Performance Analysis of Patch Antenna for Ultra-Wideband using Particle Swarm Optimization

P. Elechi[1], S. Orike[2], and C.E. Ikpo[1]
[1]*Department of Electrical/Electronic Engineering, Rivers State University, Port Harcourt, Nigeria*
[2]*Department of Computer Engineering, Rivers State University, Port Harcourt, Nigeria.*
elechi.promise@ust.edu.ng

***Abstract*—Recently, with the rapid development of fixed and portable communication systems, there is a need for very high data rates for short-distance transmissions. Ultra-Wideband (UWB) is a wireless technology that offers the advantage of low power consumption, high data rate, high time resolution, low-cost implementation, obstacle penetration, resistance to interference and co-existence with narrowband systems. To harness the benefits and advantages of UWB technology, a suitable antenna needs to be designed. In this study, a patch antenna fed by a microstrip line designed on a substrate is considerably studied and analysed for use within the UWB frequency range of 3.1GHz -10.6GHz. The antenna has been designed and simulated using COMSOL Multiphysics Software at varying frequencies using derived geometric parameters. Particle Swarm Optimization (PSO) technique was used to optimise the modelled patch antenna to achieve optimal antenna performance. Modelling and optimisation of the presented microstrip patch antenna produced results that are suitable for UWB applications.**

***Index Terms*—Microstrip Patch Antenna; Ultra-Wideband (UWB); Particle Swarm Optimization (PSO); COMSOL Multiphysics; Antenna; Frequency Range.**

I. INTRODUCTION

The antenna is an essential constituent of wireless communication technology, which plays a vital role in the telecommunication industry. It is basically employed in transmitting and receiving electromagnetic (EM) waves. In most cases, antennas are made from conducting materials such as metals, thus enabling them to receive and send waves within the electromagnetic spectrum. The shape and size of antennas differ depending on the application, such as television to large ones used in satellite communication over millions of miles. Antennas can be found everywhere; vehicles, homes and offices, roads, radar systems, parks, satellite communications buildings and military facilities, installations and gadgets. With the advent of varying technologies such as mobile phones, computers, routers, local area networks, jammers, and satellite communication, the need arose for a portable, lightweight antenna that is cheap, easy to fabricate and has good performance [1].

With the rapid development of both fixed and portable communication systems, there is a need for very high data rates for short-distance transmissions. UWB has been identified as the key technology for achieving short-range high data rates of around 500Mbps. Ultra-Wideband (UWB) is a wireless technology that offers a faster speed while utilising less power when compared to Wi-Fi and first-generation Bluetooth products. UWB transmission systems function at power levels at basically the noise floor, or below, through low power ultra-short information-bearing pulses. UWB allows for short-range, high bandwidth communications at very low energy levels by utilising a large part of the radio spectrum [2].

For efficient and effective transmission at such high frequencies, suitable antennas that can work on the UWB range need to be designed [2]. Microstrip patch antennas have been a good candidate for applications targeting specific ranges in Ultra-Wide Band. Antennas of various shapes such as rectangular, pentagon, E-shaped disc, fork, L-strip, square, circular, triangular, dipole, elliptical diamond, and reciprocal U-shaped have been realised for implementing microstrip UWB antennas [2]. Mostly used in mobile phones and laptops, microstrip patch antennas can be printed on circuit boards providing cheap, low profile and easily fabricated antenna options. The application of patch antenna is increasing in wireless communication due to their characteristic properties like low cost, ease of instalment on rigid surfaces, low profile, lightweight and easy compatibility with integrated circuits. The use of these antennas presents a lot of advantages such as lesser volume, ease to integrate, ability to handle both linear and circular polarisation and to permit double and triple frequency operations [1].

Various design techniques have been successfully applied in improving the performance of microstrip antennas. One of such techniques applied in the fabrication of microstrip antennas is optimisation algorithms [3] and [4]. Recently, Particle Swarm Optimization (PSO) has been used extensively in the signal processing field to optimise multi-objective problems (e.g., bandwidth and directivity of the antenna) [5], [6], [7] and [8]. Evolutionary computation exploits a set of potential solutions, named population, and detects the optimal ones through cooperation and competition among the individuals of the population. PSO is one of the population-based stochastic optimisation techniques inspired by the social behaviour of bird flocking [5] and [9].

In order to analyse the performance of the patch antenna in the Ultra-Wideband frequency range, the geometric parameters of the rectangular microstrip patch antenna are designed and simulated in COMSOL Multiphysics software environment using varying geometric dimensions. To enhance the performance of the UWB antenna, Particle Swarm Optimization (PSO) algorithm is implemented to determine optimal geometric parameters of the patch antenna, which directly affect the performance of the UWB antenna.

