Adaptive interferences suppression algorithm after subarray configuration for large-scale antenna array

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For the interferences suppression of a large-scale antenna array after a subarray configuration (SC), a generalised sidelobe canceller (GSC) weighting approximation at irregular subarrays algorithm is presented. First, the SC is obtained by particle swarm optimisation. Then, digital weights of the second-class subarrays and also the analogue weights of the elements and first-class subarrays are optimised in two steps by convex optimisation to approximate GSC weights to the maximum extent, which are directly applied at the element level of the whole array. Simulation results are presented that prove that the proposed algorithm achieves better performance of anti-jamming than direct GSC weighting at subarrays.

Introduction: Large and ultra-large-scale phased arrays have the advantages of substantial gain, high resolution and far detection distance, but they consist of hundreds or even thousands of antenna elements with high cost, so an irregular subarray configuration (SC) is employed to reduce the dimensionality without grating lobes. However, the performance of adaptive processing is degraded since the power of the noise of each channel is different. Therefore, Hu and Deng [1] normalised the subarray outputs, in such a way that the weight of each element should be known first. Nickel *et al.* [2] analysed the effects of the number of irregular subarrays on the adaptive digital beamforming without the optimum subarray configuration. In [3], Hu *et al.* introduced direct generalised sidelobe canceller (GSC) weighting at subarrays (GSC-SA), which can achieve a higher signal-to-interference-plus-noise-ratio (SINR) than the linearly constrained minimum variance algorithm. Nevertheless, the main-side lobe ratio (MSLR) is reduced. In this Letter, a novel algorithm, referred to as weighting approximation at irregular subarrays (WA-IS), aimed a suppressing interferences for at large-scale antenna array (LSAA) is proposed. Simulations verify that WA-IS has better performance in adaptive beamforming, i.e. a higher output SINR compared with the GSC-SA.

Signal and array model: The SC of the LSAA is displayed in Fig. 1. Let N, $N1$ and $N2$ be the number of the elements, regular first-class subarrays and irregular second-class subarrays, respectively. Let $\boldsymbol{T}_1$ be the first-class subarray transforming matrix of $N \times N1$. The arrangement of second-class subarrays is optimised by particle swarm optimisation (PSO) [4]. The TR modules at the antenna elements and first-class subarrays can be controlled in amplitude and phase, while digital weights are applied to the second-class subarrays.

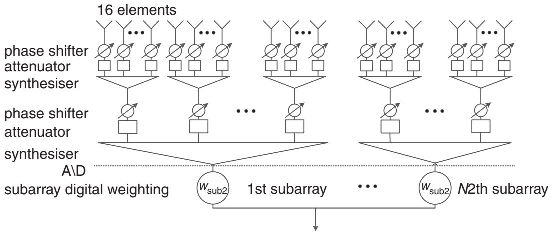

Fig. 1 *Architecture scheme of subarray configuration*

Subarray configuration optimisation: The evolution of PSO is operated according to the fitness function, i.e. the weighted sum of the MSLR and the half-power beam-width of main lobe (BWML) along the elevation axis (BW_ELE)/azimuth axis (BW_AZI), respectively. Each can be adjusted by $w1$, $w2$ and $w3$:

$$\begin{aligned}\text{Fitness} = \text{maximise } & w1 \cdot \text{MSLR} \\ & + w2 \cdot 1/\text{BW\_ELE} + w3 \cdot 1/\text{BW\_AZI}\end{aligned} \tag{1}$$

where Fitness represents the value of the fitness function used to assess the irregular SC during optimisation. After multiple iterations, the globe best of individuals, i.e. gbest which decides the SC is finally determined. Then the matrix $\boldsymbol{T}_2$ of $N1 \times N2$ dimensions which transforms the first-class subarray outputs into second-class subarray outputs is built.

WA-IS algorithm: The synthesised adaption beam pattern after subarray partition can be expressed as

$$F_{\text{ADBF}}(\varphi, \theta) = \left(\left(\boldsymbol{T}_1\boldsymbol{T}_2 w_{\text{opt\_sub2}}\right) \odot \left(\boldsymbol{T}_1 w_{\text{opt\_sub1}}\right) \odot w_{\text{ele}}\right)^{\text{H}} a(\varphi, \theta) \tag{2}$$

where $\boldsymbol{a}(\varphi, \theta)$ is the steer vector in direction (φ, θ). $w_{\text{opt\_sub2}}$, $w_{\text{opt\_sub1}}$ and w_{ele} denote the adaption weights applied at the second-class subarrays, first-class subarrays and the elements, respectively. The equivalent weighting of the array is

$$w_{\text{opt}} = \left(\boldsymbol{T}_1\boldsymbol{T}_2 w_{\text{opt\_sub2}}\right) \odot \left(\boldsymbol{T}_1 w_{\text{opt\_sub1}}\right) \odot w_{\text{ele}} \tag{3}$$

w_{opt} is optimised in a least-mean-square-error (LMSE) sense to approximate $w_{\text{ref\_ele}}$, which is obtained by GSC [5] weighting at the element level (GSC-EM) of the whole array, such that $F_{\text{ADBF}}(\varphi, \theta)$ differs as little as much from the pattern produced by the $w_{\text{ref\_ele}}$ weighting. Consequently the deep null in the direction of the interference and the high SINR can be achieved

$$w_{\text{ref\_ele}} = a_p - C_n\left(C_n^{\text{H}}\hat{R}C_n\right)^{-1}\left(C_n^{\text{H}}\hat{R}a_p\right) \tag{4}$$

