Auxiliary Array Optimization for Suppressing Co-site Spurious Interference with a Sidelobe Canceller

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***Abstract*—As the transmission power of radar and electronic warfare systems increases overtime in order to improve the performance, spurious interferences, i.e., emissions in the out-of-band spectrum, become potential threats to co-site wireless communication systems. Sidelobe Cancellation (SLC) is a promising technique for suppressing the spurious interferences. However, its performance depends on the configuration of the auxiliary array which offers the adaptive beamforming capability for interference suppression. In this paper, we propose a criterion based on interference statistics, with which the auxiliary array configurations can be evaluated easily such that it can be optimized. Simulations are then conducted to demonstrate the effectiveness and the excellent convenience of the proposed criterion.**

Keywords—sidelobe cancellation; spurious interference; co-site interference; interference cancellation; auxiliary array optimization

I. INTRODUCTION

Spurious signals emitted by high-power large phased arrays of radar and electronic warfare systems can potentially interfere co-sited wireless communication systems in adjacent frequency bands [1]. This problem is traditionally tackled by employing passive spatial and/or spectral isolation techniques. However, the passive techniques usually provide limited isolations, and are not flexible especially for space-limited platforms like vessels. A promising active interference suppression method to is to use the Sidelobe Cancellation (SLC) technique [2]. SLC requires an auxiliary array to provide adaptive beamforming capability to realize interference suppression, while the configuration of the auxiliary array is critical for the performance of SLC [3].

Currently, there is no existing method for optimizing the auxiliary array configuration of SLC for suppressing co-site spurious interference from large phased arrays. Although there are studies about auxiliary array configuration for anti-jamming purposes, these methods cannot apply here since the interference model is distinctive. To be specific, a few jammers in the far-field with unknown directions are commonly assumed in these studies [3]. However, for the problem here, the large phased arrays are located at the same site of the victim communication systems; and the spurious signals from all antennas of the large phased array are independent [4], so each antenna (or the corresponding transmitter) should be seen as an interferer. Namely, there are hundreds to thousands of interferers located at a fixed position in the near-field.

In this paper, we come up with a simple criterion that is based on interference covariance matrices, to evaluate the performance of the auxiliary array configuration, which can then be used as an objective function for optimization purposes. The proposed criterion considers the fact that the interferer (i.e., the large phased array) is fixed and the environment (i.e., the vessel) is static. Therefore, the interference statistics, in particular the interference covariance matrices, can be easily obtained by simulations or measurements, and then used for optimizing the auxiliary array.

The remaining of the paper is organized as follows. Section II presents the mathematical models of SLC, the proposed optimization criterion, and an interference model to be used in later simulations. Section III provides simulation results to demonstrate the effectiveness of our proposal. Conclusions are drawn in Section IV.

II. SYSTEM MODEL

In this section, we present the mathematical models for SLC with an auxiliary array, followed by a criterion that is proposed for optimizing the auxiliary array configuration.

A. SLC Model

The basic principle of SLC with an auxiliary array is depicted in Fig. 1.

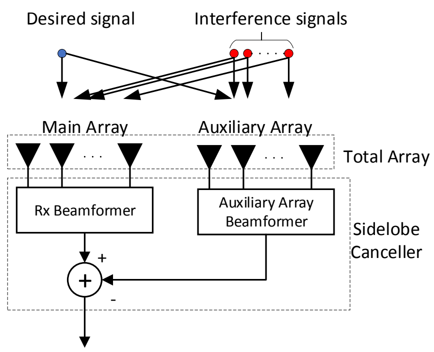

Fig. 1 SLC Model.

The output signal of the sidelobe canceller is

$$e = \mathbf{w}_{\mathrm{q}}^{\mathrm{H}}\mathbf{x}_{\mathrm{M}} - \mathbf{w}^{\mathrm{H}}\mathbf{x}_{\mathrm{A}} \tag{1}$$

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where $\mathbf{w}_q$ is the beamforming vector of the main array, $\mathbf{w}$ is the auxiliary array beamforming vector, $\mathbf{x}_M$ is the signal vector of the main array, and $\mathbf{x}_A$ is the signal vector of the auxiliary array. Define

$$\mathbf{x}_M = \mathbf{s}_M + \mathbf{c}_M + \mathbf{n}_M \tag{2}$$

$$\mathbf{x}_A = \mathbf{s}_A + \mathbf{c}_A + \mathbf{n}_A \tag{3}$$

where $\mathbf{s}$ is the desired signal vector, $\mathbf{c}$ is the interference signal vector, and $\mathbf{n}$ is the noise vector. Note that, the interference signals from all antennas of the large phased array are mutually uncorrelated, and also uncorrelated with the desired signals [4].

