International Journal of Advancements in Electronics and Electrical Engineering– IJAEEE
Volume 4 : Issue 1 [ISSN : 2319-7498]
Publication Date : 30 April, 2015

Antenna Array Pattern Nulling using Constraint Based Optimization Techniques

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Abstract— **Modern communication systems employ antenna arrays for enhanced coverage and efficiency. Such arrays need to exhibit low peak sidelobe level (PSLL) and the capability of positioning multiple asymmetrical mulls. In this paper, modified Invasive Weed Optimization (IWO) algorithm is used to estimate the complex elemental excitations required for achieving multiple nulls in specified directions while maintaining PSLL below the detectable range of -40dB. The novelty of the proposed approach is in the application of a constraint-based static penalty function during optimization of the array. The static penalty function is able to put selective pressure on the PSLL, the first null beam width (FNBW) or the accurate null positioning as desired by the application at hand lending a high degree of flexibility to the synthesis process. Several numerical results of periodic array patterns with the imposed asymmetrical multiple null conditions are presented to illustrate the performance of the proposed method.**

Keywords— **Linear antenna array; invasive weed optimization; static penalty function; side lobe level; asymmetrical nulls; null steering.**

I. Introduction

Antenna arrays are being widely used in wireless, satellite, mobile and radar communications systems. The use of antenna arrays has extended system coverages, improved signal quality and increased the spectrum efficiency through the formation of steerable beams with increased directivity. The performance of the communication system greatly depends on the efficient design of the antenna arrays. To meet the demands of long distance coverage and noise free communication, it is necessary to design antenna arrays with high directivity, narrow beam width and low side lobe levels and at the same time with an enhanced ability to position nulls in directions of undesired interferences.

Systems with narrow beam width are desired for obtaining high directivity. On the other hand, systems need to maintain low peak side lobe levels (PSLL) to avoid interference with other systems operating in same frequency band. The above mentioned requirements of SLL and beam width are in contrast to each other as arrays with narrow beam width generally do not produce lower side lobe levels and vice versa. Also, the increasing EM pollution has prompted the placing of nulls in undesired interference directions. So it is necessary to design the antenna array with low side lobe levels while maintaining fixed beam width and placing nulls in interference directions.

Low sidelobe levels and steering nulls in interference directions can be achieved by adjusting either the amplitude excitations or the phase excitations or the complex excitations of a periodic array. Otherwise the spacing between the individual elements may also be varied to form an aperiodic array. In communication environment, multiple nulls need to be positioned asymmetrically at multiple locations around the main beam. Position-only and amplitude-only optimizations are incapable of producing the asymmetrical nulls. For this purpose phase needs to be optimized. Thus, phase-only or complex optimization is of practical interest in producing the asymmetrical nulls around the main beam. Synthesis of linear antenna arrays has been extensively studied from the past 5 decades. In order to optimize this type of electromagnetic designing problems, nature inspired algorithms based on the nature laws such as genetic algorithm (GA) [1-2], Particle swarm optimization (PSO) [3, 4], cat swarm optimization (CSO) [5], Ant colony optimization (ACO) [6, 7] have been successfully applied in the design of antenna array synthesis.

The present work deals with an improved variant of the Invasive weed optimization (IWO) [8] algorithm. The classical IWO [9, 10] can be modified to incorporate a sinusoidal variation in the standard deviation of the randomly distributed solutions during the optimization. This leads to quicker detection of optimize solutions. The present work also introduces constraint handling as a new concept in antenna array synthesis through the application of the static penalty function [11]. The use of the static penalty function allows the designer to set desired values of PSLL, FNBW and null depth. This renders a great degree of flexibility to the synthesis as the different design parameters may be assigned different penalty coefficients depending on the application requirements. To the best of the author's knowledge, constraint handling using static penalty function has not yet been applied to optimize the complex excitations in linear antenna array synthesis. In this communication, several design examples are considered to show how the modified IWO using constraint handling is useful in controlling the shape of the radiation pattern while determining the optimal performance.

In this paper, the modified IWO is applied to optimize complex excitations of the individual elements to produce a radiation pattern with minimum side lobe levels while steering the nulls in directions of interferences. The configuration of

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the linear array and the problem formulation is discussed in Section II. Section III presents the IWO algorithm. Design example and detailed simulation results are discussed in section IV while Section V concludes the paper.

