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Full Length Article

Performance evaluation of two popular antennas designed using a Bacteria Foraging Algorithm

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ABSTRACT

Two popular antennas such as the Yagi-Uda Array (YUA) and the Log Periodic Dipole Array (LPDA) with the same number of dipole elements are optimally designed using Bacteria Foraging Algorithm (BFA). BFA being one of the successful optimization algorithms, used to optimize many design parameters of these two antennas to get a number of desired performance parameters. A YUA is designed here, mainly to realize high directivity, input-impedance (Z_{in}) close to 50 Ω, high Front To Back Ratio (*FTBR*), high Front-to-maximum-Side-Lobe-Level (*FSLL*), low Half Power Beam Width (*HPBW*), and appreciable bandwidth, whereas a LPDA is designed here, mainly to achieve high bandwidth, average Z_{in} close to 50 Ω, high average *FTBR*, high average *FSLL*, low average *HPBW*, and appreciable average directivity. The successful design approaches, application and comparative study of these two antennas presented here can also be extended to other antennas.

1. Introduction

Antennas should maintain proper directivity (*DR*), and radiation at desired frequency/ frequencies in almost all point to point wireless communication. Excluding *DR*, proper values of other parameters like input impedance (Z_{in}), Front To Back Ratio (*FTBR*), Front to maximum Side Lobe Level (*FSLL*), Half Power Beam Width (*HPBW*), and bandwidth (*BW*) are also equally important. Considering *DR* and Z_{in} as the most important parameters Yagi-Uda Array (YUA) antennas are preferred by Television (TV) signal receivers for line of sight communication. Considering *BW* and Z_{in} as the most important parameters, Log Periodic Dipole Array (LPDA) antennas are preferred by broadband wireless line of sight communications e.g. broadband TV signal receiver. Other additional parameters as mentioned above provided by these antennas are also satisfactory. Application of these two antennas can be extended to sky wave propagation at microwave frequencies by using these antennas suitably at the focus of a parabolic reflector. These are some of the important reasons for considering the optimum design of the YUA and LPDA using a Bacteria Foraging Algorithm (BFA). YUA and LPDA being the arrays in one plane (e.g. y-z plane) have a good number of input parameters more precisely known as design parameters such as length (l_n), diameter (D_n) of each dipole, specific spacing between dipoles (d_{mn}) in case of YUA and d_n in case of LPDA, and operating frequencies which ultimately decide the output parameters more precisely known as performance parameters such as *DR*, Z_{in}, *FTBR*, *FSLL*, *HPBW*, and *BW*. Radiation patterns in various E and H planes provide a clear picture of its field distribution and other associated characteristics. The common values of design parameters for the design of these two antennas as per the literature do not provide better performance parameters. Hence, optimization of these design parameters is extremely useful from an application point of view. However, two different design problems considered in this paper are multi-parameter, multi-objective and nonlinear in nature. Hence a suitable and powerful optimization tool must be considered for such problems.

It is very difficult and also a time taking procedure to find out the optimum parameters of any antenna using simple intuition, experience and practical measurements [1]. To get the best possible design of antenna within a minimal time several soft computing tools like Gradient Descent Learning [2], Genetic Algorithm [1,3–6], Ant Colony [7], Simulated Annealing [7,8], Particle Swarm [9–13], Differential Evolution [8,14], Bacteria Foraging [15,16], Bat Search [17,18], Cuckoo Search [19,20], Firefly Search [21], etc. can

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be used. So far as optimized results are concerned, convergence is better in case of BFA [22] and the systematic algorithm is strong enough for global optimization [23]. BFA is also suitable to achieve multi-parameter, multi-objective and nonlinear designs through optimization [22]. Though BFA is used to design various V dipoles and YUAs are explained in [16,22], the exact implementation of the BFA in designing the antenna considering the role of biological agents (bacteria) is overlooked. In this paper an appropriate elaboration of BFA is made so far as antenna designs are concerned in a step by step manner. The biological agents of the BFA here are responsible for optimum design of the said antennas through a selection of a simple and suitable fitness function for each case.

Now a day's hybrid optimization tools are very popular. These tools are used to design various multi-objective Science and Engineering problems [24–26] to achieve some desired performances. Such hybrid tools carefully combines the algorithms of two or more algorithms considering the effective implementation of their searching and selection procedure, hence improves the performance in comparison to a single algorithm. However, these tools consume more time [24] to provide optimal solution to a problem as there are more instructions required in the program code. Currently execution time is not a serious issue as we have high speed computers whose processors perform the task on the basis of multiple parallel processing. Single optimization algorithm with more number of iterations will consume more or less the same execution time as the hybrid algorithm with comparatively less number of iterations. Further, hybrid algorithms are complex [24] and needs a lot of care while combining different algorithms in order to achieve the best performance. Therefore, it is always better to choose a single robust optimization algorithm like PSO [9,10] or BFA [22,23] with more number of iterations to achieve the desired performance. In our case BFA is considered and executed with thirty iterations to optimize two problems, where as fifteen iterations are in fact sufficient to achieve the desired result.

In this paper, we describe two popular antennas, YUA and LPDA designed using BFA which is one of the most suitable and powerful algorithms for optimal design. The first design is a 12 element YUA operating at a frequency of 600 MHz, whose design parameters such as lengths, and spacings are found out using BFA and the diameter of each element is kept as 0.0032512 m (for thin wire approximation), which is Standard Wire Gauge (SWG) 10. This YUA is designed to obtain the maximum *DR*, proper Z_{in}, high *FTBR*, high *FSLL*, low *HPBW*, appreciable *BW*, etc. The second is a 12 element LPDA antenna operating in a frequency range of 470 MHz–870 MHz, whose design parameters such as lengths, spacings, and diameters are found out using BFA. The LPDA is designed to provide high *DR*, high *FTBR*, high *FSLL*, low *HPBW*, proper Z_{in}, and a good radiation pattern for a bandwidth of approximately 400 MHz. Both the design problems are important in a sense that both of them have multiple performance parameters which are nonlinear function of multiple design parameters. The *BW* provided by YUA is narrow around 2% of the operating frequency f_0 [27,p. 580], which will be around 12 MHz. So this can accommodate one TV channel properly centered at 600 MHz. Both the optimized antennas can be used to receive TV Channels, where LPDA can receive many channels, but YUA can receive at least one TV channel.

The literature on the design of YUAs with different numbers of dipoles for optimized element spacings and lengths by means of GA to achieve maximum *DR* only or the high *DR* and Z_{in} close to 50 Ω is cited in [22,28]. However, the authors have not provided other important parameters such as *FTBR*, *FSLL*, *HPBW* in E- & H-planes and *BW* in one paper and *FSLL* & *BW* in another paper which are equally important from trance-receiving of radio waves point of view. A 12 element YUA designed using BFA presented in this paper is a much better design in comparison to the design presented in [22,28]. In our case of YUA, the key idea behind the optimum design using BFA is the establishment of fitness function of l_n and d_{mn} in terms of maximum directivity (DM_n) close to 18 dB, real part of Z_{in} close to 50 Ω, imaginary part of Z_{in} close to 0 Ω, minimum *HPBW* in E- & H-planes, maximum *FTBR* and *FSLL* in E- & H-planes (close to 40 dB). After convergence of the optimization process BFA provides the optimized structures in terms of design parameters.

Usually in the case of broadband antennas, the physical dimensions of the antenna need to be changed by variation of operating frequency. Further, it may so happen that as the frequency is changed, the Z_{in} may close to the desired value, however, the *DR* deviates from the desired value. But, in a practicable frequency-independent antenna structure, all the parameters including the size should be relatively constant as far as possible over a wider bandwidth. In this regard, Rumsey's principle [29,30] proposed many angular structures and shapes, which gave birth to various frequency independent antennas, like the infinitely long LPDA. The YUA is not a broadband antenna, but its directivity is high. So this antenna is used where high directivity is desired. In contrast, LPDA is not a directive antenna, but its operating *BW* is high. So this antenna is used where large bandwidth is desired and a lot of care is to be taken in its optimum design to achieve proper bandwidth. LPDA being one of the broadband frequency independent antennas [31] became popular as it was able to offer unidirectional linearly polarized waves. The primary idea in the design of LPDA is that it considers a dipole array with progressively increasing periodic structure with frequency and period is the logarithmic of the geometric factor (τ). In such a structure, the radiating region exhibits a linear movement along the array with change in frequency and thereby introduces practical frequency independence by smooth staggering of resonance. The mathematical foundation was supported to the LPDA by Carrel [32] in a step by step manner which is considered in our structure code. The key idea behind the optimization process of a 12 element LPDA is the development of a fitness function of τ and σ (spacing factor) in terms of average Z_{in} (Z_{inAav}) close to 50 Ω, average *DR* (DR_{av}) close to 9 dB, average *FTBR* ($FTBR_{av}$) close to 40 dB, average *FSLL* ($FSLL_{av}$) close to 40 dB, minimum average *HPBW* ($HPBW_{av}$) in E- & H-planes and average value of *VSWR* at the feeder line ($VSWR_{av}$) close to 1.1. The average values are considered here since the design problem has to operate in a frequency range. The frequency range as desired is divided using a small step size. At the end of the optimization process, the BFA submits the length and diameter of the dipoles for the optimized antenna in accordance with SWG, place of the dipoles from the origin, diameter and separation between the booms. During the optimization of these two designs, a fitness function for each case is formulated considering multiple performance parameters which are nonlinear functions of multiple design parameters that are extremely important for optimization.