II. RECTANGULAR MICROSTRIP PATCH ANTENNA MODELLING

Here, the fabrication and subsequent modelling of the proposed patch antenna will be discussed. The dimensions of the antenna are determined using characteristic equations. Based on varying the derived dimensions, UWB antennas are modelled and analysed to arrive at optimal performance in the Ultra-Wideband frequency spectrum of 3.1GHz to 10.6GHz.

A. Patch Antenna, Finite Element Method (FEM)

In the patch antenna design, the Finite Element Method (FEM) is preferred for volumetric designs. The technique used in this method is a division of complete structure into several smaller units, which could be volumetric or planar surfaces for volumetric and planar structures analysis, respectively [10]. The small units, named planar elements and appearing in varying shapes, are also referred to as finite elements. The shapes may be triangular for planar structures and tetrahedral and prism-shaped for 3-D configurations or curved geometries. The integration of some basic operations is performed over the antenna by dividing it into smaller portions. This method makes it easy in analysing partial differentiation equations over complex domains of varied precisions.

The changes in the shape of the patch can be directly related to the changes in radiation pattern, antenna efficiency, and antenna impedance. There are several structure varieties of the microstrip patch antenna, including square radiating element, triangular, and semi-circular, but the rectangular element is most commonly used.

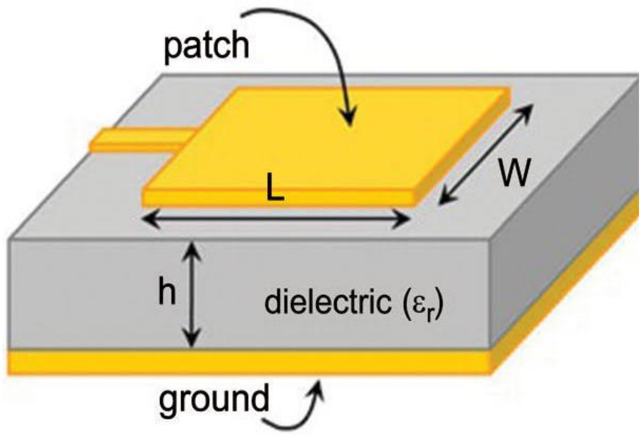

Figure 1: Diagram showing the dimensions of the Rectangular Microstrip Patch Antenna.

B. Antenna Geometry and Design Procedure

The antenna shape is obtained by creating a cavity into a ground plane, and the ground plane is extended from partial ground to antenna encasing ground. The proposed antenna structure uses the partial ground plane for the feed, and this is also extended to surround the antenna from all three sides. The empty part in the ground plane or metal is referred to as cavity or window whose size can be optimised in terms of its length and width. In this case, the design target is to optimise the cavity size to operate an antenna from 3.1 to 10.6 GHz.

The primary cause of radiation in a microstrip patch antenna is the fringing field that exists between the ground plane and the edge of the patch. A thick dielectric substrate with a low dielectric constant (<6) is preferred for optimal antenna functionality since it provides higher efficiency, larger bandwidth, and better radiation. In selecting substrate material for the microstrip patch antenna design, the thickness, dielectric constant, and loss tangent play an important role in achieving desirable features for any given application. For the proposed antenna, Flame Retardant 4(FR-4) epoxy having a dielectric constant (ε_r) of 4.4 and loss tangent of 0.02 is used as the substrate material. FR-4 has the advantage of low cost, easy availability, and good flexibility for thinner substrate thickness at higher frequencies.

C. Calculation of the Antenna Geometric Parameters

The design parameters for the antenna were estimated using transmission line model in various steps as follows [11][12]:

Step 1: Calculate the Width of the patch

$$W = \frac{C_o}{2f_o}\sqrt{\frac{2}{\mathcal{E}_r + 1}} \tag{1}$$

Step 2: Calculate Effective Dielectric constant

$$\mathcal{E}_{reff} = \frac{\mathcal{E}_r + 1}{2} + \frac{\mathcal{E}_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

Step 3: Calculate the change in length due to fringing (ΔL)

$$\Delta L = 0.412h\frac{\left(\mathcal{E}_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\mathcal{E}_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{3}$$

and Effective length (L_{eff})

$$L_{eff} = \frac{C_o}{2f_o\sqrt{\mathcal{E}_{reff}}} \tag{4}$$

Step 4: Calculate the length of the patch

$$L = L_{eff} - 2\Delta L \tag{5}$$

Step 5: Calculate the ground plane length (L_g) and width (W_g)

$$L_g = 6h + L \tag{6}$$

$$W_g = 6h + W \tag{7}$$

Step 6: To calculate the notch width, g;

$$g = \frac{\frac{v_o}{\sqrt{2\mathcal{E}_{reff}}}\,4.6 \times 10^{-12}}{f} \tag{8}$$

The bandwidth of the patch antenna can be improved in a way by increased substrate thickness or reduced dielectric constant [13], [14] and [15]. Also, changing the frequency will significantly affect the geometry of the rectangular microstrip patch antenna. Again, by the symmetrical distribution of impedance, it was proved that giving feed point location on left and right sides from the middle point does not alter the execution of the patch antenna. As impedance is symmetrically distributed from the centre of the patch towards the edges, from 0 ohms to maximum resistance value, the feeding can be given on the left side symmetrically.

