Design, Modelling, and Synthesis of Radiation Pattern of Intelligent Antenna by Artificial Neural Networks

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Abstract − The work presented in this paper refers to the synthesis of the radiation pattern of intelligent antennas by the artificial neural networks (ANN) based on linear antennas array supplied with coaxial lines. The method of synthesis implemented for this type of antennas makes it possible to approach with an optimal desired radiation pattern specified by a gauge with modifying amplitude, phase excitation and sources space distribution. The approach used is based on geometry of the antennas and the artificial neural networks (ANN) which are able to model the linear antennas array. Our principal contribution in this paper is the extension of a synthesis model of the radiation pattern. The developed synthesis is based on the neural networks technique.

I. INTRODUCTION

Intelligent antennas take advantage of both antenna and propagation technologies. It has the potential to reduce multipath interference, increase signal to noise ratio, and introduce frequency reuse within a confined environment. Several challenges remain however in the development of intelligent antennas and one of these is the availability of efficient radiating elements interfacing with the beamformer.

The interest of these systems is their capacity to be reacted automatically to a complexes environment whose interference is known a priori. They make it possible to reduce the side-lobes levels existing in there interference direction, while maintaining the main lobe in useful direction.

These systems based on antennas network, devices to calculate the angles of arrivals AOA and numerical tools for synthesis which allot weights to the elements of the antenna network in order to optimize the output signal according to preset control technique for the formation of the ways and the cancellation of interfering.

An adaptive antenna network can thus be defined like a network able to modify its radiation pattern thanks to software of synthesis ready to answer the desired specifications [1-3].

The intelligent antennas systems require in general the coefficients of the network in real time what is not possible with a traditional method of synthesis. We adapt a new method of synthesis based on neural model. This tool presents a great performance at the level of its speed of convergence.

The use of the patch elements to produce an electromagnetic radiation goes back to the Fifties, but the application of this phenomenon for the first realization of antennas dates only from the beginning of the Sixties ten, when the need to conform of the networks appeared, in particular for the missiles.

Various analytical and numerical methods of optimization (Fourier, Dolph-Tchebycheff, Woodward-Lawson, relieving, Newton, general synthesis method…) [4-6] were developed and applied to synthesize the radiation patterns of antennas networks.

Recently, severe optimisation techniques such as neural network were developed to optimize general results.

In this paper, we will present the method of neural networks which will be applied to the synthesis of linear antennas array.

II. PROBLEM OF SYNTHESIS

The antenna synthesis was reduced to seek excitation and / or the space distribution on an axis of a certain number of elements fixed yet. For the representation of the radiation patterns, there are two types of conformations [1, 7, 8]:

-A conformation in a plan, for example the two principal plans *E* and *H* In this case, the discretization goes only on the direction θ the other direction φ *is* fixed.

-A conformation in all space (θ, φ). In this case the couple (θ, φ) is discretized [1].

Let's consider a one-dimensional network with P_x elements laid out regularly in each direction (*OX).* Their radiation pattern is $F(\theta,\varphi)$.

$$F(\theta,\varphi) = f(\theta,\varphi).\sum_{m=1}^{P_x} w_m \exp(jk_0 \sin\theta.(X_m \cos\varphi)) \quad (1)$$

where

$f(\theta,\varphi)$: radiation pattern element.
X_m : co-ordinates of the element m.
W_m : complex weights an order m.
K_0 : wave numbers.

For a symmetrical one-dimensional network with (*2Nx* elements, the radiation pattern of a network is,

$$F_{Rsx}(\theta,\varphi) = \frac{1}{F_{Rsx\max}} \sum_{i=1}^{Nx} a_{xi} \cos(k_0 X_i \sin\theta\cos\varphi + \psi_{xi}) \ .(2)$$

According to this expression, we can notice that the expression of the synthesized radiation pattern is,

$$F_S(\theta,\varphi) = F_{RSx}(\theta,\varphi).f(\theta,\varphi) \quad (3)$$

with $F_{RSx}(\theta,\varphi)$ is the array factor.

