

## Research Paper

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# Material distributive topology design of UWB antenna using parallel computation of improved BPSO with FDTD

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## Abstract

In this article, the material distributive topology-based design optimization of ultra-wide band (UWB) antenna is proposed by using improved binary particle swarm optimization (BPSO) with finite difference time domain (FDTD) method. In the improved BPSO implementation, the velocity of each particle is calculated based on complete set of bits of particle position vector. The V-shaped transfer function is employed to transform all real values of velocities to values in the interval [0,1]. The fitness function of all the particles in BPSO algorithm are computed parallelly by using FDTD simulation. The usage of FDTD and the parallel computation helps in analyzing the broadband frequency characteristics of the antenna with a single simulation run. The return loss of the optimized UWB antenna obtained from FDTD, Computer Simulation Technology (CST) simulation and practical measurement are in good agreement and show good impedance matching.

## Introduction

Antennas used for ultra-wide band (UWB) applications must provide satisfactory radiation properties over the UWB spectrum (3.1–10.6 GHz) and simultaneously achieve good time domain performance. UWB antennas are also required to be compact and easy to fabricate in order to be suitable for various applications [1]. In this context, the family of printed monopole antennas has gained great attention in research community due to their attractive merits such as small planar profile, wide bandwidth, omni-directional radiation pattern, low dispersion, low cost, and ease of fabrication [2]. However, the design of UWB antennas is a challenging task. Instead of arbitrarily designing the dimensions, shape, and topology of a UWB antenna, an automatic design of optimum planar shape of the antenna by using optimization methods is more preferable to obtain the best design. Optimization of UWB antennas is to find an optimal antenna configuration which should satisfy one or more of the above mentioned performance requirements.

In UWB antenna optimization, the design of antenna shape has been formulated as an optimization problem that has fitness function which is derived based on the desired performance parameters. A numerical solution of the optimization problem starts from an initial set of design variables and proceeds through a number of iterations. For each iteration, the optimization algorithm computes new updates of the design variables in order to improve the fitness function which leads to achieve the best one.

Antenna optimization methods can be classified into three groups: sizing, shape, and topology optimization based on parameterizing the design domain. In sizing optimization, only the cross-section of the structure is optimized by a set of design variables such as width and length in that structure. Many antenna designs have been proposed based on this optimization over the past several years. Combination of the genetic algorithm (GA) with finite difference time domain (FDTD) method [3]; microgenetic algorithm with FDTD method [4]; self-organizing multi-objective GA with Ansys HFSS software [5] are the few techniques used to optimize the UWB antennas.

In shape optimization, the design variables characterize the shape of the boundary of a reference domain. For this optimization, among the many techniques, combination of particle swarm optimizer (PSO)-driven spline-based shaping approach with a method of moments (MoM)-based electromagnetic (EM) simulator, developed at the Electromagnetic Diagnostic Laboratory (ELEDIA) of the University of Trento [6]; Jumping Genes optimization algorithm with IE3D EM simulation software [7]; Pareto efficient global optimization (ParEGO) algorithm with Computer Simulation Technology Microwave Studio (CST MWS) EM simulation software [8] are few techniques that are demonstrated in the literature.

In the topology optimization, the desired space is divided into small cells and the material distribution of each cell is taken as a design variable and the presence or absence of materials is

denoted as either 1 (metal) or 0 (vacuum/air), respectively [9]. By using optimization technique, the material distribution of each cell is controlled simultaneously in each iteration step and updated based on the evaluation of objective function in order to approach the final optimum design. Since, the antenna radiation characteristics are depending on the current distribution in the geometry of the antenna [10], topology optimization has drawn considerable attention in the field of antenna design.

The material distributive approach of topology optimization combined with evolutionary optimization algorithms for the design of UWB antennas have been discussed in many literature. Ding *et al.* [11] applied the mixed model of 2-D GA and FDTD for optimizing the UWB antenna and band-notched UWB antenna [12]. Zhao *et al.* [13] designed the mirror symmetric topology material distributive optimized UWB antenna using double population GA (DPGA) and FDTD. Mirhadi and Soleimani [14] implemented the parallel binary particle swarm algorithm (BPSO) and discrete green function method with asymmetric and mirror symmetric material distributive topologies for optimizing the dual-band antennas and same has been extended to design the UWB antennas with stable radiation pattern [15]. In all these articles, the metallic patch is divided in to uniform size cells. Teirab *et al.* [16] proposed non-uniform segmentation of radiating patch for UWB antenna optimization with mirror symmetric topology. The antenna is designed using CST MWS software co-simulated with MATLAB used for GA implementation through ActiveX control. Chen and Chiu [17] implemented the multi-objective topology optimization with non-uniform pixelation in order to design the miniature UWB antenna with enhanced pulse preservation. This has been done by combining Ansoft High Frequency System Simulator (HFSS) for antenna simulation with MATLAB for controlling the strength Pareto evolutionary algorithm 2 (SPEA2) optimization algorithm.

The meta heuristic algorithms [18] are the better alternative to the traditional optimization approach for heuristic problems with less or insufficient information and less computational requirement. These algorithms can be local or global search algorithms. Hill climbing, simulated annealing, etc., are popular algorithms for local search methods. Ant colony optimization, PSO, and GA are popular algorithms for global search methods. Another most important category is single solution or population-based solution. Single solution-based strategies evaluate single candidate solution per generation. Simulated annealing is the most popular single solution based strategy. This strategy is mostly implemented for local searching and is convenient for parallel computing. Populationbased solution on the other hand evaluates multiple candidate solutions per generation. This is most convenient for parallel computing. GA and PSO are most popular techniques and can be implemented with or without swarm intelligence. Swarm intelligence-based algorithms [19] use collaborative self-organized agents to move toward the global best solution. PSO is the best example for this type of algorithm [20, 21]. GA does not use swarm intelligence, but they use crossover and mutation to pass down genetic information of best solution to next generation. In order to operate in binary problem spaces, BPSO where the particle position value is either 0 or 1 is used [22].