Table 1 shows the geometrical dimensions (parameters) of the designed antenna. The table shows that the resonance frequency has a significant impact on the antenna's geometry. As shown in the result of the computation, the higher the frequency, the smaller the size of the antenna in terms of width and length. However, the substrate thickness does not significantly affect the width of the antenna and the other geometric parameters. Therefore, to test the performance or the best values for geometry, operating parameters can be selected through numerical simulation using COMSOL Multiphysics.

Table 1
Geometric Parameters of the Proposed Antenna Derived by Varying Frequency(f_r) and Substrate Thickness(d) in Characteristic Equations.

d	f_r	W (mm)	L (mm)	F_i (mm)	w (mm)	g (mm)	L_g (mm)	W_g (mm)
2	4.0	22.822	17.203	6.368	3.729	0.125	25.203	34.821
3	4.0	22.822	16.658	6.152	5.594	0.127	25.658	40.821
4	4.0	22.822	16.068	5.919	7.459	0.128	26.068	46.821
2	6.0	15.215	11.105	4.101	3.729	0.084	19.105	27.214
3	6.0	15.215	10.509	3.866	5.594	0.086	19.509	33.214
3	8.0	11.411	7.4177	2.718	5.594	0.065	16.417	29.410
4	9.0	10.143	5.7693	2.099	7.459	0.059	15.769	34.143
4	3.5	26.082	18.705	6.899	7.459	0.146	28.705	50.082

D. Numerical Modelling/Model Definition using COMSOL Multiphysics

The rectangular microstrip patch antenna model is presented in the simulation interface of COMSOL Multiphysics version 5.5. The geometry was designed and implemented in COMSOL Multiphysics software environment, and the geometric characteristics were varied from the values given in Table 1.

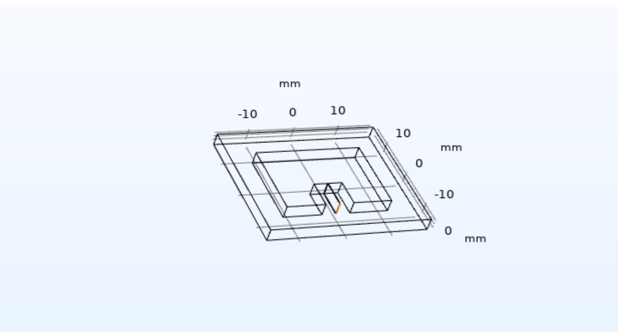

Figure 2: COMSOL Model of the Rectangular Microstrip Patch Antenna.

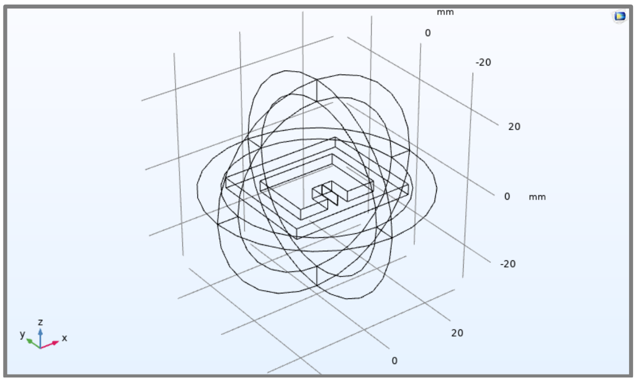

Figure 3: The Graphics Window of COMSOL Software Showing the Exterior Part of the Antenna in Air Domain.

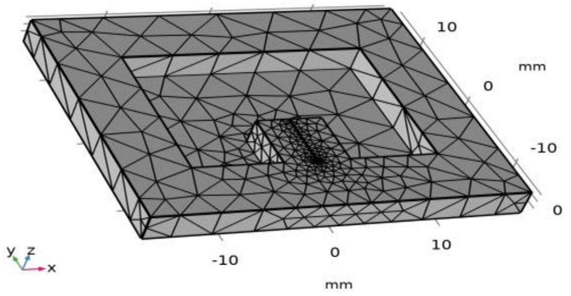

Figure 4: The Mesh Pattern of the Rectangular Microstrip Patch Antenna Elements as shown in COMSOl Multiphysics Software.

E. Application of Particle Swarm Optimization in MATLAB

Evolutionary algorithm is a family of biological evolution inspired stochastic search methods that function on a population of potential solutions using the principle of survival of the fittest in producing better approximations to a solution [16] and [17].

