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A SIMPLE DESIGN OF MULTI BAND MICROSTRIP PATCH ANTENNAS ROBUST TO FABRICATION TOLERANCES FOR GSM, UMTS, LTE, AND BLUETOOTH APPLICATIONS BY USING GENETIC ALGORITHM OPTIMIZATION

Jeevani W. Jayasinghe[1, 4, *], Jaume Anguera[2, 3], and Disala N. Uduwawala[4]

[1]Department of Electronics, Wayamba University of Sri Lanka, Sri Lanka

[2]Technology and Intellectual Property Rights Department, Fractus, Spain

[3]Electronics and Communications Department, Universitat Ramon LLull, Barcelona, Spain

[4]Department of Electrical and Electronic Engineering, University of Peradeniya, Sri Lanka

Abstract—Design of multiband antennas with low volume is of practical interest for the ever growing wireless communication industry. In this regard, the design of a small multi band microstrip patch antenna (MPA) for GSM900 (880–960 MHz), GSM1800 (1710–1880 MHz), GSM1900 (1850–1990 MHz), UMTS (1920–2170 MHz), LTE2300 (2305–2400 MHz), and Bluetooth (2400–2483.5 MHz) applications by using a genetic algorithm (GA) is proposed. The proposed GA method divides the overall patch area into different cells taking into account that cells have a small overlap area between them. This avoids optimized geometries with certain cells having only an infinitesimal connection to the rest of the patch. Therefore, the proposed method is robust for manufacturing. A shorting pin is also included for impedance matching. GA optimization combined with finite element method (FEM) is used to optimize the patch geometry, the feeding position and the shorting position. A prototype has been built showing good agreement with the simulated results. The optimized MPA has a footprint of 46 mm × 57 mm

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* Corresponding author: Jeevani Windhya Jayasinghe (jeevani@wyb.ac.lk).

($0.138\lambda \times 0.171\lambda$ at 900 MHz) and an air gap of 10 mm. It shows a reflection coefficient less than -10 dB at all six bands and can be useful for a base station antenna.

1. INTRODUCTION

Microstrip patch antennas (MPAs) consist basically of three layers, a metallic layer with the antenna element pattern, a dielectric substrate and another metallic layer as the ground plane [1–3]. These antennas are relatively easy to manufacture because of their simple planar configuration and the compact structure. They are light in weight and have the capability to be integrated with other microwave circuits. The volume constraints, often combined with large bandwidth and high efficiency specifications, make the antenna design a challenging task.

With the development in the field of wireless mobile communication, many researches started to design multi band MPAs which cover GSM900, GSM1800, GSM1900, UMTS, Bluetooth, WLAN, etc. [4–23]. Many techniques such as fractal-shapes [5, 6], reactive loads [6], stacked elements [7, 8], shorting pins [9, 10], slots on the ground plane [11] and PIFA [12–15] are being used to design multiband MPAs.

Genetic algorithm (GA) is a powerful optimization technique that has been shown to be useful in a wide area of electromagnetics [24–32]. GA is applied to design broadband [26, 27], multiband [28–30] and miniature [31, 32] MPAs. It is a robust, stochastic-based search method, which can handle the common characteristics of electromagnetic optimization problems that are not readily handled by other traditional optimization methods.

It is an interesting research problem to design broadband and multiband MPAs while keeping the size of the antenna small. In this paper, GA is used to design a multiband MPA for GSM900, GSM1800, GSM1900, UMTS, LTE2300, and Bluetooth. The patch geometry, feed position and shorting pin position are optimized by using GA to increase the number of bands while keeping a small antenna footprint. The optimized MPAs with 8 mm and 10 mm air thicknesses show quad and penta band performance respectively. The MPA is improved for hexa band operation by incorporating a shorting pin. The simulation of the MPAs and analysis of results are carried out by using HFSS (High Frequency Structure Simulator), which is a highly accurate electromagnetic solver based on FEM. The operation is written using Visual Basic Script (VBS) Writer and the VBS file is called into HFSS environment. Simulated reflection coefficients, current distributions, and radiation patterns are obtained for each optimized design and their performance is analyzed. A prototype is built for the sake of validating the simulated results.