Generally, the antenna's performance metrics are computed and analyzed by solving the Maxwell's equations. Now, there are many accurate numerical methods that allow Maxwell's equations to be solved effectively, such as the MoM, the finite element method, the FDTD method, and so on. For designing the wide-band antenna, the time domain method is more suitable than

the frequency domain method because the broad bandwidth characteristics are obtained through only one simulation run of the time domain technique code [4]. Therefore, FDTD method is more suitable for the design of UWB antenna.

In this paper, the UWB antenna is optimized by using material distributive topology with improved BPSO and FDTD. In our work, to facilitate the implementation of UWB antenna design optimization, in BPSO, the velocity of each particle is calculated by using complete set of bits of particle position vector where as single bit in original BPSO and the V-shaped transfer function is employed to transform all real values of velocities to values in the interval [0,1] instead of Sigmoid transfer function. Also, to evaluate the fitness function of each particle parallelly using FDTD, each particle is termed as an object and called with unique object identifier. FDTD simulation variables and functions for each particle are inherited from FDTD base class. Section "Optimization of UWB antenna" discusses about improved BPSO, FDTD, and implementation aspects. The results and discussion are presented in section "Results and discussion". In section "Conclusion", the conclusion is presented.

### Optimization of UWB antenna

The material distributive topology design is used in this work for a complete layout optimization of the radiating patch geometry of UWB monopole antenna. In this method, the radiating patch geometry is described by dividing the patch surface into small, equally sized elements. The material property of each element is directly mapped into a binary value of 0 or 1 which indicates air or conductor, respectively. Each element's binary values are arranged as a binary string consisting of series of 0's and 1's. Each binary string will lead to an arbitrary structure for antenna's radiating patch and the performance can be improved by automatically varying the values in the binary string without increasing the overall volume or manufacturing cost of the UWB monopole antenna. Finally, the optimal binary string satisfying the desired performance is explored over a number of iterations. The implementation of this method requires a full-wave EM solver such as FDTD for analyzing the performance of the antenna and a meta-heuristic optimization algorithm for determining the optimum antenna structure. An improved BPSO algorithm is used in this work.

### Improved BPSO

The BPSO was proposed by Kennedy and Eberhart [22] to allow PSO to operate in binary problem spaces. In this version, particles could only fly in a binary search space by taking values of 0 or 1 for their position vectors. The roles of velocities are to present the probability of a bit taking the value 0 or 1. Each particle in BPSO should consider the current position ( $X_i$ ), the current velocity ( $V_i$ ), the distance to their personal best solution ( $pbest_i$ ) and the distance to the global best solution ( $gbest$ ) to modify its position. In original BPSO, the calculation of the value of velocity of each particle is based on a single bit and Sigmoid transfer function ( $(1)/(1 + e^{-v_i^{(t)}})$ ) is used to map a continuous search space to a binary one [22]. The original version of BPSO suffers trapping in local minima [23], so in this article some modifications have been introduced in order to overcome this problem. Here, the velocity of each particle is calculated based on the complete set of bits corresponding to the particle position vectors as in equation (1) [24]. The V-shaped transfer function as in equation (2)

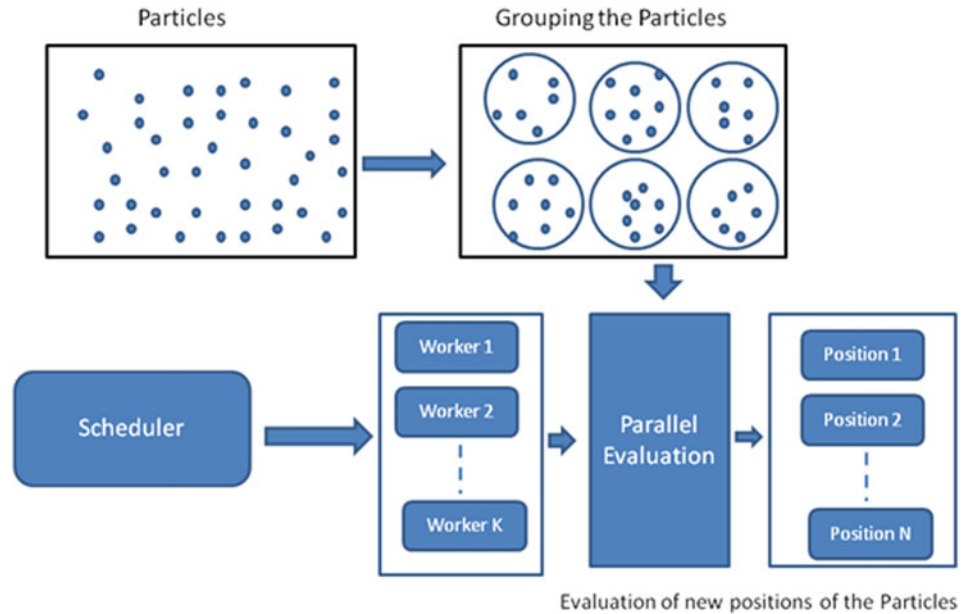


Fig. 1. Parallel computation of PSO.