II. Modified Invasive Weed Optimization

IWO algorithm was first introduced by A. R. Mehrabain and C. Lucas in 2006 [9]. IWO is inspired by weed colonization in nature and is based on weed biology and ecology. Distinctive properties of the IWO algorithm are that it allows all of the population (weeds) to participate in the reproduction process and reproduction of weeds happens without mating. This leads to a global search for the optimized solutions. The steps involved in the modified IWO are presented below.

A. *Initialization*

A finite number of seeds are initialized randomly in the N dimensional solution space with random positions. Each seed's position represents one possible solution of the optimization problem.

B. *Reproduction*

In reproduction stage the fitness value of each seed is determined. This process resembles growing of seed to flowering weed. The magnitude of the fitness value determines the reproductive capability of each seed. The number of reproduced seeds from each seed is calculated based upon the seed's own fitness value and the colony's lowest & highest fitness values. Thus, the number of seeds produced increases linearly from weed with worst fitness to weed with better fitness. That is, those weeds with worst fitness values produce less number of seeds and vice versa. The procedure is illustrates in figure 2. A significant advantage of the algorithm is that it allows all weeds to participate in the reproduction process. This is beneficial because under certain conditions, weed with worst fitness value may also have some useful information to contribute during the evolutionary process.

C. *Spatial dispersal*

The produced seeds are dispersed randomly over the search space by normal distribution with zero mean and varying standard deviation. That is, the produced seeds are scattered around the mother weed, leading to local search. The number of seeds (S) produced by each weed is given by

$$S = Floor\left[S_{min} + \left(\frac{f - f_{min}}{f_{max} - f_{min}}\right) S_{max}\right] \qquad (1)$$

where S_{max} and S_{min} are maximum and minimum number of seeds that may be produced from each weed respectively. f_{max} and f_{min} are maximum and minimum fitness values in the colony.

The standard deviation (σ_g) of the distribution at generation number g reduces nonlinearly over the generations ranging from initial standard deviation $(\sigma_{initial})$ to final standard deviation (σ_{final}) and is given by:

$$\sigma_g = \frac{(gen_{max} - g)^{nl}}{(gen_{max})^{nl}}\left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final}. \qquad (2)$$

To enhance the performance of IWO, $|\cos(gen)|$ term [8] is added for periodic variation in standard deviation, which helps in exploring the better solutions quickly. The modified standard deviation is given by:

$$\sigma_g = \frac{(gen_{max} - g)^{nl}}{(gen_{max})^{nl}}|\cos(gen)|\left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final} \qquad (3)$$

Where gen_{max} is the maximum number of generations and nl is the non linear modulation index. It is noticed from the literature [9] that, the value of nl has shown significant effect on the performance of the IWO. It was suggested that the good choice for nl is 3.

D. *Competitive exclusion*

The new seeds produced grow to flowering weeds and are placed together with parent weeds in the colony. So there is a need of limiting the number of weeds and elimination is done based on the fitness values of the weeds in the colony. Weeds with worst fitness are eliminated until the maximum number of weeds (P_{max}) in the colony is reached. Thus weeds with better fitness survive. Previous work [9, 10] has shown that IWO algorithm gives better performance when the P_{max} is chosen between 10 and 20. The selected P_{max} goes to the next generation. The steps involved in the IWO algorithm are shown in Fig. 2.

III. Problem Formulation

The geometry of a 2N element linear antenna array placed symmetrically along x axis is shown in Fig. 1.

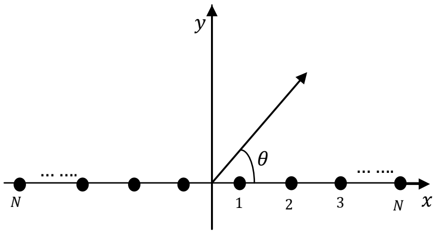

Fig. 1. Geometry of the symmetrically placed linear array.

The array factor (AF) [4, 5] of the array in the azimuth plane is

$$AF(\theta) = \sum_{n=1}^{N} A_n e^{j(2\pi(d/\lambda)\sin(\theta))} \qquad (4)$$

where θ is the azimuth angle, $d/\lambda = 1/2$ is the spacing between the elements normalized by the wavelength and $A_n = I_n e^{\varphi_n}$, I_n and φ_n are the excitation amplitude and phase of element n respectively.