$F_S(\theta,\varphi)$: characterize the radiation pattern of a linear antenna's array with N_x elements spaced of Δx following *OX.* (Fig. 1)

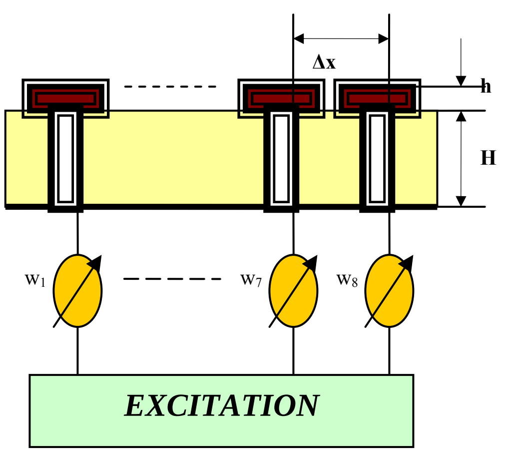

Fig. 1. Linear antenna array.

When the desired radiation pattern $F_d(\theta,\varphi)$ is specified using a gauge, the synthesized radiation pattern must hold within the limits fixed by this gauge.

The gauge can be defined in all space, part of space or only in some plans. An example of projection of gauge is given on Fig. 2, with the various parameters which make it possible to describe it, characterizing the desired radiation pattern starting from gauge (Fig. 2).

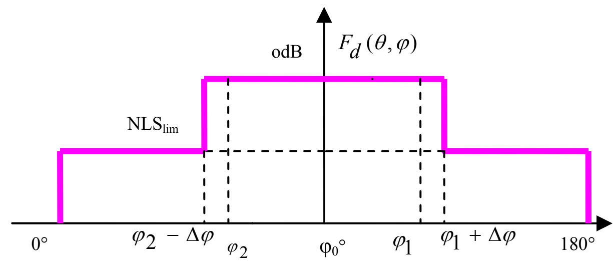

Fig. 2. Gauge characterizing the desired radiation pattern.

As the network is symmetrical, it is possible to exclusively optimize the radiation pattern by taking account the excitation of a quarter source of the linear antenna array. The excitation of the other sources is then obtained by symmetry. In order to limit the computing time, we defined the gauge only in the plan θ =90°.

III. ANTENNA DESIGN

A. *Elementary Antenna*

The produced elementary antenna [9] is rectangular (Fig. 3) and is active in the band (f=2.18GHz). The excitation is carried out starting from a coaxial cable whose central heart is welded with the ribbon of excitation and the base plate in the plan of mass. The substrate retained for our study is Plexy Glass whose characteristics are as follows the ε_r=2.5 ± 0.02, tgδ=2 10^{-2} with 1=Hz, the thickness of dielectric the h=6mm.

Fig. 3. Patch geometry.

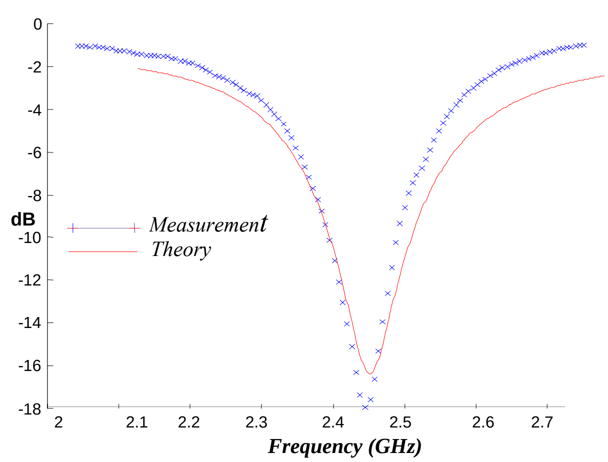

Fig. 4. Coefficient of reflection of each element.

The measurement of S_{11} shows a good adaptation to the frequency 2.45 GHz, as shown in Fig. 4.

B. Antenna Array

The prototype is composed by a network of 8 elements in plan E, band 2.45 GHz, on a plexy Glass substrate, thickness h=6mm, shown in Figs. 5 and 6. Each element is connected by a coaxial cable.

