Minimum blind area model for auxiliary array optimization in interference cancellation

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The auxiliary array optimization is the key to performance of interference cancellation, especially for the wide operating frequency of radio communication and unknown direction of interference. The blind area rule is established and the minimum blind area model is proposed for auxiliary array optimization. After deriving and simplifying the analytical solutions of weights and signal-to-interference-noise ratio after cancellation, the proposed rule inherits communicable index of radio and requirements of anti-jamming, greatly reducing complexity. The proposed algorithm focuses on minimizing blind area after cancellation in view of this rule. Hence, it leads to a remarkable improvement of optimization efficiency with different direction of arrival of interference and wide-band operating frequency. Experiments based on communication radio demonstrate that the minimum blind area model is much efficient and promising for auxiliary array optimization of anti-interference.

Introduction: The anti-interference is an eternal problem in the communication community. Compared with active method including cognitive radio, the interference cancellation technique [1, 2] which can suppress interference while retaining useful communication signal is much suitable in the situation where the interference has entered.

Recently, auxiliary array design has attached intensive attentions from interference cancellation field, applied widely and successfully to various applications, such as communication [3, 4] and radar [5]. An auxiliary subarray is added to main antenna for suppressing sidelobe interference [6]. Some can multiplex the existing when the receivers are multiple antennas, such as multiple-input multiple-output system [7–9], but the communication radio has only one antenna. Hence, it is essential to add auxiliary array for radio when the strong interference strikes in communication, and the next task is to optimize the parameters of auxiliary array, especially for antenna spacing.

Auxiliary array optimization is limited to beam pattern [10], and the depth and width of nulling are to measure the inhibition ability of interference from different direction. A complementary sparse array switching strategy is proposed for adaptive sparse array design in view of beampatterns [11]. However, whether the signal-to-interference-noise ratio (SINR) after cancellation can ensure communication of radio is unknown, and it is closely related to signal-to-noise ratio (SNR) during communication and interference-to-signal ratio (ISR) before cancellation, number of auxiliary antennas, and communicable threshold of radio. There is no model to integrate them so that the optimization result based on pattern diagram alone may not be optimal. And besides, the communication of radio is in a wide frequency band, that is, the ratio of antenna spacing to wavelength is not fixed. The auxiliary antenna spacing optimization in view of various signal wavelength are rarely studied.

In this paper, one focuses on auxiliary array optimization for interference cancellation in wide-band communication and unknown interference direction scenario. To achieve this goal, the blind area rule is proposed and minimum blind area (MBA) model is established. Firstly, the analytical solutions of weights and SINR after cancellation are derived and simplified. Secondly, the blind area rule combining with radio communicable index is analyzed. Finally, the MBA model for auxiliary array optimization is constructed. Experiments are taken to compare proposed rule the classical, and the results show the state-of-the-art performance of proposed MBA model for wide-band communication and unknown interference direction scenario.

Preliminaries: In order to suppress interference for radio communication, an auxiliary array with $M-1$ antennas is added to the main antenna, which is omnidirectional in azimuth.

As seen from figure 1, and the spacing of element is δ, the array

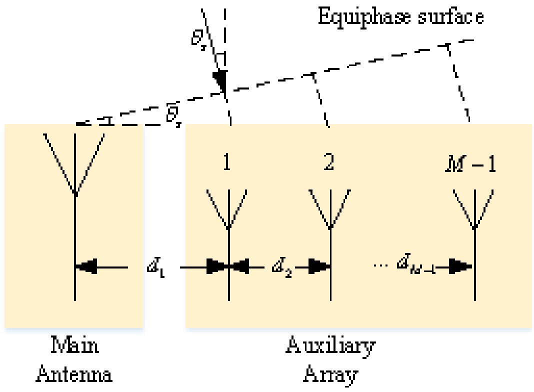

Fig 1 *Anti-interference array with auxiliary array.*

manifold is

$$\mathbf{a}(\theta) = \mathbf{g}(\theta) \odot \exp(-j \cdot \varphi(\theta)), \tag{1}$$

where $\varphi(\theta) = 2\pi\delta \sin(\theta)/\lambda$, θ is direction of arrival (DOA) of signal, and λ is wavelength.