This paper is divided into the following sections. The antenna geometry and architecture of the GA is presented in Section 2. Section 3.1 presents the performance of a rectangular shaped MPA which is used as the reference element to start the optimization process. In Section 3.2, a quad band MPA and a penta band MPA are designed by optimizing the patch geometry and the feed position. A shorting pin is included into the patch in Section 3.3 and hexa band performance is obtained. A prototype is made for validating the simulated results of the hexa band design. Finally, conclusions are given.

2. ANTENNA CONFIGURATION AND GA OPTIMIZATION PROCEDURE

Neltec NX9320 (IM) (tm) which has a relative permittivity of 3.2 and a loss tangent of 0.0025 is used as the substrate for MPAs. The patch fabricated on the substrate suspends above a ground plane (Fig. 1(a)). All MPAs are designed on a rectangular foot print of length 46 mm and width 57 mm. A simple rectangular patch of these dimensions resonates at the center frequency of frequency band from 1710 MHz to 2483 MHz [2] which covers the bands from GSM1800-Bluetooth. It is fragmented into 63 cells so as to overlap between adjacent cells with a 1 mm width in order to search for the best solution of conducting cells (Fig. 1(b)). The purpose of having overlaps between adjacent cells is to avoid cells contacting neighboring cells by infinitesimal widths. Otherwise it may pose a connection problem when manufacturing the microstrip patch due to the tolerances of chemical etching (Fig. 2).

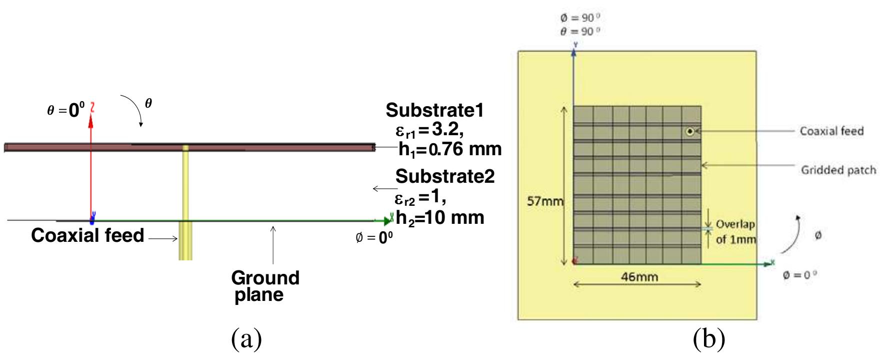
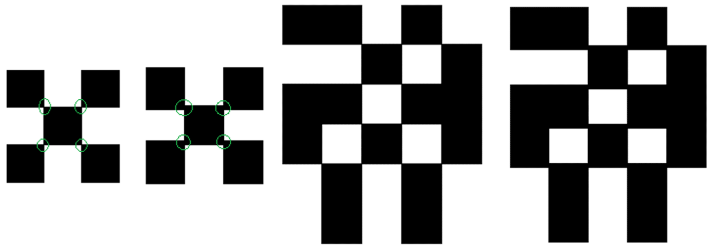


Figure 1. Antenna configuration. (a) Lateral view of the antenna. (b) Patch fragmented into 63 cells.



(a) (b) (c) (d)

Figure 2. (a) Traditional on/off building block with infinitesimal connections. (b) Proposed scheme with overlapping obtained by shifting the cells along the vertical axis. (c) An example of a possible structure obtained with GA using infinitesimal connections. (d) A possible structure with overlapping as proposed.

Moreover, the proposed technique is suitable for other fabrication methods such as stamping a metal used for the MPA in a plastic support. If the metal pieces have infinitesimal contacts, the overall patch is composed of several pieces making it difficult to assemble in a single carrier. Therefore, the proposed method simplifies the fabrication of MPA obtained through GA optimization. This may be especially critical if the structure is composed by many infinitesimal connections.