It can be derived from the results in [2] that the optimal beamforming vector of the auxiliary array is given by

$$\mathbf{w}_{\text{opt}} = \mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\mathbf{w}_q \tag{4}$$

where $\mathbf{R}_{\text{c,aux}} = \text{E}\left((\mathbf{s}_A + \mathbf{n}_A)(\mathbf{s}_A + \mathbf{n}_A)^H\right)$ is the interference-plus-noise covariance matrix, and $\mathbf{R}_{\text{c,aux-main}} = \text{E}\left((\mathbf{s}_A + \mathbf{n}_A)(\mathbf{s}_M + \mathbf{n}_M)^H\right)$ is the cross-variance matrix of the interference-plus-noise between the auxiliary array and the main array.

The SINR before cancellation is

$$\text{SINR}_{\text{before}} = \frac{\mathbf{w}_q^H\mathbf{R}_{\text{s,main}}\mathbf{w}_q}{\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q} \tag{5}$$

where $\mathbf{R}_{\text{s,main}} = \text{E}\left(\mathbf{s}\mathbf{s}^H\right)$ is the desired signal covariance matrix of the main array.

The SINR after cancellation is given by

$$\begin{aligned}\text{SINR}_{\text{after}} &= \frac{\mathbf{w}_q^H\mathbf{R}_{\text{s,main}}\mathbf{w}_q}{\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q - \left(\mathbf{R}_{\text{c,aux-main}}\mathbf{w}_q\right)^H\mathbf{R}^{-1}_{\text{c,aux}}\left(\mathbf{R}_{\text{c,aux-main}}\mathbf{w}_q\right)} \\ &= \frac{\mathbf{w}_q^H\mathbf{R}_{\text{s,main}}\mathbf{w}_q}{\underbrace{\mathbf{w}_q^H\left(\mathbf{R}_{\text{c,main}} - \mathbf{R}^H_{\text{c,aux-main}}\mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\right)\mathbf{w}_q}_{\text{residual interference-plus-noise power}}}\end{aligned} \tag{6}$$

The maximum SINR can be obtained when the interference is completely eliminated, i.e.,

$$\text{SINR}_{\max} = \frac{\mathbf{w}_q^H\mathbf{R}_{\text{s,main}}\mathbf{w}_q}{\mathbf{w}_q^H\mathbf{R}_{\text{n,main}}\mathbf{w}_q} = \frac{\mathbf{w}_q^H\mathbf{R}_{\text{s,main}}\mathbf{w}_q}{\mathbf{w}_q^H\mathbf{I}_{M_A}\mathbf{w}_q} \tag{7}$$

We then define *Interference Cancellation Ratio (ICR)* as

$$\text{ICR} = \frac{\text{SINR}_{\text{after}}}{\text{SINR}_{\text{before}}} = \frac{\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q}{\mathbf{w}_q^H\left(\mathbf{R}_{\text{c,main}} - \mathbf{R}^H_{\text{c,aux-main}}\mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\right)\mathbf{w}_q} \tag{8}$$

and

$$\text{ICR}_{\max} = \frac{\text{SINR}_{\max}}{\text{SINR}_{\text{before}}} = \frac{\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q}{\mathbf{w}_q^H\mathbf{I}_{M_A}\mathbf{w}_q} \tag{9}$$

B. The Proposed Optimization Criterion

We can observe that the amount of residual interference power depend on $\mathbf{R}_{\text{c,main}}$, $\mathbf{R}_{\text{c,aux-main}}$ and $\mathbf{R}_{\text{c,aux}}$, which are constant for a static scenario and fixed interference signal characteristics, considering long-term average. In addition, $\mathbf{R}_{\text{c,aux-main}}$ and $\mathbf{R}_{\text{c,aux}}$ are related to the auxiliary array configuration. However, $\mathbf{w}_q$ is a varying factor, which suggests that ICR and $\text{ICR}_{\max}$ varies. Therefore, a general criterion for optimizing the auxiliary array configuration is by examining the average ICR, denoted by $\text{ICR}_{\text{avg}}=\text{E}(\text{ICR})$. From Eq. (8), we see that it is hard to obtain close form of ICR_{avg}, therefore it is not a convenient measure for auxiliary array configuration optimization. To tackle this problem, we use a lower bound of it, i.e.,

