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Comparison of evolutionary algorithms for LPDA antenna optimization

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Key Points:

- An LPDA antenna has been optimized by five evolutionary algorithms.
- The best overall performance is exhibited by the IWO algorithm.
- IWO produces the best fitness value but it also has the slowest convergence.

Abstract

A novel approach to broadband log-periodic antenna design is presented, where some of the most powerful evolutionary algorithms (EAs) are applied and compared for the optimal design of wire log-periodic dipole arrays (LPDA) using NEC (Numerical Electromagnetics Code). The target is to achieve an optimal antenna design with respect to maximum gain, gain flatness, Front to Rear ratio (F/R) and SWR (Standing Wave Ratio). The parameters of the LPDA optimized are the dipole lengths, the spacing between the dipoles, and the dipole wire diameters. The evolutionary algorithms compared are the: Differential Evolution (DE), Particle Swarm (PSO), Taguchi, Invasive Weed (IWO) and Adaptive Invasive Weed Optimization (ADIWO). Superior performance is achieved by the IWO (best results) and PSO (fast convergence) algorithms.

1 Introduction

Broadband log-periodic antenna optimization is a very challenging problem for antenna design. However, up to now, the universal method for log-periodic antenna design is Carrel's method dating from the 1960s, [*Carrel*, 1961], [*Butson et al.*, 1976]. This paper compares five antenna design optimization algorithms, i.e., Differential Evolution, Particle Swarm, Taguchi, Invasive Weed, Adaptive Invasive Weed, as solutions to the broadband antenna design problem. The algorithms compared are evolutionary algorithms which use mechanisms inspired by biological evolution, such as reproduction, mutation, recombination, and selection. The focus of the comparison is given to the algorithm with the best results, nevertheless, it becomes obvious that the algorithm which produces the best fitness values (Invasive Weed Optimization) requires very substantial computational resources due to its random search nature.

Log-periodic antennas (LPDA: Log-Periodic Dipole Arrays) are frequently preferred for broadband applications due to their very good directivity characteristics and flat gain curve. The purpose of this study is, in the first place, the accurate modeling of the log-periodic type of antennas, the detailed calculation of the important characteristics of the antennas under test (gain, gain flatness, SWR, and Front-to-Rear ratio that is equivalent to SLL: Side Lobe Level) and the comparison with accurate measurement results.

In the second place, various evolutionary optimization algorithms are used, and notably the relatively new Invasive Weed Optimization (IWO) algorithm of Mehrabian & Lucas, [*Mehrabian et al.*, 2006], for optimizing the performance of a log-periodic antenna with respect to maximum gain, gain flatness, Front to Rear ratio (F/R), and matching to 50 Ohms (SWR). The multi-objective optimization algorithm is minimizing or maximizing a so-called fitness function including all the above requirements and leads to the optimum dipole lengths, spacing between the dipoles, and dipole wire diameters. In some optimization cases, a constant dipole wire radius could be adopted in order to simplify the construction of the antenna.

1.1 Classical Design Algorithm for LPDAs

The most complete and practical design procedure for a Log-Periodic Dipole Array (LPDA) is that by Carrel, [*Carrel*, 1961], [*Balanis*, 1997]. The configuration of the log-periodic antenna is described in terms of the design parameters: τ, α, and σ, related by:

$$\alpha = \tan^{-1}\left[\frac{1-\tau}{4\sigma}\right] \tag{1}$$

Once two of the design parameters are specified, the other one can be found. The proportionality factors that relate lengths, diameters, and spacings between dipoles are:

$$\tau = \frac{L_{m+1}}{L_m} = \frac{d_{m+1}}{d_m}, \qquad \sigma = \frac{S_m}{2L_m} \tag{2}$$