Particle Swarm Optimization (PSO) is a global heuristic algorithm formulated by Eberhart and Kennedy in 1995, inspired by the "information sharing" ability of groups of animals in finding the easiest and safest path to food source [18], [19] and [20]. Their research was centred on the behavioural characteristics of birds' swarm movement. The study aimed to investigate the social behaviour and the general intelligence of a flock of birds. While birds are searching for food, they either fly in a flock or disperse in different directions. During the search, there is usually at least one bird that first perceives the food. This single bird in the flock has optimal information about the food's position or at least knows the direction where the food is located. The bird shares its "knowledge" with others, and then eventually, all the birds arrive at the food source. The PSO is effective in finding the optimal solution to complex problems.

Fundamentally, PSO is centred on the principle that each solution can be represented as a particle (agent) in a swarm [21]**.** The individuals, called particles, are grouped into a swarm and fly through the problem space by following the optima particles. Each member has a memory of solutions arrived at during its quest in the problem space. In particular, each particle of the swarm has embedded knowledge of its best position among those it has visited and the best position by its neighbours. Each member of the population has a position and velocity vector, which directs its movement in the problem space and each location coordinate, represents the value of a parameter.

PSO also demands a fitness assessment function that assigns the individual's position to a fitness value. The location of the highest fitness value individually discovered by a particle is called p_{best} (personal best); and the location of the highest fitness function discovered by the swarm is called g_{best} (global best) [21].

There are three major steps of standard Particle Swarm Optimization (PSO):

1) Initialisation

This is the first step of PSO, where each individual, also referred to as particles, in a population (swarm) is allocated an arbitrary velocity $V^i k$ and position $x^i k$ to i^{th} particle at a particular time instant, k. A particle is a "point" that moves iteratively in the modelled space [22]. The position from one move to another of a particle in the designed space depends on its velocity update [23]. This step allows for the random distribution of particles in the designed space. Equations (9) and (10) derives the random position and velocity of a particle using lower and upper boundary conditions, $x_{\min}$ and $x_{\max}$, [24][25].

$$x_0^i = x_{min} + rand(x_{max} - x_{min}) \tag{9}$$

$$V_0^i = \frac{position}{time} = \frac{x_{min} + rand(x_{max} - x_{min})}{\Delta t} \tag{10}$$

2) Velocity update

This step computes the update in the speed of a particle at a time, $k + 1$. This update in velocity is centred on the fitness value of the particle's current location. The value of the fitness function describes the particle with the optimum global value P_k^g in the current population and also the best position of each particle P^i. The update in velocity at time instant $k + 1$ is given as:

$$V_{k+1}^i = wV_k^i + c_1 rand\frac{(P^i - X_k^i)}{\Delta t} + c_2 rand\frac{(P_k^g - X_k^i)}{\Delta t} \tag{11}$$

The right side of the equation is the aggregate of three pertinent terms to determine an update in velocity. These terms include the current motion of the particle, the memory influence of the particle, and the influence of the swarm. The constants w, c_1 and c_2, are the inertia factor, particle self-confidence, and swarm confidence, respectively.

3) Position Update

The last step depicts the update in the particle position at time instant, $k + 1$. This update in the position of the particle is given as follows:

$$X_{k+1}^i = X_k^i + V_{k+1}^i \Delta t \tag{12}$$

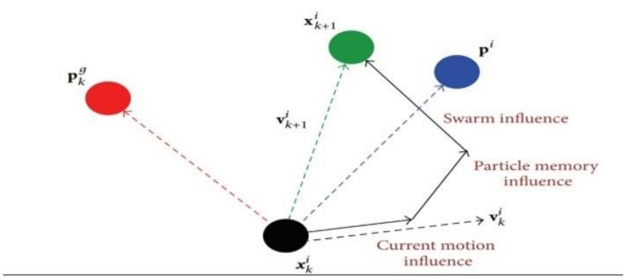

Figure 5: Illustration of Velocity and Position Updates in PSO Algorithm [25].

The next step was to obtain the required sample data points. These data points were obtained from simulations done in the previous section using COMSOL Multiphysics. This section describes the mathematical foundation that has been provided to the entire analysis and design.

III. SIMULATION RESULTS AND DISCUSSIONS

In this section, the proposed model of the rectangular microstrip patch antenna is simulated using varying geometric dimensions of the designed antenna to determine the optimal parameters as generated from Table 1. The parameters were analysed to give better performance when deployed for the UWB application.

Case 1: The rectangular Microstrip patch antenna model was simulated with a substrate thickness of 3mm and a frequency of 4GHz.