$$\begin{aligned}\text{ICR}_{\text{avg}} &\geq \text{E}\left(\frac{\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q}{\left\|\mathbf{w}_q^H\right\|_F\left\|\mathbf{R}_{\text{c,main}} - \mathbf{R}^H_{\text{c,aux-main}}\mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\right\|_F\left\|\mathbf{w}_q\right\|_F}\right) \\ &= \frac{\text{E}\left(\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q\right)}{M^2\left\|\mathbf{R}_{\text{c,main}} - \mathbf{R}^H_{\text{c,aux-main}}\mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\right\|_F}\end{aligned} \tag{10}$$

The inequality follows from $\|\mathbf{ABC}\|_F \leq \|\mathbf{A}\|_F\|\mathbf{B}\|_F\|\mathbf{C}\|_F$, where $\|\cdot\|_F$ is the Frobenius norm. In addition, $\|\mathbf{w}_q\|_F = M_M$, where M_M is the number of antennas of the main array [2]. Notice that $\text{E}\left(\mathbf{w}_q^H\mathbf{R}_{\text{c,main}}\mathbf{w}_q\right)$ is a constant for a given scenario. Therefore, maximizing ICR_{avg} is equivalent to the following new criterion

$$\text{minimize } C = \left\|\mathbf{R}_{\text{c,main}} - \mathbf{R}^H_{\text{c,aux-main}}\mathbf{R}^{-1}_{\text{c,aux}}\mathbf{R}_{\text{c,aux-main}}\right\|_F \tag{11}$$

This new criterion is only related to the interference-plus-noise covariance matrices which can be measured or simulated in practice. The performance of auxiliary array configuration is connected with the criterion through $\mathbf{R}_{\text{c,aux-main}}$ and $\mathbf{R}_{\text{c,aux}}$.

C. Interference Model

For the convenience of analysis and illustration, we derive in the following the covariance matrices employing a number of assumptions:

- The antenna spacing between the antenna elements is a half-wavelength of the carrier frequency.
- The received interference signal power at the antennas is the same for all interferers.

- Each interferer is treated as a point source in line-of-sight of the receive antenna arrays with the same distances.

Therefore, the interferers can be modeled as far-field sources scattered in a limited angular region, i.e., a region limited by the azimuth (Az) and elevation (El) angles, as illustrated in Fig. 2.

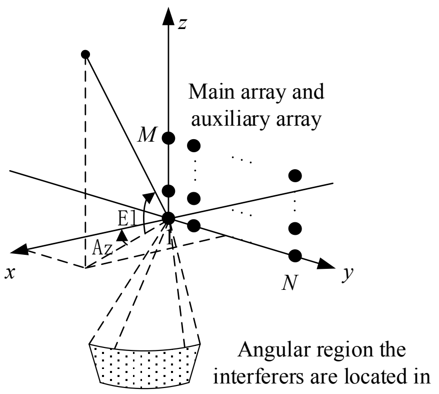


Fig. 2 Interference model and global coordinates.

As a result, we have

$$\begin{aligned}
\mathbf{R}_{\text{c,main}} &= p_{\text{c}} \cdot \frac{1}{L}\sum_{l=1}^{L} \mathbf{v}_{\text{M},l}\mathbf{v}_{\text{M},l}^{\text{H}} + \mathbf{I}_{M_{\text{M}}} \\
\mathbf{R}_{\text{c,aux}} &= p_{\text{c}} \cdot \frac{1}{L}\sum_{l=1}^{L} \mathbf{v}_{\text{A},l}\mathbf{v}_{\text{A},l}^{\text{H}} + \mathbf{I}_{M_{\text{A}}} \\
\mathbf{R}_{\text{c,aux-main}} &= p_{\text{c}} \cdot \frac{1}{L}\sum_{l=1}^{L} \mathbf{v}_{\text{A},l}\mathbf{v}_{\text{M},l}^{H} \\
\mathbf{R}_{\text{s,main}} &= p_{\text{s}} \cdot \mathbf{v}_{\text{M},0}\mathbf{v}_{\text{M},0}^{\text{H}}
\end{aligned} \tag{12}$$