The main motive is to suppress the PSLL with near constant first null beam width (FNBW) of chosen array while steering the nulls in directions of interferences by employing non

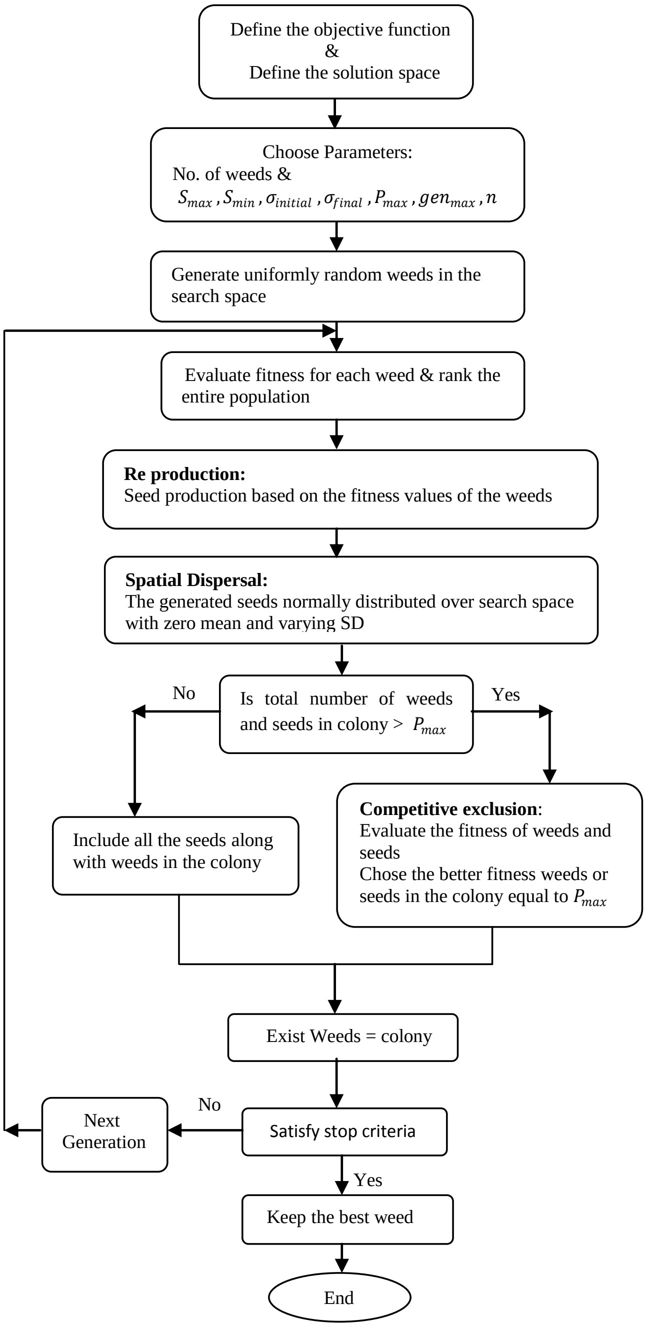

Fig. 2. Flow chart of IWO.

uniform complex excitations on individual elements of the antenna array.

So it is required to develop an objective function which will force the optimization algorithm to find the feasible solutions by satisfying all the above objectives. The effective way to combine the all the objective in a single objective is to use of static penalty function [11]. Penalty function methods transform a constrained problem to an unconstrained one by penalizing those solutions which are infeasible. The penalty function method adds a penalty whenever the solution is far distance from feasibility. In the static penalty method the penalty coefficient for each constraint is chosen in such a way that it increases in proportion to higher levels of violation. The formulation of the objective is given as

$$F(\vec{x}) = f(\vec{x}) + \sum_{i=1}^{m}\left(R_{k,i} \times max(0, g_i(\vec{x}))^2\right) \quad (5)$$