The paper is organized in six sections. After the introduction in Section 1, Section 2 describes the generalized structure of the two problems. In Section 3 brief theories behind the problems are mentioned. In Section 4 formulations of these two design problems in the light of BFA are described. Simulated results of optimized designs are explained in Section 5. Section 6 concludes the paper.

2. N element YUA and LPDA antenna

The generalized structure of N element YUA structure is as shown in Fig. 1. The physical dimensions of this antenna are systematic in nature as explained in [27]. The arrangement of dipoles and feeding to only one active element (driver, 2nd dipole from left) is as shown in Fig. 1 and has a major role. Out of all the dipoles of this antenna the largest passive dipole at its left end acts as an

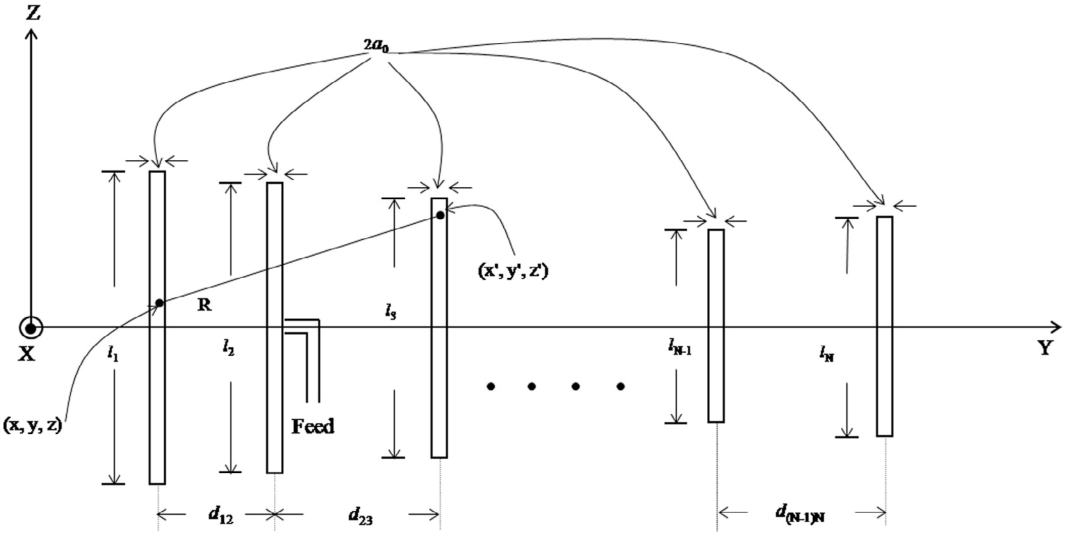

Fig. 1. Typical N element YUA antenna.

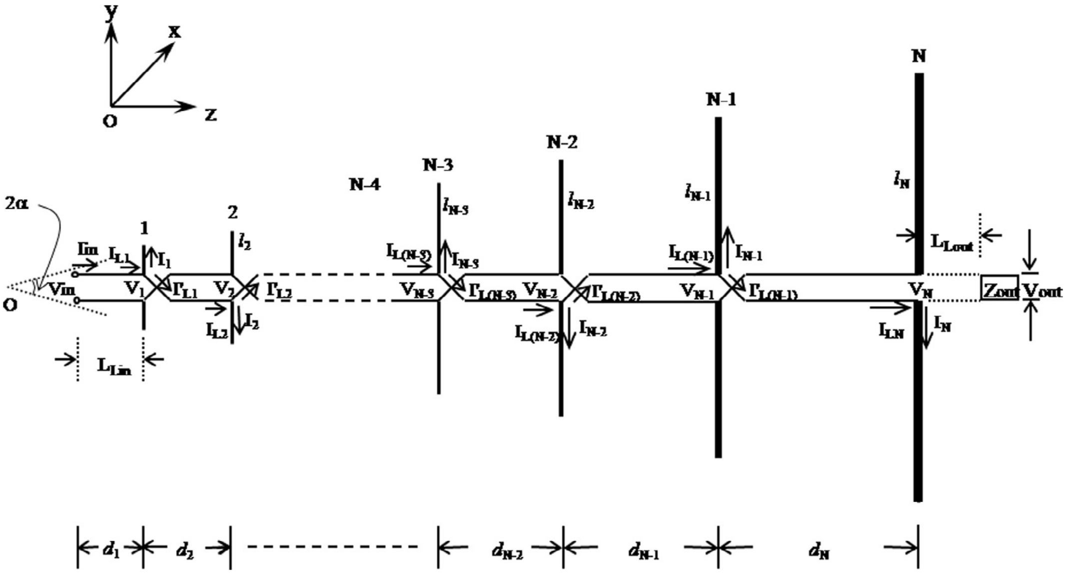

Fig. 2. Typical N element LPDA antenna.

inductive element and so a reflector [27]. All the other dipoles which are passive in nature act as capacitive elements so directors [27]. This kind of arrangement is the major reason for the directive nature of YUA.

The design parameters of this antenna which are to be optimized are as follows.

N = 12
l_n = length of the nth dipole, n∈{1, 2, . . ., N}

where the first dipole is the reflector, the second dipole is the active element and all the other dipoles are the directors.

$d_{(n-1)n}$ = distance between two neighbor dipoles, n∈{2, . . ., N}
a_0 = radius of the wire = D/2

Fig. 2 represents the N element LPDA antenna. The physical dimensions of this antenna are also systematic in nature as explained in [33]. The arrangement of transmission line, dipoles, apex angle (2α) and input voltage (V_{in}) is as shown in Fig. 2 to improve the antenna performance to a larger extent [34]. All the dipoles of LPDA structure being active can be thought of as consisting of three regions, namely capacitive, radiating, and inductive depending on its length in terms of operating wavelength [35]. This kind of arrangement is the major reason for the broadband aspect of LPDA.

The design parameters of this antenna which are to be optimized are as follows.

τ = the geometric factor
σ = the spacing factor
l_N = the length of the Nth dipole element
R_N = the position of the Nth dipole element measured from the origin
D_N = the diameter of the Nth dipole element
S_N = the separation between the arms of the Nth dipole element

3. Brief theory behind YUA and LPDA structure

The detail, analytical theory of YUA is available in [27], based on which MATLAB code of the structure has been developed which is essential for optimization through simulation. The important expression which is the root of all the subsequent derivations is as shown in Eq. (1).

$$\sum_{m=1}^{M} I_{nm}\left[(-1)^{m+1}\frac{(2m-1)\pi}{l_n}G_2(x,x',y,y'/z,\frac{l_n}{2}) + \{(\beta)^2 - \frac{(2m-1)^2\pi^2}{l_n^2}\}\times\int_0^{l_n/2} G_2(x,x',y,y'/z,z'_n)\cos\{\frac{(2m-1)\pi z'_n}{l_n}\}dz'_n\right] = j4\pi E_z^t \quad (1)$$

where

$$G_2(x,x',y,y'/z,z'_n) = \frac{e^{-j\beta r}}{R_-} + \frac{e^{+j\beta r}}{R_+} \quad (2)$$

And

$$R_\pm = \sqrt{(x-x')^2 + (y-y')^2 + (z \pm z'_n)^2 + a_0^2} \quad (3)$$

n = 1, 2, 3, . . ., N
N = Total number of dipole elements
m = 1, 2, 3, ..., M
M = Number of sections made to each wire element

Here $R_\pm$ is the spacing between the centers of two dipole elements as shown in Fig. 1.

This above equation signifies the application of the Method of Moment (MoM) to dipole arrays, which automatically incorporates mutual coupling. Mutual coupling is an important phenomenon to consider so far as practical designs of antennas are concerned. Considering this Eq. (1), the expression of Z_{in}, E- & H-fields, *DR*, *FTBR*, *FSLL*, *HPBW* in E- & H-planes and *BW* are found, which are incorporated in the structure code.