where $\mathbf{v}_{\text{M},l}$ and $\mathbf{v}_{\text{A},l}$ are the array vectors of the l-th interferer w.r.t. the main and auxiliary arrays, respectively, $\mathbf{v}_{\text{M},0}$ is the array vector of the desired signal, p_{c} and p_{s} are the average INR and SNR respectively (i.e., normalized average interference power w.r.t. the noise power), M_{M} and M_{A} are the number of antennas of the main array and the auxiliary array respectively, and L is the number of interferers. Since $\mathbf{w}_{\text{q}} = \mathbf{v}_{\text{M},0}$ for a phased array , we have $\mathbf{w}_{\text{q}}^{\text{H}}\mathbf{R}_{\text{s,main}}\mathbf{w}_{\text{q}} = p_{\text{s}}M_{\text{A}}^{2}$. Due to the common term p_{c} in Eq. (12), the criterion in Eq. (11) can be normalized as $\bar{C} = C / p_c$.

III. Numerical Results

In this section, numerical results are provided to examine the effectiveness of the proposed optimization criterion. A number of auxiliary array configurations are considered for different interference scenarios.

A. Demonstration of SLC for Co-site Spurious Interference Suppression

First, we provide some examples to showcase the suppression of co-site spurious interference. We assume that the average INR at the antenna elements is 30dB, and the SNR is 10dB. The main array size is of $M = N = 8$. The main beam is steered to [0°, 0°]. The interferers are located on a uniform grid in an angular region with Az = -45°~45°, and El = -90°~-45°. The number of bins in the azimuth is N, and M in the elevation.

Three auxiliary array configurations are analyzed, which are shown in Fig. 3, where the empty circles are the main array elements, and the filled circles are the auxiliary array elements.

A convenient way to illustrate the result of SLC is by inspecting the beam pattern of the total array. Fig. 4 presents the original main array patterns, and the total array patterns after adaptation using the three auxiliary array configurations. The red rectangles indicate the angular position of the interferers.

The ICR of the three configurations are 49dB, 36dB, and 51dB, respectively. Therefore, configuration 1 and 3 perform equally well, and much better than configuration 2. As we can see, a better auxiliary array configuration results in a deep broad null in the interference region, corresponding to the high ICR.

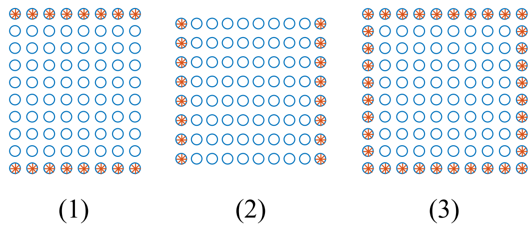
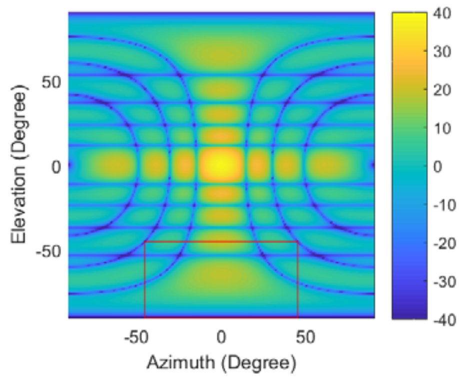
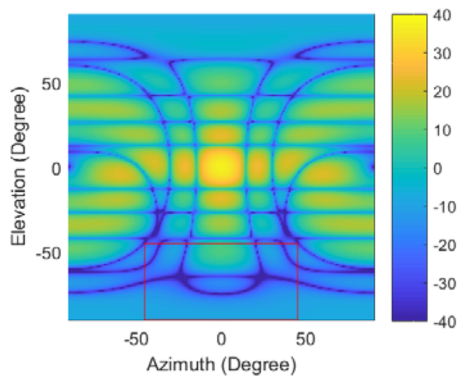


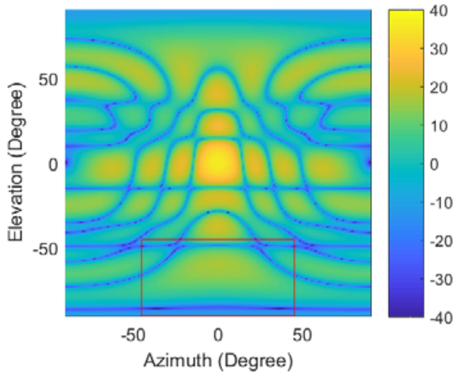
Fig. 3 Auxiliary array configurations: (1) Upper and lower (2) Left and right (3) Surrounding.