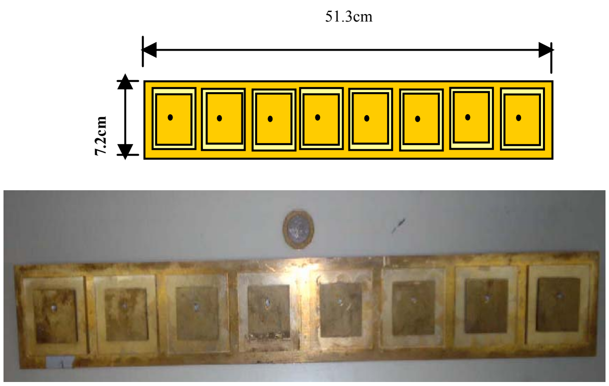

Fig. 5. Antenna array (w_x= w_y =72 mm, f=2.45 GHz, Δx= 0.5 λ, N=8 and h=6mm).

Fig. 6. Antenna array- E plan with a Wilkinson technology.

In certain cases, the gauge must be satisfied with weights answering certain technological limitations. These constraints are very often constraints of dynamics on the excitations and these constraints are not-linear. To illustrate our matter, one gives the example of a symmetrical network of 8 sources with which one must synthesize a gauge and obtain weights realized with a Wilkinson technology. In our study one will replace this technology by a neuronal networks model.

Thus, one proposes to make the synthesis of realizable weights thanks to the use of neural networks.

IV. SYNTHESIS OF RADIATION PATTERN

A. Amplitude Synthesis

1) Directing beam: The synthesis of a directing beam of linear antennas array [1, 4] consists in determining the excitation amplitude according to *OX* so the vectors $A_{xi}=[a_{x1},a_{x2},....,a_{xNx}]$ which allows the synthesized radiation pattern $F_S(\theta,\varphi)$ to approach $F_d(\theta,\varphi)$.

By considering a strictly periodic space distribution of step Δx according to *OX* positions X_i of the sources becomes [5],

$$X_i = (i-1/2)\,\Delta x \qquad i=1, N_x \quad . \tag{4}$$

Figure 7 shows the synthesis result of radiation pattern of linear antenna array with 8 elements with unit excitation amplitude A_{xi} = [1, 1..., 1].

It is very difficult to approach the desired radiation pattern with this uniform excitation. That's why we to approach with Dolph-Tchebycheff method. Then we will use the artificial neural network ANN for our synthesis.

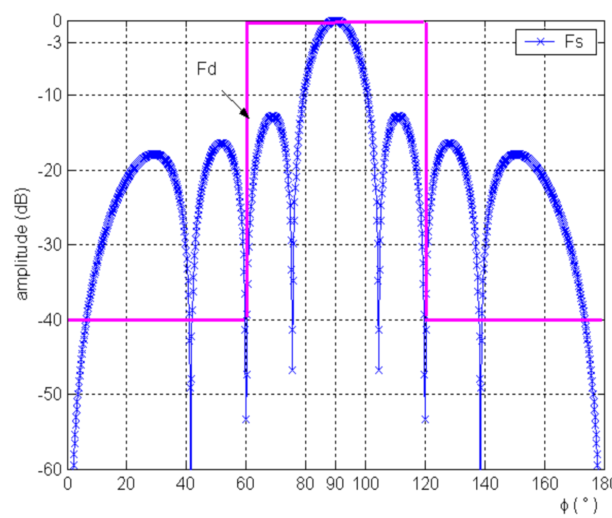

Fig. 7. Rectangular plot of beam pattern magnitude of an 8-element linear pointing at φ_0=90° with Δx=0.5λ.

The synthesized radiation pattern $F_S(\theta,\varphi)$ and desired $F_d(\theta,\varphi)$ are presented at the following Fig. 8.

We will use the algorithm of Dolph-Tchebycheff for the synthesis to minimize side lobe- level which resembles the shape of Beam pattern (linear cosinus function combination). Then we will have the same form for all the lobes with various side-lobe levels (-20dB, -30dB, -40dB, -50dB, - 60dB), shown in Fig. 9.

