w}$ is the overall weight vector and $\mathbf{f}$ is the desired response. $\mathbf{W}_s$ is not unique; its columns need only to span the null space of $\mathbf{C}$. $\mathbf{T}$ is the nonsquare rank reduction matrix, which is fixed (i.e., nonadaptive) for subarray design. The number of columns of $\mathbf{T}$ is the number of subarrays and also the number of adaptive weights. The columns of $\mathbf{W}_s\mathbf{T}$ must be orthogonal to those of the constraint matrix, $\mathbf{C}$, to prevent cancellation of the desired signal; this will be an important issue in our design. Adaptive algorithms control the adaptive weight vector, $\mathbf{w}_o$, in order to minimize the average output power of the GSC output.

We shall apply the PS and the WSS methods to a narrowband planar array to find a prototype matrix $\mathbf{T}_{\rm ps}$. Each method produces a square $\mathbf{T}$ matrix with ordered columns such that the leftmost M columns form a $\mathbf{T}_{\rm ps}$ matrix that is best for M adaptive weights. In other words, the leftmost columns of $\mathbf{W}_s\mathbf{T}$ form the best M auxiliary channels (according to the respective cost functions of the PS and WSS methods), and each column generally has no zero elements. We will observe for the planar array that the leftmost beams have aperture illumination functions that are the smoothest, or "lowest order," implying that the elements with the largest magnitude weights appear in clusters within the aperture. Our proposed approach is first to create the subarrays by turning off the elements with the smallest weight magnitudes and second, to recover the required orthogonality to the constraint matrix by iteratively projecting the vectors of the fixed weights into the null space of the constraint matrix.

We consider two options for how to decide which elements to turn off. Option 1 is to remove the elements below a certain threshold level, resulting in subarrays with different numbers of elements. Option 2 is to remove a certain percentage elements to produce subarrays with same number of elements.

The design of the subarray is summarized as follows:

1) design $\mathbf{T}_{\rm pa}$ using either the PS method or the WSS method for the partially adaptive GSC;
2) calculate the element magnitudes of $\mathbf{w}_i = \mathbf{W}_s\mathbf{t}_i$, where $\mathbf{t}_i$ is the ith column of $\mathbf{T}_{\rm pa}$;
3) remove the jth element from the auxiliary beam by substituting a zero into $\mathbf{w}_i$, either if $w_j < \gamma_t$ or if $w_j \in K$th percentile of elements having the smallest magnitude of $\mathbf{w}_i$, where w_j is the magnitude of the weight on the jth sensor. γ_t is the threshold level in option 1 and K is the desired percentile in option 2. This procedure initializes $\mathbf{T}_{\rm sa} = [\mathbf{t}_1, \mathbf{t}_2, \ldots, \mathbf{t}_M]$ with $\mathbf{t}_i = {\rm NULL}(\mathbf{w}_i)$. M is the maximum number of beams considered for the design and NULL represents the element nulling operation according to either option 1 or option 2.
4) Apply the projection, $\mathbf{P} = \mathbf{I} - \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H$, to $\mathbf{T}_{\rm sa}$, followed by the nulling procedure.
5) Repeat 4 until the orthogonality is recovered, i.e., $\mathbf{T}_{\rm sa}^{(k)} = {\rm NULL}\left\{\mathbf{P}\mathbf{T}_{\rm sa}^{(k-1)}\right\}$, for $k = 1, 2, \ldots, K$, where K satisfies ${\mathbf{T}_{\rm sa}^{(K)}}^H \mathbf{w}_c \approx \mathbf{0}$.

III. Design Example

We consider a 64-element uniform rectangular array (URA) with $\lambda/2$ spacing and a single look-direction main-beam constraint for a desired signal of $(\theta, \phi) = (30^\circ,\ 50^\circ)$ and 0-dB signal-to-noise-ratio (SNR), where θ and ϕ denote the elevation and azimuth, respectively. For the PS design of $\mathbf{T}_{\rm pa}$, 500 random jamming scenarios were used in which three jammers, each with a jammer-to-noise power ratio (JNR) of 40 dB, were uniformly distributed in angle over an annulus of 5° inner radius and 65° outer radius, centered on the desired signal. For the WSS design, we sampled the given angular range of jammers with a 0.5° interval. Fig. 3(a) and (b) show the magnitude of $\mathbf{W}_t$'s for the first nine significant beams designed with the PS and the WSS methods, respectively.