where, L_m and $d_m = 2\,r_m$ are respectively the length and the diameter of the m-th dipole, while S_m is the spacing between the m-th and (m+1)-th dipoles as depicted in Figure 1. However, for many practical log-periodic antenna designs, wire dipoles of equal diameters d_m are used, or for some advanced designs, three or four groups of equal diameter dipoles are used to cover the whole frequency range. In order to reduce some anomalous resonances of the antenna, a short-circuited stub is usually placed at the end of the feeding line at some distance behind the longest dipole. Directivity (in dB) contour curves as a function of τ for various values of σ are shown in [*Balanis*, 1997], as they have been corrected by [*Butson et al.,* 1976]. A set of design equations and graphs are used, but in practice it is much easier to use a software incorporating all the necessary design procedure, such as LPCAD, [*LPCAD*, 2015]. Moreover, LPCAD produces a file that can be used for the detailed simulation of the antenna using the Numerical Electromagnetics Code (NEC) software. NEC employs the Method of Moments for wire antennas and is well documented, [*Burke et al.,* 1981], [*Cebik*, 2000], [*Qsl.net*, 2015]. The NEC model of the log-periodic antenna employs an ideal transmission line for feeding the antenna dipoles characterized only by its characteristic impedance Z_0. Furthermore, the thin-wire approximation is monitored during the execution of the NEC algorithm, and it is confirmed that it not violated.

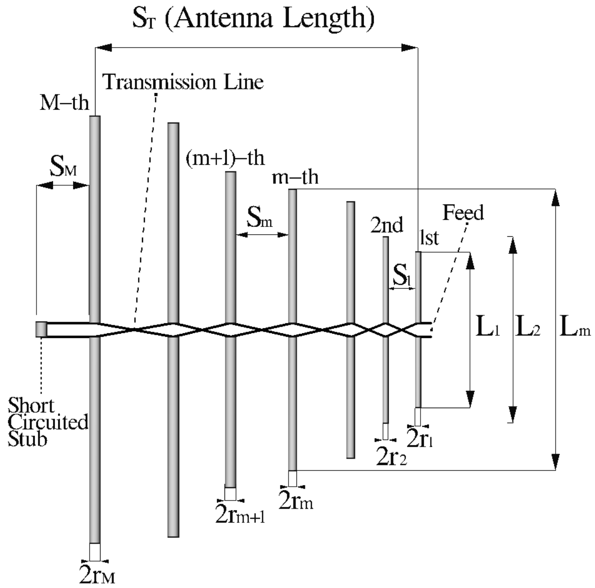

Figure 1. Construction details of a broadband log-periodic antenna.

2 Simulations and results

The evolutionary optimization algorithms compared in this study are: Invasive Weed Optimization (IWO), [*Li et al.,* 2011], [*Sedighy et al.,* 2010], [*Mallahzadeh et al.*, 2008], [*Pal et al.*, 2011], [*Zaharis et al.,* 2014], [*Lazaridis et al.,* 2014], Adaptive IWO (ADIWO), [*Zaharis et al.,* 2014, 2015, 2013], Particle Swarm Optimization (PSO), [*Pantoja et al.,* 2007], [*Golubovic et al.* 2006], [*Aziz-ul-Haq et al.,* 2012], [*Zaharis et al.,* 2007], Differential Evolution (DE), [*Kampitaki et al.*, 2006], and Taguchi. In order to compare the results of each optimization algorithm, the algorithms were applied to an LPDA antenna for the UHF-TV band (470-790 MHz) with 10 dipoles and a rear shorting stub. A slightly larger frequency band of 450MHz to 800MHz was used for the optimization with respect to maximum gain, gain flatness, Front to Rear ratio (F/R) and matching to 50 Ohms, or, equivalently Standing Wave Ratio (SWR). Consequently, the fitness function to be minimized is a linear combination of the above four performance indicators:

$$f\left(L_{1,} ..., L_M, S_1, ..., S_{M-1}, d_1, ..., d_M, Z_0, S_M\right) = w_1\left[\max\left(GF, 2\right) - 2\right] - w_2\left(G_{\min} - 10\right) + w_3\left[\max\left(SWR_{\max}, 1.5\right) - 1.5\right] - w_4\left[\max\left(FR_{\min}, 20\right) - 20\right] \tag{3}$$