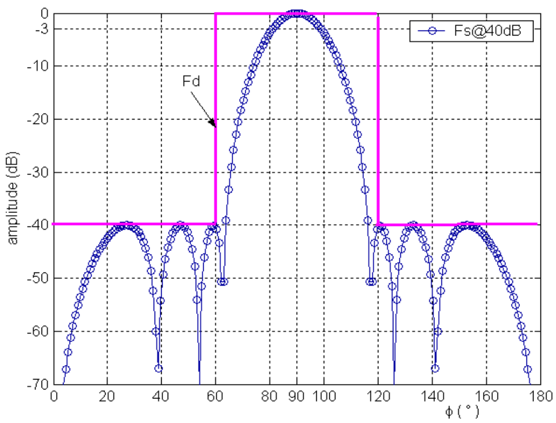

Fig. 8. Rectangular Plot of Beam pattern Magnitude of an 8-element linear with Dolph-Tchebycheff amplitude distribution pointing at φ_0=90°with Δx=0.5λ.

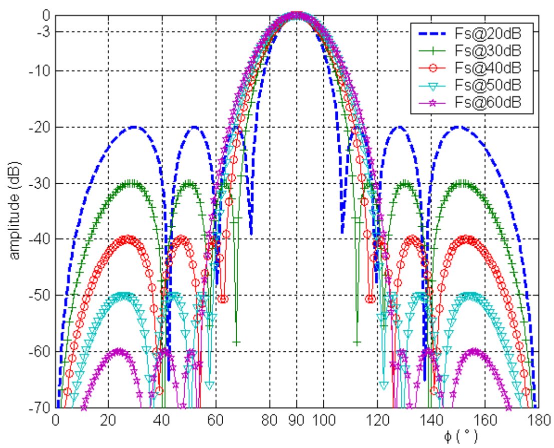

Fig. 9. Side-lobes levels (20 dB, 30 dB, 40 dB, 50 dB, 60 dB pointing at φ_0=90°with Δx=0.5λ.

Figure 10 shows the result of excitation synthesis using the Dolph-Tchebycheff method with various side-lobes levels NLSlim = -60 dB, -50 dB, -40 dB, - 30 dB, -20 dB [5].

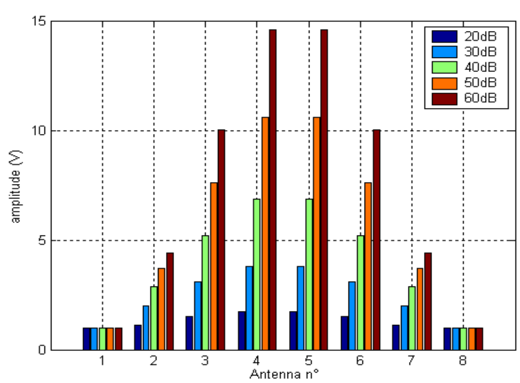

Fig. 10. Synthesized excitations with Dolph-Tchebycheff method of an 8-element linear pointing at φ_0=90°with Δx=0.5λ.

2) Multibeam: A multi-beam is necessary to cover several sources simultaneously, with possible total angular field sweeping of the radiofrequency [3].

We present two examples of synthesis with 2 & 3 beams (Figs. 11 and 12)

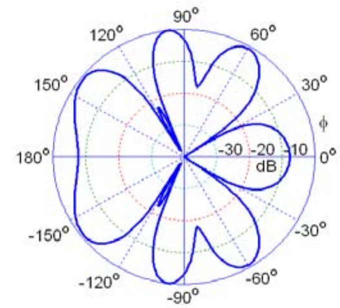

Fig. 11. Polar plot of three beams patterns. Magnitude of an 8-element linear array. Pointing at φ_0=60°, 96°, 144 ° with Δx=0.5λ.

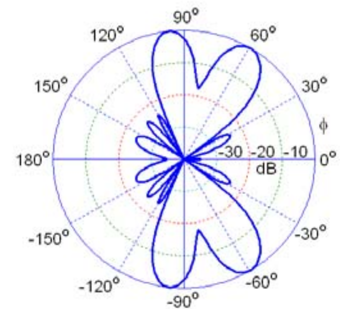

Fig. 12. Polar plot of two beams patterns. Magnitude of an 8-element linear array. Pointing at φ_0=60°, 96° with Δx=0.5λ.

Figures 11 and 12 show the synthesis result [3, 10] of radiation pattern of linear antennas array with 8-elements and Δx=0.5λ. Figure 11 presents the radiation pattern of 3 beams pointing at (60°, 96°, and 144°). Figure 12 presents the radiation pattern of 2 beams pointing at (60°, 96°). Figure 13 shows the radiation patterns of 2 beams patterns at (60°, 144°) and a zero at (96°) of an 8-element linear with Δx=0.5λ.