63 bits are used to define the patch geometry, by assigning conducting or non-conducting properties to each cell. As there are only two possible values, binary coding is used. Another five genes of the chromosome are used to define the feed position. When a shorting pin is included in the design, five more genes are added into the chromosome subsequently. The shorting pin gives extra degrees of freedom useful for matching purposes. A $50\,\Omega$ coaxial cable is used to feed the antenna. Moreover, asymmetric geometric solutions are allowed in the optimization as it gives more flexibility to the GA to find a solution.

The fitness function is the summation of reflection coefficient values taken at 10 MHz intervals including the GSM900, GSM1800, GSM1900, UMTS, LTE2300, and Bluetooth bands, ranging from $f_1 = 880\,\text{MHz}$ to $f_2 = 960\,\text{MHz}$, from $f_3 = 1710\,\text{MHz}$ to $f_4 = 2170\,\text{MHz}$ and from $f_5 = 2300\,\text{MHz}$ to $f_6 = 2480\,\text{MHz}$. The fitness function F which is maximized in the search for the optimum solution is written as:

$$F = \frac{-\left(\sum_{f_i=f_1}^{f_2} L(f_i) + \sum_{f_i=f_3}^{f_4} L(f_i) + \sum_{f_i=f_5}^{f_6} L(f_i)\right)}{10 \cdot N} \tag{1}$$

where N is the total number of samples ($N = 75$), and $L(f_i)$ is defined as

$$L(f_i) = \begin{cases} \rho(f_i)_{\text{dB}} & \rho(f_i)_{\text{dB}} \geq -10\,\text{dB} \\ -10\,\text{dB} & \rho(f_i)_{\text{dB}} < -10\,\text{dB} \end{cases} \tag{2}$$

where $\rho(f_i)_{\text{dB}}$ is the reflection coefficient in dB at frequency f_i. The fitness function is defined in such a way that broadband solutions are preferred instead of narrowband solutions with very low reflection coefficient values. The maximum value of F is unity and it is taken as the termination criterion of the algorithm.

The optimization process focuses only on the reflection coefficient and therefore there is no any constraint on the radiation pattern. If other constraints are required, the fitness function can be modified accordingly. Thus, the purpose here is to find a MPA optimized with GA that achieves a reflection coefficient less than -10 dB in the frequency bands given by GSM900, GSM1800, GSM1900, UMTS, LTE2300, and Bluetooth.

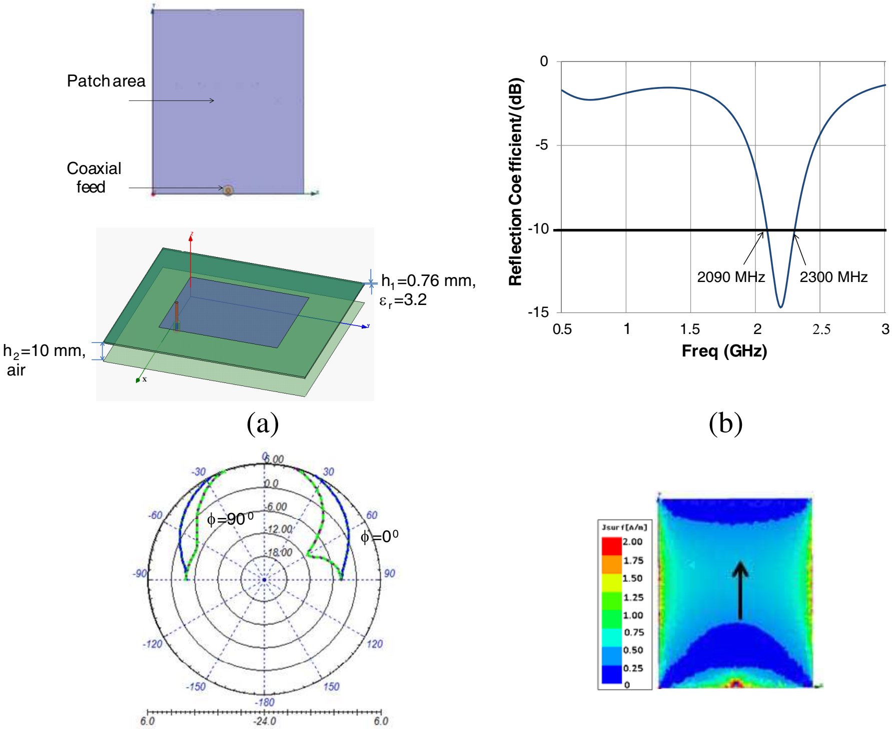
To achieve the aforementioned objective, the GA architecture employs 20 chromosomes per generation in all designs. The cross over operation is performed with probability of 100% and one bit is mutated in 60% of the individuals within a generation. Tournament selection method is used for generation replacement and preservation of higher fitness values is guaranteed.