The important expression which is essential to understand the radiation behavior of the array is as in Eq. (4).

$$E_{YUA} = \frac{j\omega\mu e^{-j\beta r}}{4\pi r}\sin\theta\sum_{n=1}^{N}\left[e^{j\beta(x_n\sin\theta\cos\varphi + y_n\sin\theta\sin\varphi)} \times\sum_{m=1}^{M}(I_{nm})\left\{\frac{\sin(Z^+)}{Z^+} + \frac{\sin(Z^-)}{Z^-}\right\}\right] \quad (4)$$

where

$$Z^\pm = \left\{\frac{(2m-1)\pi}{l_n} \pm (\beta\cos\theta)\right\}\frac{l_n}{2} \quad (5)$$

Other terms in Eqs. (4) and (5) are standard notations as used and explained in [27].

The detailed analytical theory of LPDA is available in [32,33], using the network model and transmission line approach to this array. Considering all those associated equations available in [32,33], MATLAB code of the structure has been developed which is essential for optimization through simulation. In case of LPDA a unique relation exist between the physical dimensions and the τ and all the dimensional increase follows a logarithmic pattern [27] as depicted by the following Eq. (6)

$$\frac{1}{\tau} = \frac{l_N}{l_{N-1}} = \frac{R_N}{R_{N-1}} = \frac{D_N}{D_{N-1}} = \frac{S_N}{S_{N-1}} \quad (6)$$

where

R_{N-1} is the distance of the (N−1)th dipole element from the apex
S_{N-1} is the separation between the arms of the (N−1)th dipole

The following expression as in Eq. (7) indicates the number of dipole elements (N) required to design an LPDA [33].

$$N = 1 + \frac{\log_e[B\times\{1.1 + 7.7(1-\tau)^2\cot[\tan^{-1}\{(1-\tau)/4\sigma\}]\}]}{\log_e(1/\tau)} \quad (7)$$

where *B* is the desired bandwidth.

The important expression which is essential to understand the radiation behavior of the array is as in Eq. (8).

$$E_{LPDA} = \sum_{n=1}^{N}\frac{j\eta|I_n|e^{-j\beta r}}{2\pi r_n} \times \frac{[\cos\{\beta(l_n/2)\sin\theta\sin\phi\} - \cos\{\beta(l_n/2)\}]}{\sqrt{1-\sin^2\theta\sin^2\phi}} \quad (8)$$

where

$$r_n = r - R_n\cos\theta = r - (d_1 + d_2 + \cdots + d_n)\cos\theta \quad (9)$$

Other terms in Eqs. (8) and (9) are standard notations as used and explained in [27].

4. YUA and LPDA problems in light of BFA

The objective of this paper is to understand the exact implementation of BFA to design two typical antennas. The designs of these antennas are completely different from each other. YUA is designed at a particular operating frequency, so has unique performance parameters, whereas LPDA antenna is designed for a frequency band, so average performance parameters are considered. The BFA considered in this paper is a popular optimization algorithm, whose logical steps of operation and flow chart are available in [16].

The important design parameters of an N element YUA are l_1, l_2, l_3, . . ., l_N, d_{12}, d_{23}, . . . $d_{(N-1)N}$, a_0, and M which ultimately decide the different performance parameters such as *DR*, Z_{in}, . . ., etc.

The YUA optimized here using BFA provides the performance parameters as desired, requires the following design approximations

- The ratio of length to diameter (*l*/D) is kept at 100 for all the 12 dipoles, so that the dipoles approximate as thin wires. Therefore the current distribution can be considered as sinusoidal in all the radiating elements.
- Radius of each dipole is kept fixed i.e. a_0 = 0.0032512 m for simplicity.

The performance parameters considered during the optimum design of YUA are

- *DR* (*x*) = Directivity in dB.
- DM_n = Maximum desired *DR*.
- Re {Z_{in} (*x*)} = Real part of the Z_{in} in Ωs.
- Im {Z_{in} (*x*)} = Imaginary part of the Z_{in} in Ωs.
- *EHPBW* (*x*) = Half power beam width in E plane in degrees.
- *HHPBW* (*x*) = Half power beam width in H plane in degrees.
- *FTBR* (*x*) = Front to back ratio in the E plane in dB {EFTBR (x)}.
  = Front to back ratio in the H plane in dB {HFTBR (x)}
- *FSLL* (*x*) = Front to maximum side lobe level in E plane in dB,

where *x* = *f*{l_1, l_2, l_3, . . ., l_N, d_{12}, d_{23}, . . ., $d_{(N-1)\,N}$, a_0, N}

The desired performance parameters of YUA optimized using BFA have been set as: Re {Z_{in} (x)} = 50 Ohms, Im {Z_{in} (x)} = 0 Ohms, DM_n = 18 dB, $FTBR_d$ = 40 dB, $FSLL_d$ = 40 dB, $EHPBW_d$ and $HHPBW_d$ = as low as possible.

In our YUA design, the values of l_ns are taken from the range of 0.4 λ to 0.6 λ and d_{mn}s from the range of 0.2 λ to 0.5 λ based on the suggestion in [27].

In case of LPDA, since the aim of the design is to cover the whole UHF TV spectrum to receive 49 channels, it is required to identify some preferred performance parameters like YUA antenna. However, in the case of commercial LPDA design for establishment of transmission in the range of 50 MHz to 1000 MHz, the preferred performance parameters considered are Z_{in}, DR, $FTBR$, and $VSWR$ [27]. In case of our design, the performance parameters are set as follows:

- Z_{inAav} = Average Z_{in} in Ωs at the feed point
- DR_{av} = Average DR in dB
- $FTBR_{av}$ = Average $FTBR$ in E plane = Average $FTBR$ in H plane
- $FSLL_{av}$ = Average FSLL in dB
- $VSWR_{av}$ = Average VSWR
- $EHPBW_{av}$ = Average HPBW in E-Plane
- $HHPBW_{av}$ = Average HPBW in H-Plane

The whole frequency spectrum from 470 MHz to 870 MHz is divided into small bands of 3 MHz width, in our BFA based optimization process. Consequently, there will be 134 numbers of computations for each of the LPDA performance parameters [33]. Thus, the average performance parameters are considered here for LPDA which is the average of 134 computations. From practical application consideration, the desired average performance parameters of LPDA are taken as:

$|Z_{inAav}|$ = 50 Ω, DR_{av} = 9 dB, $FTBR_{av}$ = 40 dB, $FSLL_{av}$ = 40 dB, $VSWR_{av}$ = 1.1, $EHPBW_{av}$ and $HHPBW_{av}$ = minimum possible value (it may not be wise to set a particular value for beam width as this is not a directive antenna rather a broadband antenna).

In commercial applications, the number of dipoles of LPDA typically from 15 to 21 elements for the operating range of 50 MHz to 1000 MHz [27]. In the case of our design, the values of τ are taken in between 0.7–0.98 and σ in between 0.04–0.22 based on suggestions in [35]. N for a 400 MHz bandwidth (BW) can be found using Eq. (7) with knowledge of τ, and σ. The computed N may not be an integer. Thus, N is to be rounded to nearest integer, and keeping the same value of τ, a new value of σ is calculated by Eq. (7). The process is continued for several τ and σ combinations within the predefined range. In such a situation, for a fixed value of N, the corresponding τ and σ are to be optimally searched to achieve desired performance parameters.

The LPDA antenna optimized using BFA to attain the specified performance is obtained considering the following approximations from the practical application consideration.

- The gap distance between the two arms of all the dipoles is kept fixed same as the boom spacing (s) i.e. S_N = s, N = 1, 2, . . ., 12, in favor of the proper mechanical and electrical assembly of the dipoles.
- The l/D ratio is taken as 100 to consider the current distribution as sinusoidal in all the dipoles.
- The boom diameter (D_b) is taken to be the same as the diameter of the biggest (12th) dipole, for convenience in mechanically assembling the boom with the dipoles and suitable electrical connectivity.
- The diameters of all the 12 numbers of dipoles are calculated as in [27] with l/D as 100 are later converted to the nearest standard wire gauge to get the benefit of commercially available wires. However, such modification of dipole diameters would change the l/D ratios, thus; the average of l/Ds. for all the dipoles is taken as the actual l/D in the succeeding computation.