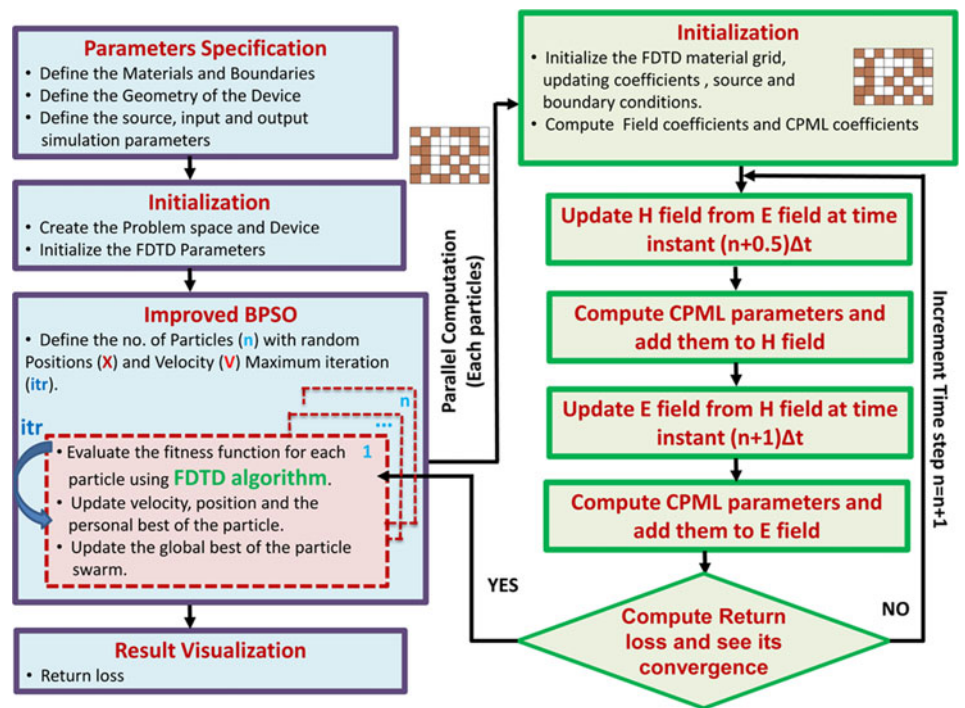


Fig. 2. Implementation of improved BPSO with FDTD method for UWB antenna optimization.

is employed to transform all real values of velocities to probability values in the interval [0,1] [23]. After converting velocities to probability values, position vectors of particles could be updated with the probability of their velocities as given in equation (3).

$$V_i = w * V_i + c_1 r_1 * (pbest_i - X_i) + c_2 r_2 * (gbest - X_i), \tag{1}$$

where  $w$  is the inertia weight. Initially, the value of this weight is chosen as 1, and for every iteration, it is damped with the value of 0.95.  $c_1$  and  $c_2$  are the acceleration constants in the interval [0, 2].

$r_1$  and  $r_2$  are the random values in the range [0, 1].  $pbest_i$  and  $gbest$  represent the best previous position of the  $i^{th}$  particle and the global best position of the swarm (all particles), respectively.

$$T(V_i) = \left| \frac{2}{\pi} \arctan\left(\frac{\pi}{2} V_i\right) \right|. \tag{2}$$

Position of particles can be updated as follows,

$$x_i^k(t+1) = \begin{cases} 0 & \text{If } rand < T(v_i^k(t+1)) \\ 1 & \text{If } rand \geq T(v_i^k(t+1)) \end{cases}, \tag{3}$$

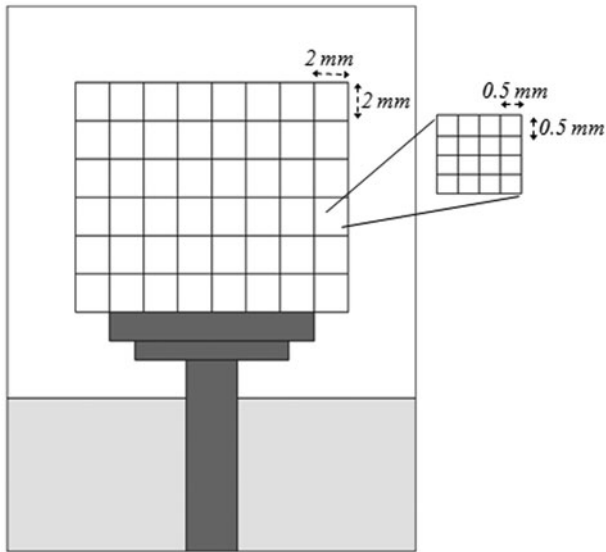


Fig. 3. Initial Antenna Layout - Pixelated radiating patch geometry used in the optimization of UWB antenna.

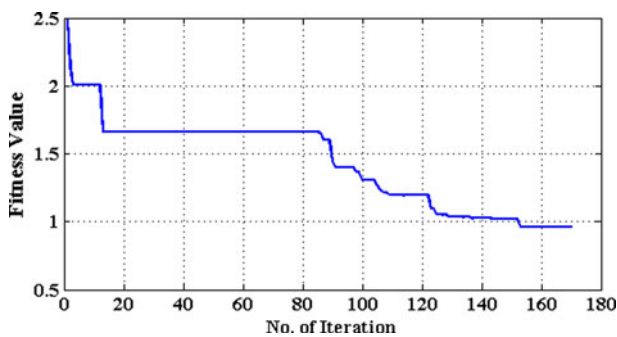


Fig. 4. Convergence curve of fitness value in the optimization of UWB antenna.

where  $v_i^k$  is the velocity of  $k^{th}$  bit of  $i^{th}$  particle.