3. RESULTS

For simulations, an Intel Core i7 processor with 2 GHz speed and a RAM with 6GB capacity have been used. Initially, the performance of a rectangular shaped conventional MPA is checked. Thereafter, two designs with air gaps of 8 mm and 10 mm are presented. All the simulations are carried out for an infinite ground plane. Once the solution is found, the size of the ground plane is made finite with a minor impact in the reflection coefficient plot.

3.1. Rectangular Shaped Patch

The performance of the rectangular shaped MPA with 10 mm air gap (Fig. 3(a)) is analyzed. The best feed position which gives good



(a) (b)

(c) (d)

Figure 3. Simulation results of the rectangular shaped patch. (a) Top view and 3-D view of the MPA. (b) Reflection coefficient. (c) Radiation pattern. (d) Current distribution (the black arrow indicates the direction of current).

matching in the required frequency bands is selected after several trials. The MPA resonates around 2200 MHz. The -10 dB impedance bandwidth ranges from 2090 MHz to 2300 MHz (Fig. 3(b)). This geometry is used as a starting point in the search for optimum geometry using GA. As shown in Fig. 3(c), the rectangular shaped MPA radiates perpendicular to the plane of the patch (broadside radiation) at the resonance frequency (2200 MHz). It has a maximum gain of 6 dB and the current distribution is parallel to y axis following the typical fundamental TM_{01} mode distribution (Fig. 3(d)).

Table 1. Format of the chromosome for GA generated patch.

Patch geometry	Feed position				
0, 1, ..., 62	63	64	65	66	67

3.2. GA Generated Patch Antennas (Quad Band and Penta Band)

To achieve multiband performance, both the patch geometry and the feed position of the antenna with an air gap are optimized using the proposed GA. First 63 genes of the chromosome define the patch geometry, while next five genes define the feed position. The format of the chromosome is shown in Table 1. The solution space consists of 2^{68} chromosomes. It takes about one minute to run one design and a generation consists of 20 designs.

Results of the optimized designs with air gaps of 8 mm and 10 mm are shown in Fig. 4. The corresponding reflection coefficient plots are shown in Fig. 4(b). When the air gap is 10 mm, the optimized MPA shows better performance by having -10 dB bandwidth from 1700 MHz to 2520 MHz covering GSM1800, GSM1900, UMTS, LTE2300, and Bluetooth bands. When the air gap is decreased to 8 mm, the optimized MPA resonates from 1710 MHz to 2130 MHz and from 2290 MHz to 2490 MHz, but unable to cover UMTS band. Thus, the height of the air gap is fixed to 10 mm in the antenna design with a shorting pin (Section 3.3).

In the penta band antenna ($h_2 = 10$ mm), current distribution simulation shows that certain areas of the antenna are more excited than others (Fig. 5(a)). The radiation patterns shown in Fig. 5(b) indicate that the antenna displays nearly broadside radiation characteristics with a gain of about 6 dB in all resonant bands.

3.3. Shorted GA Generated Patch (Hexa Band)

The target is to design a hexa band MPA with the same size (foot print of 46 mm $\times$ 57 mm) including GSM900. This is achieved with the use of a shorting pin. A rectangular antenna without a shorting pin would require a patch area of 96 mm $\times$ 115 mm to obtain a resonance at GSM900 in the fundamental mode. In the design all three parameters: geometric shape, feed position and shorting position are optimized and five more bits are added to define the shorting position. As a result, the number of genes in a chromosome has increased to 73 bits. The format of the chromosome is shown in Table 2.