Generally, the antenna of auxiliary and the main are omnidirectional for ultra-short wave communication, and $\mathbf{g}(\theta) = 1$, the received signals are

$$\mathbf{x}(t) = \mathbf{a}(\theta_S) \cdot s(t) + \mathbf{a}(\theta_J) \cdot j(t) + \mathbf{n}(t), \tag{2}$$

where $s(t)$,$j(t)$,$\mathbf{n}(t)$ represent communication, interference and noise signal, θ_S,θ_J represent DOA of communication and interference. The output signal after cancellation with weights $\mathbf{w}$ is

$$\mathbf{y}(t) = \mathbf{w}^{\mathbf{H}} \cdot \mathbf{x}(t), \tag{3}$$

and MMSE rule is adopted

$$\min E\left\{\|\mathbf{y}(t)\|^2\right\} \text{ s.t. } \mathbf{w}^{\mathbf{H}} \cdot \mathbf{a}(\theta_s) = 1. \tag{4}$$

Introducing Lagrange multipliers and setting partial derivative to zero, the adaptive weights can be calculated:

$$\mathbf{w} = R_{\mathbf{xx}}^{-1}\mathbf{a}(\theta_s)\left(\mathbf{a}^H(\theta_s) R_{\mathbf{xx}}^{-1}\mathbf{a}(\theta_s)\right)^{-1}. \tag{5}$$

Then the SINR γ after cancellation can be calculated by

$$\gamma = \frac{E\left\{\left|\mathbf{w}^{\mathbf{H}}\mathbf{a}(\theta_s)\, s(t)\right|^2\right\}}{E\left\{\left|\mathbf{w}^{\mathbf{H}}\mathbf{a}(\theta_J)\, j(t)\right|^2 + n(t)\right\}}. \tag{6}$$

Minimum blind area model: One can obtain the covariance of received under the irrelevant assumption between interference and communication:

$$R_{\mathbf{xx}} = P_S\mathbf{a}(\theta_S)\mathbf{a}^{\mathbf{H}}(\theta_S) + P_J\mathbf{a}(\theta_J)\mathbf{a}^{\mathbf{H}}(\theta_J) + P_N\mathbf{I}_{M\times M}, \tag{7}$$

where, P_S,P_J,P_N represent power of useful, interference and noise, $\mathbf{I}$ represents unit matrix. Let $\theta_s = 0$, the intersection is θ_Δ, and $\theta_j = \theta_\Delta$.

According to analysis of Appendix A, the adaptive weights calculated with (7) in (5) is the equivalent to that calculated with the covariance of interference and noise $R_{\mathbf{jn}}$:

$$R_{\mathbf{jn}} = P_N\mathbf{I}_{M\times M} + P_J\mathbf{a}(\theta_\Delta)\mathbf{a}^{\mathbf{H}}(\theta_\Delta). \tag{8}$$

According to inverse lemma of matrix $(A+BCD)^{-1} = A^{-1} - A^{-1}B\left(C^{-1}+DA^{-1}B\right)^{-1}DA^{-1}$, we can get

$$\begin{aligned} R_{\mathbf{jn}}^{-1} = \tfrac{1}{P_N}\mathbf{I} - \tfrac{1}{P_N}\mathbf{I}\cdot\mathbf{a}(\theta_\Delta) \\ \cdot\left(\tfrac{1}{P_J} + \mathbf{a}^{\mathbf{H}}(\theta_\Delta)\cdot\tfrac{1}{P_N}\cdot\mathbf{I}\cdot\mathbf{a}(\theta_\Delta)\right)^{-1} \\ \cdot\,\mathbf{a}^{\mathbf{H}}(\theta_\Delta)\,\tfrac{1}{P_N} = R_{\mathbf{a}}/\chi_0, \end{aligned} \tag{9}$$

where,

$$R_{\mathbf{a}} = \begin{bmatrix} P_N+(M-1)P_J & -P_Je^{j\varphi} & \dots & -P_Je^{j(M-1)\varphi} \\ -P_Je^{-j\varphi} & P_N+(M-1)P_J & \dots & -P_Je^{j(M-2)\varphi} \\ \dots & \dots & \dots & \dots \\ -P_Je^{-j(M-1)\varphi} & -P_Je^{-j(M-2)\varphi} & \dots & P_N+(M-1)P_J \end{bmatrix},$$

$\chi_0 = P_N(P_N + M\cdot P_J)$.