For example, the upper-left box in Fig. 3(a) shows the weight magnitudes for the 8×8 array corresponding to the best auxiliary beam. We observe patterns that may be useful for grouping the elements in both methods. For example, the upper-left beam does not use the middle elements as much as the elements on the right and left sides of the aperture. We observe that the WSS patterns are different from the PS ones, but they have the same characteristic that the complexity of the pattern increases with beam number.

Based on these magnitudes, we remove some of the elements using option 1 and option 2. Fig. 4 illustrates the cosine angles between $\mathbf{w}_c$ and the 63 columns of the nulled matrix $\mathbf{T}_{\rm sa}^{(k)}$ designed by the PS method at iteration k. Option 1 using $\gamma = 0.8$ requires about 200 iterations for a near-zero value of cosine angle, while option 2 using 80% element nulling requires about 40 iterations for a near-zero value. The 80% removal in option 2

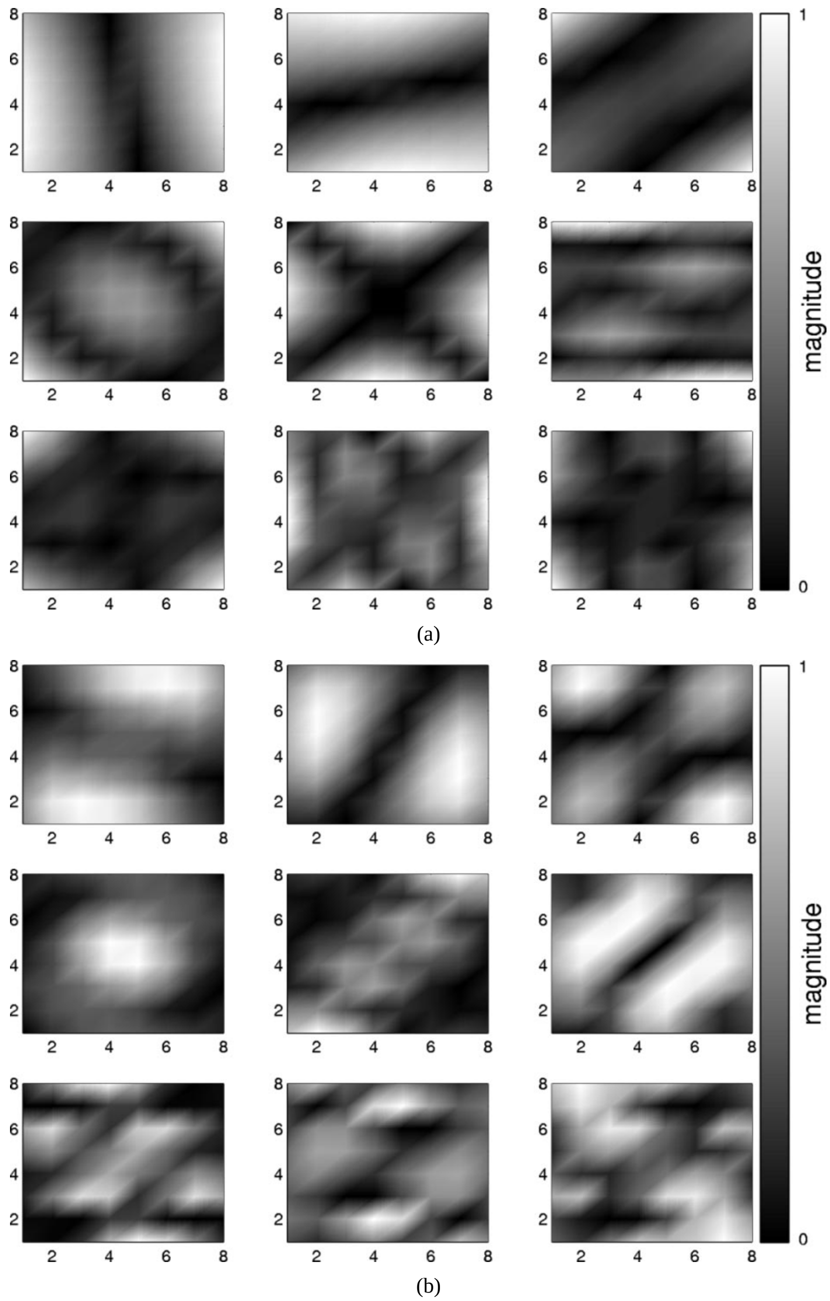


Fig. 3. Weights for beams of partially adaptive uniform rectangular array. (a) Beam weights designed by PS. (b) Beam weights designed by WSS.

