Amplitude-Only Synthesis of Multi-Subaperture Antenna Array by Nonlinear Least-Square Method

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Abstract **─** An improved nonlinear least-square method is presented to the synthesis of multi-subaperture antenna array for SAR application. This method changes the traditional nonlinear least-square method's shortness of being sensitive to its initial value. The whole aperture and the subapertures can generate different radiation beams. Also, the whole aperture and the several subapertures can work simultaneously. The mathematical model of nonlinear least-square method is given and the amplitudes of the array elements are optimized. The Peak Side Lobe Level (PSLL) is controlled effectively. The simulation results show the feasibility and effectiveness of the presented method in the synthesis of array antenna.

Index Terms **─** Antenna array, multi-beam, nonlinear least-square method, pattern synthesis.

I. INTRODUCTION

Pattern synthesis of antenna arrays has been paid more and more attention in recent years. Many methods have been developed in the synthesis of antenna arrays, such as Genetic Algorithm (GA) [1], Particle Swarm Optimization (PSO) [2], and Differential Evolution (DE) algorithm [3]. These methods are global optimization algorithms and can usually get a satisfied result. However, these methods have the disadvantage of time consuming, so many other methods have been introduced into the synthesis of antenna arrays, such as Fast Fourier Transform (FFT) method [4,5], Projection Matrix Algorithm (PMA) [6], and Convex (CVX) optimization [7]. These methods are iterative methods and have the advantage of being fast. Also, some microwave simulation softwares such as HFSS and CST have been used in the analysis of array antenna [8-10].

Multi-subaperture antenna array is to divide the whole array aperture into several sub-arrays and multi-beams are usually obtained by these sub-arrays. Multi-beam array antennas have many applications in communication and radars. Several synthesis methods are introduced and some kinds of radiation patterns are synthesized [11-15]. A comparison study between phase-only and amplitude phase synthesis of symmetric dual-pattern linear antenna arrays using floating-point or real-valued genetic algorithms is presented in [11]. An iterative method based on the method of successive projections for power synthesis of reconfigurable arrays of arbitrary geometry is introduced in [12]. A novel mixed-integer optimization formulation for the optimal design of a reconfigurable antenna array with quantized phase excitations is proposed in [13]. Three approaches for the synthesis of the optimal compromise between sum and difference patterns for sub-arrayed linear and planar arrays are presented in [14]. An analytical technique based on Almost Difference Sets (ADSs) for the design of interleaved linear arrays with well-behaved and predictable radiation features is proposed in [15].

Amplitude-only optimization is one of the most popular methods in the pattern synthesis of array antenna. Because only the excitation amplitudes of the array elements are optimized, the computational complexity will be reduced greatly. Low side lobe synthesis thesis using amplitude-only tapering on the turned ON elements of large circular thinned arrays is presented in [16]. In [17], an efficient method based on Bees Algorithm (BA) for the pattern

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synthesis of linear antenna arrays with the prescribed nulls is presented. An amplitude-only optimizing method is presented to synthesize the multiple beams of an array antenna for multi-mode SAR application [18].

Nonlinear least-square method is an iterative method and has no special requirements for the positions of the array elements. In this paper, improved nonlinear least-square method is employed in the synthesis of multi-subaperture antenna array, which makes the algorithm not sensitive to its initial value. The whole aperture of the antenna array is divided into several subapertures. The whole aperture and each subaperture have different radiation patterns. Also, all the beams generated by the whole array aperture and every subaperture are synthesized simultaneously. The paper is organized as follows. Section II is devoted to present the mathematical model of the nonlinear least-square method. The optimization steps are given in section III. Section IV gives the simulation results. Finally, conclusions are given.

