Sidelobe Reduction through Subarray Overlapping for Wideband Arrays

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Abstract - For wideband arrays, the contiguous subarray architecture using phase shifters at the element level and true time delays at the subarray level results in higher sidelobes due to subarray dispersion and grating-lobe generation. In this paper, sidelobe reduction using overlapping subarray architecture is discussed. The architecture is effectively applied to an experimental AMRF-C (Advanced Multifunction RF Concept program) receive system. It is shown that, in addition to aperture weight distribution at different stages, the overlap ratio between subarray aperture size and subarray step size primarily affects the array sidelobe performance. Excellent sidelobe reduction using overlapping subarray architecture and its applications to an experimental AMRF-C receive system. We show here that the "overlap ratio" between the subarray aperture size and the subarray step size primarily affects the array sidelobe performance. Sidelobe improvement by the aperture weight distributions at different stages is also discussed.

I. INTRODUCTION

For high gain phased array antennas, it is not feasible for cost and complexity reasons to process all array element outputs individually. It also greatly exceeds the degrees of freedom required for solving the interference cancellation problems if adaptive digital beamforming (ADBF) is implemented. In addition, the array antenna squints if the frequency-independent phase shifters are used at each element to steer the beam in wideband operation. Although the array size is not directly related to the absolute squint angle, it does affect the requirements for wideband operation. The array limited instantaneous bandwidth in percent is approximately equal to the array beamwidth in degree, which apparently is affected by the aperture size [1]. Therefore elements of large arrays are often contiguously grouped into subarrays [2]. The array is steered via phase-limited phase shifters at the element level and time delays at the subarray level. The time delays at the subarray level can be implemented using switched delay lines, fiber optics delay lines or digital processing. In this paper, we consider digital processing at the subarray level. This type of (partial) digital beamforming performed at the subarray level makes it possible to generate multiple cluster beams and achieve pattern control or interference cancellation simultaneously.

For wideband arrays, due to subarray dispersion and grating-lobe generation, the above subarraying and partial digital true time-delay beamforming architecture results in higher sidelobes. Appropriate weighting at the subarray level controls the array pattern of subarrays (the array factor) to some extent. However, the grating lobes are hardly eliminated. The beam broadening caused by the applied weights further degrades the sidelobe performance. Although frequency diversity and frequency management will somewhat improve the performance, the strategy can only be applied to very specific cases. To reduce the array sidelobes, one option considered in the design of AMRF-C array antenna is to implement the overlapping subarray architecture. This allows us to push the grating lobes away from the mainlobe and shape the subarray patterns in such a way that all grating lobes are suppressed in the subarray's low sidelobe region.

This paper describes in detail the array sidelobe reduction using overlapping subarray architecture and its applications to an experimental AMRF-C receive system. We show here that the "overlap ratio" between the subarray aperture size and the subarray step size primarily affects the array sidelobe performance. Sidelobe improvement by the aperture weight distributions at different stages is also discussed.

II. SUBARRAY ARCHITECTURE AND PARTIAL DIGITAL BEAMFORMING

Digital beamforming at the element level for a large array is not feasible due to the per-element cost and complexity. The computation requirements at the present time for such an architecture also prohibit its implementation. It indeed has more degrees of freedom that than are required to solve the interference cancellation problems if ADBF is implemented. Therefore, subarraying and partial digital beamforming is frequently employed in phased arrays. Figure 1 shows a generalized form of this subarray architecture. From the ADBF viewpoint, this configuration can be considered as the "adaptation before beamforming by direct subarray weighting", which is in contrast with the "post-beamforming adaptation" such as in a generalized sidelobe canceller system.

In Fig. 1, the array is steered via phase-limited phase shifters at the element level and time delays D at the subarray level. Aperture tapering at Stage 1 and pattern optimization at Stage 2 are used to control the overall sidelobe performance. Minimum amplification spread and equalization of A/D gain and noise power may be achieved through appropriate weight control at each stage. If ADBF is implemented, the processor P calculates the optimal covariance matrix $\hat{Q}$ at the subarray output through matrix transformation $\hat{Q} = T^H QT$, where $Q$ is the covariance matrix
of the element outputs and \( T \) is a matrix transferring signals to those at the subarray level. The beamforming network then forms a beam with optimal weighting \( W_{opt} = \hat{Q}^{-1}W \)
where \( W \) is the final weighting at Stage 2. Multiple cluster beams can be generated through the signal divider at the element level (not shown here) and the control of true time delays at the subarray level.

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\[ \text{Stage 1} \rightarrow \text{Processor, P} \]

\[ \text{Stage 2} \rightarrow \Sigma \text{ or } \Delta \]

Fig. 1 A generalized subarray architecture (Partial digital beamforming by direct subarray output weighting).