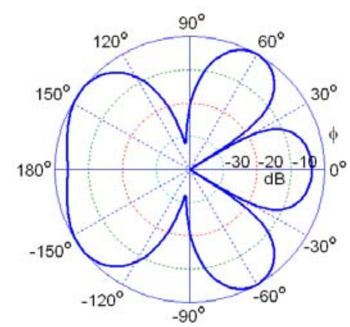

Fig. 13. Polar plot of two beams patterns. Magnitude of an 8-element array pointing at φ_0=60°, 144° and a zero at 96° with Δx=0.5λ.

B. Amplitude & Space Distribution Synthesis

This approach is based on the design of linear antennas array in which [9] we affect the 2 parameters amplitude & space distribution of the sources [8]. The idea is to find the 2 vectors $X = [\Delta_{x1}, \Delta_{x2},.... \Delta_{xNx}]$ & $A_{xi}= [a_{x1}, a_{x2},...., a_{xNx}]$ permitting optimized radiation pattern $F_d(\theta,\varphi)$.

The method of synthesis is based [1] on the space distribution of the sources and the amplitude of excitation to optimize the desired radiation pattern.

According to Fig. 14, we notice that radiation pattern is function of the distance between patches: the radiation pattern is directing and main lobe increases in-3dB increases when we decrease the distance between patches.

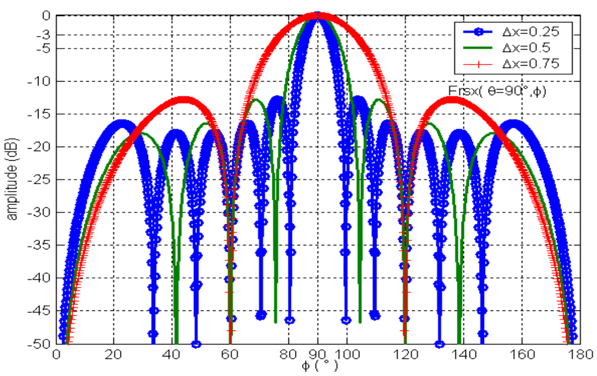

Fig. 14. Rectangular Plot of Beams patterns Magnitude of a 8-element linear pointing at φ_0=90°with Δx=0.25λ, Δx=0.5λ, and Δx=0.75λ.

Figure 15 shows the 2 synthesised $F_S(\theta,\varphi)$ and desired radiation pattern $F_d(\theta,\varphi)$and the whole neural networks training [11] with 8-elements.

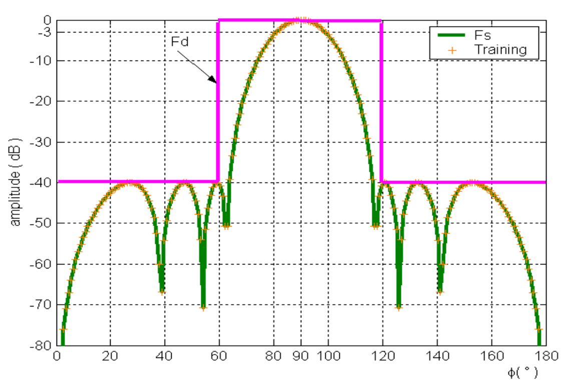

Fig. 15. Rectangular plot of synthesized beams patterns, magnitude and desired patterns of an 8-element linear pointing at φ_0=90°with (NLSlim=-40dB, Δx=0.5λ).

We notice, according to Fig. 15, that radiation patterns are contained within the limits imposed by the gauge.

C. Phase Synthesis

The radiation patterns depend on excitation levels [12] which control the side-lobes level and the maximum oscillation amplitude of the main-lobe, [9] in different zones constituting the forming plan (gauge). The angular fields' specifications are necessary for the gauge. In that case, we consider 15 angular fields that start from T_1 to T_{15}, as shown in Fig. 16.

- For diagrams composed by 3 main-lobe, we define all angular zones from T_1 to T_{15}.
- For diagrams composed by 2 main-lobe or 1 main-lobe and zero, there are $T_1=T_2=T_3=T_4=T_5=T_6$.
- For diagrams composed by only 1 main-lobe $T_1 = T_2 = T_3 =T_4=T_5=T_6=T_7=T_8=T_9=T_{10}$.