If constraint is satisfied $(g_i(\vec{x}) \leq 0)$ then $max(0, g_i(\vec{x})) = 0$, otherwise $max(0, g_i(\vec{x})) = g_i(\vec{x})$. Where $\vec{x}$ is the vector of variables, $g_i(\vec{x})$ is the i^th constraint, m is the total number of inequality constraints, $R_{k,i}$ is the i^th penalty coefficient, $f(\vec{x})$ is unpenalized objective function, k=1, 2,.., q, where q is the number of levels of violation defined by the user. The design problem is modeled as

$$F(\vec{x}) = |FNBW_O - FNBW_D| + (R_1 \times max[0, |PSLL_O - PSLL_D|]^2 + R_2 \times \sum_{i=1}^{n} max[0, |Null_{Oi} - Null_{Di}|]^2) \quad (6)$$

Where $\vec{x}$ is the element complex excitation vector, θ_0 is angular region excluding the main lobe, $FNBW_O$ & $FNBW_D$ are the optimized FNBW and desired FNBW respectively, $PSLL_O = max\left(AF_{dB}^{\vec{x}}(\theta_0)\right)$ & $PSLL_D$ are the optimized PSLL and desired PSLL respectively, $Null_{Oi} = AF_{dB}^{\vec{x}}(\theta_i)$ & $Null_{Di}$ are the optimized null depth and desired null depth respectively of the i^{th} null at θ_i for n number of nulls.

IV. Numerical Illustrations

In this paper, a 20 element linear array is synthesized using the method of IWO. The element spacing of the array is taken as $\lambda/2$, where frequency of operation is 1GHz. The mutual coupling between the antenna elements is ignored in this analysis. IWO is applied to optimize complex excitations of the individual elements for obtaining deep nulls at different interference directions. The obtained results are compared to the non-optimized periodic array with a 40dB Taylor profile amplitude distribution, referred to herein after as TADPA. The desired first null beam width is maintained constant at the beam width of the non-optimized 20 element TADPA. The beam width tolerance was set at $\pm 5\%$. For all the examples, the desired FNBW, PSLL and null depth level are set at 21^0, -40dB and -60dB respectively. The values of R_1 and R_2 are set at 10^7 and 10^3 respectively for all the design cases.

IWO algorithm is implemented using MATLAB. The parameters of the IWO algorithm are given in the Table I. These parameters were set after experimental verification while complying with the guidelines provided in literature [8, 9]. The radiation pattern of the array is computed at 720 angles in the azimuth region of -90^0 to 90^0. All the computations are performed on a PC operating at 3GHz with 2GB of RAM. The optimized complex excitations are summarized in Table II.

Table I. Parameter setup for IWO

Parameter	S_{max}	S_{min}	$\sigma_{initial}$	σ_{finial}	P_{max}	nl	Pop. size
Value	4	0	0.1	0.00015	20	3	10

The first example illustrates the synthesis of a 20 element TADPA with two nulls imposed at 21^0 and -42^0. The obtained far field radiation pattern and the corresponding convergence of the fitness value by controlling the phase excitations, while maintaining a Taylor profile for the amplitude excitations is shown in Figs. 3 and 4 respectively.

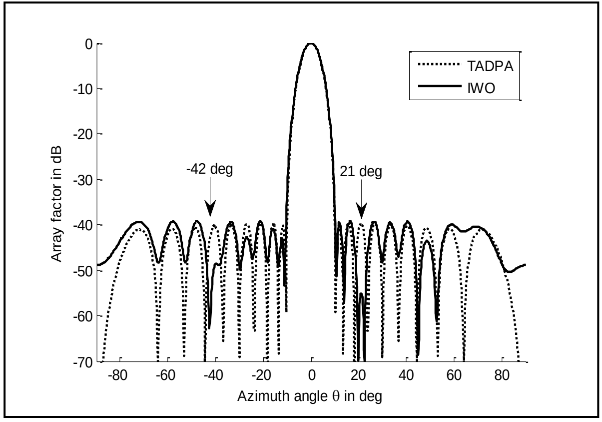

Fig. 3. The normalized radiation pattern with imposed nulls at 21° and -42°.