specifies 14 elements for each subarray out of 64 elements. We observe that the iteration is effective in both options to recover the orthogonality between main beam and auxiliary beams. We note that option 2 is more efficient than option 1 in terms of convergence.

Fig. 5 shows the SINR performance of the adaptive subarrays based the PS method. We use 250 and 100 iterations for option 1 and option 2, respectively. To account for potential signal cancellation, we use the SINR index instead of the MSE. Denoting the SINR of the partially adaptive subarray as $\mathrm{SINR}_{\mathrm{sa}}$, and the SINR of the full-aperture and fully adaptive array as $\mathrm{SINR}_{\mathrm{fa}}$, we define the SINR loss as

$$\text{SINR loss (dB)} = 10\log_{10}\left\{\frac{\mathrm{SINR}_{\mathrm{sa}}}{\mathrm{SINR}_{\mathrm{fa}}}\right\}.$$

We computed the SINR loss for each scenario in a set of 500 random jamming scenarios. This set was generated using the same distributions as the set used for the PS design, but is statistically independent. For option 1, shown in Fig. 5(a) and (b), we calculate average SINR loss in (a) and the worst case SINR loss in (b) for the 500 random scenarios. In the figure, the smaller value of threshold level means more elements for a subarray. The performance becomes worse as fewer beams and fewer elements/beam are used. However, if 4-dB worst-case SINR loss is tolerable, then 18 beams with a 0.7 threshold level or the 12 beams with approximately a 0.5 threshold level can be used. The results in Fig. 5(c) and (d) use option 2, where the subarrays were obtained by deleting a percentage of insignificant elements. The mark points in (c) and (d) correspond to 0, 5, 12, 18, 25, 31, 37, 44, 50, and 57 elements' removal, respectively.

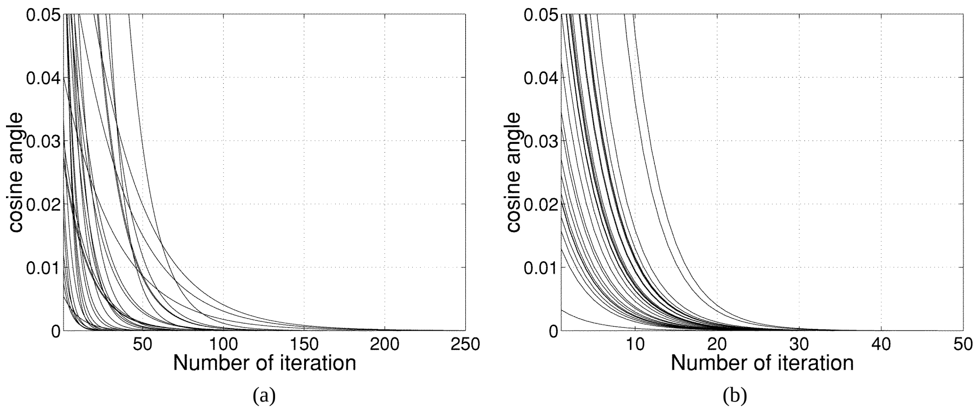


Fig. 4. Iterative projection with element removal based on the PS method. (a) By threshold level (0.8). (b) By percentage (80%).

