Design method of high-efficiency sparse array for ultra-wideband radar

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Compared with sequential single-input–multiple-output array, a novel design method of high-efficiency sparse array is proposed to achieve the similar azimuth resolution and lower grating-lobe level. Theoretical analysis and numerical experiments demonstrate that the designed array is irredundant and the efficiency is increased. The work can benefit the development of high-resolution imaging and low-cost ultra-wideband radar.

Introduction: Recently, multiple-input–multiple-output (MIMO) and single-input–multiple-output (SIMO) arrays have been widely used in many applications, such as remote sensing, satellite communications and so on. For the ultra-wideband radar regime, MIMO and SIMO arrays are applied to obtain a beam pattern with high resolution and low grating-lobe level (GLL) [1, 2]. Moreover, the sparse array with a small number of antennas is exploited to simplify the radar system. In [3], an array design method of the sequential SIMO (SSIMO) array is researched to achieve the beam pattern with high resolution and low GLL. However, the designed SSIMO array is redundant and is not efficient when the number of antennas is greater than or equal to five, which motivates the investigation of this Letter.

As pointed in [2], compared with amplitude tapered or random arrays, one-way arrays which are periodic and uniformly weighted usually have higher azimuth resolution and lower GLLs. The ideal GLL (IGLL) of the array can be given by

$$\mathrm{IGLL} = 20\log_{10}\left(\frac{1}{N_{\mathrm{EA}}}\right)\mathrm{dB} \tag{1}$$

where N_{EA} is the number of elements in a periodic one-way array.

Correspondingly, the azimuth resolution is in the following [4]:

$$\rho = \frac{0.886\lambda}{N_{\mathrm{EA}}d} \tag{2}$$

where d is the inter-element spacing of the array and λ is the signal wavelength.

In general, the beam pattern of a two-way array can be obtained by analysing its effective array. Conducting spatial convolution of the transmitting and receiving arrays of a two-way array can lead to the effective array, which is shown in the formula

$$E_{\mathrm{A}} = \{x_{\mathrm{EA}} | x_{\mathrm{EA}} = x_{\mathrm{T}} + x_{\mathrm{R}}, x_{\mathrm{T}} \in S_{\mathrm{T}}, x_{\mathrm{R}} \in S_{\mathrm{R}}\} \tag{3}$$

where x_{EA}, x_{T} and x_{R} are the positions of the effective array antenna, the transmitting element and the receiving element, respectively. S_{T} denotes the antenna coordinate set of the transmitting array and S_{R} signifies the antenna coordinate set of the receiving array.

Design method and discussion: To obtain a beam pattern with high resolution and low GLL, a design method of SSIMO array was proposed in [3] and the related antenna positions were

$$[x_1, \ldots, x_N] = \left[-\frac{L}{2}, -\frac{(N-3)L}{2N-4} : \frac{L}{N-2} : \frac{(N-3)L}{2N-4}, \frac{L}{2}\right] \tag{4}$$

where x_i, $i = 1, 2, \ldots, N$ indicate the abscissas of the N antennas and L denotes the length of the physical array.

Since all of the elements of the SSIMO array are transmitters and all other antennas would act as receivers when one antenna transmits the signal, the effective array of the SSIMO array can be given by

$$E_{\mathrm{A}} = \{x_{\mathrm{EA}} | x_{\mathrm{EA}} = x_i + x_j, 1 \le i, j \le N, i \ne j\} \tag{5}$$

where x_i and x_j represent the transmitter and the receiver, respectively.

By straightforward arithmetical manipulations, the effective array of (4) is

$$E_{\mathrm{A}} = \left\{-\frac{(2N-5)L}{2N-4}, -\frac{(2N-7)L}{2N-4} : \frac{L}{2N-4} : \frac{(2N-7)L}{2N-4}, \frac{(2N-5)L}{2N-4}\right\} \tag{6}$$

We can conclude that the method in [3] is highly redundant and inefficient due to that the number of effective elements $4N-11$ is much smaller than that of the transmitting/receiving (T/R) pairs $N(N-1)$. Redundancy results from the selection of the SSIMO array. Here, a modified design method on how to select the transmitters and the corresponding receivers is studied to improve the efficiency of the SSIMO array.