Parallelization in BPSO can be done by two methods [25]. First parallelization of computations, where computation of each particle is performed in parallel. Second parallelization of population, in which population is split in different groups and computation can be done in parallel as shown in Fig. 1. We chose later one which is more suitable for less complex implementation. Parallel computation can be done in two ways, i.e centralized and distributed. Centralized parallel algorithm is suitable for simplicity. In our model, in every iteration, the particles in the population are grouped and a centralized scheduler allocates workers for each group. Worker is responsible for doing the computations necessary to evaluate the new position of the particle and update the global best solution. They work independently. Number of workers depends on the computational capacity of the system. If the worker finishes the work, it will return to the worker pool, then the scheduler may allocate it to the new waiting group if any or just wait for next iteration.

**FDTD**

The FDTD method, introduced by K. Yee in 1966, is the most popular technique used to solve a variety of EM problems [26].

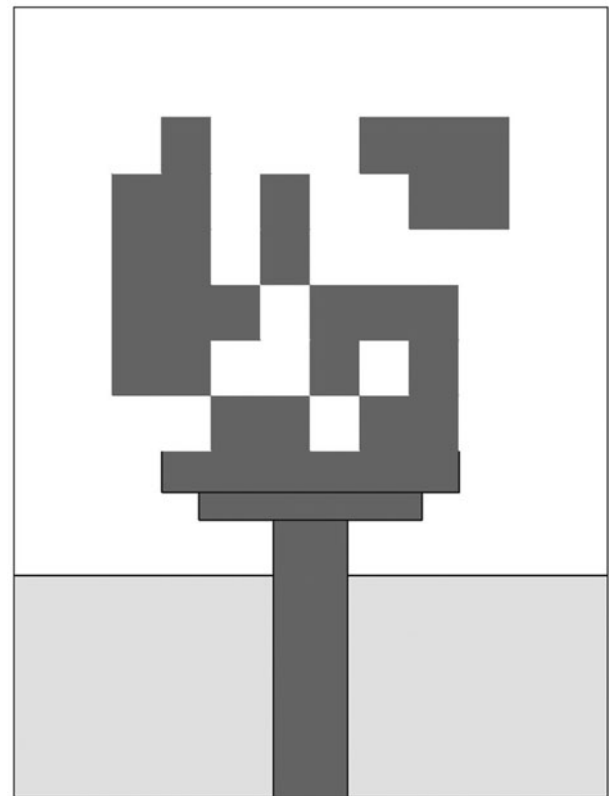


Fig. 5. Optimized UWB antenna design.

This method is implemented by discretizing the Maxwell’s curl equations in the space and time domains. The Yee’s FDTD algorithm divides the problem geometry into spatial grid where the electric and magnetic field components are arranged at certain discrete positions in space based on leapfrog manner. Also, it solves the Maxwell’s equation in time at discrete time instances. The update equations for electric and magnetic fields based on central finite difference are derived from Maxwell’s curl equations as explained in detail in many literature [27, 28]. These updated equations allow to compute magnetic and electric field values with a recursive procedure in time and space. Also, in order for the FDTD simulation to work properly, the spatial and time discretization increments should satisfy the Courant Friedrichs Lewy (CFL) stability condition [27]. Since the computational storage space is finite, FDTD problem space needs to be truncated by special boundary conditions such as absorbing boundary conditions (ABCs) [27]. These boundary conditions are used to presume that the EM waves propagate continuously beyond the computational space. The imperfect truncation of the problem space will create numerical reflections which will corrupt the results [27]. Among many ABCs available in the literature, the convolutional perfectly matched layer (CPML) proposed by Roden and Gedney [29] assumes a special medium surrounding the problem space to create the wave impedance matching conditions. The CPML approach is also independent of material medium and can be extended for dispersive media, anisotropic media, or non-linear media [28, 29]. For these reasons, this method is adopted in this work. In antenna problems, the aim is to find the radiated fields that are far away from the antenna. With the FDTD technique, the direct evaluation of far field needs excessively large