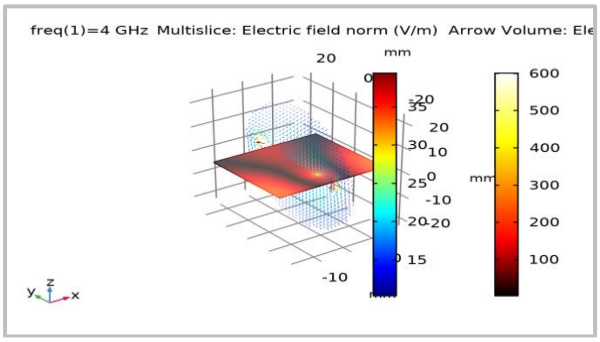

Figure 6: The Electric Field Norm of the Antenna at 4GHz Showing More Intensity along the Radiation Edges.

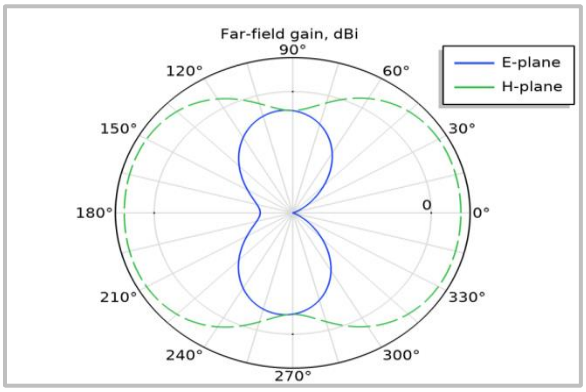

Figure 7: 2D Far-Field Radiation Pattern (gain in dBi) of the antenna at 4GHz showing gain of -4.7dB

Antenna gain, usually expressed in dB, simply refers to its direction of maximum radiation. The directivity can be evaluated when plotting the 3D far-field pattern. Here, the antenna gain is -4.7dB with maximum directivity of 6.9dB at the resonating frequency of 4GHz.

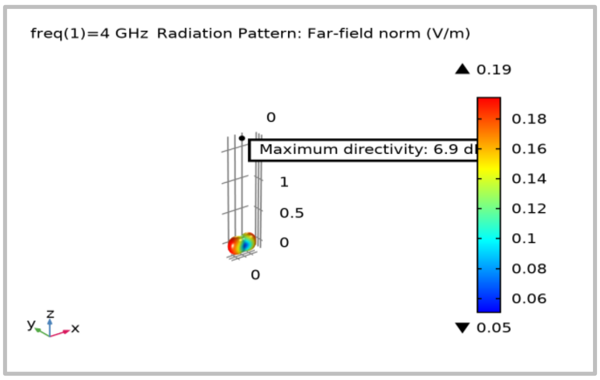

Figure 8: 3D Far-field Radiation Pattern of the Antenna at 4GHz showing Maximum directivity

Case 2: The rectangular Microstrip patch antenna model was simulated with a substrate thickness of 2mm and a frequency of 6GHz.

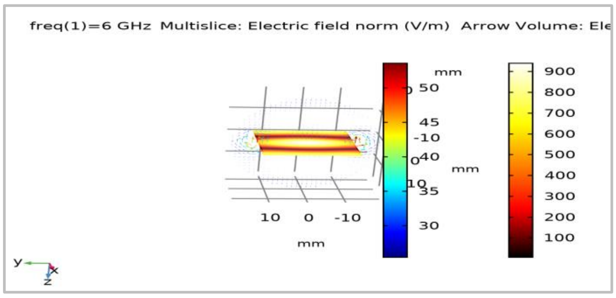

Figure. 9: Showing the Distribution of the Electric Field Norm (V/M) on the antenna at 6GHz.

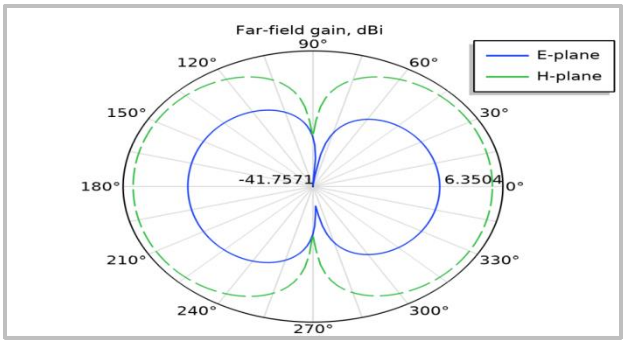

Figure 10: The Far-Field Radiation Pattern of The Antenna at 6GHz with Antenna Gain of 6.35dBi

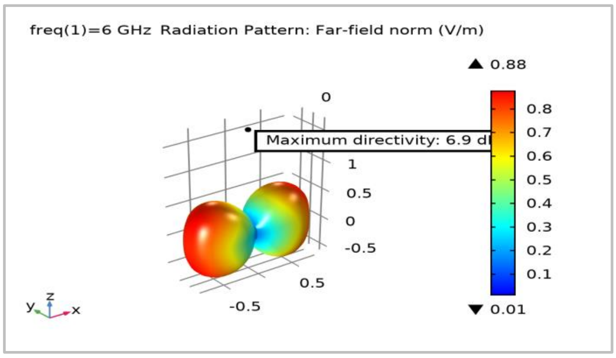

Figure 11: 3D Far-field Radiation Pattern of the Antenna at 6GHz Showing Maximum Directivity at 6.9dB.

