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Overview of Recent Subarray Applications in Wide-Angular Scanning Linear Arrays

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Abstract

Subarray application for increasing the wide-angular scanning capability of a linear array is discussed in this paper. The original linear array is a sparse array where element locations fit in a $\lambda/2$ grid. Empty places in the grid allow for integrating small subarrays. There are two subarray configurations considered, in-line and cross-line subarrays. The in-line subarray is a 3 elements array with the extra element on the left and right sides of the center element. This subarray has been proven to compensate for the scan-loss and to suppress the sidelobes by optimizing the subarray pattern. In the optimum subarray, the phase relative to the center element equals $\Psi = \pm 140°$ because this value gives the best trade-off between a high pattern at the direction of scanning and a null pattern in the other direction. The cross-line subarray utilizes extra elements on top and bottom of a center element in the dense part of a linear array. In the paper, we consider the case of a linear dense array with 41 elements. After sparsing and addition of phase shifters, inline subarray elements are positioned in empty places. The elements in the center part of the linear array are replaced by cross-line subarrays. When the antenna is scanned to large scan angles, this array exhibits 2.7 dB increase in directive gain, scan loss reduction of 1.3 dB and 3.9 dB lower peak sidelobe level (PSLL) compared to a uniform linear array (ULA) with the same length.

1 Introduction

In modern radar applications, a wide-angular beam scanning capability becomes highly demanded. The beam scanning is realized by adjusting the phase excitation of each array element using phase shifter. However, the directive gain while scanning will be reduced significantly by the element pattern (EP), particularly when scanning from $-60°$ up to $60°$ with respect to the determined broadside direction of the antenna's facet.

In a typical radiator with a $\cos(\theta)$-type pattern, a 6-dB loss is obtained at $\pm 60°$. This degradation is not suitable for the preferred application and needs to be tackled. The solution must not only focusing on the scan-loss compensation (SLC), but also the first sidelobe level (FSLL) for the sensitivity and the PSLL for the false-alarm mitigation.

In the recent papers [1-6], the use of subarrays with an optimized pattern integrated into an array can significantly overcome this issue. The optimized subarray pattern can compensate for the scan-loss in the scanned direction while keeping the SLL low on the other side. The subarrays are located in the empty spaces of the sparse linear array configuration. Therefore, this paper summarizes subarray applications for increasing wide-angular scanning performance.

There will be two subarray configurations discussed in this paper. The first subarray locates the extra elements in-line with the array axis. This configuration has two purposes, for realizing the desired pattern and for compensating scan-loss while keeping the sidelobe level (SLL) as low as possible. Meanwhile, the second subarray locates the extra elements perpendicular to the array axis. This configuration can increase the directive gain with the consequence of reducing the beamwidth of the elevation pattern.

2 Subarray In-Line with the Array Axis

A. Subarray for Realizing the Desired Pattern

The subarray needs to be optimized to produce the desired pattern before applying to the array configuration. In this example, the desired pattern should be able to compensate the EP with a $\cos(\theta)$-type pattern. In [3, 4], the subarray with three elements is used and located in a $\lambda/2$ grid. All elements get the same phase feeding via a power divider. The amplitude of the subarray elements are adjusted such that EP compensation is realized.

The result of the subarray optimization is a subarray with amplitudes of A = [-0.145; 1; -0.145], for the left, center, and right side elements, respectively. By employing an isotropic radiator, this subarray produces a (blue-colored) pattern shown in Fig. 1. It can be seen that the pattern at broadside direction is slightly low, -0.14 dBi, but it enhances significantly up to 4.87 dBi at 60°. This pattern is preferred to be the desired pattern for this application.

The subarray pattern multiplied by the $\cos(\theta)$ together with the $\cos(\theta)$-pattern are indicated with a purple and black-dashed line colors in Fig. 1, respectively. By observing these patterns, it can be seen that the pattern of the subarray times $\cos(\theta)$ has only 2.2 dB degradation in the broadside direction, but it is 2.8 dB higher than $\cos(\theta)$ pattern at 60°. This improvement is essential because the pattern degradation can be compensated almost two times higher by using an optimized subarray pattern. To conclude with, the amplitude of the subarray can be adjusted to

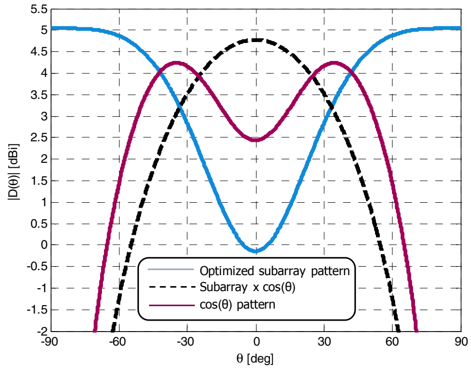


Figure 1. Optimized Subarray pattern compared with $\cos(\theta)$ patterns.

obtain the desired pattern for compensating the degradation by the EP in a wide-angular scanning array.