**Table 1.** Summary of the methods and parameters for UWB antenna design using topology optimization

Ref.	Simulation method	Optimization method	Topology parameters	Parallel computation	Fitness parameters	Antenna description
[11]	FDTD	2D-GA	<sup>a</sup> Asymmetric	No	$S_{11}$ below – 15 dB	Teflon $\epsilon_r = 2.65$
	$dx = 0.53$ mm	Population size = 100	<sup>b</sup> 80			thickness = 0.8 mm
	$dy = 0.53$ mm	crossover prop. 80%	<sup>c</sup> $2.385 \times 2.65$ mm <sup>2</sup>			$23.85 \times 34.45$ mm <sup>2</sup>
	$dz = 0.265$ mm	mutation prop. 20%	<sup>d</sup> $21.2 \times 23.9$ mm <sup>2</sup>			
	$dt = 0.53$ ps					
	$130 \times 120 \times 37$					
[13]	FDTD	DPGA	<sup>a</sup> Symmetric	No	VSWR below 2	FR4 $\epsilon_r = 4.4$
	$dx = 0.4$ mm	1 <sup>st</sup> Population size = 6	<sup>b</sup> 70			thickness = 1.6 mm
	$dy = 0.5$ mm	2 <sup>nd</sup> Population size = 10	<sup>c</sup> $1.6 \times 2$ mm <sup>2</sup>			$43 \times 33.6$ mm <sup>2</sup>
	$dz = 0.4$ mm		<sup>d</sup> $24 \times 20$ mm <sup>2</sup>			
	$84 \times 86 \times 40$					
[15]	DGF-FDTD	BPSO	<sup>a</sup> Symmetric	Yes	VSWR below 2	Rogers RT6002 $\epsilon_r = 2.94$
	$dx = 0.4$ mm	32 Particles	<sup>b</sup> 60	8 Processors	Stable E and H plane	thickness = 1.6 mm
	$dy = 0.4$ mm		<sup>c</sup> $1.6 \times 1.6$ mm <sup>2</sup>		Radiation patterns	
	$dz = 0.4$ mm		<sup>d</sup> $16 \times 19.2$ mm <sup>2</sup>			
[16]	CST	GA	<sup>a</sup> Symmetric	No	$S_{11}$ below – 12 dB	FR4 $\epsilon_r = 4.4$
		Population size = 200	<sup>b</sup> 130			thickness = 1.6 mm
		crossover prop. 80%	<sup>c</sup> $1 \times 1$ mm <sup>2</sup>			$47 \times 47$ mm <sup>2</sup>
		mutation prop. 5%	<sup>c</sup> $2 \times 2$ mm <sup>2</sup>			
			<sup>c</sup> $4 \times 4$ mm <sup>2</sup>			
			<sup>d</sup> $40 \times 29$ mm <sup>2</sup>			
[17]	HFSS	SPEA2	<sup>a</sup> Symmetric	No	$ S_{11} $	FR4 $\epsilon_r = 4.4$
		Population size = 140	<sup>b</sup> 50		broadside antenna gain	thickness = 1.6 mm
		crossover prop. 50%	<sup>c</sup> Variable size		group delay	$30 \times 30$ mm <sup>2</sup>
		mutation prop. 3%	<sup>d</sup> $15 \times 15$ mm <sup>2</sup>			
Present work	FDTD	Improved	<sup>a</sup> Asymmetric	Yes	$S_{11}$ below – 12 dB	FR4 $\epsilon_r = 4.4$
	$dx = 0.5$ mm	BPSO	<sup>b</sup> 48	12 Processors		thickness = 1.6 mm
	$dy = 0.5$ mm	60 Particles	<sup>c</sup> $2 \times 2$ mm <sup>2</sup>			$24 \times 28.5$ mm <sup>2</sup>
	$dz = 0.4$ mm		<sup>d</sup> $16 \times 12$ mm <sup>2</sup>			
	$dt = 0.75$ ps					
	$88 \times 97 \times 44$					

<sup>a</sup> Type of topology.

<sup>b</sup> Number of bits used to represent the topology.

<sup>c</sup> Size of a cell.

<sup>d</sup> Dimension of topology design domain.

computational domain which is not practically possible. Therefore, Huygens surface equivalence theorem has been implemented at the output boundary to obtain near-to- far field transformation [27, 28].

### Implementation

Topology-based antenna optimization problem is a NP- hard problem. It is a global optimization problem. It has large solution space which demands populationbased strategy. This leaves us the

two most popular candidate algorithms to solve the problem which are PSO and GA. Primary need of algorithm for our solution is less computation, less complexity, and cooperation among population. PSO is the most possible candidate for these requirements. Figure 2 shows the flow chart for the overall implementation of the proposed model. The first step of the FDTD algorithm is to initialize the field values, source, updating coefficients, boundary conditions and CPML coefficients. After the initialization, the improved parallel BPSO algorithm is used to find the optimal topology for UWB antenna.

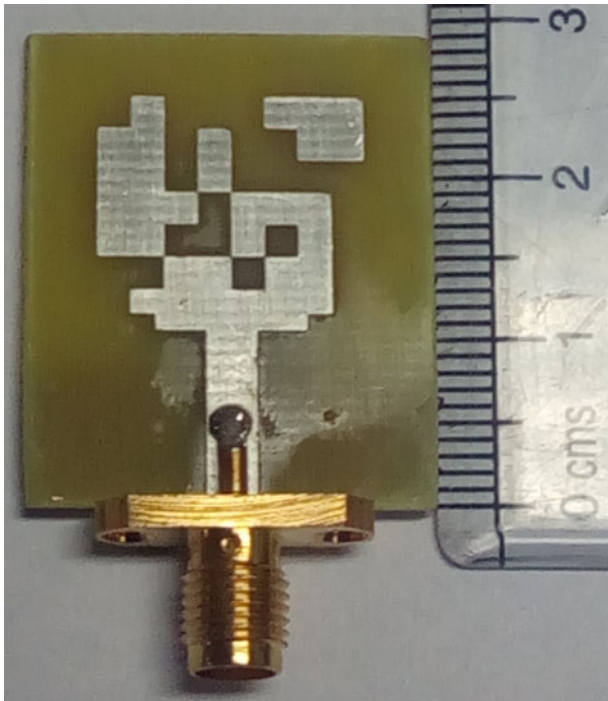


Fig. 6. The fabricated prototype of the optimized UWB antenna.