II. MATHEMATICAL MODEL

The structure of a linear multi-subaperture array is as shown in Fig. 1. The array elements are disposed along x axis. The array antenna has N elements and the coordinate of the first element is 0. The whole array aperture is divided into S subapertures which are expressed as Sub_s, $s=1,2,\cdots,S$. The whole array aperture can obtain a radiation pattern and each subaperture can get a different radiation beam. So, the whole array antenna can produce S+1 different beams simultaneously. If the adjacent elements spacing is d_i, $i=1,2\cdots,N$, the position of each element can be written as:

$$x_i=(i-1)d_i\,,\ i=1,2,\cdots,N\,. \tag{1}$$

The array factor of the whole aperture can be given by:

$$AF^{(\mathrm{Whole})}(\theta)=\sum_{n=1}^{N}A_nE_n(\theta)\exp(jkx_n\cos\theta)\,, \tag{2}$$

where $\theta\in[0,\pi]$ is the angle respect to the array axis, $k=2\pi/\lambda$ is wave number, λ is wavelength, x_n is the position of the nth element, A_n is the complex excitation coefficient of the nth element, $E_n(\theta)$ is the radiation pattern of the nth element.

In order to simply the optimization procedure, assuming each subaperture has the same number of array elements, the array element number of each subaperture is N/S. The array factor of sth subaperture is written as:

$$AF^{(\mathrm{Sub}_s)}(\theta)=\sum_{n=N_s}^{N_s'}A_nE_n(\theta)\exp(jkx_n\cos\theta)\,, \tag{3}$$

where $N_s=(s-1)N/S+1$ and $N_s'=sN/S$, $s=1,2,\cdots,S$, are the lower and upper element boundary of sth subaperture, respectively.

In order to fulfill the optimization of nonlinear least-square method, the radiation angle θ is divided into M equal parts. Then, the angle of each discrete point is given by:

$$\theta_m=\frac{m-1}{M-1}\pi\,,\ m=1,2,\cdots,M. \tag{4}$$

After the radiation angle is discretized, the array factors of the whole aperture and sth subaperture can be shown as follows:

$$\begin{aligned}AF^{(\mathrm{Whole})}(\theta_m)&=\sum_{n=1}^{N}A_nE_n(\theta_m)\exp(jkx_n\cos\theta_m)\\&=\sum_{n=1}^{N}T_{mn}A_n\,,\end{aligned} \tag{5}$$

$$\begin{aligned}AF^{(\mathrm{Sub}_s)}(\theta_m)&=\sum_{n=N_s}^{N_s'}A_nE_n(\theta_m)\exp(jkx_n\cos\theta_m)\\&=\sum_{n=N_s}^{N_s'}T_{mn}A_n\,,\end{aligned} \tag{6}$$

where $T_{mn}=E_n(\theta_m)\exp(jkx_n\cos\theta_m)$.

The sets of the equations in (5) and (6) can be expressed in the following matrix form [18]:

$$\begin{bmatrix} & & \mathbf{T}^{(\mathrm{Whole})} & \\ \mathbf{T}^{(\mathrm{Sub}_1)} & \mathbf{0} & \cdots & \mathbf{0}\\ \mathbf{0} & \mathbf{T}^{(\mathrm{Sub}_2)} & \cdots & \mathbf{0}\\ & & \vdots & \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{T}^{(\mathrm{Sub}_S)}\end{bmatrix}\begin{bmatrix}A_1\\A_2\\A_3\\\vdots\\A_N\end{bmatrix}=\begin{bmatrix}\mathbf{AF}^{(\mathrm{Whole})}\\\mathbf{AF}^{(\mathrm{Sub}_1)}\\\mathbf{AF}^{(\mathrm{Sub}_2)}\\\vdots\\\mathbf{AF}^{(\mathrm{Sub}_S)}\end{bmatrix}, \tag{7}$$

where $\mathbf{T}^{(\mathrm{Whole})}=[T_{mn}]$ is $M\times N$ matrix and $\mathbf{T}^{(\mathrm{Sub}_s)}=[T_{mn}]$, $N_s\le n\le N_s'$, $s=1,2,\cdots,S$, is $M\times N/S$ matrix. $\mathbf{0}$ denotes a $M\times N/S$ zero matrix. $A_n=I_n\exp(j\alpha_n)$ is the complex excitation coefficient of the nth element. I_n and α_n are excitation amplitude and phase of the nth element, respectively.