The optimisation was considered for two cases by varying the frequency to compute the patch width and substrate thickness to obtain the ground plane width or substrate width. The steps and the result of the optimisation are shown below:

Optimisation case 1: Varying frequency of 3.1 – 9GHz with dielectric constant as 4.4.

The optimisation of the width of the antenna patch is achieved by varying the resonance frequency to obtain the best value since the patch width depends on the frequency and dielectric constant.

The result of the optimisation is shown below, as the width of the patch:

Figure 12: MATLAB Interface Showing the Optimised Value for Patch Width.

It shows that the best value for the patch width selected by PSO is within 10.1430 mm. Therefore, the corresponding frequency for a patch width of 10.1430 is 9GHz, as shown in Table 1.

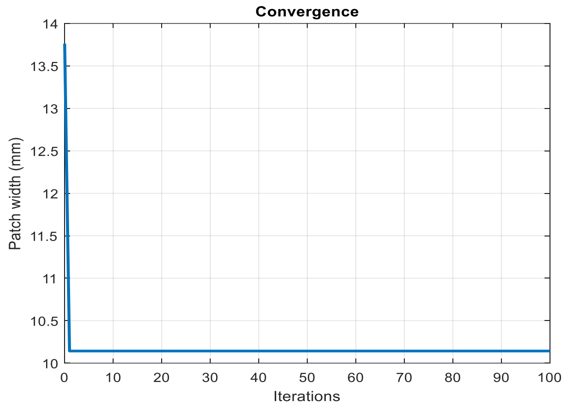

Figure 13: The Convergence Graph Showing the Point of Convergence after Optimisation of Patch Width.

Optimisation case 2: Varying the substrate thickness (d) between 2 – 5 mm to compute the ground plane's width (W_g).

The optimal value for the ground plane width computed by varying the substrate thickness is given below as;

Figure 14: MATLAB Interface Showing the Optimised Value for the Ground Plane Width of the Antenna.

Therefore, the corresponding substrate thickness for a 22.1430mm ground plane width from Table 1 is given to be 2 mm. The convergence plot is shown below.

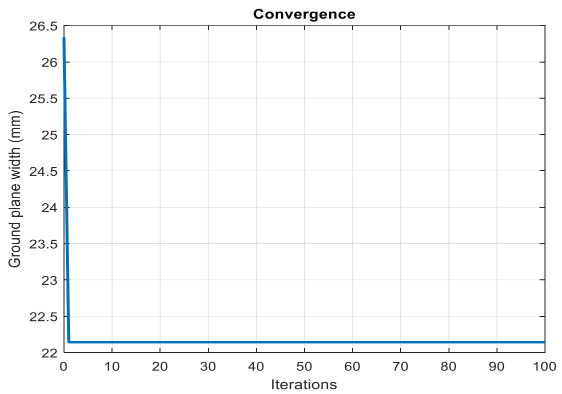

Figure 15: Showing the Point of Convergence after Optimisation of Ground Plane Width

Testing for the geometric parameters of the optimal conditions in Case 1 and 2, i.e., inputting a resonance frequency of 9 GHz and substrate thickness of 2mm, we have the corresponding patch width of 10.1430 mm and ground plane width of 22.1430 mm. The corresponding parameters were generated from Table 1 and utilised in the patch antenna design for optimal performance.

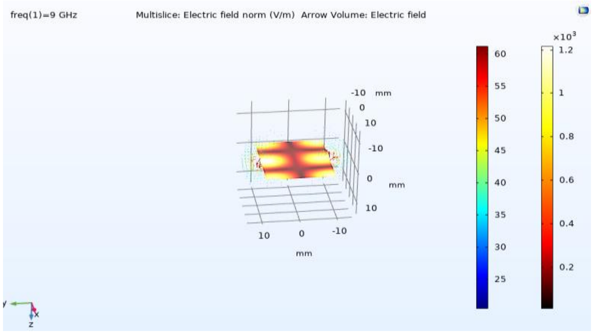

Figure 16: The Electric Field Norm (V/M) distribution on the Antenna's Surface at 9GHz frequency.

It is observed from the figure above that the electric field intensity has its peak value of 1200V/m in a broader surface area of the patch at 9GHz frequency. The arrow plot shows the dominant direction of polarisation of the electric field at the antenna boresight.

The simulated radiation pattern shows plots of the 2D radiation pattern and gains the value of 7dBi for the proposed antenna at 9GHz.