The subarray architecture is being implemented in the design of the AMRF-C array antennas. The AMRF concept is a multi-band, multi-functional RF system, which employs shared apertures to reduce the number of antennas on the ship. The integrated AMRF-C system would have the capabilities of performing the combined radar, communication and electronic warfare functions. The AMRF-C basic structure is the physical separation of receive and transmit arrays and the partitioning of the 1-20 GHz frequency coverage into two bands. The initial AMRF-C low-band (1-5 GHz) experimental system arbitrarily uses an element spacing of 1.6" and is capable of generating 3 to 24 independent beams depending on the allocation of the proposed 8 subarrays.

III. ARRAY PERFORMANCE

A narrowband phased array with contiguous subarray architecture shows superior performance when aperture tapering is applied across the entire array. However, for wideband signals, the non-identical subarrays (due to the tapering) squint with frequency and cannot be coherently combined to form an array with desirable low-sidelobes [3]. Indeed, when the frequency is changed over a wide bandwidth \( \Delta f \), the subarray beam squints by an angle \( \Delta \theta = -(\Delta f/f) \tan \theta_s \). The beam squinting is most noticeable for large scan angles \( \theta_s \) and is not affected at the boresight [1]. This beam squinting along with the formation of grating lobes in the array factor complicates the coherent combination of subarrays, causing a loss in array gain as well as degradation in sidelobes.

If complex aperture weight distributions are used at the subarray level, the array factor will be broadened which further degrades the sidelobe performance. In the following, we first consider a linear array combining 8 subarrays with 8 elements each. Figure 2a depicts the uniform subarray pattern and array factor for this contiguous subarray system where a -40 dB, \( H = 8 \) Taylor weighting is applied at the subarray level. Figure 2b indicates the resultant array pattern. The array is scanned to 30° off boresight at the frequency of 3.175 GHz, which is 250 MHz off from the center frequency of 3.3 GHz. Clearly the sidelobes are split and the peak sidelobe level is raised to -18 dB. Also seen in Fig. 2a is the movement of the subarray pattern away from the broadside due to the decrease of operating frequency. Further degradation occurs if the outer beams of a cluster beam are generated through digital true time delays at the subarray level and moved at the directions opposite to the squinting subarray.

As a logical step, we considered improving the sidelobe performance with digital beamforming at the subarray level. We derived weights through optimal processing as discussed in Section 2 to shape the array factor and minimize the grating-lobe effects. It became clear that deep nulls can be placed anywhere except at the mainbeam and grating lobe directions without suffering severe penalty on array performance. Other approaches to improving sidelobe performance include the use of (1) irregular subarrays, (2) pattern average over the bandwidth, (3) time delays at the element level [4], and (4) overlapping subarray architecture. The approach (4) and its applications are discussed next.

![Figure 2a](image-url)
IV. OVERLAPPING SUBARRAY ARCHITECTURE FOR A WIDEBAND ARRAY

In reference to Figs. 1 and 2a, we know that the grating lobes at the subarray level cause higher sidelobes. One possible way to improve sidelobes performance is to control the subarray patterns in such a way that all grating lobes are suppressed in the subarray's low sidelobe region. With the considerations of beam squinting caused by the wideband operation and beam broadening by the subarray shaping, we must push the grating lobes far away from the mainbeam (see Fig. 2a). Since the distance between the subarray phase centers, defined here as the "subarray step size", determines the grating lobe locations, the above tactics can be realized through the overlapping of subarrays. Figure 3 shows the partially overlapping subarray architecture which is applicable to the AMRF-C receive system.

In an ideal case, we would like to have the grating globes away from their mainbeam as far as possible while keeping the subarray beam reasonably small. As an example, we use 16 beam switching and forming networks as configured in Fig. 3 to form an array. Figure 4a shows the array factor with a $-40$ dB, $n=8$ Taylor weighting and the subarray pattern that is shaped by an optimum process, i.e., having nulls positioned at the grating lobe locations. Note that, in this linear array case, the first grating lobe initially locating at $13^\circ$ in a contiguous system (see Fig. 2a) has moved to near the subarray's second null location at $-3.4^\circ$. Figure 4b indicates the resultant array pattern. In Fig. 5, a Taylor weight ($-40$ dB, $n=8$), instead of an optimum weight, is applied to the subarray elements to suppress the grating lobes. Both Figs. 4 and 5 demonstrate adequate sidelobe performance with a peak sidelobe level near $-40$ dB.
sizes of 8, 6, 4 and 3 elements are used to form the resultant arrays. The actual array sizes are 64, 62, 68 and 68 elements, respectively. It is shown in Fig. 6 that the first peak sidelobes are farther away from the mainbeam when \( \rho \) becomes larger. The grating lobes can be suppressed to below \(-40\) dB when the overlapping ratio is 2 or larger.