In order to synthesize the radiation patterns more accurately, the normalized radiation patterns are used here. The normalized radiation patterns of the antenna array can be expressed as:

$$F_m^{(\mathrm{Whole})}=\frac{1}{AF_{\max}^{(\mathrm{Whole})}}\sum_{n=1}^{N}T_{mn}I_ne^{j\alpha_n}\,,m=1,2,\cdots,M, \tag{8}$$

$$F_m^{(\mathrm{Sub}_s)} = \frac{1}{AF_{\max}^{(\mathrm{Sub}_s)}} \sum_{n=N_s}^{N_s'} T_{mn} I_n e^{j\alpha_n} \text{ , } s = 1, 2, \cdots, S, \tag{9}$$

where $AF_{\max}^{(\mathrm{Whole})}$ and $AF_{\max}^{(\mathrm{Sub}_s)}$ are the maximum value of $\mathbf{AF}^{(\mathrm{Whole})}$ and $\mathbf{AF}^{(\mathrm{sub}_s)}$, respectively. The normalized radiation patterns of the whole aperture and each subaperture can be expressed in the following vector form:

$$\mathbf{F} = [\mathbf{F}^{(\mathrm{Whole})} \quad \mathbf{F}^{(\mathrm{Sub}_1)} \quad \mathbf{F}^{(\mathrm{Sub}_2)} \quad \cdots \quad \mathbf{F}^{(\mathrm{Sub}_S)}]^{\mathrm{T}}, \tag{10}$$

where the superscript T denotes the transpose symbol. The total element number of vector **F** is $(S+1)\times M$.

The vector of the normalized desired radiation patterns of the whole aperture and the sth subaperture are depicted by $\mathbf{f}^{(\mathrm{Whole})}$ and $\mathbf{f}^{(\mathrm{Sub}_s)}$, $s=1,2,\cdots,S$. Similar to be shown in (10), the normalized desired radiation patterns can be expressed in the following vector form:

$$\mathbf{f} = [\mathbf{f}^{(\mathrm{Whole})} \quad \mathbf{f}^{(\mathrm{Sub}_1)} \quad \mathbf{f}^{(\mathrm{Sub}_2)} \quad \cdots \quad \mathbf{f}^{(\mathrm{Sub}_S)}]^{\mathrm{T}} . \tag{11}$$

The objective function of nonlinear least-square method is determined by the absolute error of the synthesized and desired radiation patterns which can be given by:

$$r_j(\xi) = \left\| F_j \right| - f_j \right|, \;\; j = 1, 2, \cdots, (S+1)M, \tag{12}$$

where f_j and F_j, $j=1,2,\cdots,(S+1)M$, are the jth element of **f** and **F**, respectively. The vector of the optimized parameters is $\xi=[I_1,I_2,\cdots,I_N]$. $|F_j|$ can be given as follows:

$$\left| F_j \right| = \frac{1}{AF_{\max}^{(\mathrm{Whole})}} \sqrt{\left(\sum_{n=1}^{N} a_n \right)^2 + \left(\sum_{n=1}^{N} b_n \right)^2}, \tag{13}$$
$$1 \le j \le M$$

$$\left| F_j \right| = \frac{1}{AF_{\max}^{(\mathrm{Sub}_s)}} \sqrt{\left(\sum_{n=N_s}^{N_s'} a_n \right)^2 + \left(\sum_{n=N_s}^{N_s'} b_n \right)^2}, \tag{14}$$
$$sM + 1 \le j \le (s+1)M \text{ , } s = 1, 2, \cdots, S$$

where $a_n=I_n\cos(kx_n\cos\theta_m+\alpha_n)$ and $b_n=I_n\sin(kx_n\cos\theta_m+\alpha_n)$.

In this paper, the desired radiation patterns are pencil beams and the scanning angle of each radiation pattern is 90°. So, the excitation phases are set to be zero and only the excitation amplitudes are optimized.

The optimization objective is to minimize the total absolute error of the synthesized and desired radiation patterns. Considering the constraints of excitation amplitudes, the mathematical model of nonlinear least-square method can be expressed as:

$$\begin{cases} \min\left(\sum_{j=1}^{(S+1)M} r_j(\xi) \right). \\ s.t. \, 0 \le I_n \le 1, \; n = 1, 2, \cdots, N \end{cases} \tag{15}$$

In performing the beamforming of array antenna, only the good agreement between the synthesized and desired radiation pattern in the main lobe area is concerned. The shape of the radiation pattern in side lobe area is not considered. Only the maximum value of the side lobe level should be restricted. Then, the desired radiation pattern can be expressed as:

$$f_j = \begin{cases} \mathrm{HB}_j, & \left| F_j \right| > \mathrm{HB}_j \\ \left| F_j \right|, & \mathrm{LB}_j \le \left| F_j \right| \le \mathrm{HB}_j \text{ ,} \\ \mathrm{LB}_j, & \left| F_j \right| < \mathrm{LB}_j \end{cases} \tag{16}$$
$$j = 1, 2, \cdots, (S+1)M$$

where HB_j and LB_j are real and positive functions, which denote the upper and lower bounds of the desired radiation pattern, respectively.