Where, Z_0 is the characteristic impedance of the antenna boom and the antenna dimensions are defined in Figure 1. The construction of the fitness function is based upon the following requirements: 1. $SWR_{\max} \leq 1.5$, 2. $G_{\min}$ (the minimum gain) close to or higher than a target gain of $10dBi$, 3. $GF \leq 2dB$ (Gain Flatness), and 4. $FR_{\min} \geq 20dB$ (Front to Rear ratio). In the fitness expression positive terms (GF and $SWR_{\max}$) are minimized while negative terms ($G_{\min}$ and $FR_{\min}$) are maximized. The weights used for this particular optimization are: $w_1 = 8, w_2 = 6, w_3 = 12, w_4 = 20$ meaning that impedance matching and Front to Rear ratios are emphasized in this case. The resulting optimized antenna performance significantly depends on the weights used in the fitness function formula. Therefore, it is crucial to assign relative weights to each performance indicator in order to emphasize particular properties, e.g. F/R performance over gain. The antenna performance indicators are calculated by applying the NEC engine in the 4NEC2 software. The latter is an implementation of the NEC algorithm. For every candidate solution, i.e. for each set of design parameters, the antenna performance is calculated for all frequencies by steps of 10MHz, i.e. for 35 discrete frequencies. The optimized parameters of the antenna are the dipole lengths, the dipole diameters, as well as the spacings between the dipoles and the characteristic impedance of the transmission line that feeds the dipoles, i.e. in this case 31 variables. Each evolutionary algorithm has been coded in Matlab and was executed for a total of 44,000 fitness evaluations, i.e. 44,000 NEC calculations. At the end of the execution of each algorithm the best fitness and the geometry of the optimized antenna were produced. The geometry of the optimized antenna was then extracted to a '.nec' file. The 4NEC2 software was used to run the NEC file produced by Matlab, to derive the SWR, Gain, F/R Ratio, while the convergence diagram figures were derived directly from the optimization algorithms. The PSO parameters are: particle swarm size is 22, and the gbest model using $\varphi = 4.1$ with constriction coefficient $k = 0.73$ is adopted in the PSO code. Furthermore, there is a limitation on the particle's velocity. The velocity components are restricted to 15% of the actual search space in the respective dimension. Regarding the IWO method, the population size is 22 weeds, in order to facilitate comparison with the PSO method. Moreover, the number of seeds produced by a weed are between 5 and 0, the standard deviation limits are between 0.15 and 0, and the nonlinear modulation index is 2.5.

In Figure 2 the comparison of SWR between the evolutionary algorithms which were used to generate the geometries of five different LPDAs shows that the results are very satisfying for all of the algorithms, since the SWR values are all below 1.8. Nonetheless, as it is expected, some algorithms performed better than others, with PSO being the leading algorithm with the lowest values across the frequency range while the Adaptive IWO had the poorest results, being the only method which exceeded the value of 1.5. The Differential Evolution, Taguchi and Invasive Weed methods show a standing wave ratio which oscillates around the 1.25 value, which translates to a return loss of 19.1dB. Comparing the gain of the LPDAs generated by each algorithm provides a better view of the performance of the algorithms than the SWR figure where all the algorithms have a similar average.