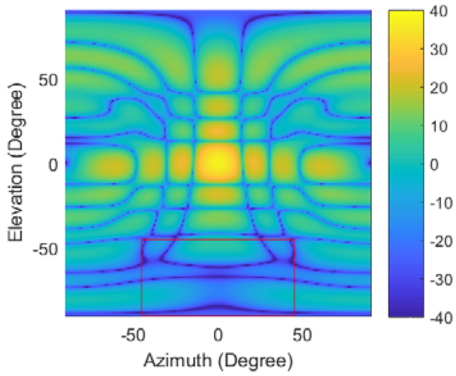
(a) Original main array pattern



(b) Auxiliary array configuration 1



(c) Auxiliary array configuration 2



(d) Auxiliary array configuration 3

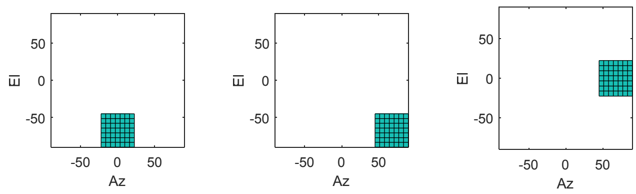
Fig. 4 Beam patterns of the original main array pattern and the total array after adaptation with different auilixary configurations.

B. *Auxiliary Array Optimization*

Now we turn to the evaluation of our proposed optimization criterion for selecting the auxiliary array configuration. We assume that $M = 16$, and $N = 8$. The average INR is 30dB, and average SNR is 10dB. Three auxiliary array configurations of the same style in the last subsection are considered. In addition, three interference scenarios are considered, which are illustrated in Fig. 5: (A) Az = -22.5°~22.5°, El = -90°~-45°; (B) Az = 45° ~90°, El = -90°~-45°; (C) Az = 45°~90°, El = -22.5°~22.5°. The interferers are uniformly spread in the angular bins. The number of bins in the azimuth is N, and M in the elevation. The main beam direction are restricted in the angular region, Az = -45° ~45°, El = 0°~30°, which is split into a 11×11 grid.

Table 1 presents the normalized criterion value, average ICR, average ICR_{max}, and average ICR_{max}-ICR, in dB, for the scenarios and auxiliary array configurations mentioned above. The number of stars in the second column indicates the superiority of the auxiliary array configurations, the more stars the better. We can observe that:

- The proposed criterion correctly indicates the superiority of the auxiliary array configurations. That is, a low criterion value is correlated with a higher average ICR value or a lower average ICR_{max}-ICR.
- A rule-of-thumb is to place the auxiliary array next to the main array at the axis that the interferers and the main array are aligned in. For example, in Scenario C, the interferers are aligned with the main array in the horizontal axis (or azimuth), thus Configuration 2 performs better although it has fewer antennas.
- Configuration 3 is always the best choice in terms of performance, however, it uses more antenna elements than the other two. Since on a vessel platform, Scenario A and B are the usual case, Configuration 1 may be more preferred as tightly the same performance can be achieved but fewer antennas are used.



(A) (B) (C)

Fig. 5 Interference scenarios.

TABLE 1 CRITERION VALUE AND ICR FOR DIFFERENT SCENARIOS AND AUXILIARY ARRAY CONFIGURATIONS.

Scenario	Auxiliary Array	Norm. Criterion Value	Average ICR (dB)	Average ICR_{max} (dB)	Average ICR_{max}-ICR(dB)
A	1**	17.2107	53.1259		2.2865
	2*	31.8200	46.8876	55.4124	8.5248
	3***	11.6521	53.9093		1.5031
B	1**	0.8495	56.2396		0.3983
	2*	34.2971	46.7217	56.6379	9.9162
	3***	0.2558	56.4361		0.2018
C	1*	33.2299	43.5152		19.8395
	2**	27.5996	54.2437	63.3547	9.1110
	3***	23.7274	55.3436		8.0110

IV. CONCLUSIONS

In this paper, we have proposed a criterion for optimizing the auxiliary array configuration of SLC to suppress co-site spurious interference from large phased arrays. Simulation results have validated the effectiveness of the proposed criterion. In addition, a rule-of-thumb we have found is to place the auxiliary array next to the main array at the axis that the interferers and the main array are aligned in.

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