Substituting (9) into (5), the weight will be written as

$$\mathbf{w} = \left(\left(P_N + M P_J \right) \mathbf{I}_{M\times 1} - P_J \frac{1-e^{jM\varphi}}{1-e^{j\varphi}} \mathbf{a}\left(\theta_\Delta\right) \right) / \chi_1 , \tag{10}$$

where $\chi_1 = M\left(P_N + MP_J\right) - P_J \left(\frac{1-e^{-jM\varphi}}{1-e^{-j\varphi}}\right)\left(\frac{1-e^{jM\varphi}}{1-e^{j\varphi}}\right)$, and the SINR can be written as

$$\gamma = \frac{P_S}{P_J \mathbf{w}^{\mathbf{H}} \mathbf{a}\left(\theta_\Delta\right) \mathbf{a}^{\mathbf{H}}\left(\theta_\Delta\right) \mathbf{w} + P_N}, \tag{11}$$

Substituting (10) into (11):

$$\gamma = \frac{P_S}{P_J {P_N}^2 X / \chi_1^2 + P_N}, \tag{12}$$

where $X = \frac{1-e^{-jM\varphi}}{1-e^{-j\varphi}} \frac{1-e^{jM\varphi}}{1-e^{j\varphi}}$.

When $\gamma \le \gamma_0$, the signal after cancellation is still unable to maintain communication, γ_0 is threshold. The formula (12) can be simplified as

$$P_N \left| \frac{1-e^{jM\varphi}}{1-e^{j\varphi}} \right| / \chi_1 \ \ge \chi_2, \tag{13}$$

where $\chi_2 = \sqrt{\left(\frac{P_S}{\gamma_0} - P_N\right)/P_J}$, and we can get new form by introducing χ_1,

$$P_N \left|\frac{1-e^{jM\varphi}}{1-e^{j\varphi}}\right| / \left(M\left(P_N + MP_J\right) - P_J \frac{1-e^{jM\varphi}}{1-e^{j\varphi}} \frac{1-e^{-jM\varphi}}{1-e^{-j\varphi}} \right) \ \ge \chi_2. \tag{14}$$

According to analysis of Appendix B, we can get the blind area rule (BAR) of communication:

$$\left| \frac{1-e^{jM\varphi}}{1-e^{j\varphi}} \right| \ge \chi, \tag{15}$$

where $\chi = \sqrt{M^2 + M\frac{P_N}{P_J} + \frac{P_N^2}{4P_J^2\chi_2^2}} - \frac{P_N}{2P_J\chi_2}$.

Actually, it is difficult to obtain P_S,P_J,P_N, but feasible for SNR r_{SNR} during communication and possible maximum ISR r_{ISR}.

After that, the threshold χ of BAR in (14) can be rewritten as:

$$\chi = \sqrt{M^2 + \frac{M}{r_{\mathrm{INR}}} + \chi_3^2} - \chi_3, \tag{16}$$

where,

$$r_{\mathrm{INR}} = r_{\mathrm{ISR}} . r_{\mathrm{SNR}}, \tag{17}$$

$$\chi_3 = \frac{1}{2r_{\mathrm{SNR}}} / \sqrt{\frac{1}{\gamma_0} \cdot \frac{1}{r_{\mathrm{ISR}}} - \frac{1}{r_{\mathrm{INR}}}} . \tag{18}$$

Clearly, the time complexity $O\left(M\right)$ of BAR is much lower than the classical $O\left(M^3\right)$.

Let $F\left(\delta, f, \theta\right) = \left|\frac{1-e^{j2\pi M\delta f \sin(\theta)/c}}{1-e^{j2\pi\delta f \sin(\theta)/c}}\right|$, and construct the MBA model of auxiliary array optimization with blind area rule, which focuses on minimizing blind area in different DOA of interference and wide-band communication after cancellation.

$$\begin{aligned} &\min_{\delta} \iint_{f\in B_w \ 0\le\theta_\Delta\le\pi/2} d\left(\kappa_1 f\right) d\left(\kappa_2 \theta_\Delta\right) \\ &s.t. F\left(\delta, f, \theta_\Delta\right) \ge \chi \end{aligned} \tag{19}$$

where κ_1, κ_2 are weights of blind factors.