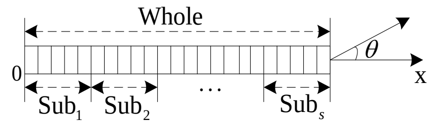

Fig. 1. Structure of a linear multi-subaperture array antenna.

III. OPTIMIZATION STEPS

In order to overcome the impact of matrix singular on the computing precision, Levenbert-Marquardt method is used to solve the model of nonlinear least-square method [19]. The algorithm steps are given as follows:

Step 1. Choose $\xi^{(0)}$ as the initial value, let $\xi_{\mathrm{best}}=\xi^{(0)}$, where ξ_{best} is the best solution of the optimization parameters. Calculate the initial synthesized radiation patterns of the whole aperture and subapertures by (7) and they are normalized by (8) and (9). The error between the synthesized and desired radiation patterns is calculated by (12). Set $r_{\mathrm{best}}=(r_j(\xi^{(0)}))^{\mathrm{T}}r_j(\xi^{(0)})$, where r_{best} is the minimum optimization error. Give $m_{\max}$ and $k_{\max}$, where $m_{\max}$ and $k_{\max}$ are the maximum iterative steps for outer and inner iterative procedure. Let $m=0$.

Step 2. Give $\beta\in(0,1)$, $\mu_k>1, \nu>1$ and $\varepsilon>0$, $\varepsilon_0>0$, $0<\Delta\varepsilon<1$, let $k=0$. Where β, μ_k and ν are the parameters used in the optimization procedure. ε

and ε_0 are the thresholds of the outer and inner iterative procedure which are very small numerical values. $\Delta\varepsilon$ is the maximum offset value of the excitation amplitude in each outer iterative procedure.

Step 3. For j=1,2,⋯, $(S+1)M$, calculate $r_j(\xi^{(k)})$ by (12) and $S(\xi^{(k)})$ is determined by $(r_j(\xi^{(k)}))^T r_j(\xi^{(k)})$.

Step 4. For j=1,2,⋯,$(S+1)M$, calculate $\nabla r_j(\xi^{(k)})$, where $\nabla r_j(\xi^{(k)})=[J_{ij}(\xi^{(k)})]$, $J_{ij}=\partial r_j(\xi^{(k)})/\partial \xi_i^{(k)}$, and i=1,2,⋯,N. Moreover, $\partial r_j(\xi^{(k)})/\partial \xi_i^{(k)}$ can be determined as follows:

If $|F_j|-f_j \geq 0$, then

$$\frac{\partial r_j(\xi^{(k)})}{\partial \xi_i^{(k)}} = \frac{\partial |F_j|}{\partial I_i^{(k)}} = \frac{1}{AF_{\max}^{(\text{Whole})}} \left(\frac{\sum_{n=1}^{N} a_n \cos(kx_i \cos\theta_m + \alpha_i)}{\sqrt{(\sum_{n=1}^{N} a_n)^2 + (\sum_{n=1}^{N} b_n)^2}} + \frac{\sum_{n=1}^{N} b_n \sin(kx_i \cos\theta_m + \alpha_i)}{\sqrt{(\sum_{n=1}^{N} a_n)^2 + (\sum_{n=1}^{N} b_n)^2}} \right), \quad (17)$$

$$1 \leq j \leq M, 1 \leq i \leq N$$

$$\frac{\partial r_j(\xi^{(k)})}{\partial \xi_i^{(k)}} = \frac{\partial |F_j|}{\partial I_i^{(k)}} = \frac{1}{AF_{\max}^{(\text{Sub}_s)}} \left(\frac{\sum_{n=N_s}^{N_s'} a_n \cos(kx_i \cos\theta_m + \alpha_i)}{\sqrt{(\sum_{n=N_s}^{N_s'} a_n)^2 + (\sum_{n=N_s}^{N_s'} b_n)^2}} + \frac{\sum_{n=N_s}^{N_s'} b_n \sin(kx_i \cos\theta_m + \alpha_i)}{\sqrt{(\sum_{n=N_s}^{N_s'} a_n)^2 + (\sum_{n=N_s}^{N_s'} b_n)^2}} \right). \quad (18)$$