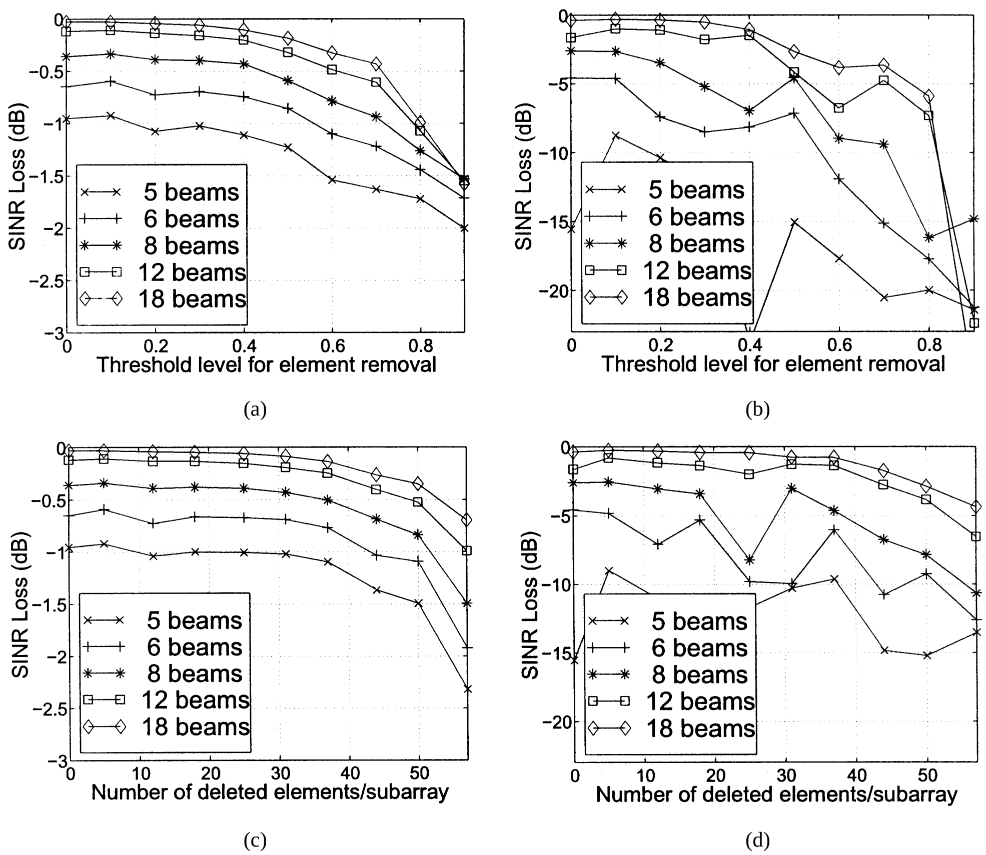


Fig. 5. Element removal based on the PS method. (a) Average (b) and worst case penalties penalties for option 1. (c) Average and (d) worst case penalties for option 2.

For the same tolerance of 4-dB worst-case SINR loss, 12 beams with 14 elements/beam can be used for the adaptive subarrays. Fig. 6 shows the element locations for the 12 beams designed by option 2. For example, the circles in the upper-left square define the first subarray; that is, the circles mark the elements in the 8×8 array that would be nonadaptively and linearly combined to form the first auxiliary beam. The next square in that row defines the second subarray, and so forth. If one wanted only four adaptive weights, then this procedure recommends that the subarrays in the first four squares in Fig. 7 be used. We observe that the first and third subarrays share some elements. It is interesting to observe the edge clustering in the first nine beams; edge clustering has been observed to perform well by previous authors [7], [8].

The results of the WSS method are given in Fig. 7. The performance is a little lower than that of PS method. For the tolerance of 4 dB SINR loss, again 12 beams with 14 elements/beam can be used, however the element locations are different as shown in Fig. 8.

For comparison, we considered three other subarray design methods: (i) regular subarrays without overlapping; (ii) regular subarrays with overlapping; and (iii) irregular subarrays based on the magnitude of tapers. In particular, (iii) is the method suggested by Nickel [3] with a design requirement of low-sidelobe level for the sum and difference beams as well as interference resistance. For (iii), we apply the Taylor (for the sum pattern) and Bayliss (for the difference pattern) tapers with 40-dB sidelobe levels and evenly quantize the relative