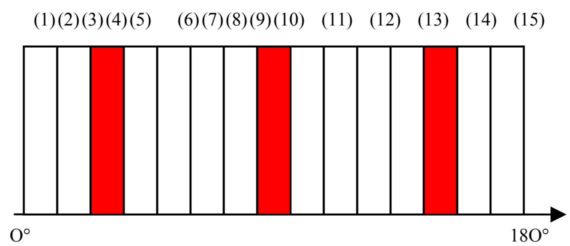

Fig. 16. Specifications.

The synthesis depend on amplitude and (or) phase and in certain cases on amplitude and position of patches. In present case, we are interested in phase synthesis. Figure 17 shows the radiation patterns of a linear antennas array composed by 8 patches using different angular fields starting from T_1 until T_{15} (φ_0 = 12°, 24°, 36°, 48°, 60°, 72°, 84°, 96°, 108°, 120°, 132°, 144°, 156°, 168°, 180°) and depicted by Δ x=0.5λ. Results given with total sweeping in angular space are presented in Fig 17.

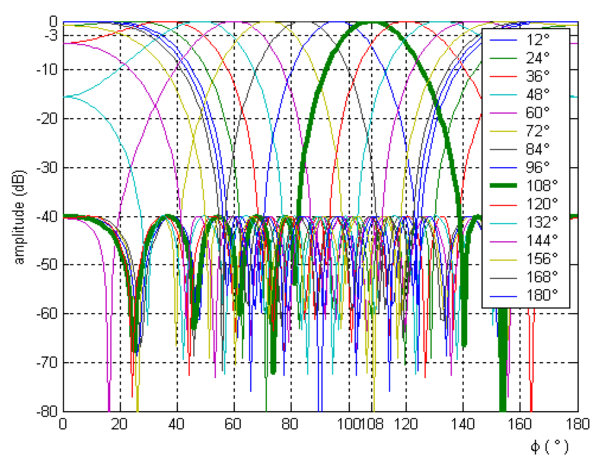

Fig. 17. Rectangular Plot of Beams patterns Magnitude of a 8-element linear pointing at (φ_0=12° ,24° ,36° ,48° ,60° ,72° ,84°, 6°, 108°, 120°, 132°, 144°, 156°, 168°, 180°with Δx=0.5λ) .

D. Simulation and Measurement Examples

Table 1 shows the simulation results of the proposed approach when it is used with prescribed steering and null design. Table 2 shows the simulation results of the proposed approach when it is used with prescribed multiple steering lobes.

Table 1. Excitations for different steering lobes and interference nulling.

	Synthesized excitations (phases)		
	-10° (steering) and –10° (interfering)	-40° (steering) and 0° (interfering)	-50° (steering) and -10° (interfering)
	ϕ	ϕ	ϕ
1	-145	-42	223
2	-60	94	32
3	-37	-173	158
4	-8	-69	-79
5	8	69	79
6	37	173	-158
7	60	-94	-32
8	145	42	-223

As Figs. 18 to 20 indicate, we can observe the performance of our algorithm. These figures show good agreement between the simulation and the measurement results in terms of accuracy, efficiency and reliability of the model. We can see that a broad null (lower than –30 db) is easily available. It is interesting to notify that the method allows the control of nulling level to the detriment of the adjacent side lobes energy, which is pushed up. Also, solutions with 2 or 3 lobes can be reached with acceptable solutions.

Table 2. Excitations for different multiple steering lobes.

	Synthesized excitations (phases)		
	-50° and – 20°	-30° and 30°	-40°, 20° and 50°
	ϕ	ϕ	ϕ
1	240	5	95
2	50	185	315
3	180	180	279
4	310	360	126
5	50	360	234
6	180	180	81
7	310	175	45
8	120	355	265

This method does not only hold the examples presented above, but also appears to be general for all cases of synthesized desired characteristics of steered beams.