$$sM+1 \leq j \leq (s+1)M,$$
$$(s-1)N/S+1 \leq i \leq sN/S,\ s=1,2,\cdots,S$$

If $|F_j|-f_j<0$, a minus is added to the right hand side of (17) and (18), $\partial r_j(\xi^{(k)})/\partial \xi_i^{(k)}$ can be obtained.

Step 5. Calculate $\nabla S(\xi^{(k)})=(\nabla r_j(\xi^{(k)}))^T r_j(\xi^{(k)})$.

Step 6. Let $\mathbf{Q}=(\nabla r_j(\xi^{(k)}))^T \nabla r_j(\xi^{(k)})$, solve equation $[\mathbf{Q}+\mu_k \mathbf{I}]\mathbf{d}^{(k)}=-\nabla S(\xi^{(k)})$, where $\mathbf{I}$ represents the unit diagonal matrix. Then, $\mathbf{d}^{(k)}$ can be calculated.

Step 7. Set $\xi^{(k+1)}=\xi^{(k)}+\mathbf{d}^{(k)}$, if $\max(\mathbf{d}^{(k)})<\varepsilon$ or $k>k_{\max}$, go to step 10, otherwise, go to step 8.

Step 8. If $S(\xi^{(k)})<S(\xi^{(k)})+\beta(\nabla S(\xi^{(k)}))^T\mathbf{d}^{(k)}$, set $\mu_k=\mu_k/\nu$, go to step 9, otherwise, set $\mu_k=\mu_k\times\nu$, go to step 6.

Step 9. Let $k=k+1$, go to step 3.

Step 10. If $S(\xi^{(k+1)})<\varepsilon_0$ or $m>m_{\max}$, $\xi_{\text{best}}=\xi^{(k+1)}$, terminate iteration, otherwise, if $S(\xi^{(k+1)})<r_{\text{best}}$, set $\xi_{\text{best}}=\xi^{(k+1)}$, $\xi^{(0)}=\xi^{(0)}+\Delta\varepsilon\times\xi^{(0)}\times\text{rand}(0,1)$, where rand(0,1) is uniformly distributed random numbers between [0,1], normalize the excitation amplitudes, let $m=m+1$, go to step 2.

Among the above steps, another layer of iteration is added to the traditional nonlinear least-square method. If the solution does not meet the requirements, another vector nearer the former initial value is selected as the initial value and the computation is repeated. The best solution of all the iterations is saved as the ultimate result. This improves the traditional nonlinear least-square method's shortness of dependence on the initial value and increases the optimization ability of nonlinear least-square method.

IV. SIMULATION RESULTS

In this section, several simulation results are presented. The achieved results show the effectiveness and feasibility of the proposed method. Let us refer to the linear array of Fig. 1, consisting of N elements and S subapertures. The adjacent elements spacing is chosen as $\lambda/2$. Assuming all elements are isotropic sources; i.e., $E_n(\theta)=1$. The parameters used in those above expressions are as follows: $\mu_k=|r_j(\xi^{(k)})|$, $\nu=1.5$, $\Delta\varepsilon=0.3$, $\varepsilon=10^{-6}$, $\varepsilon_0=0.01$, $M=361$, $k_{\max}=500$, $m_{\max}=200$. A normal personal computer Intel Core i3 530 @ 2.93 GHz CPU and 2 GB of RAM is used and the synthesis is programmed by MATLAB version 7.1.