The optimized design is obtained after simulation time of about

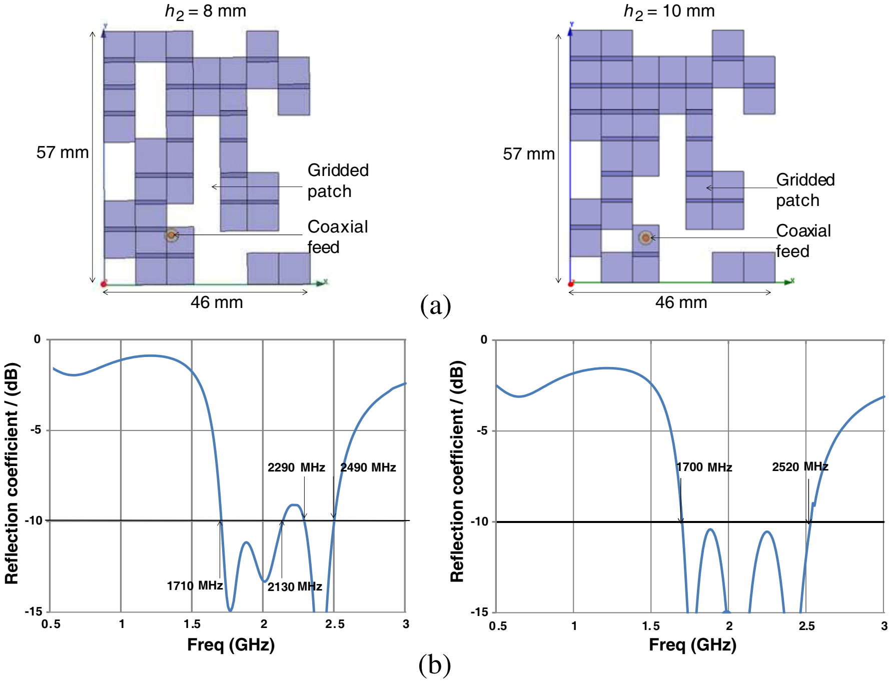


Figure 4. Simulation results of the optimized MPAs with 8 mm and 10 mm air gaps. (a) MPA. (b) Reflection coefficient.

Table 2. Format of the chromosome for shorted GA generated patch.

Patch geometry	Feed position					Shorting position				
0, 1, . . . , 62	63	64	65	66	67	68	69	70	71	72

50 hours (Fig. 6). If we considered all the possible solutions (the number of possible geometries alone are 2^{63}) for simulation without using GA (e.g., if each simulation takes 1 s), it would take approximately 292×10^9 years to search all the antenna geometry space.

The optimized design is fabricated using a substrate of 80 mm × 90 mm and a copper ground plane having the same dimensions (Fig. 6). The optimized design with finite ground plane displays −10 dB impedance bandwidths in frequency ranges 880 MHz–960 MHz and 1700 MHz–2520 MHz covering all six frequency bands (Fig. 7). The reflection coefficient plot of the fabricated antenna, measured from an Agilent vector network analyzer using a SMA connector underneath the ground plane, shows good agreement with the simulated results.