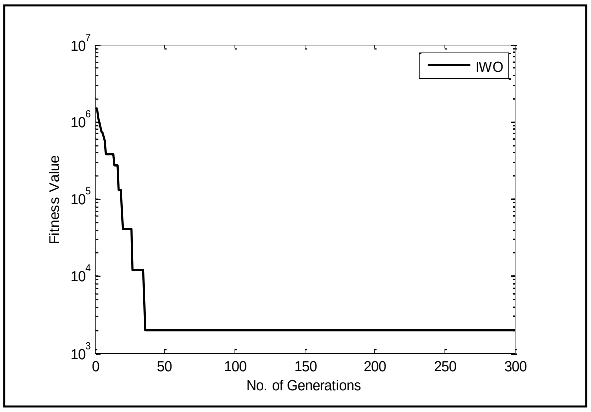

Fig. 4. The fitness value of IWO algorithm for optimizing phase excitations of TADPA with nulls imposed at 21° and -42°.

Fig. 5 shows the far field radiation pattern with two nulls imposed at 21^0 and 33^0 by optimizing the phase excitations of the TADPA. The convergence of the fitness value for the 20 element array with imposed nulls at 21^0 and 33^0 using IWO is shown in Fig. 6.It is seen from Figs. 3 and 5, that nulls as deep as -70dB are obtained at the interference directions, while maintaining the PSLL less than -40dB and FNBW same as that of TADPA.

In the third example, the synthesized pattern with three nulls imposed at different interference directions is presented. The normalized array pattern with nulls imposed at 27^0 , -33^0 and -40^0 using the optimized complex excitations and the corresponding convergence curve are shown in Figs. 7 and 8 respectively. It is seen from Fig. 7, the IWO algorithm is able to place three nulls as deep as -60dB at imposed null directions.

The above three examples demonstrate that by proper synthesis it is possible to create pattern nulls in the exact directions as dictated by the application at hand. This synthesis is accurate irrespective of whether the multiple null directions are very close to each other or are adjacent to the main beam.

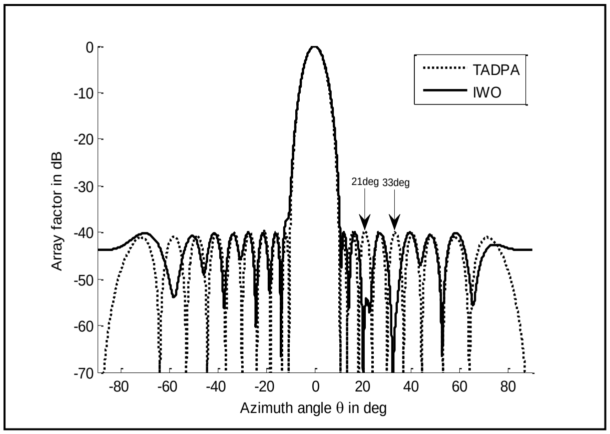

Fig. 5. The normalized radiation pattern with imposed nulls at 21° and 33°.

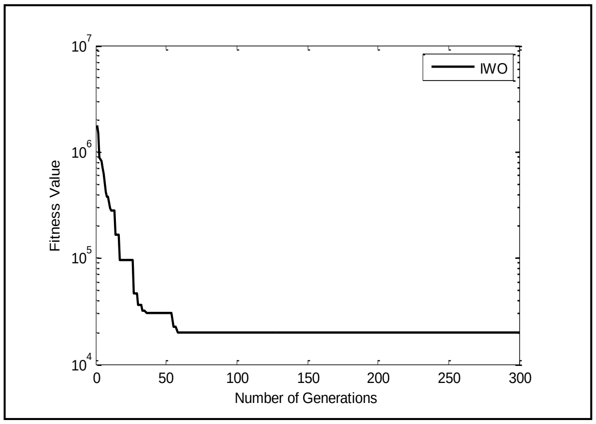

Fig. 6. The fitness value of IWO algorithm for optimizing phase excitations of TADPA with nulls imposed at 21° and 33°.