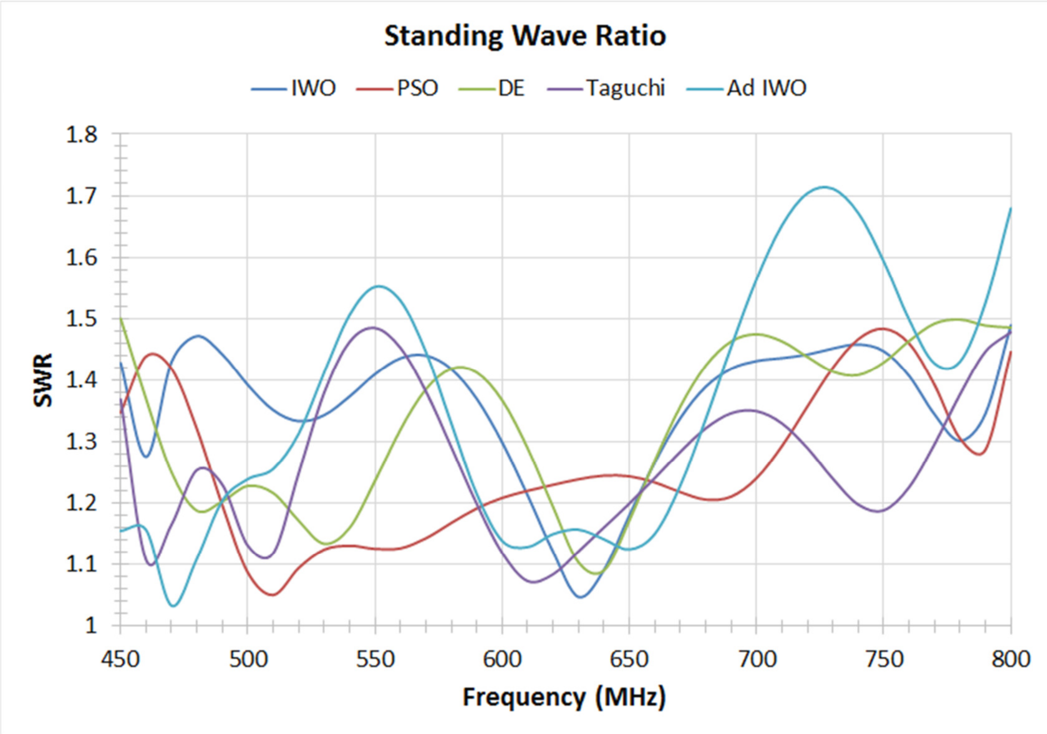

Figure 2. Standing Wave Ratio (SWR) of the optimized antenna derived using various methods.

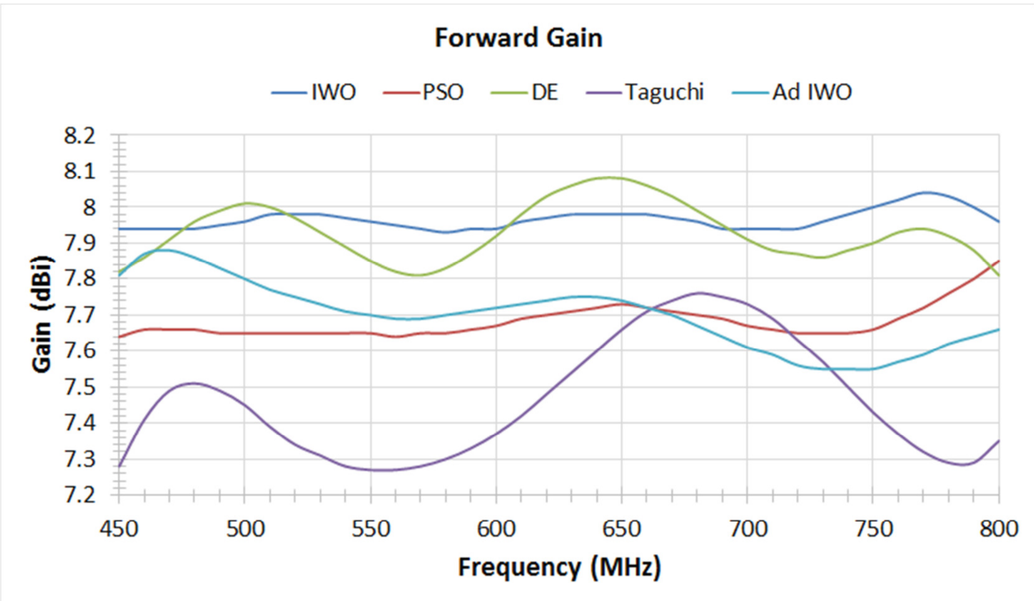

Figure 3. Gain of the optimized antenna derived using various methods.