B. Subarray for Compensating Scan-Loss and Suppressing the SLL

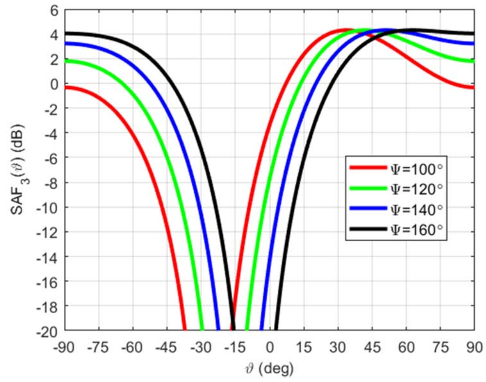
In a wide-angular scanning application, scan-loss is strongly affected by the EP shape. Therefore, in the previous section, the amplitudes of the subarray elements are optimized to produce a desired pattern for compensating the degradation. However, the scanned array pattern results still have a high SLL [3, 4]. In [1], the optimization of the subarray pattern includes the amplitude and phase of the subarray elements located in a $\lambda/2$-grid.

The array is thinned to produce empty spaces for accommodating the subarrays. Thinning techniques such as Cyclic Difference Sets (CDS) [7] and Dynamic Programming (DP) [8] have been used due to a no grating-lobe in the array pattern [3, 4]. In addition, these techniques are producing many empty spaces and can accommodate up to seven 3-element subarrays.

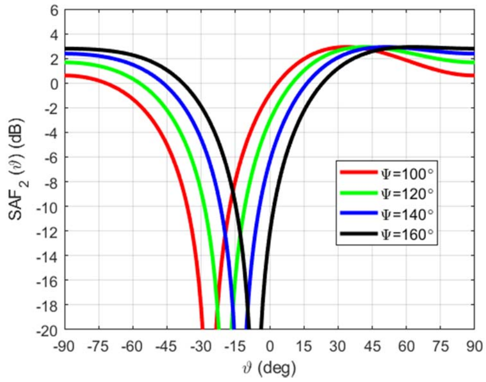
A different thinning technique is used in [1], it produces empty spacing by calculating the Moving Average (MA) of a selected amplitude distribution with the same length as the array configuration. The detailed steps are already discussed in [1]. This configuration can accommodate four 3-element subarrays and two 2-element subarrays.

In [1, 4, 5] the subarray demonstrators are realized and measured. There are two types of subarrays which are realized, 3-element and 2-element subarrays. The demonstrator including the power divider network. Some power divider designs that have been realized and implemented for these subarrays are reported in [1, section IIIC]. These designs completely rely on the coupler structures to govern the amplitude distribution over the subarray, thereby avoiding the use of attenuators that can degrade power efficiency.

For compensating the scan-loss, one of the most important parameters of the subarray optimization is Ψ value. It determines the phase of subarray elements relative to its center element to produce a scanned subarray pattern in the direction where the array is scanned [1]. The scanned subarray pattern can compensate for the scan-loss and also suppressing the SLL. Therefore, the analysis of this parameter becomes an essential and important subject in this paper.



(a)



(b)

Figure 2. Subarray patterns with Ψ value variations. (a) 3-element subarray, (b) 2-element subarray.

The pattern formulation of the 3-element subarray SAF_3 is shown in Eq. (1),

$$SAF_3(\vartheta) = \sum_{n=1}^{3} A_n e^{jkx_n \sin(\vartheta)+\alpha_n} \quad (1)$$

Where,
A_n is the amplitude of the n-th element,
k is the wave propagation factor,
x_n is the location of the n-th element,
ϑ is the observation angle, and
α_n is the phase shift factor for the n-th element.