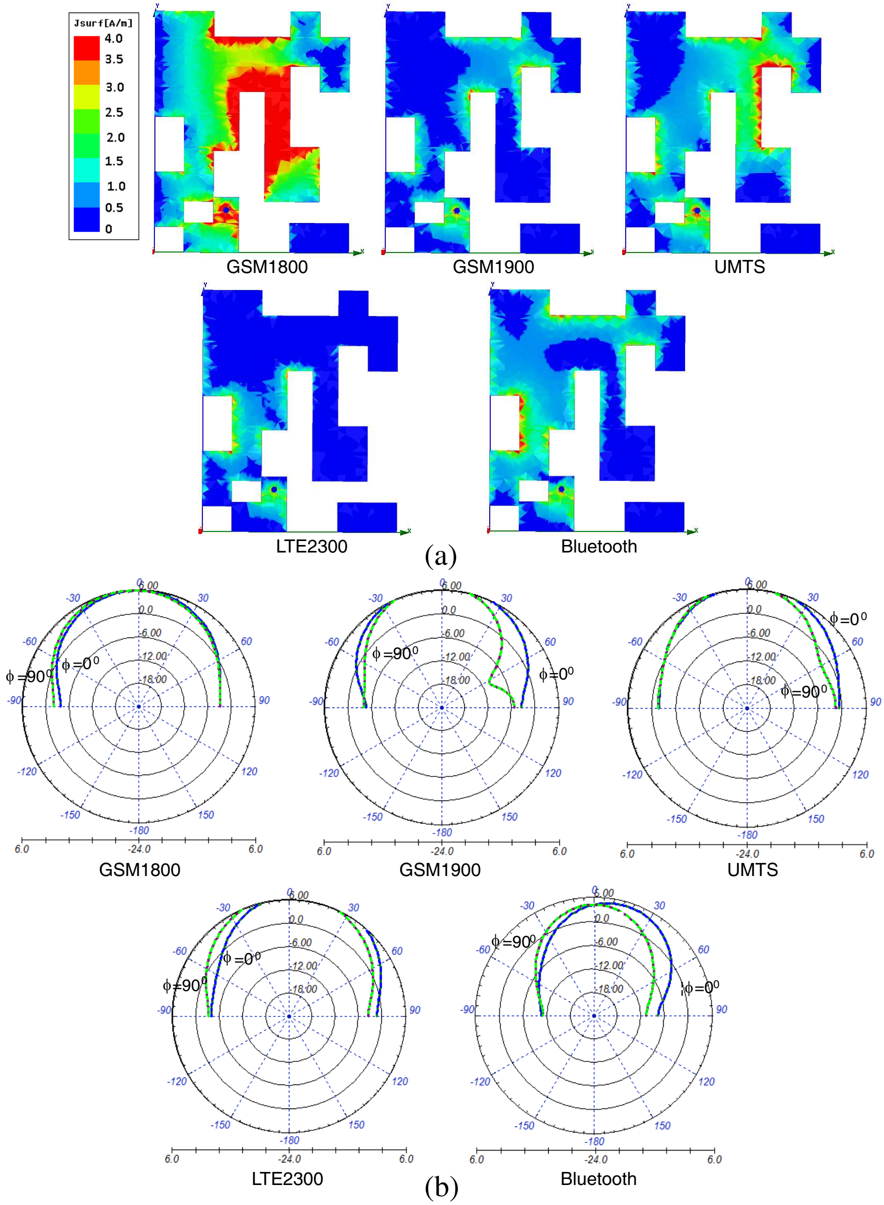


Figure 5. Simulation results of the penta band MPA (air gap with 10 mm). (a) Current distribution at center frequency of each band. (b) Radiation patterns for $\phi = 0^\circ$ and $\phi = 90^\circ$ planes at center frequency of each band.