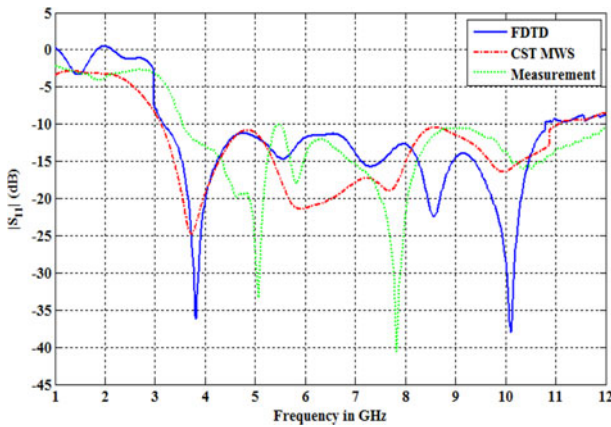


Fig. 7. The calculated, simulated, and measured return loss of the optimum UWB antenna.

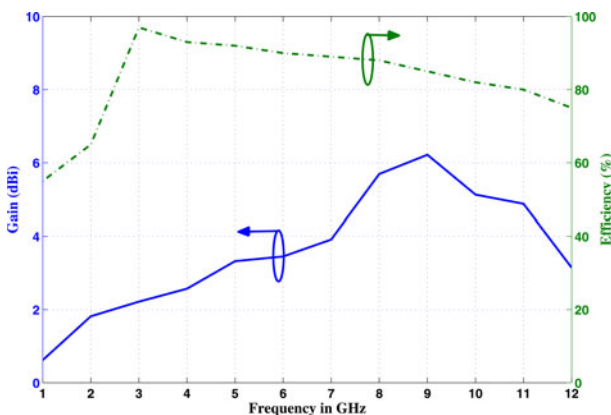


Fig. 8. The simulated gain and efficiency of the optimum UWB antenna.

The fitness function is computed by using FDTD parallelly for all the particles and it is defined as:

$$Fitness = F_1 + F_2 + F_3. \tag{4}$$

Here,  $F_1$ ,  $F_2$ , and  $F_3$  represent the fitness functions of three different frequency regions. Let  $\delta$  be the sample spacing of the frequency ( $f$ ). For frequency region 1 to  $(3.1 - \delta)$  GHz with  $N_1$  as the number of frequency components in this region, fitness function  $F_1$  can be expressed as,

$$F_1 = \frac{1}{N_1} \sum_{f=1 \text{ GHz}}^{(3.1-\delta) \text{ GHz}} S_1(f). \tag{5}$$

Where,

$$S_1 = \begin{cases} -5 \text{ dB}, & \text{If } S_{11}(f) \geq -5 \text{ dB} \\ S_{11}(f), & \text{If } S_{11}(f) < -5 \text{ dB}. \end{cases} \tag{6}$$

Here,  $S_{11}(f)$  is the return loss over frequency  $f$ .

For frequency 3.1–10.6 GHz with  $N_2$  as the number of frequency components in this region, fitness function  $F_2$  can be expressed as,

$$F_2 = \frac{1}{N_2} \sum_{f=3.1 \text{ GHz}}^{10.6 \text{ GHz}} S_2(f). \tag{7}$$

Where,

$$S_2 = \begin{cases} -12 \text{ dB}, & \text{If } S_{11}(f) \leq -12 \text{ dB} \\ S_{11}(f), & \text{If } S_{11}(f) > -12 \text{ dB}. \end{cases} \tag{8}$$

For frequency  $(10.6 + \delta)$  to 12 GHz with  $N_3$  as the number of frequency components in this region, fitness function  $F_3$  can be expressed as,

$$F_3 = \frac{1}{N_3} \sum_{f=(10.6+\delta) \text{ GHz}}^{12 \text{ GHz}} S_3(f). \tag{9}$$

Where,

$$S_3 = \begin{cases} -5 \text{ dB}, & \text{If } S_{11}(f) \geq -5 \text{ dB} \\ S_{11}(f), & \text{If } S_{11}(f) < -5 \text{ dB}. \end{cases} \tag{10}$$

Parameters of the particles are inherited from base FDTD object. These parameters are updated independently. This object structure facilitates the parallel computation.

For each iteration, after the evaluation of the fitness function using parallelization for all the particles,  $pbest_i$  is identified as the  $i^{th}$  particle's best position. If current iteration  $pbest_i$  is better than previous iteration's  $pbest_i$ , then the  $pbest_i$  will be updated. The best particle's  $pbest_i$  value will be updated to  $gbest$ . As discussed in section "Improved BPSO", the velocity and position of each particle will be updated using (1) and (3), respectively. This will continue as long as the algorithm converges. After the convergence, the return loss results of the optimal UWB antenna topology is visualized and verified.