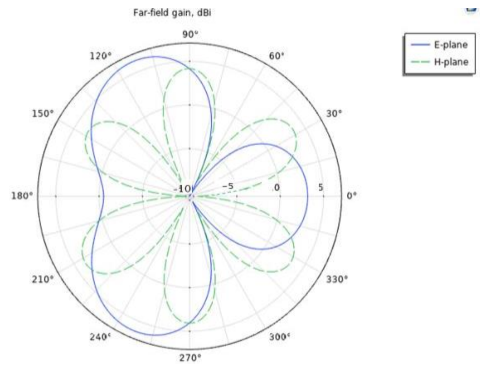

Figure 17: The Far-field Radiation Pattern showing Antenna Gain of 7dB at 9GHz.

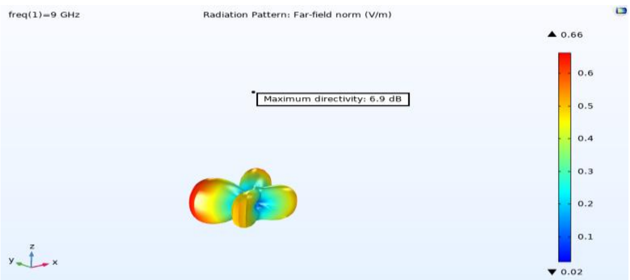

Figure 18: 3D Far-Field Radiation Pattern of the Proposed Antenna at 9GHz Showing Maximum Directivity at 6.9dB.

IV. CONCLUSION

This work proposed implementing the PSO algorithm to fabricate a patch antenna for application in the UWB frequency spectrum of 3.1GHz to10.6GHz to enhance its performance. As a result of the complexity in the relationship between the antenna geometry and the electromagnetic fields, it is often challenging to estimate the properties of a particular antenna shape approximately. To overcome this limitation, simulation of the patch antenna is carried out in the COMSOL Multiphysics environment, and resultant plots of the radiation pattern, radiation frequency, and electric field intensity are obtained. It is observed that the variations in the geometry of the antenna and patch are directly related to the changes in antenna efficiency, antenna impedance and radiation pattern. From the different plots, it can be deduced that the optimum frequency is located at 9 GHz for maximum efficiency, impedance matching and antenna gain. In this work, the resonant frequency and dielectric substrate thickness play an important role in the performance of the rectangular microstrip antenna designed for UWB applications. In the first simulation case of 4GHz resonant frequency with 3mm dielectric substrate thickness, it was observed that low frequency applied with low substrate thickness yields deficient antenna performance.

In comparison, the microstrip patch antenna designed with high resonant frequencies and low substrate thickness exhibited better performance. This study deduced that for the geometric design of rectangular microstrip patch antennas, higher frequency should be applied with lower substrate thickness while lower frequency works better with higher substrate thickness. Although, higher frequency produces a smaller size of the rectangular patch antenna while lower frequency produces a larger dimension of the patch antenna. The simulation results of the optimised antenna are presented for each case scenario to demonstrate the efficiency of PSO in producing a functional and practical design. PSO has been successfully implemented as a heuristic approach to determine optimised values for the geometric dimensions of the proposed Ultra-Wideband antenna.

This work provides a framework for the future design of any antenna shape to be deployed for any frequency range and can be considered a potential candidate for cost-effective UWB applications. The dimensions of the antenna geometry can be varied following the optimal values generated from the PSO optimisation in this work.

REFERENCES

[1] Z.U. Abedin and Z. Ullah. "Design of a Microstrip Patch Antenna with High Bandwidth and High Gain for UWB and Different Wireless Applications". (IJACSA) International Journal of Advanced Computer Science and Application. 2017, vol. 8, iss.10, pp. 379-382.

[2] N. Aggarwal and J. Malhotra. "Design and Optimisation of Rectangular Microstrip Antenna for UWB Applications". International Journal of Signal Processing, Image Processing and Pattern Recognition. 2015, vol.8, iss. 9, pp.347-352

[3] N. Ahuja, R. Khanna and J. Kaur. "Dual Band Defected Ground Microstrip Patch Antenna for WLAN/WiMax and Satellite Application". International Journal of Computer Applications. 2011, vol.48, iss. 22, 147-152.

[4] J. Amed, S. Bhattacharjee, S. Dani, S. Mishra and S. Chatterjee. "Microstrip Antenna Design using Particle Swarm Optimization". Anandapur: Heritage Institute of Technology. 2006.

[5] S.K. Behera and Y. Choukiker. "Design and Optimisation of Dual Band Microstrip Antenna Using Particle Swarm Optimization Technique". National Institute of Technology, Electronics & Communication Engineering, Rourkela. 2010, doi:10.1007/s10762-010-9722-0

[6] R. Garg, P. Bhartia, I. Bahl and A. Ittipiboon." Microstrip Antenna Design Handbook". Artech House. 2001.