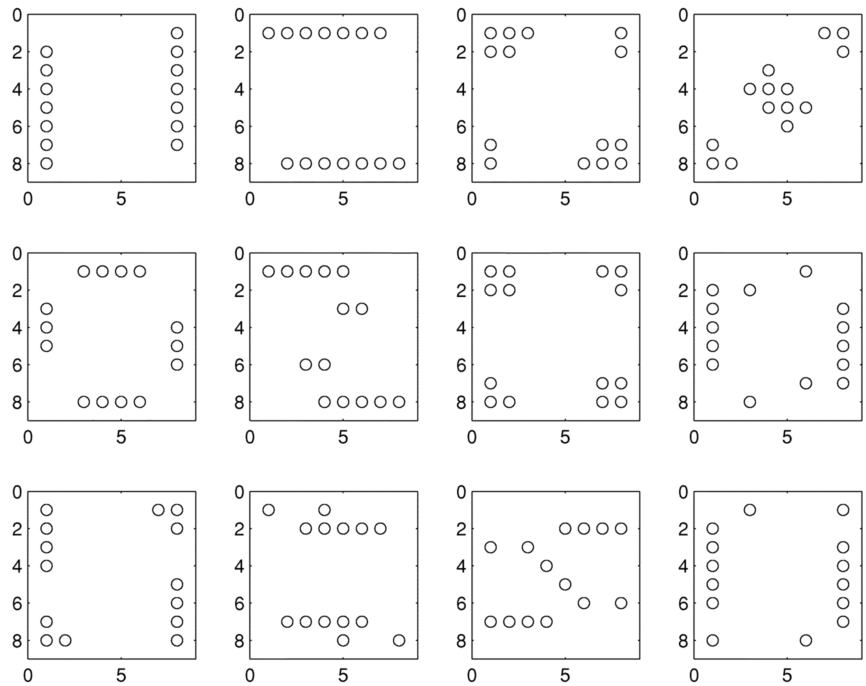


Fig. 6. Element locations for 12 beams and 14 elements/beam based on the PS method and option 2 element removal.

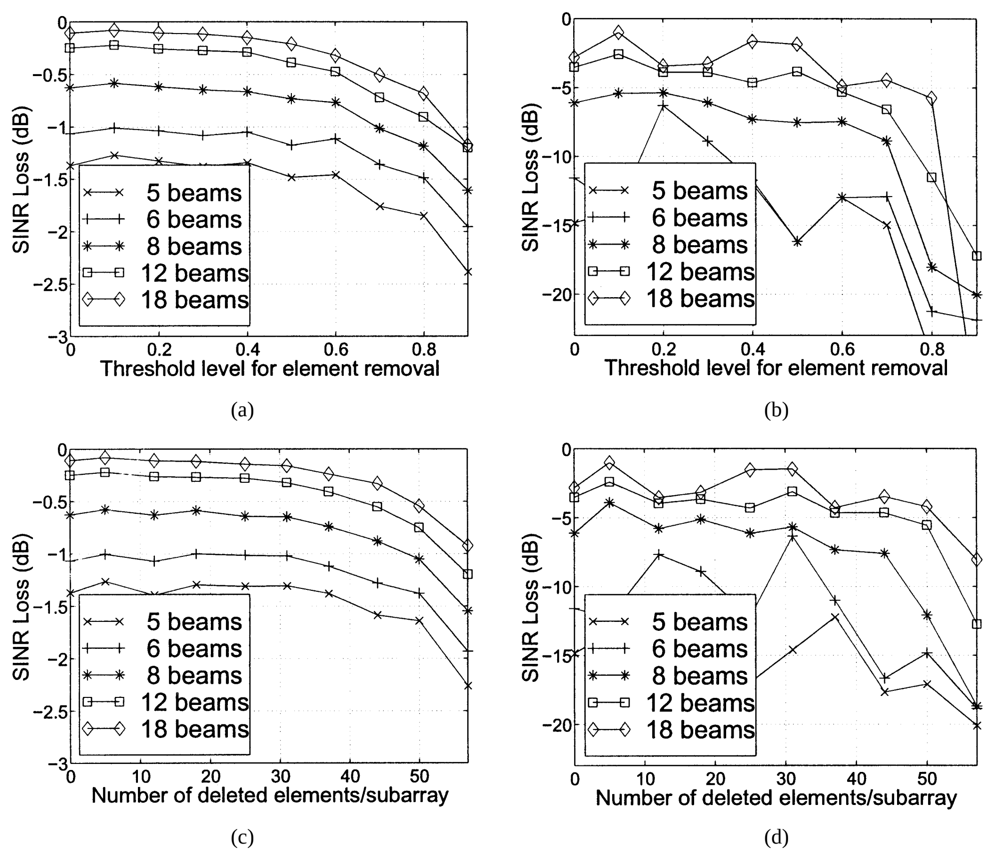


Fig. 7. Element removal based on the WSS method. (a) Average penalties. (b) Maximum penalties. (c) Average penalties. (d) Maximum penalities.