Table 1: Algorithm to search irredundant T/R pairs

1	$s_1 = \emptyset, s_2 = \emptyset$
2	**for** $i = 1 \rightarrow N-1$
3	**for** $j = i+1 \rightarrow N$
4	**if** $x_i + x_j \notin s_1$
5	$s_1 = s_1 \cup \{x_i + x_j\}$
6	$s_2 = s_2 \cup \{(x_i, x_j)\}$

Redundant T/R pairs deriving from the SSIMO array should be removed to enhance the efficiency. We propose a method by searching irredundant T/R pairs based on (4), which is given in Table 1. The irredundant T/R pairs are contained in s_2 and are presented in Table 2. Note that x_{N-1} and x_N act as the receivers corresponding to the transmitters x_i, $i = 3, 4, \ldots, N-2$. Then, Table 2 can be simplified by exchanging the roles of them and Table 3 provides the results.

Table 2: Irredundant T/R paris

Transmitter	Receiver(s)
x_1	$x_i, i = 2, 3, \ldots, N$
x_2	$x_i, i = 3, 4, \ldots, N-2, N$
x_3	$x_i, i = N-1, N$
M	M
x_{N-2}	$x_i, i = N-1, N$
x_{N-1}	x_N

Possessing exactly $4N-11$ irredundant T/R pairs, Table 3 is irredundant and is taken as the proposed method. Compared with the SSIMO array, the proposed method is much more efficient and has the following advantages:

(i) The computational amount is dramatically eased and data acquisition takes less time because of much fewer T/R pairs.
(ii) Since the SSIMO array is not uniformly weighted, the data channel should be normalised to get lower GLL. However, as for the proposed method, normalising is not necessary due to the uniformly weighted effective array.
(iii) Hardware costs less, since only four antennas should be both transmitters and receivers.

Although the proposed design method is no longer a SSIMO array, assuming that the array is a SSIMO array beforehand makes it easier to find the optimum T/R pairs. Hence, the SSIMO array was worthy of discussing in [3].

Table 3: Proposed method

Transmitter	Receivers
x_1	$x_i, i = 2, 3, \ldots, N$
x_2	$x_i, i = 3, 4, \ldots, N-2$
x_{N-1}	$x_i, i = 3, 4, \ldots, N-2$
x_N	$x_i, i = 2, 3, \ldots, N-1$

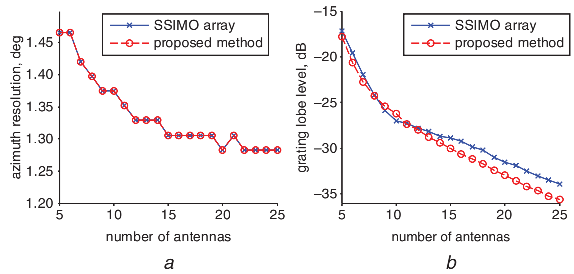

Fig. 1 *Comparisons of azimuth resolution and GLLs*

a Azimuth resolution
b GLLs of SSIMO array and proposed method

Comparisons of the azimuth resolution and GLLs between the proposed method and the SSIMO array are shown in Fig. 1. In the simulations, the length of the employed physical array is set as 3.5 m; the frequency band range of the transmitting stepped frequency continuous wave is 0.3–3 GHz and the step size is 3 MHz. Results indicate that the proposed method can achieve a similar azimuth resolution and low GLL to those of SSIMO array but a higher efficiency.

Conclusion: An improved design method of high-efficiency sparse array, based on the SSIMO array, is proposed to remove redundant T/R pairs. In the designed array, only four antennas are used as both transmitters and receivers and the data processing can be simplified. Therefore, the proposed method is much more efficient than the SSIMO array.

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

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