The BFA optimization technique is employed using the optimization code developed in MATLAB. The YUA and LPDA antenna codes also developed in MATLAB, computes several performance parameters using the equations as indicated in the preceding section and also available in the standard literature. The software link between the two codes is achieved by a function call and fitness value return using a suitable fitness function [22]. This fitness function is a multi-objective, multi-parameter nonlinear function which is same as the effort by the bacterium spends in search space, which is recognized as the desired cost or fitness function. The purpose of the BFA here is to get the fitness value of the fitness function as minimum as feasible, certainly with few computations. The fitness functions for the optimization of the YUA and LPDA antenna are formulated as mentioned below.

The following expression FT (x) is the multi-objective fitness function as considered by the BFA for the YUA antenna with the active element close to half wavelength.

$$\begin{aligned}\mathrm{FT}(x) = 1/[&\mathrm{a}/|DR\text{-}18| + b/|\mathrm{Re}(Z_{\mathrm{in}})\text{-}50| + \mathrm{c}/|\mathrm{Im}(Z_{\mathrm{in}})| \\ &+ \mathrm{d}/|EHPBW| + \mathrm{e}/|HHPBW| + \mathrm{f}/|FTBR\text{-}40| \\ &+ \mathrm{g}/|FSLL\text{-}40|]\end{aligned} \tag{10}$$

DR, Z_{in}, $EHPBW$, $HHPBW$, $EFTBR$ and $EFSLL$ are functions of x.

The following expression FT (τ, σ) is the multi-objective fitness function as considered by the BFA for the LPDA antenna for a frequency range of 400 MHz (470 MHz–870 MHz).

$$\begin{aligned}\mathrm{FT}(\tau,\sigma) = &\mathrm{a}' \times |Z_{inAav}\text{-}50| + \mathrm{b}' \times |DR_{av}\text{-}9| + \mathrm{c}' \times |FTBR_{av}\text{-}40| \\ &+ \mathrm{d}' \times |FSLL_{av}\text{-}40| + \mathrm{e}' \times |VSWR_{av}\text{-}1.1| \\ &+ \mathrm{f}' \times |EHPBW_{av}| + \mathrm{g}' \times |HHPBW_{av}|\end{aligned} \tag{11}$$

Z_{inAav}, DR_{av}, $FTBR_{av}$, $FSLL_{av}$, $VSWR_{av}$, $EHPBW_{av}$, and $HHPBW_{av}$ are functions of τ and σ.

where a, b, c, d, e, f, g, a′, b′, c′, d′, e′, f′, and g′ are constants. In this BFA based optimization process, the values of the constants are: a = 6, b = 1, c = 1, d = 10, e = 10, f = 5, and g = 5 for YUA [22] and a′ = 0.003, b′ = 0.02, c′ = 0.004, d′ = 0.004, e′ = 0.4, f′ = 0.0001, and g′ = 0.0001 for LPDA [33] in order that the fitness value can lie in the range of FT (τ, σ or x)$|_{min}$ = 0 and FT (τ, σ or x)$|_{max}$ = 1. The fitness functions considered for two different designs as shown in Eqs. (10) and (11) are both in fact results the lowest fitness value for best optimum design. They are the two different ways to consider the fitness function for optimization process. Other different formats are also possible. Either of the two types considered can be used to design any optimized antenna.

The biological activities of bacteria can be understood by the behavior of *E. coli* bacterium [36,37]. These bacteria principally undertake two types of motions, i.e. swim and tumble. A typical chemotactic behavior (chemotaxis) of *E. Coli* bacterium is shown in Fig. 3.

A single *E. Coli* bacterium in this example, initiates its movement from starting position. The symbols for flagella rotation is shown in the inset. At the starting position the symbol is for anticlockwise, hence the bacterium moves to 2nd position by swimming. A similar argument is applicable for movement from the 3rd position where the flagella exhibit the symbol for clockwise rotation. Hence the movement from 3rd to 4th position is through the process of tumble.

The movement features of bacterium in BFA, such as swimming, tumbling, and swarming are accountable for the change in design parameters (l_n, d_{mn}) of YUA and the design parameters (τ, σ) of the LPDA antenna, in order to make the fitness values of the fitness functions FT (x) and FT (τ, σ) as small as possible and thereby producing BFA optimized YUA and LPDA structures to attain all the performance parameters of course within reasonable computational time. Fig. 4 explains the chemotaxis of bacteria in association with the optimization of the two antennas. For these optimization problems, four bacteria are considered for simplicity. These bacteria are placed at four random positions and normally take almost equal numbers of chemotactic steps during their life span. Every location in the problem space has a unique value of fitness, as each case intimates the health of the bacterium, lesser the

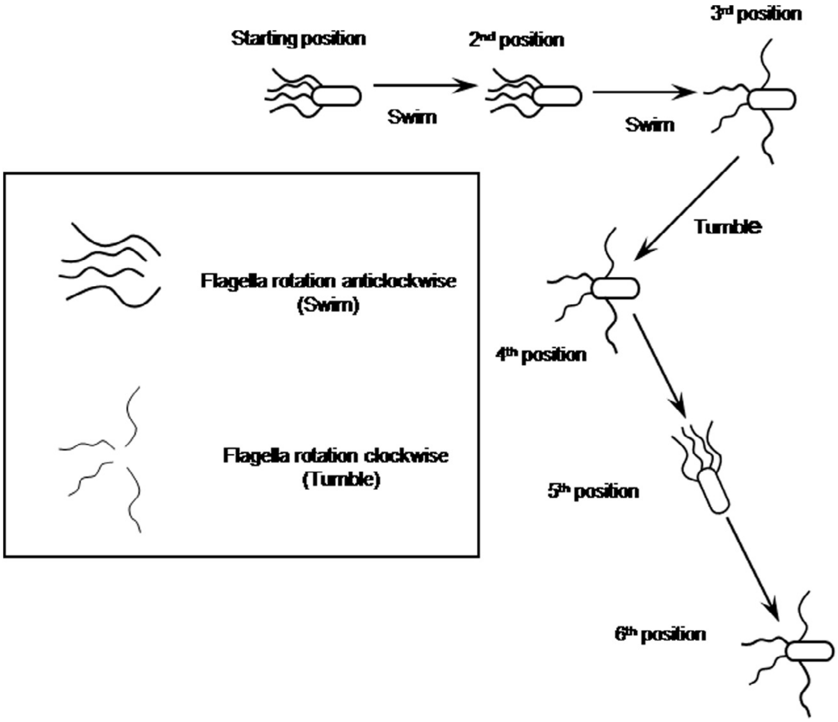

Fig. 3. Chemotactic behavior of *E. Coli* bacterium.

fitness value due to the performance parameters, the healthier the bacterium. The fitness of the 1st bacterium at the initial location is designated as FT_{11}^{OO}. The representations considered here have some distinctive sense.

The preferred symbol of fitness function in terms of antenna design parameters as shown in Fig. 4 is represented by either $FT_{ji}^{pq}(x_{ji}^{pq})$ or $FT_{ji}^{pq}(\tau_{ji}^{pq}, \sigma_{ji}^{pq})$,

where, j = number of the bacteria, 1, 2, 3, and 4.

i = position of the bacteria, 1, 2, . . ., 10.
p = type of motion by bacterium to arrive at $(i-1)$th position.
q = type of motion by bacterium to arrive at ith position.

$$p, q = \begin{cases} S \text{ designate swim} \\ T \text{ designate tumble} \\ O \text{ designate starting condition} \end{cases}$$

As per biology, the bacteria attain their fitness on the basis of the amount of nutrients they consume. However, in the antenna domain the fitness is found using Eqs. (10) and (11) with the specific values of performance parameters which are found by taking the suitable values of the antenna design parameters l_n, d_{mn} of YUA and τ and σ of LPDA. As the bacterium changes its position, the value of fitness is also altered. At each ith new position, the value of fitness with that of $(i-1)$th position is compared. Basing on the value, either swimming or tumbling motion is initiated at the present position. Accordingly, if $FT_{ji}^{pq} \leqslant FT_{j(i-1)}^{pq}$, the geometric factor τ_{ji}^{pq}, spacing factor σ_{ji}^{pq}, and thereby design parameters of LPDA gets modified as given by Eq. (12) and all the design parameters x_{ji}^{pq} of YUA modified as given by Eq. (13) following the swim movement.

$$\tau_{ji}^{pq} = \tau_{j(i-1)}^{pq} + \Delta_S \times \tau_{j(i-1)}^{pq} \tag{12-a}$$

$$\sigma_{ji}^{pq} = \sigma_{j(i-1)}^{pq} + \Delta_S \times \sigma_{j(i-1)}^{pq} \tag{12-b}$$

$$x_{ji}^{pq} = x_{j(i-1)}^{pq} + \Delta_S \times x_{j(i-1)}^{pq} \tag{13}$$

where Δ_S is taken as 0.03 to perform the computation within a small time. However, if $FT_{ji}^{pq} > FT_{j(i-1)}^{pq}$, a tumble movement makes x_{ji}^{pq} of YUA and τ_{ji}^{pq}, and σ_{ji}^{pq} of LPDA to consider any random value, from the predefined range of τ and σ for LPDA and x for YUA [27].