In Figure 3, it is evident that the best performance comes from IWO and Differential Evolution. IWO is the best performer since its gain is approximately flat with a value of approximately 8dBi and is higher compared to the other algorithms across the whole UHF-TV band. The Differential Evolution optimized antenna performs similarly but its gain values are oscillating across the desired frequency range, which is clearly worse than the flat frequency response of the IWO-based optimization. On the other extreme, the Taguchi-optimized antenna exhibits the poorest performance with relatively low gain. Similarly to the gain figure, the Front to Rear ratio figure, confirms the previous conclusion that the best results are produced by the LPDAs generated from the IWO and Differential Evolution algorithms with F/R ratio values much higher compared to the rest of the algorithms. The PSO method exhibits an average performance while the poorest results are again shown by the Taguchi method (lowest F/R ratio across the desired frequency range) and the Adaptive IWO (very poor low frequency F/R ratio values).

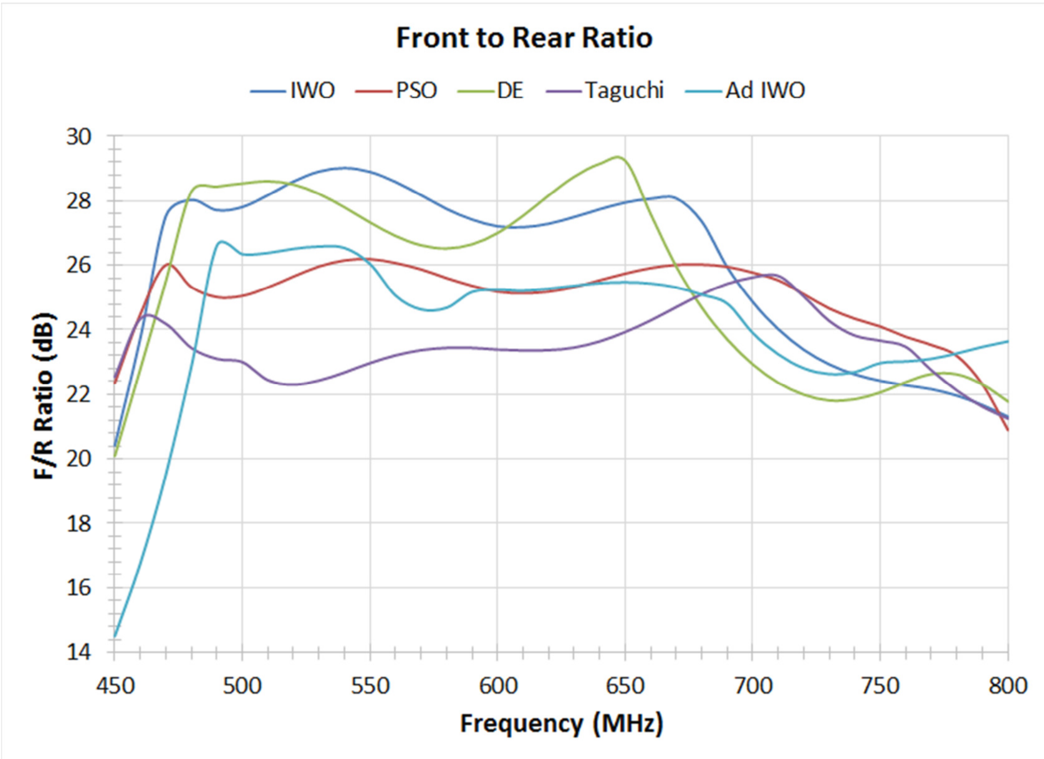

Figure 4. Front to Rear ratio of the optimized antenna derived using various methods.