A. Simulation result for N=60 and S=3

In this simulation example, the whole array aperture is divided into 3 subapertures. So, the number of the radiation patterns to be synthesized is 4. The Peak Side Lobe Level (PSLL) of the desire radiation pattern is selected as –25 dB. Every subaperture has 20 elements. Figure 2 shows the excitation amplitudes distribution of the antenna array. From this figure, we can see that Sub_1 has the minimum amplitudes values. So, the gain of Sub_1 is the smallest. Figure 3 shows the radiation patterns for the whole aperture and subapertures. The beam parameters of this multi-subaperture antenna array are given in Table 1. We can find that the PSLL of all the synthesized beams is lower than –16 dB. The 3 dB beam width is less than 3° for the whole aperture and is less than 6° for each subaperture. To get this simulation result, the simulation time is about 710 seconds. The dynamic range ration (I_{max}/I_{min}, DRR) of this antenna array is 16.7.

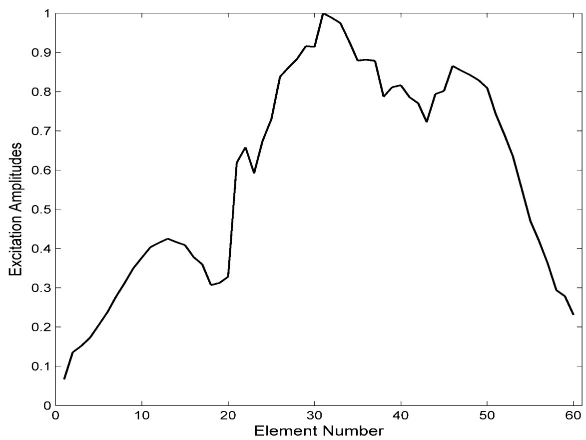

Fig. 2. Excitation amplitudes distribution for *N*=60 and *S*=3.

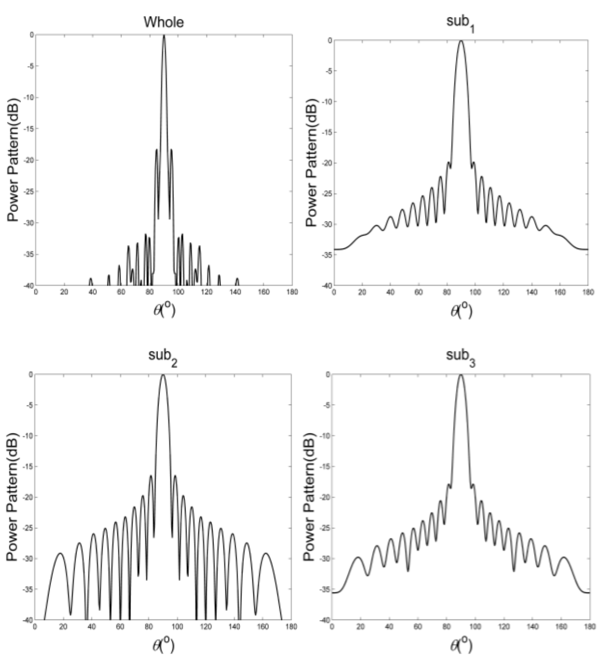

Fig. 3. Radiation patterns for *N*=60 and *S*=3.

Table 1: Beam parameters for *N*=60 and *S*=3

Beam Parameters	Whole	Sub_1	Sub_2	Sub_3
PSLL (dB)	-18.2	-19.8	-16.4	-17.8
Gain (dB)	31.0	15.6	24.4	22.1
3 dB beam width (°)	2.11	5.96	5.35	5.78
Main beam width (°)	8.0	15.0	13.0	14.0

B. Simulation result for *N*=60 and *S*=5

In order to indicate the feasibility of the algorithm in the synthesis of antenna array, another simulation example is introduced. In this simulation example, the whole array aperture is divided into 5 subapertures. So, the number of the radiation patterns to be synthesized is 6. The PSLL of the desired radiation pattern is also selected as –25 dB. The element number of every subaperture is 12. The excitation amplitudes distribution is shown in Fig. 4. From this figure, we can find that the excitation amplitudes distribution for each subaperture has a peak value. Figure 5 depicts the radiation patterns for the whole aperture and the five subapertures. The beam parameters of the radiation patterns are given in Table 2. It can be found from Table 2 that the PSLL for the radiation patterns is lower than -16 dB. The 3 dB beam width is less than 2° for the whole aperture and is less than 10° for the subaperture. Sub_5 has the minimum gain of 13.4 dB. In order to obtain these six radiation patterns, the simulation time is about 990 seconds. The dynamic range ration of the excitation amplitudes is 6.5.