[7] S. Gezici, T.Zhi, G. Giannaki, H. Kobayashi, A. Molisch, H. Poor and Z. Sahinoglu. "Localisation Via Ultra-Wideband Radio: a Look At Positioning Aspects for Future Sensor Networks". IEEE Signal Processing Magazine. 2005, vol. 22, iss. 4. pp. 58-63.

[8] S.K. Goudos,K. Christos and M. Raj. "Evolutionary Algorithms Applied to Antennas and Propagation: A Review of State of the Art". International Journal of Antennas and Propagation. 2016, vol. 2016, iss. 12, pp. 258-266.

[9] V. Gungor and G. Hancke. “Industrial Wireless Sensor Networks: Challenges, Design Principles and Technical Approaches”. IEEE Transactions on Industrial Electronics. 2009, vol. 56, iss.10, pp. 95-99.

[10] S. John and K. Manoj. “Microstrip Patch Antennas UWB Applications: A Review”. IOSR Journal of Electronics and Communication Engineering, 2014, vol. 9, iss. 2, pp. 34-37.

[11] N. Kalambe, P. D. Thakur and P.S. Paul. “Review of Microstrip Patch Antenna Using UWB for WIreless Communication Devices”. International Journal of Computer Science and Moblie Computing. 2015, vol. 4, iss. 1, pp. 128-133.

[12] L. Mirchandani, L. Solanki, A. Karwa and A. Mathur. “A Rectangular Microstrip Patch Antenna for Ultra-Wideband Application Using HFSS Software”. IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE). 2017, vol. 12, iss. 3, pp. 10-13.

[13] K. Ramna and A. S. Sappal. “Design of a Rectangular Microstrip Patch Antenna Using Particle Swarm Optimization”. International Journal for Advanced Research in Computer and Communication Engineering. 2013, vol. 2, iss. 7, pp. 97-109.

[14] T. Saeidi, I. Ismail, W. P. Wen, A. Alhawari and A. Mohammadi. “Ultra-Wideband Antennas for Wireless Communication Applications”. International Journal of Antennas and Propagation. 2019, vol. 14, no. 8, pp. 54-62.

[15] S. Sahoo, L. P. Mishra and M. N. Mohanty. “Optimisation of Z-Shape Microstrip Antenna with I-Slot using Discrete Particle Swarm Optimization (DPSO) Algorithm”. 2nd International Conference on Intelligent Computing, Communication & Convergence. 2016, iss.92, pp. 91-98.

[16] S. Sethi, and M. Mehta. “Microstrip Patch Antenna for UWB Applications: An Overview”. International Journal of Engineering Science and Computing. 2016, vol. 6, iss. 6, pp. 7501-7504. doi:10.4010/2016.1775

[17] S.M. Sheikh, W. Abu-Al-Saud and A. B. Numan. “Directive Stacked Patch Antenna for UWB Applications”. International Journal of Antennas and Propagation. 2013, vol. 8, no. 6, pp. 58-63.

[18] I. Singh and D. V. Tripathi. “Microstrip Patch Antenna and its Applications: a Survey”. International Journal of Computer Applications in Technology. 2011, vol. 2. Iss. 5, pp. 1595-1599.

[19] P.A. Soontornpipit “Dual-Band Compact Microstrip Patch Antenna for 403.5MHz and 2.45GHz on Body communications”. International Electrical Engineering Congress. 2016, vol. 86, pp. 232-235.

[20] P. Subramanian, and P. S. Therese. “U-Slot Patch Antenna Using Space Reduction Optimization. International Journal of Recent Technology and Engineering (IJRTE). 2019, vol. 8, iss. 11, pp. 612-622.

[21] T. Suganthi, D. S. Robinson, G. Kanimolhi and T. Nagamoorthy. “Design and Analysis of Rectangular Patch Antenna for GSM Application”. IJISET- International Journal of Innovative Science, Engineering & Technology. 2014, vol. 1, iss. 2, pp. 95-103.

[22] M. A. Trimukhe and B.G. Hogade. “Design of the Compact Ultra-Wideband (UWB) Antenna Bandwidth Optimisation Using Particle Swarm Optimization Algorithm”. Iranian Journal of Electrical and Electronic Engineering. 2019, vol. 15, iss. 2, pp. 195-202.

[23] E. Vikas, B. Kaur and K. Sherdia. “Microstrip Patch Antenna for UWB Applications”. International Journal of Advanced Research in Computer and Communication Engineering. 2014, vol. 3, iss. 6, pp. 6963-6965.

[24] B. Vyhnalek,. “Bio-Inspired Optimization of Ultra-Wideband Patch Antennas Using Graphics Processing Unit Acceleration. Cleveland: Cleveland State University. 2009.

[25] M. Zubair, and M. Moinuddin. Joint Optimisation of Microstrip Patch Antenna Using Particle Swarm Optimization for UWB Systems. International journal of Antennas and Propagation.2013, vol. 8, vol. 8, pp. 102-111.