Due to the reduction in the power of the signal produced by the attenuators at elements and first-subarrays, two constraints are added as below:

$$\begin{aligned}&\min_{W_{\text{opt2\_sub2}}, W_{\text{opt\_sub1}}} \left\|\left(\boldsymbol{T}_1\boldsymbol{T}_2 w_{\text{opt\_sub2}}\right) \odot \left(\boldsymbol{T}_1 w_{\text{opt\_sub1}}\right) \odot w_{\text{ele}} - w_{\text{ref\_ele}}\right\|^2 \\ &\text{s.t. } \|w_{\text{ele}}\|_{\propto} \le 1,\ \left\|w_{\text{opt\_sub1}}\right\|_{\propto} \le 1\end{aligned} \tag{5}$$

where $\|\,\|^2$ and $\propto$ represent 2-norm and $\propto$-norm, respectively.

For w_{opt} approximating $w_{\text{ref\_ele}}$ to the maximum extent, the optimisation is conducted in two steps.

Step 1: The weights of first-class subarrays w_{sub1} and w_{ele} are optimised to approximate $w_{\text{ref\_ele}}$:

$$\begin{aligned}&\min_{W_{\text{sub1}}, W_{\text{ele}}} \|(\boldsymbol{T}_1 w_{\text{sub1}}) \odot w_{\text{ele}} - w_{\text{ref\_ele}}\|^2 \\ &\text{s.t. } \|w_{\text{ele}}\|_{\propto} \le 1\end{aligned} \tag{6}$$

Step 2: $w_{\text{opt\_sub2}}$ and $w_{\text{opt\_sub1}}$ are jointly optimised to approximate w_{sub1}:

$$\begin{aligned}&\min_{W_{\text{opt\_sub2}}, W_{\text{opt\_sub1}}} \left\|\left(\boldsymbol{T}_2 w_{\text{opt\_sub2}}\right) \odot w_{\text{opt\_sub1}} - w_{\text{sub1}}\right\|^2 \\ &\text{s.t. } \left\|w_{\text{opt\_sub1}}\right\|_{\propto} \le 1\end{aligned} \tag{7}$$

In (6) and (7), it is necessary to evaluate the logarithm of the weights to be optimised since they are the Hadamard production of w_{sub1} and w_{ele}, $w_{\text{opt\_sub2}}$ and $w_{\text{opt\_sub1}}$, respectively. Afterwards, (6) and (7) are transformed into the following problem that can be solved by convex optimisation (CVX) [6]:

$$\begin{aligned}&\min_{W_{\text{sub1}}, W_{\text{ele}}} \|W_{\text{sub1}} + W_{\text{ele}} - W_{\text{ref\_ele}}\|^2 \\ &\min_{W_{\text{opt\_sub2}}, W_{\text{opt\_sub1}}} \left\|W_{\text{opt\_sub2}} + W_{\text{opt\_sub1}} - W_{\text{sub1}}\right\|^2 \\ &\text{s.t.} \|W_{\text{ele}}\|_{\propto} \le 1,\ \left\|W_{\text{opt\_sub1}}\right\|_{\propto} \le 1\end{aligned} \tag{8}$$

Simulation results: A planar rectangular large array of 3840 active elements is assumed. The maximum number of the elements along the x coordinate is 64 while that along the y coordinate is 60, where x and y denote the coordinates of the array in the aperture plane. Suppose the carrier frequency is 1.5 GHz. The distances between elements are set as $dx = 0.1$ m and $dy = 0.08$ m, respectively. There are $N1 = 240$ first-class regular subarrays, each containing 4×4 elements, and $N2 = 46$ second-class irregular subarrays. In Fig. 2, first-class subarrays belonging to different second-class subarrays are marked by distinct symbols.

Suppose the azimuth angle and elevation angle of the signal are $(0, 0)°$ and those of the interferences are $(-20, 20)°$ and $(10, 25)°$, respectively. Let the signal-to-noise ratio be 0 dB and the interference-to-noise ratio be 40 dB. The MSLR is given priority in the SC optimisation in this Letter, so in (1) the weight coefficients are set as follows: $w1 = 0.6$, $w2 = 0.3$ and $w3 = 0.3$.