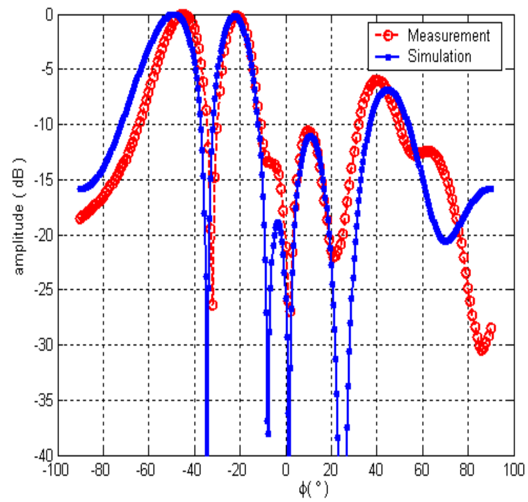

Fig. 18. Two steering lobes at (-50° and -20°).

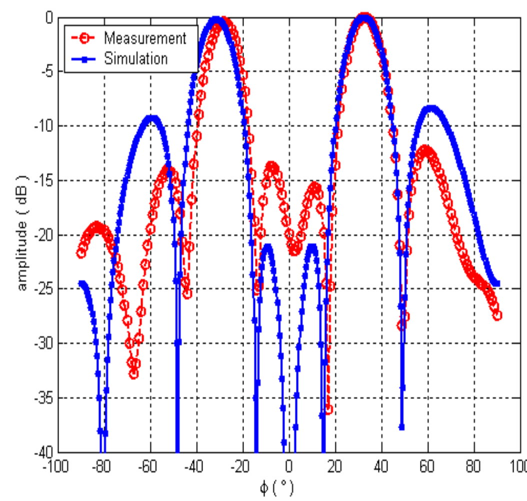

Fig. 19. Two steering lobes at (-30° and 30°).

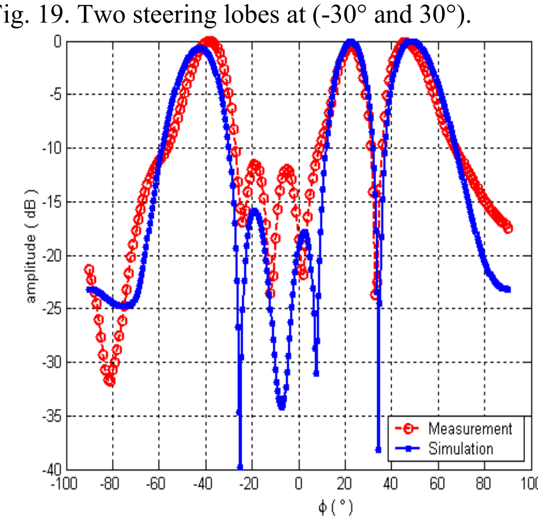

Fig. 20. Three steering lobes at (-40°, 20°, and 50°).

V. SYNTHESIS BY ARTIFICIAL NEURAL NETWORKS

The artificial neural networks ANN is a numerical approach inspired of the structure and behaviour of the biological neural. They are composed by inter-connected units which we call formal or artificial neural able to fulfil certain particular and special functions [7, 9].

The ANN allows approaching the nonlinear relationship with significant degrees complexity. The input cells are intended to collect information which is transformed by hidden cells to the output cells.

This network is composed by 1 or more hidden layers. In general, we use a sigmoid activation function,

$$g(x) = \frac{1}{1+\exp(-x)} . \tag{5}$$

The phase φ_i and amplitude A_i are calculated according to the direction of arrival of the signal carries out us to form a neural network made up of 2 neurons at the entry and 8 neurons at the exit (8 patchs). Several simulations were made, the optimal network obtained after the adjustment of the various parameters [3, 13]. The neural networks used in the study of this antenna are the continuous linear neural networks that's the activation function is a linear with threshold.

The calculation expression of the new values of synaptic weights connecting the neurons is given by the following relation [14],

$$w_{ij}(k+1) = w_{ij}(k) + \eta \frac{\partial E_K}{\partial w_{ij}} \tag{6}$$

and

$$E_k = \frac{1}{2}\sum_{i=1}^{q}\left(F_s(i) - F_d(i)\right)^2 , \tag{7}$$

with

η : coefficient of training or the grain of adaptation.

E_K : the quadratic error.

W ij : weight associated with the connection of neuron i towards the neuron j.