The 1st movements of bacteria are always the swim, as there is no value of fitness function at the starting position. Therefore, the fitness value at the 2nd position of the 1st bacterium is symbolized by FT_{12}^{OS}. The change of position from 2nd to 3rd one, the fitness value is represented as either FT_{23}^{SS} or FT_{23}^{ST} basing upon the type of movement. The other bacteria also follow the same taxonomy. At the initial position, the fitness value is symbolized as FT_{11}^{OO} and the relevant values of the design parameters are x_{11}^{OO}, τ_{11}^{OO}, and σ_{11}^{OO}. The first YUA and LPDA designs are accomplished with this first group of design parameters and thereby generating the first fitness value FT_{11}^{OO}. As the bacteria change their position, 23 parameters of YUA and τ and σ (37 design parameters: 12 lengths and 12 diameters of the 12 dipoles + 11 spacings due to 12 dipoles + 1 boom diameter + 1 spacing between booms) of LPDA are also get changed and consequently a new YUA and LPDA antenna is obtained with a fresh fitness value for each. In the proposed BFA optimized YUA and LPDA antenna design process, one swarming process is taken up after every four numbers of chemotaxis to minimize the computational time. From the biological perspective, the decline in YUA and LPDA antenna design time is revealed by the method of information communication to signal the hungry bacteria about the place of rich nutrient. After every swarming process the chemotaxis continue. The total numbers of chemotactic steps decides the number of swarming processes. In the optimization code implemented for the YUA and LPDA antenna designs, the swarming process starts after the completion of the required chemotactic steps and with a middle value i.e. 0.5 for the fitness function. The fitness functions with value less than 0.5 are unchanged while those more than or equal to 0.5 are replaced with the lowest fitness value.

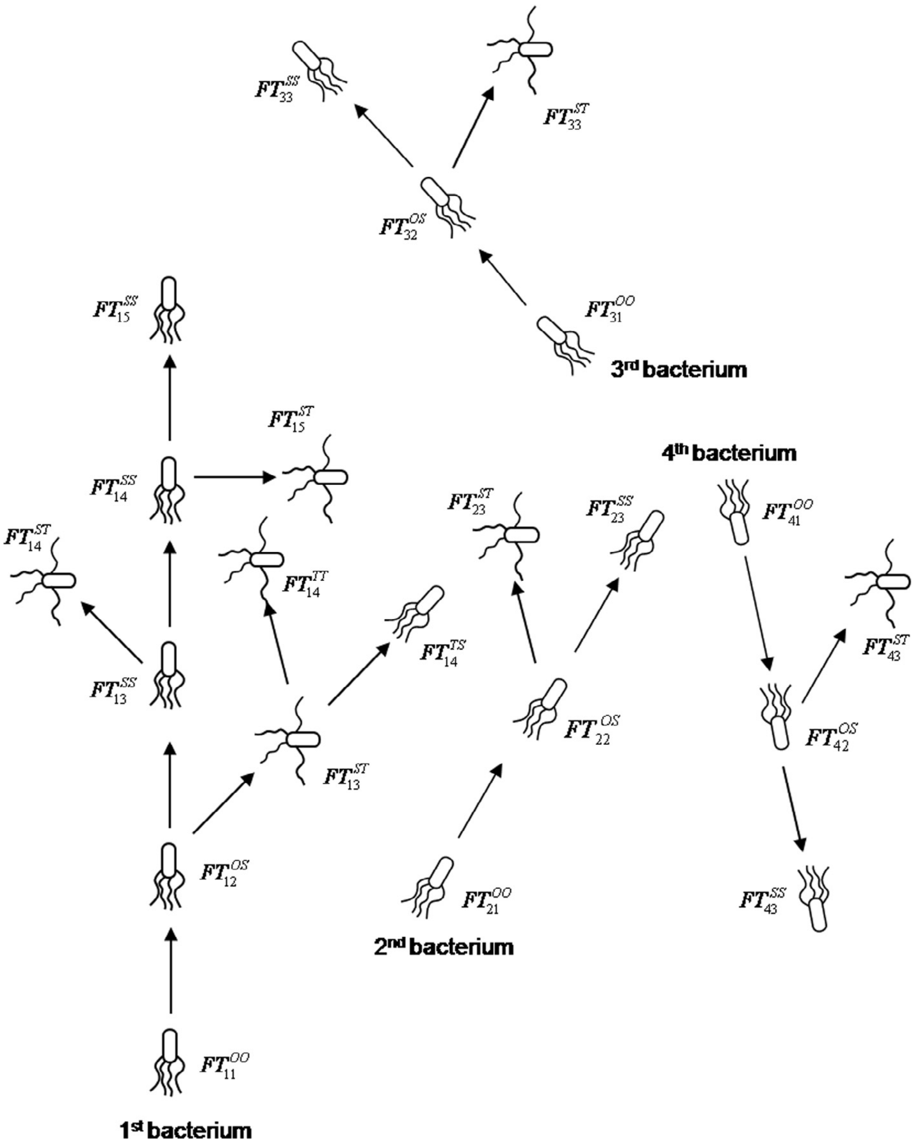

Fig. 4. Chemotaxis of bacteria in the light of antenna optimization using BFA.

The reproduction or generation step begins after the chemotaxis and swarming step. In this cycle, 50% of the total YUA and LPDA antenna designed are rejected basing on poorer fitness values, whereas the other 50% go through a reproduction phase with replication of fitness value in order to keep the bacterium count (YUA and LPDA antenna designs) unchanged. After the completion of each reproduction step the chemotaxis and swarming are initiated again. As the generation or reproduction stage is finished, the YUA and LPDA antenna design enters the final stage i.e. elimination/dispersal. During this stage, 25% of the total YUAs and LPDAs designed are either rejected or redesigned. The rejection is based on very poor values of the fitness while the redesigned is carried out with random values of all the design parameters of YUA and τ and σ of LPDA within the desired range of respective parameters. The rest 75% designs remain same. The whole process is continued again. The above biological stages associated with BFA have been referred in [22]. The similarity among the biological parameters, the YUA and LPDA antenna designs together with the computational performance is highlighted in Table 1.

5. Simulation results and discussion

The design of YUA and LPDA using BFA is obtained in a computational environment using Intel® Core™ 2 duo processor T7500 (2.2 GHz, 800 MHz FSB, 4 MB L2 cache) with 2 GB RAM. First of all a 12 element LPDA without any optimization is designed using our own program for the 400 MHz UHF band. The design parameters such as length to diameter ratio, boom diameter, source impedance, and load impedance are maintained at 100, 0.5 cm, 50 Ω, and 50 Ω respectively. Other design parameters are found using Eq. (6). All of these parameters are as presented in Table 2. The diameter of each of the dipoles as shown in Table 2 are presented without any modification, as found using Eq. (6), hence none of them are coming under SWG category. For the set of design parameters of the LPDA as in Table 2, the corresponding performance parameters are evaluated at fifteen different frequencies in the same UHF band and subsequently averaged. The average performance parameters are found to be as $Z_{\text{inAav}} = 52.643 - j3.304\ \Omega$, $DR_{\text{av}} = 5.7334$, $FTBR_{\text{av}} = 31.8478$ dB,

Table 1
Similarity among the biological parameters with the YUA and LPDA antenna designs.

Symbol	Biological parameters represented	Biological parameter counts	Equivalent antenna parameters	Time taken by the BFA code for 12-element YUA for a single run (in Seconds)	Time taken by the BFA code for 12-element LPDA for a single run (in Seconds) [33]
B	Number of bacteria in the search space	4/6/4	Preliminary set of YUA/LPDA selected	57.297 for the 1st set of parameter counts	797.406 for the 1st set of parameter counts
N_C	Number of chemotactic steps	4/6/10	Number of times the YUA/LPDA redesigned		
N_S	Maximum number of swim	4/4/4	Maximum number of times each YUA/LPDA is redefined	258.486 for the 2nd set of parameter counts	4626.714 for the 2nd set of parameter counts
N_{re}	Number of generation	1/2/1	Better YUA/LPDA designs are retained		
N_{ed}	Number of dispersal/ elimination	1/1/1	Optimized YUA/LPDA is obtained	144.657 for the 3rd set of parameter counts	4993.937 for the 3rd set of parameter counts
P_{ed}	Dispersal/ elimination probability	0.25/0.25/ 0.25	25% of total YUAs/LPDAs designs are either rejected or redesigned		

Table 2
Design and performance parameters of the conventional (non-optimized) YUA and LPDA.