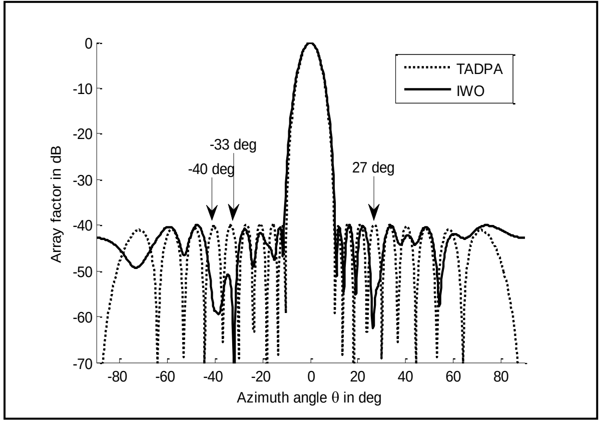

Fig. 7. The normalized radiation pattern with imposed nulls at 27°, -33° and -40°.

V. Conclusion

In this communication, the static penalty function is incorporated with a modified IWO algorithm for the synthesis of linear antenna array. Modified IWO is successfully applied for the synthesis of linear array by optimizing complex excitations of the individual elements with the use of static penalty function. The obtained results are compared with the pattern of the 40 dB Taylor amplitude distributed periodic array.

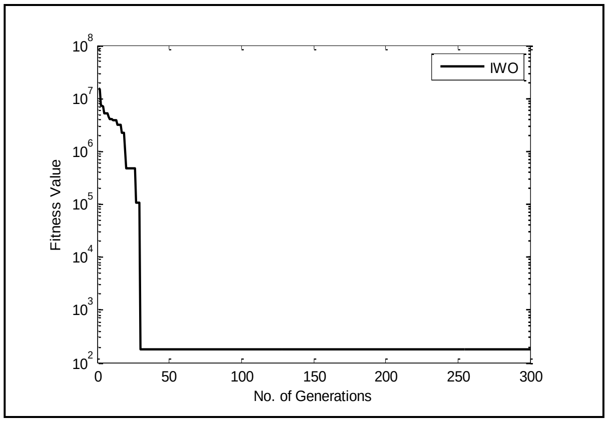

Fig. 8. The fitness value of IWO algorithm for optimizing phase excitations of TADPA with nulls imposed at 27°, -33° and -40°.

Table II. Optimized copmlex excitations obtained with IWO for steering nulls in undesired interference directions.

Design Example		Optimized complex Excitations
1	Amp.	0.0967 0.1494 0.2468 0.3645 0.5027 0.6304 0.7615 0.8727 0.9673 0.9996 0.9996 0.9511 0.8699 0.7535 0.6392 0.4970 0.3643 0.2481 0.1492 0.1046
	Phase in rad	0.0408 -0.0034 0.0010 0.0361 -0.0387 -0.0087 -0.0265 -0.0196 -0.0247 0.0097 -0.0098 -0.0283 -0.0047 -0.0097 0.0127 -0.0109 -0.0083 0.0007 0.0039 0.0216
2	Amp.	0.0759 0.1430 0.2245 0.3416 0.4878 0.6164 0.7331 0.8390 0.9465 0.9998 0.9999 0.9749 0.9109 0.7943 0.6758 0.5317 0.3868 0.3163 0.1568 0.1182
	Phase in rad	0.0160 0.0906 0.0392 0.0348 0.0095 0.0293 0.0212 -0.0100 0.0084 0.0149 -0.0198 -0.0286 -0.0044 -0.0002 0.0006 -0.0208 -0.0507 0.0059 -0.0136 0.0406
3	Amp.	0.0706 0.1371 0.2129 0.3379 0.4571 0.6095 0.7517 0.8443 0.9521 0.9977 1.0000 0.9654 0.9001 0.7535 0.6380 0.4849 0.3512 0.2422 0.1286 0.0777
	Phase in rad	0.1241 0.0101 -0.0021 -0.0357 -0.0324 -0.0157 0.0005 -0.0013 0.0046 -0.0194 0.0092 0.0097 0.0281 0.0035 0.0426 0.0452 0.0097 0.0011 0.0336 -0.0583

The obtained results are compared with the pattern of the 40 dB Taylor amplitude distributed periodic array. Results show that, nulls as deep as around -60 to -70dB are achieved in the interference directions while maintaining low PSLL (< -40dB) for the design examples. This complex-only optimization method using IWO offers a new degree of flexibility over the conventional method of amplitude-only optimization by placing nulls asymmetrically at multiple locations. Thus the performance of the wireless communication system can be greatly enhanced by incorporating this proposed array design. This design will help in management of jammers and interferes by proper null placement.

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