For a more straightforward comparison between the optimization methods, Figures 5, 6, and 7, provide the minimum, average and maximum values of SWR, gain and F/R ratio of each optimization method throughout the whole frequency band which was used. At this point it should be noted, that the performance of the optimization algorithms is mainly judged by their ability to produce the lowest possible fitness value, which as mentioned before is a linear combination of the SWR, gain, and the F/R ratio. This means that the algorithm that is capable to produce the lowest fitness value is expected to derive the LPDA with the best performance. The antenna dimensions for the IWO optimized and the PSO optimized antennas are shown in Tables 1 and 2 respectively. It is easily seen that although the antenna performance is quite similar, the antenna dimensions are in some cases very different, especially regarding the dipole diameters, shorting stub position behind the longest dipole, and boom characteristic impedance.

Table 1. IWO optimized antenna dimensions. Boom characteristic impedance is $Z_0 = 113\,\Omega$.

Dipole	*Length (cm)*	*Spacing (cm)*	*Diameter (mm)*	*Stub spacing (cm)*
1	12.32	-	4.0	1.53
2	14.10	2.10	7.0	
3	14.92	2.36	7.8	
4	16.68	2.65	5.4	
5	17.96	2.94	6.8	
6	20.78	3.27	4.8	
7	23.26	3.63	5.4	
8	24.82	3.99	8.0	
9	29.56	4.44	3.2	
10	31.16	4.89	9.6	

Dipole	*Length (cm)*	*Spacing (cm)*	*Diameter (mm)*	*Stub spacing (cm)*
1	12.32	-	4.8	3.20
2	14.12	1.61	5.6	
3	15.62	2.38	3.4	
4	16.16	1.93	6.6	
5	18.00	2.97	6.6	
6	21.08	3.25	5.0	
7	23.80	3.63	4.2	
8	26.60	4.01	6.6	
9	30.22	4.49	4.6	
10	33.04	4.48	6.8	

Table 2. PSO optimized antenna dimensions. Boom characteristic impedance is $Z_0 = 87\,\Omega$.

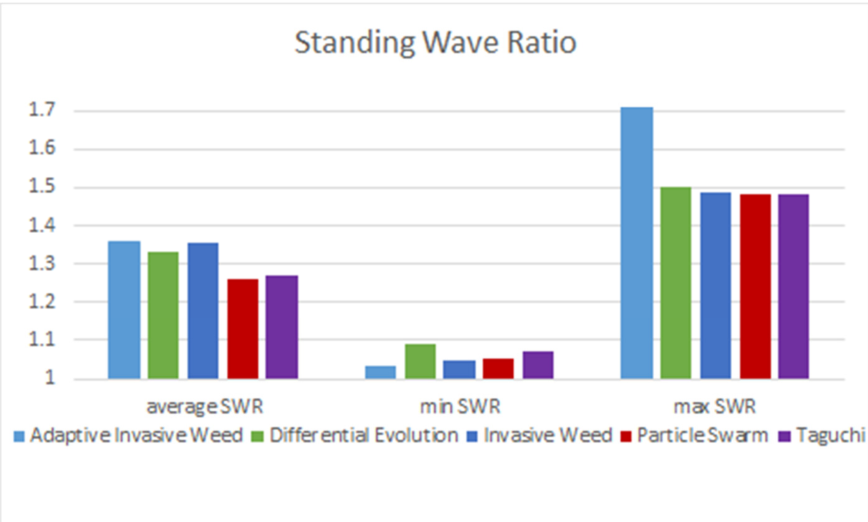

Figure 5. Average, minimum, and maximum SWR for various optimization methods.