For 3-element subarray, the phase shift factor of each element is determined as,

$$\begin{aligned} \alpha_2 &= -kx_2\sin(\vartheta_0) \\ \alpha_1 &= \alpha_2 + \Psi \\ \alpha_3 &= \alpha_2 - \Psi \end{aligned} \quad (2)$$

The phase of the center element is indicated with α_2, while α_1 and α_3 determine the phase of the left and right side elements, respectively. The use of $+\Psi$ and $-\Psi$ in element left and right side elements are for scan-loss compensation application purposes. A detailed explanation can be found in [1].

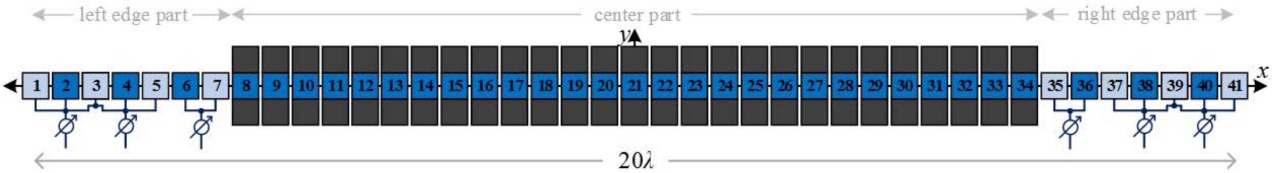


Figure 3. Linear array configuration with integrated in-line and cross-line subarrays in the center part. The cross-line subarray elements are indicated with black squares.

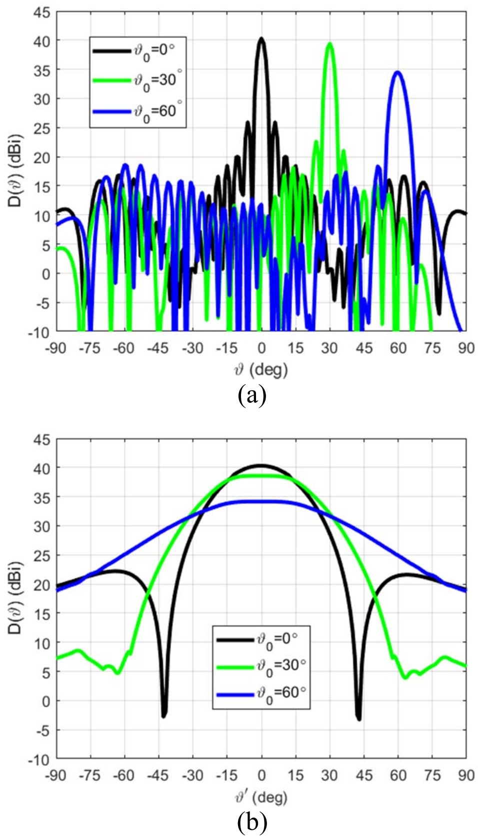


Figure 4. Patterns while scanning of the array presented in Fig. 3. (a) H-plane, (b) E-plane.

Meanwhile, the pattern formulation of the 2-element subarray SAF_2 is shown in Eq. (3),

$$SAF_2(\vartheta) = \sum_{n=1}^{2} A_n e^{jkx_n \sin(\vartheta) + \beta_n} \tag{3}$$

Where, β_n is the phase shift factor for the *n*-th element and determined as,

$$\begin{aligned} \beta_1 &= -k(x_1 + 0.25)\sin(\vartheta_0) + \frac{\Psi}{2} \\ \beta_2 &= -k(x_2 - 0.25)\sin(\vartheta_0) - \frac{\Psi}{2} \end{aligned} \tag{4}$$

β_1 is the phase of the left element, while β_2 is the phase of the right element. The use of $+\frac{\Psi}{2}$ and $-\frac{\Psi}{2}$ have the same purpose as in the 3-element subarray.

The analysis of the subarray pattern is conducted by adjusting the Ψ value. It starts from 100° to 160° with 20° steps. The values of A_n and x_n have been determined in [1]. Besides that, an isotropic radiator is used in this analysis. The pattern plots for 3-element and 2-element subarrays with Ψ value variation are shown in Fig. 2a and 2b.

It can be observed from Fig. 2 that the mainlobe is located in the positive ϑ angle, while the pattern null is located in the other direction. This high mainlobe is for compensating the EP, while the null is for suppressing the SLL. The subarray pattern is shifted more to the right (positive ϑ angle) when the Ψ value is increased. From our analysis, we selected $\Psi = 140°$ because it gives the best performance among all values and the reason can be seen here (Fig. 2). The subarray pattern for $\Psi = 140°$ has a high pattern at $\vartheta = 60°$, while the null is not precisely at $\vartheta = 0°$. This is important because a null at $\vartheta = 0°$ can significantly degrade the directive gain at broadside scanning.