weights for 14 levels to achieve low-sidelobe levels in the adapted sum and difference patterns, which results in 12 subarrays. Fig. 9 shows the subarray definitions for (i) and (iii). In the figure, the elements having the same number compose a subarray. 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 I. For this comparison, we did not list subarrays based on the WSS-de-

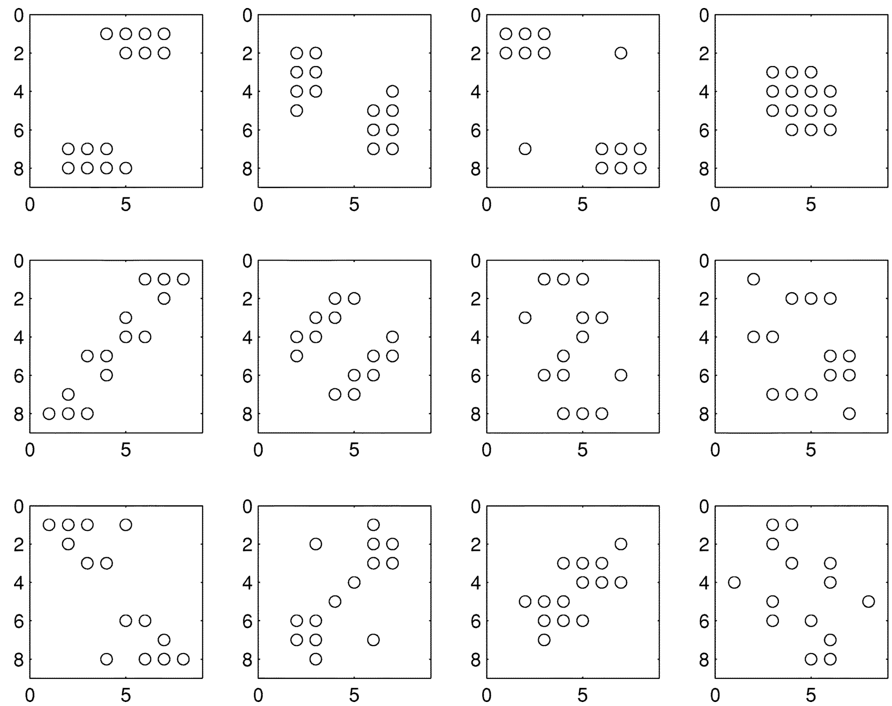
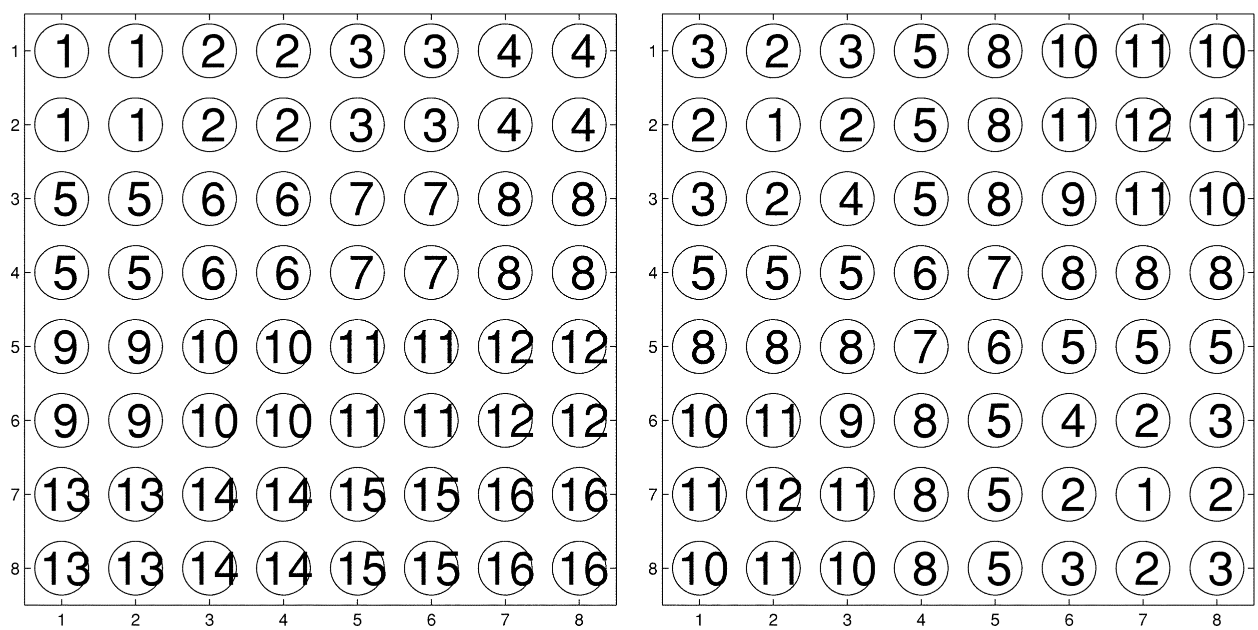