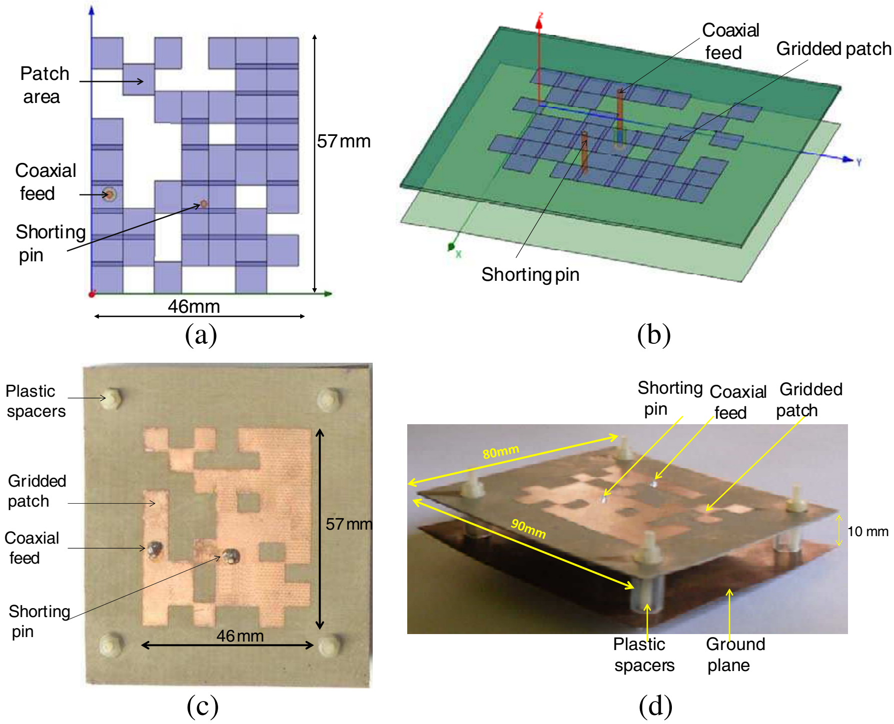


Figure 6. The optimized (hexa band) MPA with a shorting pin and a 10 mm air gap. (a) Top view. (b) 3D view. (c) Photo of the fabricated antenna (top view). (d) Photo of the fabricated antenna (3D view).

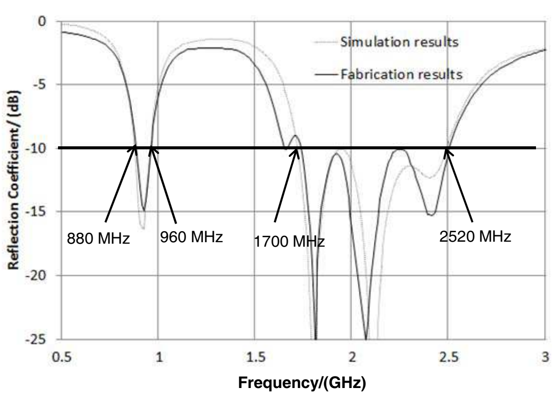


Figure 7. Reflection coefficient of the haxa band MPA.