Element number (n)	YUA with 12 nos. of dipoles			LPDA with 12 nos. of dipoles			
	Fixed design parameters: D = 0.0032512 m, l/D > 100, f_0 = 600 MHz			Fixed design parameters: l/D = 100, τ = 0.9104, σ = 0.16904, α = 0.13174 rad, D_b = 5.0 mm, s = 5.6224 mm, BW = 400 MHz			
	Length l_n in m	Spacing d_{mn} in m	SWG	Length l_n in m	Spacing d_n in m	Diameter D_n in mm	SWG
1	0.2550	–	10	0.11357	–	1.1357	Unknown
2	0.2450	0.125	10	0.12474	0.04217	1.2474	Unknown
3	0.2250	0.150	10	0.13702	0.04633	1.3702	Unknown
4	0.2225	0.150	10	0.15050	0.05088	1.5050	Unknown
5	0.2200	0.150	10	0.16532	0.05589	1.6532	Unknown
6	0.2175	0.150	10	0.18159	0.06139	1.8159	Unknown
7	0.2150	0.150	10	0.19946	0.06744	1.9946	Unknown
8	0.2125	0.150	10	0.21909	0.07407	2.1909	Unknown
9	0.2100	0.150	10	0.24065	0.08136	2.4065	Unknown
10	0.2075	0.150	10	0.26434	0.08937	2.6434	Unknown
11	0.2050	0.150	10	0.29035	0.09818	2.9035	Unknown
12	0.2000	0.150	10	0.31893	0.10780	3.1893	Unknown
	Performance parameters			Performance parameters			
1	Z_{in} (Ωs) = 45.845 + j3.7203			Z_{inAav} (Ωs) = 52.643 – j3.304			
2	DR (dB) = 12.453			DR_{av} (dB) = 5.7334			
3	$FTBR$ (dB) = 10.0622			$FTBR_{av}$ (dB) = 31.8478			
4	$FSLL$ (dB) = 16.478			$FSLL_{av}$ (dB) = 30.4653			
5	$EHPBW$ (^{0}) = 29.29			$EHPBW_{av}$ (^{0}) = 80.214			
6	$HHPBW$ (^{0}) = 30.81			$HHPBW_{av}$ (^{0}) = 108.003			
7	$VSWR$ = 1			$VSWR_{av}$ = 1.0936			
	Fitness value			Fitness value			
FT	FT = 0.37926			FT = 0.17015			

$FSLL_{av}$ = 30.4653 dB, $VSWR_{av}$ = 1.0936, $EHPBW_{av}$ = 80.214, and $HHPBW_{av}$ = 108.003. Similarly a 12 element YUA without any optimization is also designed using our own program at 600 MHz, the center frequency of the UHF band. The design parameters of this YUA are selected based on the suggestion in [27,p.579] and presented in Table 2. For this set of design parameters of the YUA, the corresponding performance parameters are Z_{in} = 45.845 + j3.7203 Ω, DR = 12.453 dB, $FTBR$ = 10.0622 dB, $FSLL$ = 16.478 dB, $EHPBW$ = 29.29^0, and $HHPBW$ = 30.81^0.

To understand the effect of optimization a 12 element YUA and a 12 element LPDA are designed using BFA. The structure codes together with optimization codes are developed in MATLAB 7.2, and linked to each other for the optimization process. This optimization process continues for thirty numbers of iterations for each of the antenna array and subsequently their optimal performance parameters are recorded. The performance parameters and their importance are elaborated in the following paragraphs.

The lengths and spacings of various dipoles of a 12 element YUA for higher DR, Z_{in} close to 50 Ω, and other desired performance parameters as mentioned simulated using BFA code as the main program and structure code as the function program and the corresponding Z_{in}, DR, $EHPBW$, $HHPBW$, $FTBR$ in E plane, and $FSLL$ in E-plane are obtained as shown in Table 3. The lengths, diameters, and spacings (derived considering τ and σ) of various dipoles of a 12 element LPDA for higher BW, Z_{inAav} close to 50 Ω, and other desired performance parameters as mentioned simulated using BFA code as the main program and structure code as the function program and the corresponding Z_{inAav}, DR_{av}, $EHPBW_{av}$, $HHPBW_{av}$, $FTBR_{av}$ in E plane, $FSLL_{av}$ in E plane and $VSWR_{av}$ are obtained as in Table 3. The result found in case of YUA here is superior to the result in [22,28]. The E plane and H plane field pattern of YUA are as in Figs. 5(a) and 6(a) and the E plane and H plane field patterns of LPDA are as in Figs. 5(b) and 6(b). The E plane and H plane field patterns of YUA as expected is highly directional in nature and

Table 3
BFA optimized design and performance parameters of the 12 element YUA operated at 600 MHz and the 12 element LPDA operated in whole UHF TV spectrum.

Element number (n)	YUA with 12 nos. of dipoles			LPDA with 12 nos. of dipoles			
	Fixed design parameters: D = 0.0032512 m, l/D > 100, f_0 = 600 MHz, BW = 12 MHz Optimized design parameters:			Optimized design parameters: τ = 0.9124, σ = 0.1891, α = 0.1155 rad, N = 12, D_b = 3.2512 mm, s = 3.6434 mm, l/D ≈ 100, BW = 400 MHz			
	Length l_n in m	Spacing d_{mn} in m	SWG	Length l_n in m	Position R_n in m	Diameter D_n in mm	SWG
1	0.2460	–	10	0.1154	0.4978	1.2192	18
2	0.2435	0.1130	10	0.1264	0.5456	1.2192	18
3	0.2205	0.1140	10	0.1386	0.5980	1.4224	17
4	0.2110	0.1030	10	0.1519	0.6554	1.6256	16
5	0.2140	0.1130	10	0.1665	0.7183	1.6256	16
6	0.2130	0.2240	10	0.1824	0.7872	1.8288	15
7	0.2120	0.1980	10	0.2000	0.8628	2.0320	14
8	0.2110	0.1860	10	0.2192	0.9457	2.3368	13
9	0.2120	0.2260	10	0.2402	1.0365	2.3368	13
10	0.2080	0.2170	10	0.2633	1.1360	2.6416	12
11	0.2100	0.2230	10	0.2885	1.2450	2.9464	11
12	0.2140	0.1630	10	0.3162	1.3646	3.2512	10
	Performance parameters			Performance parameters			
1	Z_{in} (Ωs) = 50.0075 + j1.0506			Z_{inAav} (Ωs)=53.8213 – j3.0537			
2	DR (dB) = 16.3391			DR_{av} (dB) = 9.0395			
3	$FTBR$ (dB) = 18.2209			$FTBR_{av}$ (dB) = 35.5169			
4	$FSLL$ (dB) = 12.3298			$FSLL_{av}$ (dB) = 32.3190			
5	$EHPBW$ (^{0}) = 24.6027			$EHPBW_{av}$ (^{0}) = 73.560			
6	$HHPBW$ (^{0}) = 25.3909			$HHPBW_{av}$ (^{0}) = 110.240			
7	$VSWR$ = 1			$VSWR_{av}$ = 1.1062			
	Fitness value			Fitness value			
FT	FT = 0.0072			FT = 0.0849			

highest radiation intensity is in the direction of axis Y as in Fig. 1, whereas the E plane and H plane field patterns of LPDA are of appreciable directivity in comparison to other design as in [27]. There are three radiation patterns of LPDA with three different colors corresponding to f1, f2, and f3 frequencies as shown in Fig. 5(b) as well as Fig. 6(b). The reason behind the display of three radiation patterns is that the LPDA operates in a band and we need to see its performance. The frequencies f1, f2, and f3 here are 470 MHz, 600 MHz, and 870 MHz respectively. In case of YUA normalized values of the electric fields are shown in radiation patterns as in Figs. 5(a) and 6(a). Whereas, in case of LPDA dB equivalent of normalized values of the electric fields are shown in radiation patterns as in Figs. 5(b) and 6(b). The dB conversion is essential in case of LPDA in order to avoid the large variation of electric field values.

The optimized Z_{in} of YUA is found to be 50.0075 + j1.0506 Ohms at 600 MHz, whereas that for LPDA is found to be close to 50 Ω (Z_{inAav} = 53.8213 – j3.0537 Ohms) for the whole range UHF for which the design is taken up. This is as shown in Fig. 7. This shows that matching is not a problem for either YUA or LPDA.