The proposed optimization method can be summarized in MBA model.

MBA Model: Spacing Optimization Precedure

Task: Minimizing blind area in different θ_Δ and wide B_w.

Input: B_w, γ_0, r_{SNR}, r_{ISR}, M, κ_1 and κ_2.

Output: Optimal antenna spacing δ.

1: Compute JNR r_{INR} with r_{ISR} and r_{SNR}.

2: Calculate the threshold of BAR with (16), (17), (18).

3: Discretize B_w and θ_Δ according to radio channel.

4: Make sure κ_1 and κ_2 in view of requirements of radio.

5: Solve the discrete form of (19), and obtain optimal δ.

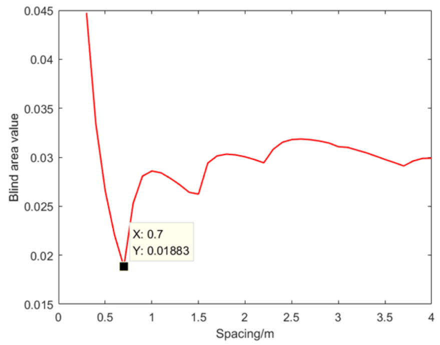

Fig 2 *Theoretical results of MBA model.*

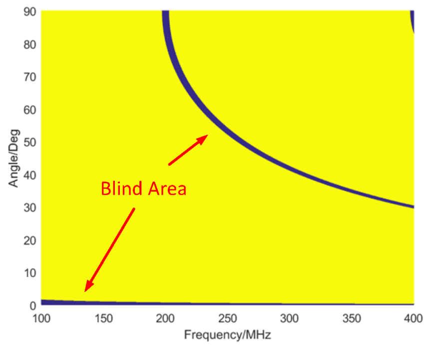

Fig 3 *Blind area of classical method.*

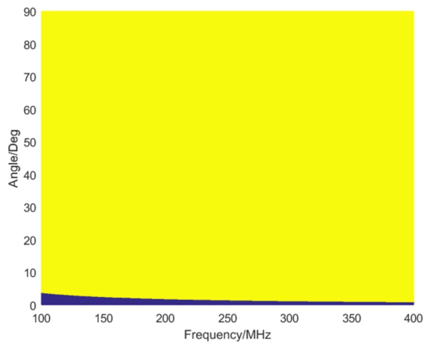

Fig 4 *Blind area of MBA model.*

Experiments: Experiments are taken in interference cancellation of ultra-short wave radio operating in 100 MHz to 400 MHz, and an auxiliary array is set up.

Firstly, to measure the performance of cancellation whether to maintain communication, we set the threshold $\gamma_0 = 3$dB, in other words, SINR below 3dB will be unable to keep communication, even adopting cancellation.

We adjust the antenna spacing, and then calculate the blind area with (19), here, two factors are weighted equal value $\kappa_1 = \kappa_2$. As seen from figure 2, the concave point 0.0188@0.7m with minimum blind area is the optimal spacing, not the big or small.

To highlight the proposed MBA method, experiments are taken to compared it with the classical method, such as the half of maximum wavelength of signal.

The blind area of communication with different spacing δ is clearly shown in figure 3 and figure 4, where the shadow area is the blind area of communication after cancellation. The high spacing leads to multiple blind area, shown in figure 3, because of multiple grating lobe. Compared with the previous, the optimal spacing with MBA method acquires the least blind area, as shown in figure 4.