3 Subarray Perpendicular with the Array Axis

In the previous section, the in-line subarrays with optimized patterns have been analyzed and integrated in the array. However, the in-line subarray can only be integrated when there are empty spaces in the linear array. This becomes a problem when limited spaces are provided by the array configuration.

Another subarray configuration, with the extra elements located perpendicular to the array axis, can be integrated in the dense part of the linear array. This subarray configuration is named as a cross-line subarray [6] with equal-split power divider between the top, middle, and bottom elements. This subarray can narrow the elevation beamwidth and increase directive gain due to the extra elements. The cross-line subarrays are only applied in the center part of the final configuration obtained from [1]. The integrated cross-line subarray in the center part of the linear array configuration is shown in Fig. 3. The extra elements of the cross-line subarrays are indicated with black squares and located in the top and bottom from 8th to 34th elements.

The H-plane and E-plane pattern plots while scanning of this configuration are shown in Fig. 4a and 4b, respectively. All SLLs in the H-plane patterns are below -13 dB. It also can be observed that the maximum directive gain is higher than the scanned pattern in [1]. The SLL of the H-plane pattern is marginally affected. In addition, the widest E-plane pattern beamwidth is at 60° scanning while for the broadside and 30° scanned pattern low side lobes appear.

Table 2 summarizes the array scanning performance between ULA, array with and without cross-line subarrays

Table 2. Key radiation performance of arrays with and without cross-line subarrays in the center part and ULA configuration

Cross-line Sub.	Scanning θ_0	D_{max} (dBi)	Scan-Loss (dB)	HPBW (deg)	FSLL (dB)	PSLL (dB)
No [1]	0°	35.8	0.0	3.3	-15.3	-15.3
	30°	35.5	-0.3	2.9	-17.9	-17.9
	60°	30.7	-5.1	5.1	-15.8	-13.8
Yes	0°	40.3	0.0	3.4	-14.4	-14.4
	30°	39.4	-0.9	3.3	-16.8	-16.8
	60°	34.5	-5.8	5.8	-16.1	-15.8
ULA	0°	38.9	0.0	2.3	-13.3	-13.3
	30°	36.9	-2.0	2.6	-13.6	-13.6
	60°	31.8	-7.1	4.8	-11.9	-11.9

in the center part. The use of cross-line subarrays are strongly affecting the directive gain and elevation beamwidth. When the cross-line subarrays are used, the maximum directive gain is 4.5 dB higher at broadside and 3.8 dB higher at 60° scanning compared with an array without cross-line subarray. When compared with ULA, 0.4 dB and 2.7 dB increments of the maximum directive gain are obtained at broadside and 60° scanning, respectively. The elevation beamwidth is, therefore, narrower than ULA and without cross-line subarrays. A narrow beam pattern can increase the resolution in radar application. Meanwhile, the FSLL and PSLL are marginally affected by the cross-line subarray except for the PSLL at 60° scanning, which is -2 dB and -3.9 dB lower than without cross-line subarray and ULA, respectively. In addition, the scan-loss becomes 0.7 dB larger due to the use of cross-line subarrays, but still smaller than ULA. This is unavoidable because this configuration has no extra scan-loss compensation in the center part filled with cross-line subarrays.

4 Conclusions

Applications of subarrays integrated in a linear sparse array for increasing the wide-angular capability have been discussed. All elements in the sparse array have constant amplitudes and use phase shifters for beam scanning. The in-line subarray, formed by the extra elements in-line with the array axis, is applied for realizing such a desired pattern, for compensating scan-loss, and also for suppressing the SLL. The optimization of the subarray pattern was conducted by adjusting the amplitude and phase of the subarray elements. The cross-line subarray, formed by the extra elements perpendicular to the array axis, gives the following performance enhancement: 2.7 dB peak directive gain increment, 4.2 dB and 3.9 dB lowering of the FSLL and PSLL, respectively, and up to 1.3 dB improvement of the maximum directive gain at 60° scanning compared with a ULA with the same length. If desired, further optimization of both in-line and cross-line subarrays can be done to achieve a better trade-off among those three performance parameters.

5 Acknowledgments

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