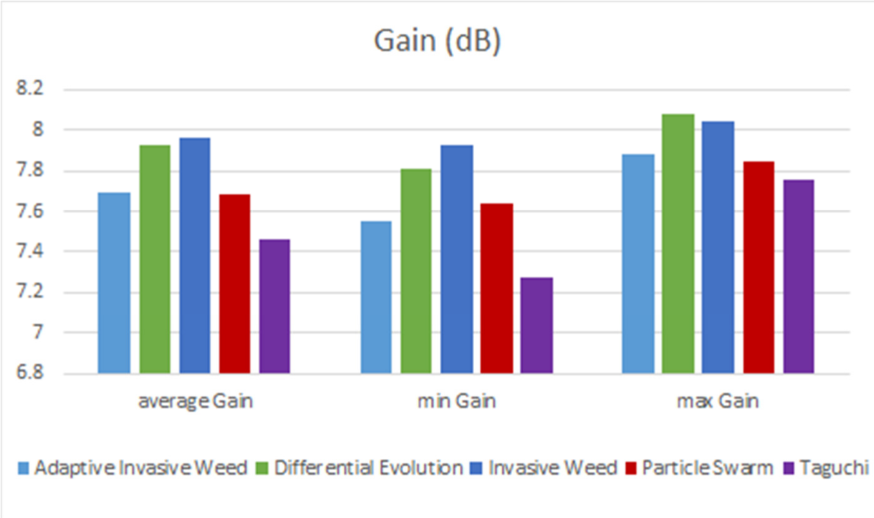

Figure 6. Average, minimum, and maximum gain for various optimization methods.

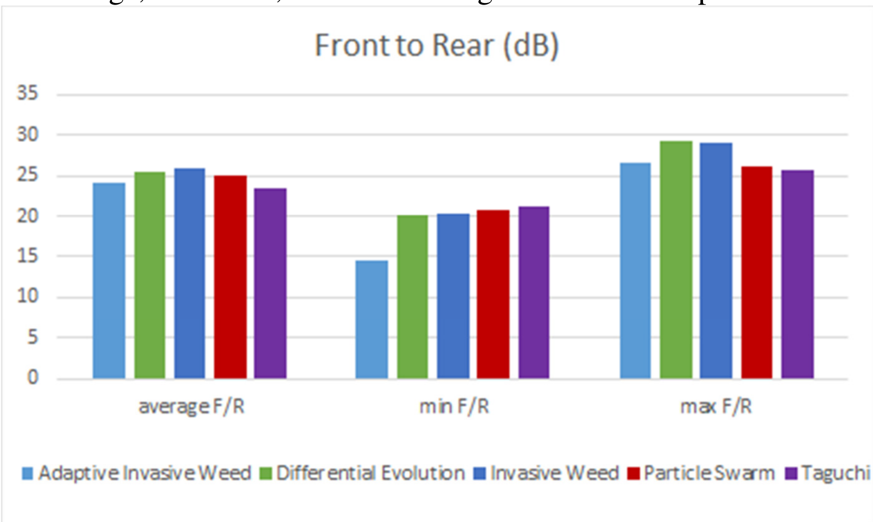

Figure 7. Average, minimum, and maximum F/R for various optimization methods.

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Figure 8 depicts the convergence diagram (fitness value versus number of fitness evaluations, or equivalently, calls to the NEC calculation engine) of all of the algorithms for a total of 44,000 fitness evaluations except for the Taguchi method which terminates automatically at about 4,400 fitness evaluations. This number of total fitness evaluations was chosen in order to show which algorithm produces the best fitness value, because after this point, the algorithms are unable to reduce much further the fitness value. This is obvious from an observation of the last 10,000 fitness evaluations in Figure 8, where the curves are almost horizontal, and convergence is very slow.