V. SIDELOBE REDUCTION USING OVERLAPPING SUBARRAY ARCHITECTURE

It is clear from the general array principle that the subarray aperture size and weight distribution determine the subarray beamwidth and null positions. For instance, the first-nulls of a subarray pattern occur at \( \theta_n \) such that
\[
\sin \theta_n = \sin \theta = \pm \frac{\lambda}{s} \text{ or } \pm \frac{\lambda}{d} \text{ when the uniform or Hamming weighting is applied, respectively. Here } s \text{ indicates the "subarray aperture size" and } \theta_n \text{ is the subarray scan angle.}
\]
In addition, the grating lobes, such as those in the array factor discussed in Sections III and IV, appear at \( \theta_G \) with \( \sin \theta_G = \sin \theta = \pm \frac{n}{d} \) and are independent of the weight distribution. Here \( \lambda \) is the wavelength, \( n \) is an integer, and \( d \) is the subarray step size defined previously. Accordingly, with a given weight distribution, the variable \( \rho = s/d \) controls the relative position between the grating lobes and the subarray’s first-nulls. This parameter, the subarray overlap ratio, is the ratio between the subarray aperture size and the subarray step size and indeed characterizes the array sidelobe performance.

Although a larger \( \rho \) is needed for lower sidelobes as discussed above, this subarray overlap ratio must be compromised with the design cost and complexity and kept as small as possible. In shaping the subarray patterns, application of amplitude weights, as compared to the application of optimal weights that are complex, is equally effective and simpler (Fig. 5 vs. 4b). Again considering the configuration with 8 elements per subarray as in Fig 5, we show in Fig. 6 the linear array patterns for different subarray overlap ratios, \( \rho = 1, 1.3, 2 \) and 2.7. Here the operating frequency is 3.175 GHz, off slightly from the center frequency of 3.3 GHz. Also 8, 10, 16 and 21 subarrays (beam forming networks) with the respective subarray step

Figure 7a shows the subarray patterns for \( \rho = 2 \) over a wide bandwidth extending from 3.05 GHz to 3.55 GHz, i.e., with an instantaneous bandwidth of 500 MHz (±250 MHz). The subarray patterns at off-center frequencies are broadened and squinted toward or away from the broadside with some gain loss. However, all the pushed-away grating lobes formed on the array pattern of subarrays are suppressed. Figure 7b shows the resultant array patterns at the frequencies 3.3, 3.05 and 3.55 GHz. All peak sidelobes are below \(-40\) dB.

Figure 7a The wideband subarray patterns.
VI. APPLICATION TO A PLANAR ARRAY

Here we apply the overlapping subarray architecture to an experimental AMRF-C receive system. We simply expand the linear overlapping subarrays shown in Fig. 3 into a two-dimensional configuration. The subarray overlap ratio of 2 is considered. In this case, the planar array requires 4,624 (68x68) radiation elements from which the signals (except those at array corners) are divided and fed into two or four beam switching and forming networks. The total number of subarrays formed is 256 and parts of the subarrays are overlapped, double-overlapped or non-overlapped. The required 256 beam switching and combining networks function the same way as in a comparable case where contiguous subarrays are used. In applying overlapping architecture to a planar array, the complexity comes from the installation and packaging of signal dividers incurred to the shared array elements. Figures 8 through 10 show the 2-D color pattern plots at the frequencies of 3.3, 3.05 and 3.55 GHz. Clearly the azimuth-cut array patterns are nearly the same as those shown in Fig. 7b for a linear array case. It is interesting to see in Figs. 8 through 10 that all the sidelobes appearing on and off the principal axes are below -40 dB.

For a fair comparison (by considering the same subarray step size), we show in Fig. 11 the resultant pattern for the same 4,624 element array which contains 289 contiguous subarrays with 4x4 elements each at the frequency of 3.55 GHz (250 MHz off the center frequency). The array patterns at the principal axes are shown in Fig. 12 by the red lines for the contiguous case and the blue lines for the overlapping case. In both cases, the grating lobes have been pushed away from the mainbeam due to the subarray step-size reduction. However, it is impossible to shape the subarray pattern in the contiguous case to suppress all the grating lobes below -40 dB.

Fig. 7b The wideband array patterns.

Fig. 8 The array pattern with overlapping planar subarrays at 3.3 GHz.

Fig. 9 The array pattern with overlapping planar subarrays at 3.05 GHz.

Fig. 10 The array pattern with overlapping planar subarrays at 3.55 GHz.
The array pattern with overlapping planar subarrays at 3.05 GHz.

The array pattern with overlapping planar subarrays at 3.55 GHz.

The array pattern with contiguous planar subarrays at 3.55 GHz.

The azimuth and elevation cuts for array patterns in Figs. 10 and 11.

VII. CONCLUSIONS

Subarray architectures with a phase shifter at each element and true time delay at each subarray are used for large phased arrays to reduce the cost, complexity and computation. For wideband signals, the subarray architecture can also improve the limitation of instantaneous bandwidth. However, the sidelobe performance is severely degraded due to subarray dispersion and grating-lobe generation in the array factor. It is shown here that sidelobe performance can be greatly improved using overlapping subarray architecture. The results are first demonstrated for a linear array. Similar results are obtained for a planar array designed for use in the AMRF-C receive system. The overlap ratios between the subarray aperture size and the subarray step size primarily affect the array sidelobe performance. Excellent sidelobe performance is achieved over a large bandwidth when the overlap ratio is close to 2 and typical Taylor weight distributions are used at both element and subarray levels.

REFERENCES


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