Figure 21 shows the result of synthesis with the artificial neural networks ANN of radiation pattern pointing at 108° of a linear antennas array with a sides-lobes level - 40 dB (Fig. 22) [7]. One notes that the synthesis makes it possible to strongly reduce the maximum sides-lobes levels.

Figure 23 shows the system; in fact, it consists of a linear antennas array and neuronal model.

The calculated quadratic error E_K, by this comparison is returned to the network for retro-propagation. This training is directed because the completely known state can be imposed like exit wished on the network after each step of calculation.

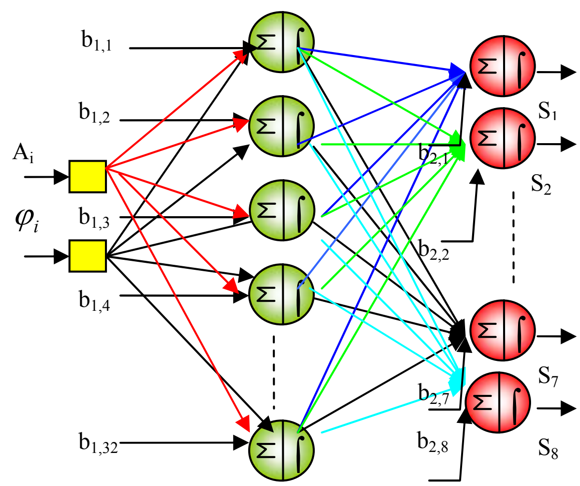

Fig. 21. Neural network topology.

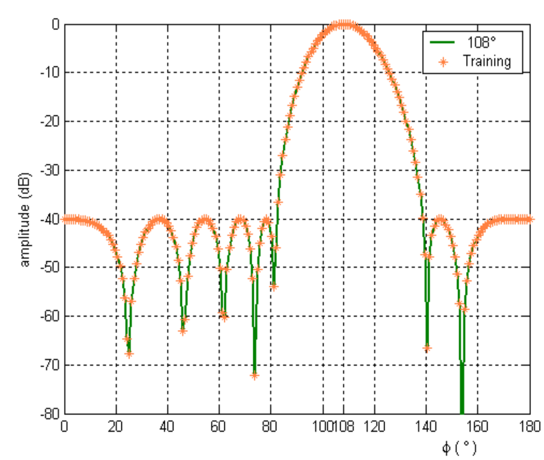

Fig. 22. Rectangular Plot of synthesized Beam pattern Magnitude of a 8-element linear pointing at φ_0=108°with (NLSlim=-40dB, Δx=0.5λ).

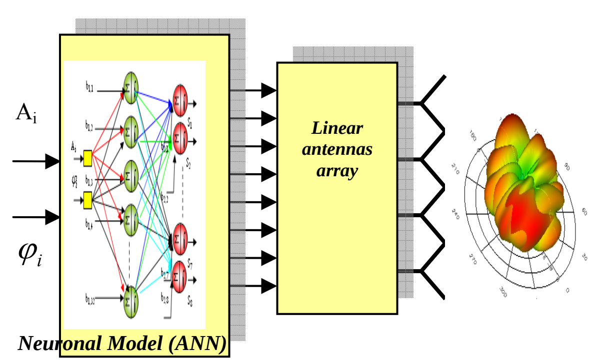

Fig. 23. Identification of a neural model of a dynamic system (forced training).

VI. CONCLUSION

The intelligent antenna is a powerful technique to reduce multi- user interference and increase system capacity. In this paper, we developed two approaches of synthesis of intelligent antennas starting from a technique of total optimization based on the neural networks , by action on the excitation in amplitude, phase and on the localization of the sources by using the specification of the angular fields starting from T_1 to T_{15} to sweep the totality of the angular space by an intelligent way and reduce the existing level of side-lobe in the interference direction, while maintaining main lobe in useful direction [6].

Results given by our approach prove the ability of intelligent system to distinguish desired signals from others and minimize the side-lobe level while maintaining main lobe in desired direction.

The artificial neural network ANN structure presents interesting results in synthesis of linear antennas array and permits a simultaneously electrical and geometrical control of the network. Due to the stochastic aspect of this method and for each execution algorithm, the results are not always identical but similar.

The artificial neural networks (ANN) is characterized by a slow total convergence compared to deterministic methods. However, the method speed depends on electric and geometrical parameters of the network.

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