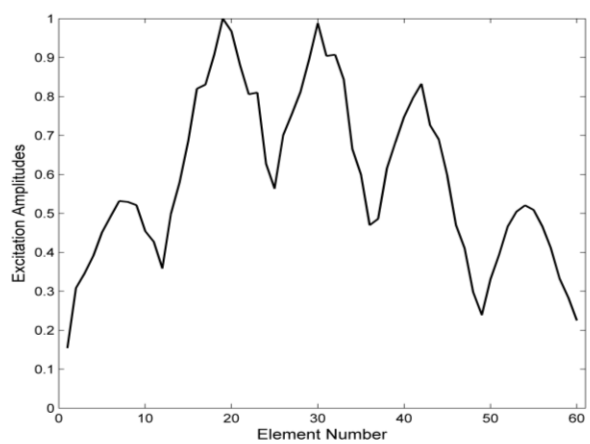

Fig. 4. Excitation amplitudes distribution for *N*=60 and *S*=5.

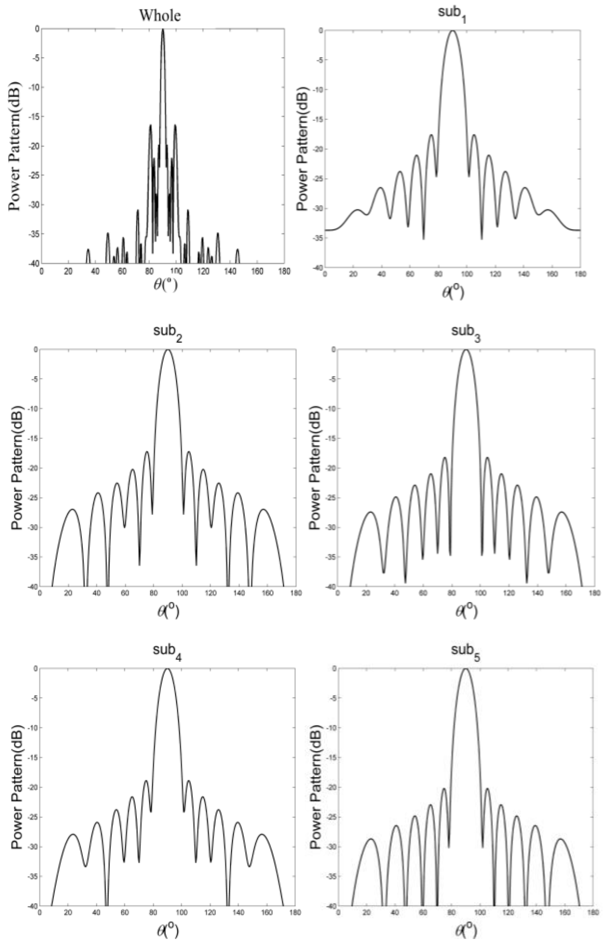

Fig. 5. Radiation patterns for N=60 and S=5.

Table 2: Beam parameters for N=60 and S=5

Beam Parameters	Whole	Sub_1	Sub_2	Sub_3	Sub_4	Sub_5
PSLL (dB)	-16.3	-17.6	-17.2	-18.2	-18.9	-20.2
Gain (dB)	31.0	13.9	19.5	19.2	17.3	13.4
3 dB beam width (°)	1.96	9.60	9.24	9.37	9.60	9.71
Main beam width (°)	10.0	23.0	22.0	22.0	23.0	24.0

C. Simulation result for N=90 and S=5

In this example, the element number of the array antenna is increased to 90 and the number of the subaperture is 5. So, each subaperture has 18 elements. Figure 6 depicts the excitation amplitudes distribution. From Fig. 6, we can find that the excitation dynamic range ration is 12.9. The radiation patterns of this kind of antenna array are shown in Fig. 7. The beam parameters of the radiation patterns are given in Table 3. Compared with the synthesis result when N=60, we can get that the PSLL reduces to −17.2 dB and the beam width is narrower. The total computational time is about 1400 seconds to get these six radiation patterns.