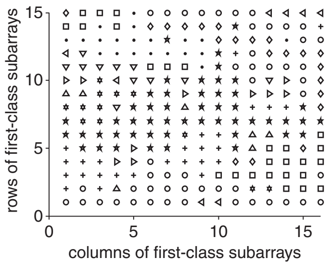

Fig. 2 *Irregular subarray configuration*

Fig. 3 shows the maximum gain of the adaption pattern of WA-IS is in the direction of the signal and the nulls are exactly in the direction of the interferences. It is shown that the performance of the adaption beam pattern produced by WA-IS is better than that of GSC-SA in Fig. 4. The comparison is provided in Table 1.

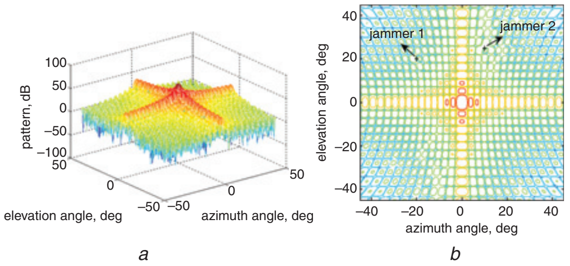

Fig. 3 *Adaption beam pattern by WA-IS and its contour plot*

a Adaption beam pattern by WA-IS
b Contour plot of adaption beam pattern

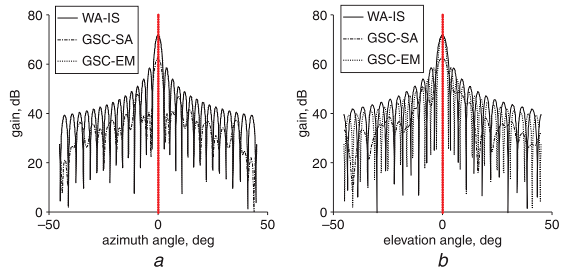

Fig. 4 *Sectional view of adaption beam pattern by WA-IS, GSC-SA and GSC-EM in direction of signal*

a Azimuth view
b Elevation view

Table 1: Comparison of gain of main lobe (GML), MSLR and BWML between adaption beam patterns produced by WA-IS and GSC-SA

Algorithm	GML (dB)	MSLR (dB)	BWML (deg)	
			Elevation angle	Azimuth angle
WA_IS	71.64	13.25	3.1	2.4
GSC-SA	62.44	12.18	3.9	2.7

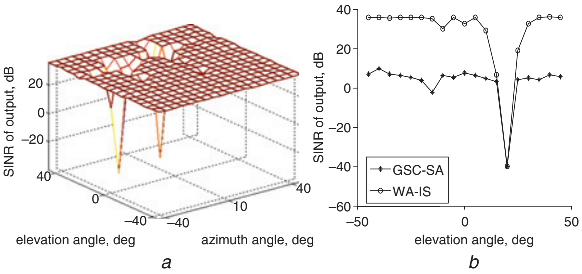

Fig. 5 *SINR of output data by WA-IS and its comparison with GSC-SA*

a SINR of output data by WA-IS
b Sectional view of SINR of output data by WA-IS and GSC-SA

Deep nulls can be produced in the direction of interferences through both methods, while the output SINR of WA-IS is much higher than that of GSC-SA, as shown in Fig. 5.

Conclusion: A weighting approximation method for irregular subarrays of the LSAA called WA-IS is proposed to suppress the interferences. First, the LSAA is partitioned into regular first-class subarrays and then the irregular SC is optimised through PSO. Secondly, the optimum weights at the subarray and the element level are produced through CVX to approximate the GSC-EM in two steps. Finally, it is shown that the GML and MSLR of the adaptation beam pattern of WA-IS are higher than that produced by GSC-SA, while the BWML is narrower. As a result, the output SINR is higher.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Hu, H., and Deng, X.H.: 'An approach based on normalization processing for two-dimensional subarray level ADBF'. IEEE Int. Symp. on Antennas, Propagation and EM Theory, Guilin, China, October 2006, pp. 1–4, doi: 10.1109/ISAPE 2006. 3523358

2 Nickel, U., Richardson, P.G., Medley, J.C., and Briemle, E.: 'Array signal processing using digital subarrays'. IET Int. Conf. on Radar Systems, Edinburgh, UK, October 2007, pp. 1–5, doi: 10.1049/cp:20070591

3 Hu, H., Liu, E.X., and Xiao, Y.: 'ADBF at subarray level using a generalized sidelobe canceller'. IEEE Int. Symp. on Microwave, Antenna, Propagation and RMC Technologies for Wireless Communications, Beijing, China, October 2009, pp. 697–700, doi: 10.1109/MAPE.2009.5355964

4 Naha, A., and Deb, A.K.: 'Particle swarm optimization with Kalman correction', *Electron. Lett.*, 2013, **49**, (7), pp. 465–467, doi: 10.1049/el.2012.4637

5 Hong, J., Park, S., Jeong, S., and Hahn, M.: 'Adaption mode controller using multiple signal classification for GSC-based beamforming', *Electron. Lett.*, 2013, **49**, (17), pp. 1076–1078, doi: 10.1049/el.2013.1587

6 CVX Research: 'CVX: Matlab software for disciplined convex programming, version 2.1', http://www.cvxr.com/cvx, accessed March 2015