To verify the theoretical analysis of MBA, experimental platform has been built, as seen from figure 5. While two radio are communicating,

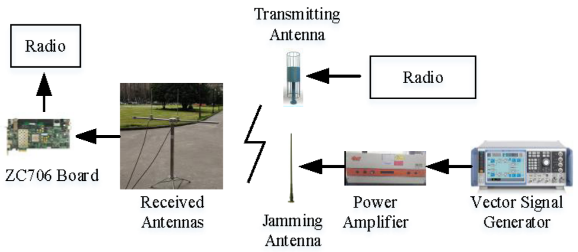

Fig 5 *Experimental platform.*

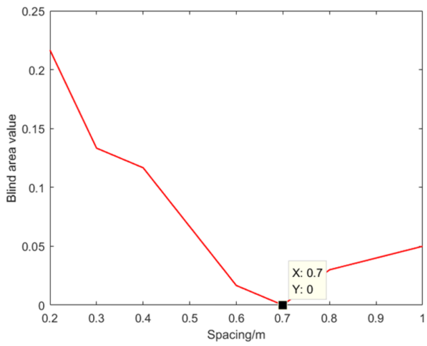

Fig 6 *Experimental results of MBA model.*

the interference are enteren by power amplifier and vector signal generator, leading to communication interruption. The signal from received antennas enters digital board, where the interference are cancelled, and then sent to received radio.

Here, the communicating frequency of radio are setting to 150MHz, 225MHz, and 300MHz, the spacing of antennas δ is selected from 0.2 to 1 meter. The communicating distance is 75 meters, and the distance between transmitting and jamming is selected from 1 to 10 meters, equivalent to varying interference direction θ_Δ. The experimental results of MBA model is shown in figure 6, clearly, the minimum blind area point is the spacing @0.7m, demonstrating theoretical analysis of MBA model.

Conclusion: Aiming to the auxiliary array optimization, the blind area rule is proposed and the MBA optimization model is established. The cancellation strategy based on MMSE cannot deal with about 0 degree between interference and communication, and large spacing of antenna would deteriorate the SINR with higher probability. The blind area rule inherits communicable index of radio well, and visually displays the area after cancellation under a certain spacing. The simplified SINR model and blind area after cancellation leads to a remarkable improvement of optimization efficiency with different DOA of interference and wideband operating frequency. The proposed MBA optimization model can achieve the optimal spacing of antenna, and it is much suitable for auxiliary array optimization of anti-interference. How to optimize the spacing with non-uniform array is our further work.

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Theorem 1. *The weight calcaculated by interference is the same as that by interference and desired signal.*

The formula (7) can be rewritten as:

$$R_{\mathbf{xx}} = P_S \mathbf{a}(\theta_S)\,\mathbf{a}^{\mathbf{H}}(\theta_S) + R_{\mathbf{jn}}. \tag{20}$$

In view of inverse lemma of matrix, we can obtain:

$$\begin{aligned} R_{\mathbf{xx}}^{-1} &= R_{\mathbf{jn}}^{-1} - R_{\mathbf{jn}}^{-1}\cdot \mathbf{a}(\theta_S) \\ &\cdot \left(\tfrac{1}{P_S} + \mathbf{a}^{\mathbf{H}}(\theta_S)\,R_{\mathbf{jn}}^{-1}\mathbf{a}(\theta_S)\right)^{-1}\mathbf{a}^{\mathbf{H}}(\theta_S)\,R_{\mathbf{jn}}^{-1}. \end{aligned} \tag{21}$$

Substituting (21) into (5):

$$\mathbf{w} = R_{\mathbf{jn}}^{-1}\mathbf{a}(\theta_s)\left(\mathbf{a}^{H}(\theta_s)\,R_{\mathbf{jn}}^{-1}\mathbf{a}(\theta_s)\right)^{-1}. \tag{22}$$

Theorem 2. *Proof of proposed blind area rule.*

Since $\chi_1 > 0$, the formula (14) can be rewritten as

$$P_J\chi_2 X + P_N\sqrt{X} - M\left(P_N + MP_J\right)\chi_2 \geq 0. \tag{23}$$

Because of $P_J\chi_2 > 0$, the formula (23) is equivalent to a univariate quadratic inequality with opening upward.

In the case of $\Delta = P_N^2 + 4P_J\chi_2^2 M\left(P_N + MP_J\right) > 0$ and $\sqrt{X} \geq 0$, we can get the solution of formula (23)

$$\sqrt{X} \geq \sqrt{M^2 + M\frac{P_N}{P_J} + \frac{P_N^2}{4P_J^2\chi_2^2}} - \frac{1}{2P_J\chi_2}, \tag{24}$$

and another form:

$$\left|\frac{1 - e^{jM\varphi}}{1 - e^{j\varphi}}\right| \geq \chi. \tag{25}$$

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