The optimized DR of YUA is found to be 16.3391 dB at 600 MHz, whereas that for LPDA is found to be close to 9 dB (DR_{av} = 9.0395 -dB) for the entire UHF range. This is as shown in Fig. 8. This figure shows that YUA is more highly directive than LPDA for a small range of frequency.

The optimized $FTBR$ of YUA is found to be 18.2209 dB at 600 MHz, whereas that for LPDA is found to be close to 35 dB ($FTBR_{av}$ = 35.5169 dB) for the entire UHF range. This is as shown in Fig. 9. Though the $FTBR$ of LPDA is better than YUA, the corresponding radiation patterns do not show directive in nature. The main reason behind this is that the power is not exactly radiated in one direction which is observed from Figs. 5 and 6.

The optimized $FSLL$ of YUA is found to be 12.3298 dB at 600 MHz, whereas that for LPDA is found to be close to 30 dB

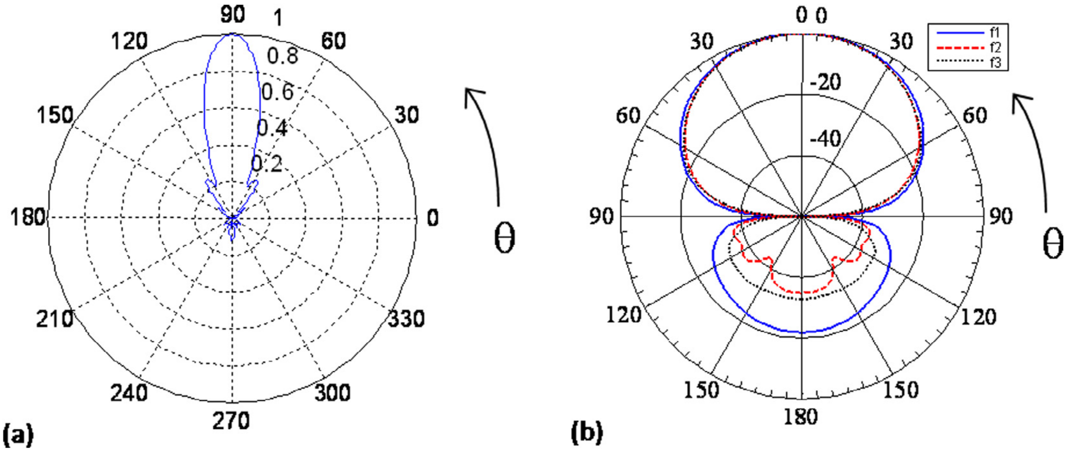

Fig. 5. E-plane pattern of BFA optimized antenna a) 12 element YUA b) 12 element LPDA.

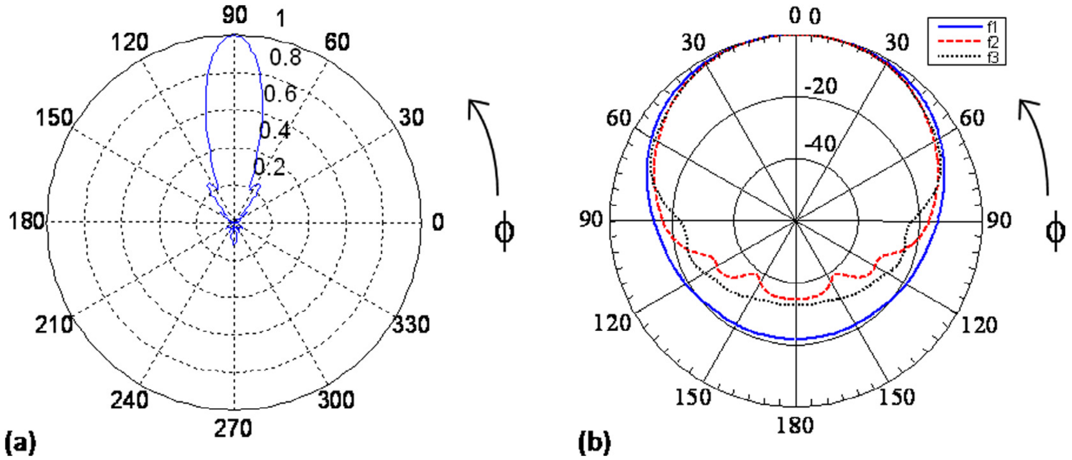

Fig. 6. H-plane pattern of BFA optimized antenna a) 12 element YUA b) 12 element LPDA.

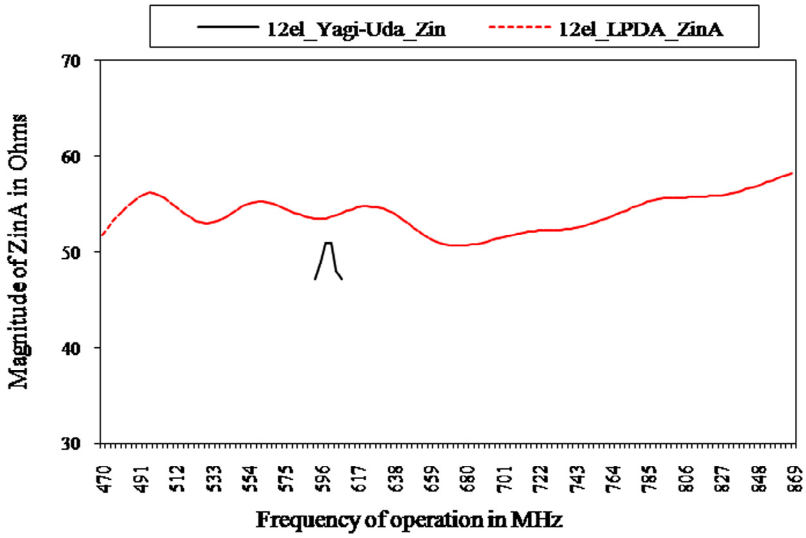

Fig. 7. Magnitude of input impedance vs. frequency plot for BFA optimized 12 element YUA and LPDA.

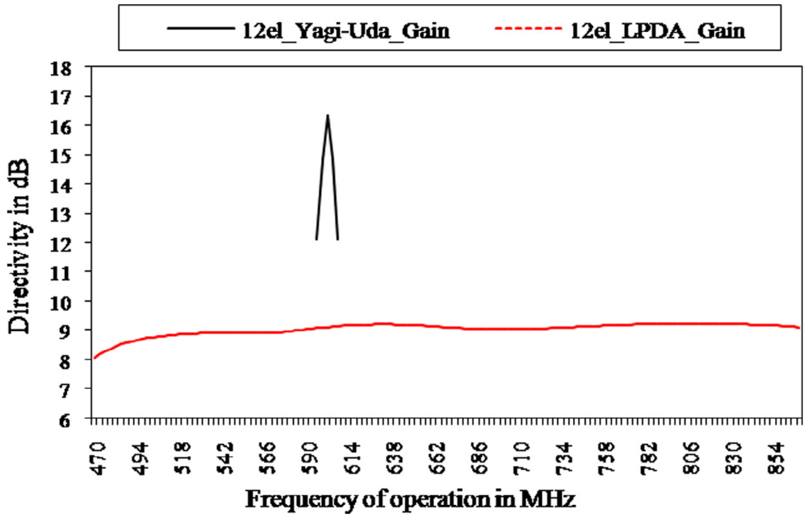

Fig. 8. Directivity vs. frequency plot for BFA optimized 12 element YUA and LPDA.

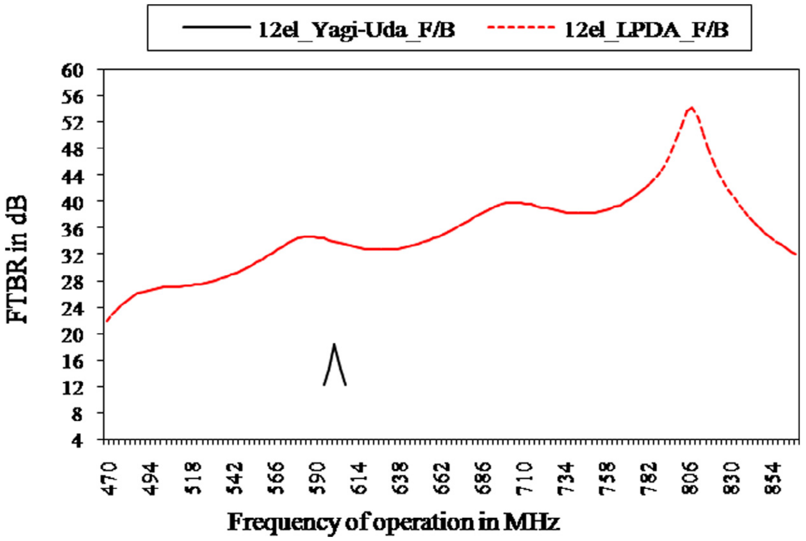

Fig. 9. Front-to-Back ratio vs. frequency plot for BFA optimized 12 element YUA and LPDA.