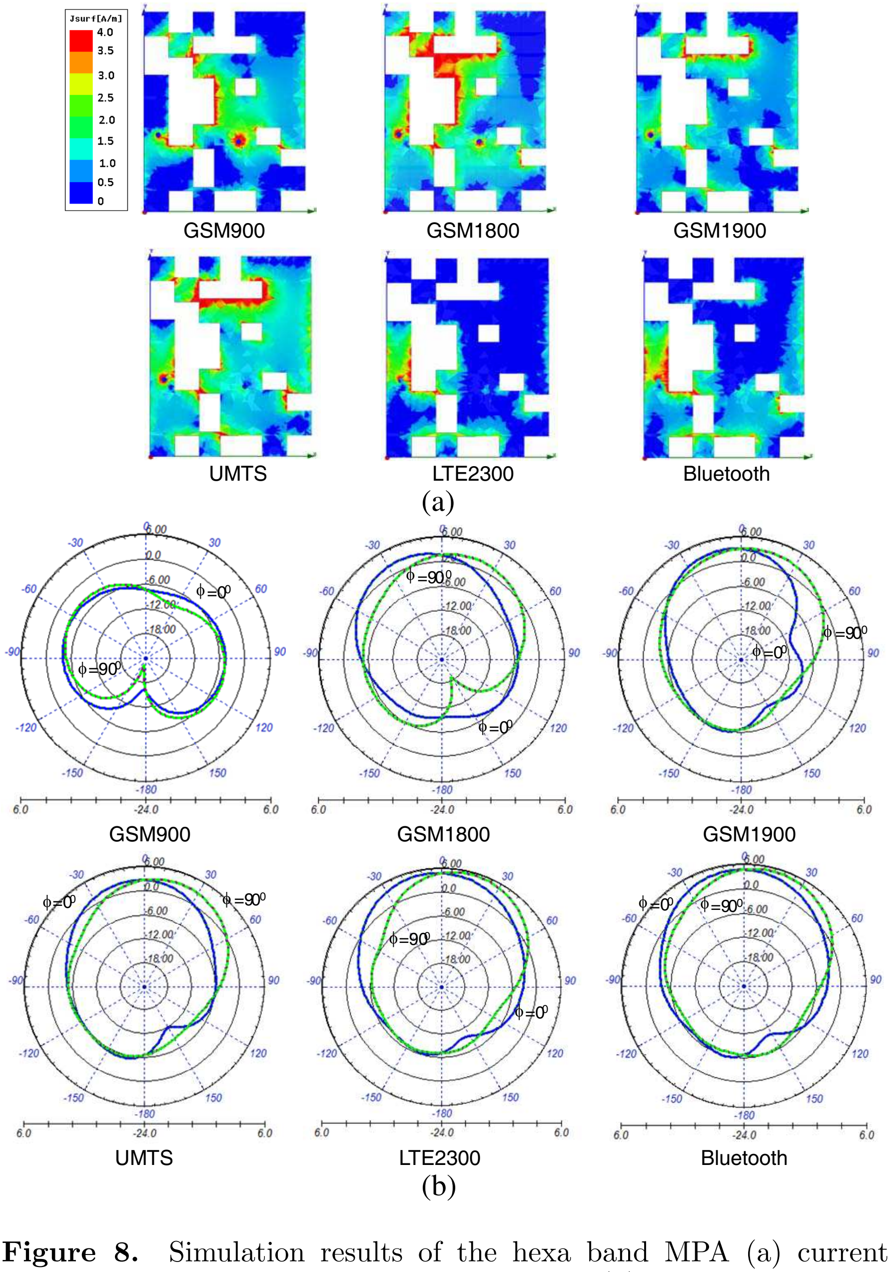


Figure 8. Simulation results of the hexa band MPA (a) current distribution at center frequency of each band. (b) Radiation patterns for $\phi = 0°$ and $\phi = 90°$ planes at center frequency of each band.

Current distribution simulation shows what areas of the antenna are excited (Fig. 8(a)). It is interesting to note that the current distribution does not follow any regular pattern as in the case of regular shapes. At GSM1800, GSM1900, UMTS, LTE2300, and Bluetooth bands, the gain values are 3.3 dB ($\theta = 22°$), 5.1 dB ($\theta = 8°$), 4.6 dB ($\theta = 10°$), 6 dB ($\theta = 14°$) and 5.9 dB ($\theta = 10°$) respectively (Fig. 8(b)). Thus, the antenna displays nearly broadside radiation characteristics for all bands. It should be emphasized that if the vertical pin radiates, then the radiation pattern would be more like that of a monopole. But at the high bands (GSM1800 and above), radiation patterns are broadside and not like that of a monopole. Therefore, the contribution of the shorting pin is much less than the effect of the patch. However, at the lowest band (GSM900) the radiation pattern presents a combination of the patterns of a monopole and the patch.

4. CONCLUSIONS

It is difficult to obtain multiband performance using conventional rectangular shaped MPAs since bands are dictated by the mode distribution. To overcome this problem, GA generated MPAs have been proposed in this paper. A compact MPA with an air gap and a shorting pin has been designed to operate in GSM900, GSM1800, GSM1900, UMTS2000, LTE2300, and Bluetooth frequency bands. The patch size is 46 mm × 57 mm ($0.138\lambda \times 0.171\lambda$ at 900 MHz) and it is comparable with the size of a rectangular shaped patch resonating in its fundamental mode around 2200 MHz. The shorting pin adds extra degree of freedom and makes the antenna resonant at the lowest band (GSM900), while maintaining the compactness. Due to its multiband behavior and compact size, it can be useful as a base station antenna.

The proposed GA uses a gridded patch with overlapping cells, which makes the design robust to tolerances in the fabrication process. The main objective of this study is to optimize impedance bandwidth to achieve multiband behavior. The radiation patterns in these bands can also be taken into account by modifying the fitness function. This topic is underway.

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