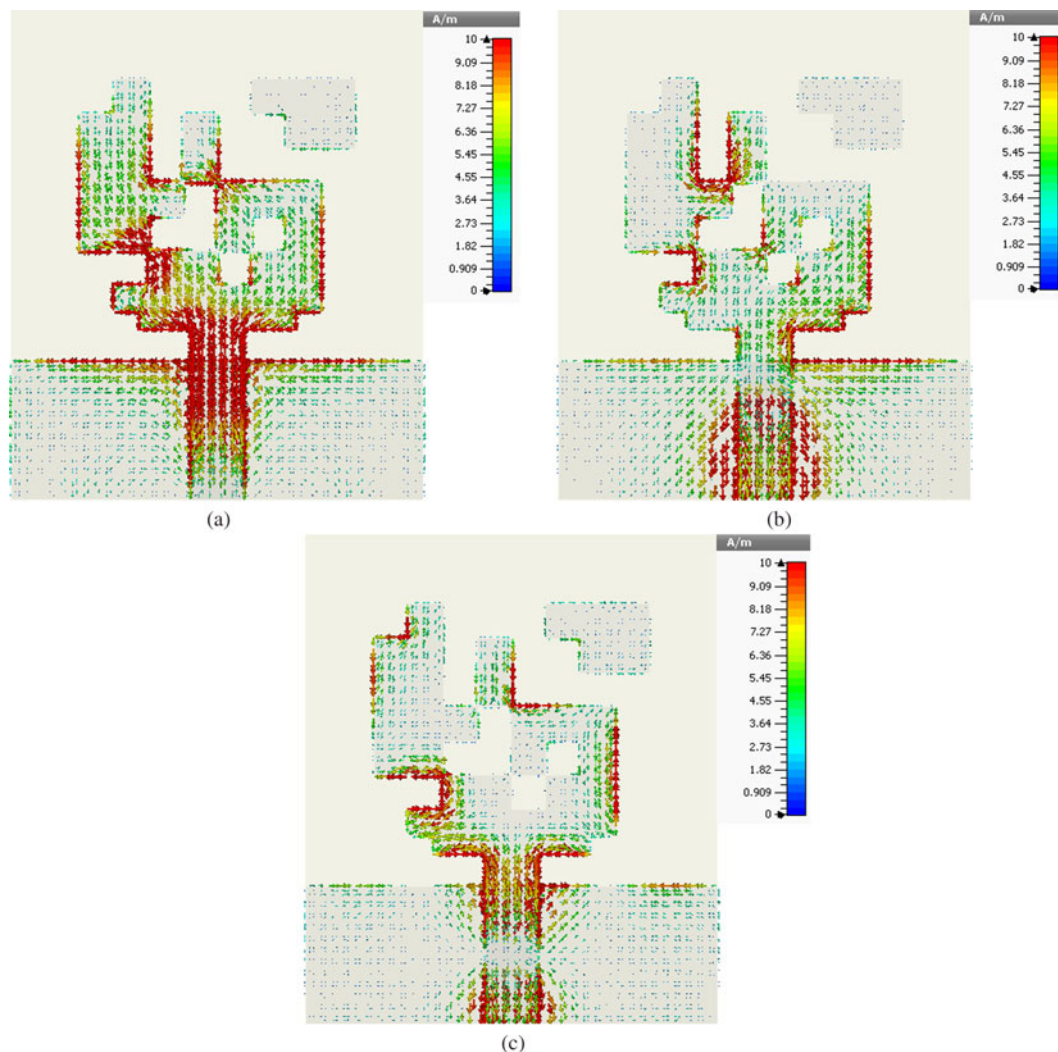


Fig. 9. Simulated total current distribution of the optimum UWB antenna at different frequencies (a) 3.5 GHz, (b) 6.5 GHz, and (c) 10.5 GHz.

## Results and discussion

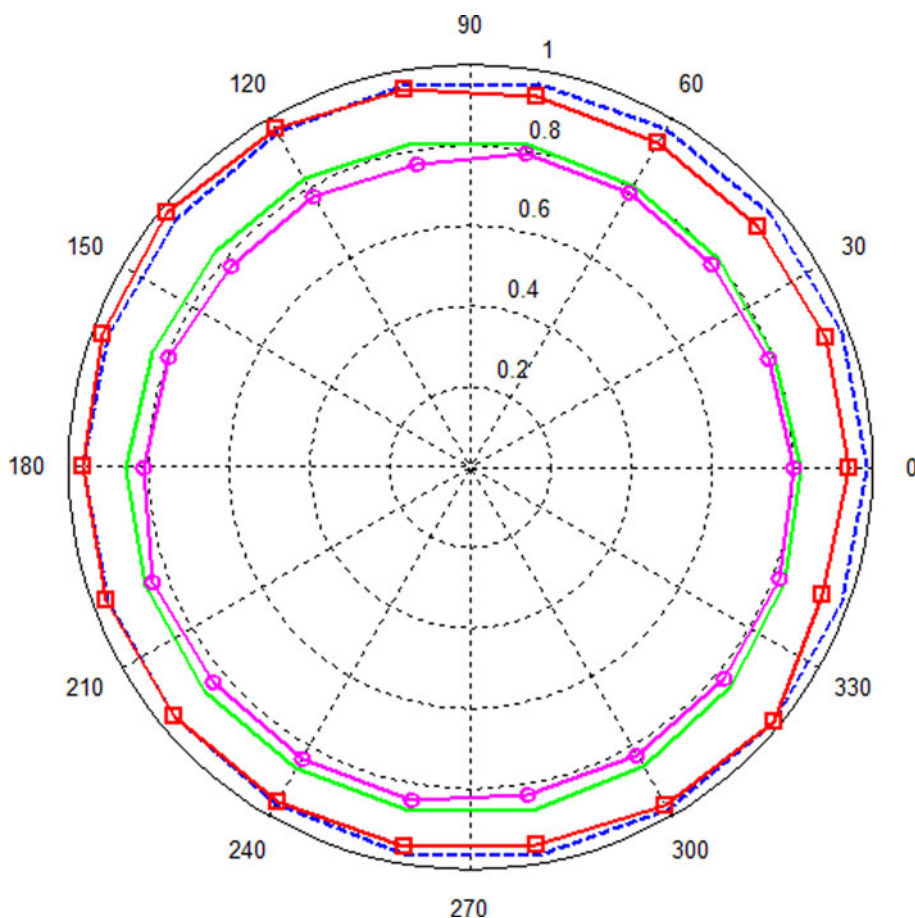
In the FDTD analysis, the step sizes for  $x$ ,  $y$ , and  $z$  directions are 0.5, 0.5, and 0.4 mm, respectively. To satisfy the CFL stability condition, the time step  $\Delta t$  is taken as 0.75 ps. The total computation domain consists of the antenna geometry, excitation source, the 10 layers of air boundary, and the 10 layers of conventional PML which is used as the absorbing boundary. Unit amplitude Gaussian pulse is used to excite the antenna at the end of the feed line. The total time steps of 5000 is taken here but it is limited by the convergence of return loss.