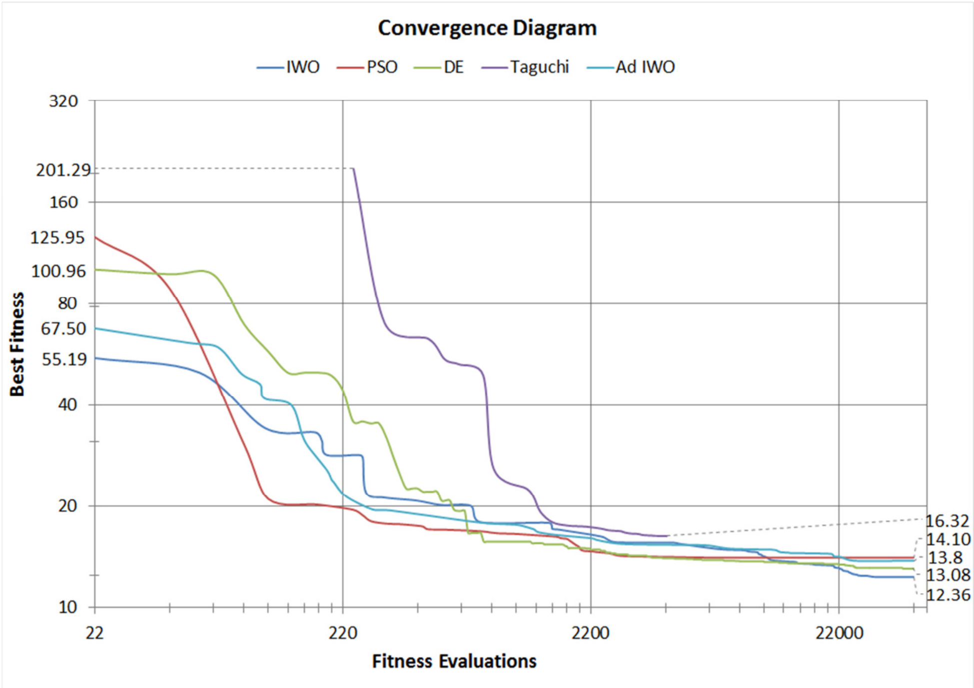

Figure 8. Convergence diagram for the five optimization algorithms used in this study.

As expected, the algorithm which produced the lowest fitness value is IWO (best fitness is 12.36) also exhibited the best performance shown in the previous figures, while Differential Evolution produces the second best fitness value of 13.08. Nonetheless, another factor which should be taken into consideration is the convergence rate of the fitness value for each algorithm. A higher convergence rate indicates that a lower fitness value will be generated within a certain amount of time which equals faster results with less computational resources. It is remarkable that PSO (fitness 14.1) has a very fast average convergence rate compared to the other algorithms (three times higher than IWO). Table 3 provides a comparison between the average convergence rate and the best fitness of each optimization method.

Table 3. Average fitness convergence rate (%) and best fitness values per optimization method.

Optimization Method	Differential Evolution	Particle Swarm	Invasive Weed	Adaptive Invasive Weed
Average Fitness Convergence Rate (%)	0.1997	0.2862	0.0971	0.1534
Best Fitness	13.08	14.1	12.36	13.8

The convergence rate of each optimization method is calculated using the following formula.

$$\frac{\sum_{n=1}^{N}\left(f_{n+1}-f_{n}\right)}{N} \qquad (4)$$

where: f_n is the fitness of the $n-th$ evaluation, and N the total number of evaluations.

Comparing the results in Figure 8 and Table 3 it is observed that the better the best fitness value the slower the average convergence (PSO shows a 0.2862% average convergence rate and a best fitness of 14.1 while IWO shows a 0.0971% average convergence rate while its best fitness has the lowest value of 12.36). Similarly, the adaptive IWO (fitness 13.8 has a better initial convergence rate compared to IWO and Differential Evolution, but not quite as fast as the PSO. Finally, the Taguchi method has the worst fitness of 16.32 but at just one tenth of the computation time (Taguchi optimization is using a fixed number of iterations, much lower than the other methods, and therefore it is not included in Table 3 and it is not compared to the rest of the methods).

5 Conclusions

Five evolutionary algorithms were employed to design Log-Periodic Dipole Arrays, to compare their performance, and to have the opportunity for the first time to find the algorithm that shows the best performance in the case of LDPA design. All of the algorithms generated LPDA geometries with very satisfying properties (SWR, Gain, gain flatness, and F/R Ratio). Some algorithms, however, demonstrated a faster average convergence rate compared to others (PSO and Adaptive IWO), while Invasive Weed and Differential Evolution show the best final results and lowest fitness values. Overall, the IWO algorithm exhibits the best performance, while PSO the fastest average convergence rate. This study proves that further research is required in order to improve the accuracy, the convergence properties, and execution speed of evolutionary algorithms.

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