($FSLL_{av} = 32.3190$ dB) for the entire UHF range. This is as shown in Fig. 10. The reason behind this is the same as above.

The optimized *EHPBW* and *HHPBW* of YUA are found to be 24.6027^0 and 25.3909^0 respectively at 600 MHz, whereas that for LPDA are found to be close to be 73.560^0 and 110.240^0 respectively for optimized case. This is observed from Figs. 5 and 6.

The *VS*WR parameter is important for antenna like LPDA, where all the active elements are connected with transmission lines. *VSWR* should be close to 1 for best performance. The optimized *VSWR* for case of LPDA is close to 1.1 ($VSWR_{av} = 1.1062$) for the entire UHF range. This is as shown in Fig. 11. However, this parameter has much less importance in case of YUA, as the feed is applied to one active element (driver), all the dipoles are not connected to each other hence matching is not at all a problem.

The optimization process for each antenna array is terminated after thirty numbers of iterations. However, the optimal performance parameters are achieved immediately after fifteen numbers of iterations. This is clearly visible from the convergence graph for both the antenna arrays as shown in Fig. 12. To complete thirty number of iteration BFA optimized YUA consumes a time of 28 min and 40 s, whereas for the same iteration BFA optimized LPDA consumes a time of 6 h 38 min and 42 s. The reason behind this large time for the LPDA design is quite clear from the explanation as provided in Section 4.

Design of a 12 element YUA and a 12 element LPDA without optimization and with optimization are explained as above. The design and performance parameters of these two arrays without optimization and with optimization are presented in Tables 2 and 3 respectively for a better comparison. The total length of the conventional YUA and LPDA, as shown in Table 2, are 1.625 m and 1.273 m respectively. But the total length of the optimal YUA and LPDA, as shown in Table 3, are 1.88 m and 1.3646 m respectively. Further, the fitness values of the conventional YUA and LPDA, as shown in Table 2, are 0.37926 and 0.17015 respectively. But the fitness values of the optimal YUA and LPDA, as shown in Table 3, are 0.0072 and 0.0849 respectively. In case of conventional (non-optimized) designs the design parameters of these two antennas are obtained using suggestion from text book, where as in case of optimized designs the design parameters of these two antennas are obtained using BFA. These design parameters, obtained using BFA, are responsible for the better performance of the antennas. So far as performance parameters and

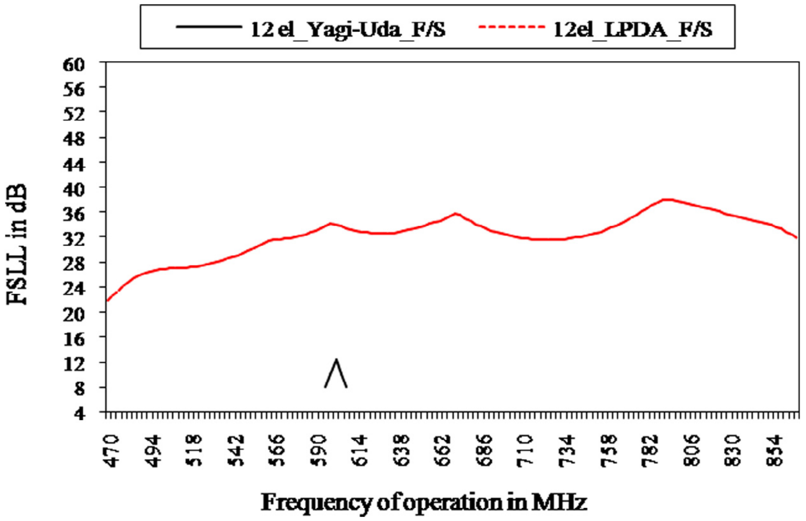

Fig. 10. First side lobe level vs. frequency plot for BFA optimized 12 element YUA and LPDA.

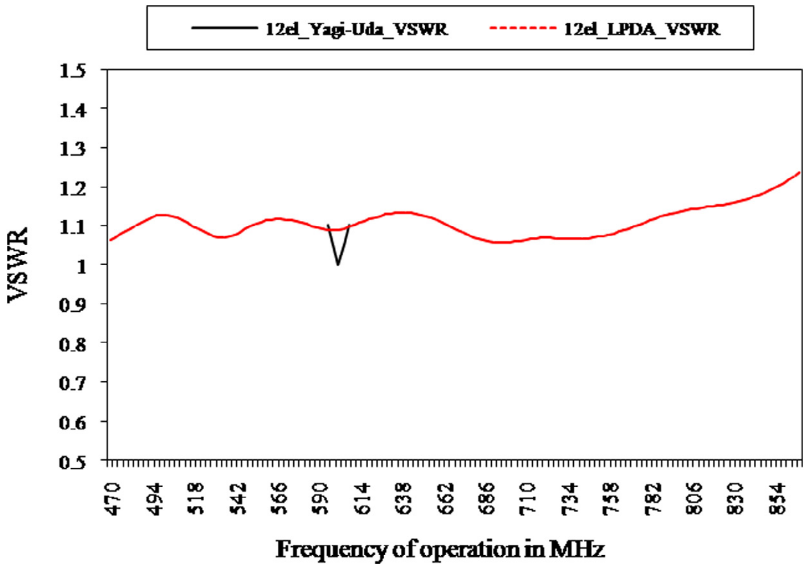

Fig. 11. VSWR vs. frequency plot for BFA optimized 12 element YUA and LPDA.

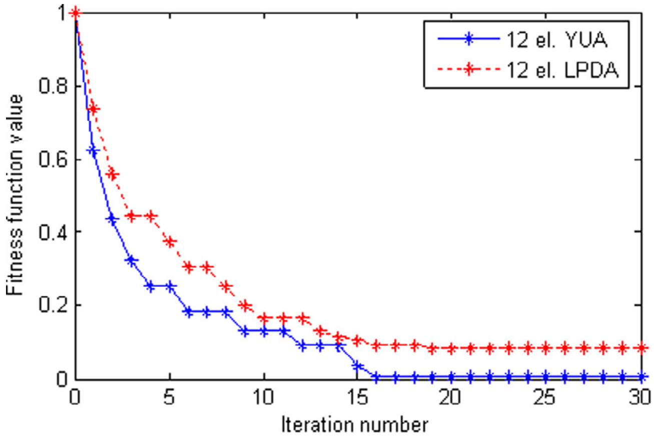

Fig. 12. Convergence graph for twelve element YUA and LPDA optimized using BFA.

fitness values of these antennas are concerned the results indicate that the optimized YUA and LPDA designs are far better than the non-optimized YUA and LPDA designs, with a very small increment in total length of the array.

6. Conclusion

In this paper, two popular designs such as YUA and LPDA with equal number of elements are optimized using BFA. The important parameters in the design of YUA are the lengths (l_n) of each dipole and spacing (d_{mn}) between two neighbor dipoles, the values of which are taken in the range of 0.2 λ–0.6 λ and 0.1 λ–0.45 λ respectively and for the LPDA design are the spacing factor (σ) and geometric factor (τ), whose values are taken in the ranges of 0.7–0.98 and 0.04–0.22 respectively to simplify the extensive computations behind the algorithm. Such computations help to achieve the required design of a 12 element YUA and a 12 element LPDA wherein all the performance parameters desired are attained to a greater level. The computations are the outcome of the successful development of structure codes and optimization codes and of course a proper link between them using a suitable fitness function. The radiation patterns, in two orthogonal field planes, prove the importance of these designs with respect to improved *DR*, *HPBW*, *FTBR*, and *FSLL*. The simulation results based on the BFA in the design of such antenna array in a step by step manner indicate its further application to other arrays. Optimal design of the 12 element YUA here indicates its supremacy over the similar design by other authors. Specifically, in case of the 12 element LPDA, it can be effectively used as a single receiving antenna to cover 470 MHz to 870 MHz band i.e. the UHF spectrum which accommodates 49 TV channels. The comparative study of these two antennas indicates that a large number of UHF TV channels can be received by LPDA with lower directivity, whereas at least one UHF TV channel can be received by YUA with much higher directivity.

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