Fig. 8. Element locations for 12 beams and 14 elements/beam based on the WSS method and option 2 element removal.



(a) (b)

Fig. 9. Elements for other subarrays. (a) Regular structure. (b) Irregular structure.

TABLE I
PERFORMANCE COMPARISON OF THE ADAPTIVE SUBARRAYS

Design Method	No. of Subarrays	No. of Elements	Worst case SINR Loss	Average SINR Loss
Opt. 1 (PS)	12	8.17	-7.31	-1.07
Opt. 2 (PS)	12	14	-3.84	-0.52
(i)	16	4	-24.37	-3.38
(ii)	12	16	-18.23	-9.51
(iii)	12	5.33	-39.19	-7.37

signed transformation. In Table I, the second column gives the number of subarrays, which is also the number of adaptive weights. For option 1 and method (iii) the number of elements/subarray is given as an average number of elements because the subarrays are irregularly sized. We applied the same 500 random interference scenarios to all five designs. The numerical values in the table are SINR losses in dB relative to the averaged full aperture and fully adaptive SINR of 17.26 dB. Among these methods, our proposed design using option 2 provides the best performance in worst-case SINR loss and average SINR loss. Method (iii), which designs for low sidelobes, shows the worst cancellation performance.

IV. Conclusion

A new method was suggested for designing adaptive subarrays based on interference cancellation-related cost functions. The proposed method nulls insignificant elements from the full-aperture partially adaptive GSC beams designed by the PS and WSS methods. Constrained iterative projection recovers the orthogonality between the main beam and auxiliary beams after element nulling. Two design options were tested for element nulling. The PS approach combined with the option that provides the same number of elements for all subarrays showed the least SINR loss in computer simulations in comparison with several existing design techniques for a uniform rectangular array with 64 elements.

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Ho Yang received the B.S. and M.S. degrees from Yonsei University, Seoul, Korea, and the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1987, 1989, and 1998, respectively.

From 1988 to 1989, he was a Research Assistant with the Department of Biomedical Engineering, Yonsei University, working in medical image processing. From 1989 to 1991, he was a Research Engineer at the Electronics and Telecommunications Research Institute, Taejon, Korea. From 1993 to 1998, he was a Research Assistant with the School of Electrical and Computer Engineering at the Georgia Institute of Technology, where he worked on partially adaptive space–time processing for interference cancellation. From 1999 to 2001, he was a Senior DSP Engineer with Nixxo technologies, Inc., San Jose, CA, where he was involved with the development of wireless mobile terminals. In 2001, he joined the Samsung Advanced Institute of Ttechnology, Korea, as a Senior Researcher. His research interests include statistical signal processing and telecommunication systems.

Mary Ann Ingram (SM'84–M'89) received the B.E.E. and Ph.D. degrees in electrical engineering from the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1983 and 1989, respectively.

From 1983 to 1986, she was a Research Engineer with the Georgia Tech Research Institute, Atlanta, where she performed studies on radar electronic countermeasure (ECM) systems. In 1986, she became a Graduate Research Assistant with the School of Electrical and Computer Engineering, Georgia Tech, where in 1989, she became a Faculty Member and is currently an Associate Professor. Her early research interests were optical communications and radar systems. Since 1997, her research interests include the application of multiple antenna systems to wireless communications and measurement and modeling of the wireless channel.