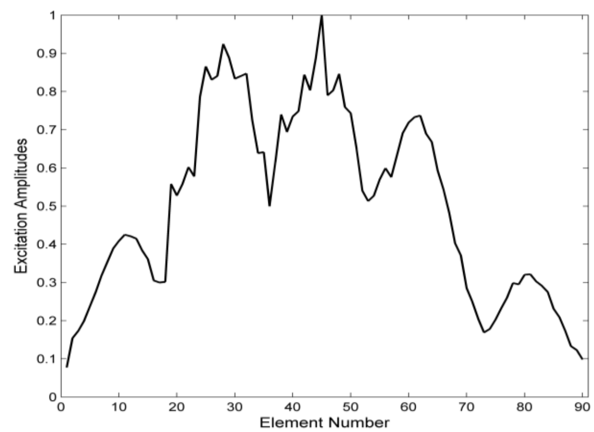

Fig. 6. Excitation amplitudes distribution for N=90 and S=5.

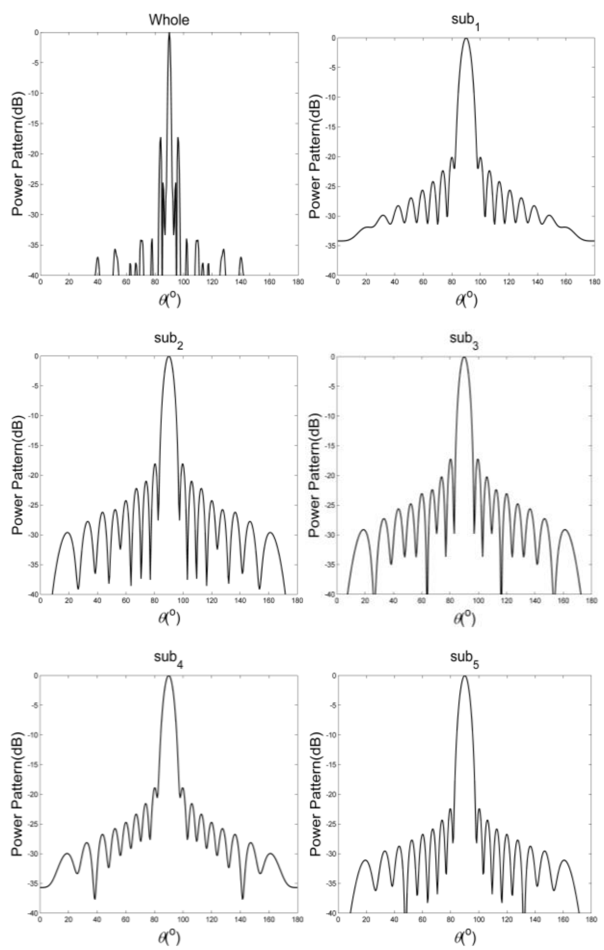

Fig. 7. Radiation patterns for N=90 and S=5.

Table 3: Beam parameters for N=90 and S=5

Beam Parameters	Whole	Sub_1	Sub_2	Sub_3	Sub_4	Sub_5
PSLL (dB)	-17.2	-20.1	-18.1	-17.2	-18.9	-22.4
Gain (dB)	33.2	14.8	22.3	22.4	19.8	12.3
3 dB beam width (°)	1.86	5.58	6.16	6.22	6.44	6.43
Main beam width (°)	5.0	16.0	15.0	15.0	16.0	16.0

V. CONCLUSION

Multi-subaperture antenna array is synthesized by an improved nonlinear least-square method. The whole array aperture is divided into several subapertures. A new method is given to determine the desired function for the nonlinear least-square method. The whole aperture and the subapertures can generate different radiation patterns. The excitation amplitudes are optimized in order to reduce the PSLL of the radiation beams. The PSLL is lower than –16 dB for the synthesized radiation patterns. Also, the beam width of the radiation patterns can be controlled effectively. When N=60, the dynamic range ratio of the excitation amplitudes distribution is less than 17 for S=3 and is less than 7 for S=5. When N=90 and S=5, the dynamic range ration is less than 13. Also, the beam width becomes narrower as the increase of element number of the whole array aperture or each subaperture. Moreover, this method can also be used in the synthesis of phase-only multi-beam antenna arrays.

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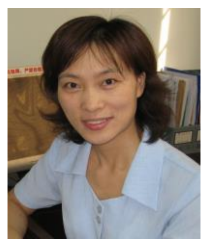

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