The initial design of antenna consists of a  $50\Omega$  microstrip feed line with ( $3\text{ mm} \times 10\text{ mm}$ ), two steps of ( $9\text{ mm} \times 1.0\text{ mm}$ ) and ( $12\text{ mm} \times 1.5\text{ mm}$ ), a rectangular patch of ( $16\text{ mm} \times 12\text{ mm}$ ), and a ground plane of ( $24\text{ mm} \times 8\text{ mm}$ ). The overall dimensions of the antenna is  $24\text{ mm} \times 28.5\text{ mm}$ . The antenna is printed on a FR4 epoxy substrate of relative permittivity 4.4 and 1.6 mm thickness.

The rectangular patch is divided into  $8 \times 6$  cells, each cell size being  $2\text{ mm} \times 2\text{ mm}$  as shown in Fig. 3. Each cell is mapped as a bit and hence the 48 cells in the patch is represented as a 48-bit binary string. Each combination of 48 bits is considered as a particle of BPSO, wherein the cell with metal is considered as “1” and

with vacuum as “0”. In the improved BPSO implementation, a total of 60 particles are selected for optimization of the antenna. For parallel computation implementation, the optimization process utilizes 12 parallel processors. Therefore, for a 60-particle swarm, FDTD simulation is repeated five times within each iteration of optimization to evaluate the fitness function of all particles. The good converged optimization is obtained after 170 iterations and convergence curve is plotted in Fig. 4. These computations were carried out on a 64-bit system with 12-core 2.10 GHz CPU and 16 GB RAM. The total time and the memory usage for optimization are about 200 h and 10 GB, respectively. The optimized UWB antenna after the convergence is shown in Fig. 5. The methods and parameters used for topology optimization-based UWB antenna design is summarized in Table 1. From this, it is observed that the area used for topology optimization and antenna overall dimensions are small compared with others.

The fabricated prototype of the optimized UWB antenna is shown in Fig. 6. The measurement of the S parameters is carried out by using Keysight ENA series E5071C vector network analyzer over the frequency range of 1–12 GHz. Calculated and measured return loss ( $S_{11}$ ) of the optimized antenna are shown in Fig. 7. The  $S_{11}$  obtained for the optimized antenna simulated using CST microwave simulation tool is also plotted for



**Fig. 10.** SFF values of the optimum UWB antenna: simulated fidelity patterns for fifth-order Gaussian pulse (solid green line), sine-modulated Gaussian pulse (dashed blue line), and measured fidelity patterns for fifth-order Gaussian pulse (circle marked magenta line), sine-modulated Gaussian pulse (square marked red line).

comparison. It can be seen that the designed antenna shows the desired return loss performance over the frequency range of interest, using FDTD calculations, CST simulation, and from the practical measurement.

The gain and radiation efficiency of the optimally designed UWB antenna obtained from CST simulation are shown in Fig. 8. The peak gain of the antenna varies from 2.216 to 4.875 dBi in the 3–11 GHz frequency range. The radiation efficiency is maintained above 80%. The current distribution of the antenna at frequencies 3.5, 6.5, and 10.5 GHz are shown in Fig. 9. At 3.5 GHz, the current gets distributed over the entire optimized structure of the patch. As the frequency increases, the current is traveled only in the edges of the patch.

In IR-UWB systems, the information should be transmitted and received in the form of very narrow pulses with minimal distortion. The system fidelity factor (SFF) which is derived from the system transfer function ( $S_{21}$ ) is used to measure the correlation between the received signal and transmitted signal [30]. Hermitian processing method is used to convert the measured  $S_{21}$  to time domain impulse response [1,31].  $S_{21}$  is measured by keeping two identical antennas at a distance of 200 mm away from each other and connected to the ports of Agilent ENA series vector network analyzer. In the  $S_{21}$  measurement, the transmitted antenna is stationary and the received antenna is rotated in steps of 20°. The  $S_{21}$  is also obtained from the CST simulation.

In order to calculate the SFF, two different transmitted pulses such as fifth-order Gaussian pulse with pulse parameter  $\alpha = 60$  ps and sine-modulated Gaussian pulse with a carrier frequency of 6 GHz, pulse parameter  $\alpha = 350$  ps are considered. From

Fig. 10, it is observed that for both input pulses, SFF values obtained from simulation and measurement are almost linear with above 75% and the input pulses experience minimal distortion in all angular directions around the antenna.

## Conclusion

The optimized UWB antenna is designed based on material distribution topology by using improved BPSO with FDTD. The implementation of the improved BPSO algorithm combined with the FDTD method is highly efficient due to their discrete nature. Since all particles within an iteration are evaluated independently, the fitness function evaluation of particles can be performed simultaneously and in parallel by using FDTD. Effectiveness of this method is verified by CST simulation. The optimized antenna structure has been fabricated and experimentally validated the simulation results. Also, the optimized antenna has relatively stable peak gain with less variation and good radiation efficiency over the UWB frequency band.

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