A Semi-defected Ground Plane and a Binary Genetic Algorithm for Designing a Very Compact Triple-band PIFA Antenna

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ABSTRACT

We suggest in this study a very compact triple-band PIFA antenna for mobile and wireless applications.by using the binary genetic algorithm and a semi-defected ground plane. This antenna with the dimensions of $38\times40\times1.9$ mm^3 is dedicated to LTE Band 11 (1427.9-1495.9 MHz), HIPERLAN/2 (5.15-5.35 GHz), WLAN (5.15-5.35 GHz) and 5G Sub-6GHz applications. To accomplish triple-band operation with acceptable performance, the genetic algorithm is use to dictate the form of the ground plane of the antenna. The simulation results showed that the developed PIFA antenna has optimal operation on three frequencies. The first resonance frequency is 1.32 GHz with a bandwidth (S11 < -10 dB) from 1.28 GHz to 1.38 GHz. The middle and higher bands are centred respectively at 3.12 GHz and 5.2 GHz, with a bandwidth from 3.05 to 3.17 GHz and from 4.93 to 5.44 GHz, respectively.

KEYWORDS

1. INTRODUCTION

Due to the rapid evolution of communication standards and devices operating in multiple frequency bands, the development of new antennas has become necessary to meet new demands. Planar antennas are a type of antenna that has all the desirable characteristics; one of them is the planar inverted-F antenna (PIFA). PIFAs are the best candidate to meet the requirements for mobile device antennas due to their tiny volume and low profile [1]. The biggest problem with PIFA antennas is the narrow bandwidth. Several techniques exist in the literature to improve the bandwidth of these antennas by modifying the geometries of the radiating plane [2], modifying the ground plane [3], adding parasitic elements [4] or using metamaterials [5].

The effect of the antenna's ground plane remains one of the most widely used techniques for obtaining different resonant frequencies [6]-[9]. Several research studies have investigated the effect of ground plane geometry on improving antenna performance. The impact of using defected ground structure DGS can increase the bandwidth from 30% to 119% without increasing the antenna volume as presented in [10]. In [11], the authors have shown that the use of a shaped ground plane allows for improving the gain without any effect on the impedance bandwidth and the radiation characteristics. In [12]-[13], the study presents a slotted antenna with a deformed ground plane. The proposed antenna's ground plane is deformed to enable multi-resonant wideband operation. The authors in [14] show that a PIFA antenna with a ground plane composed of multi-trip connection allowed to have ultra wideband. Other conceptions are exhibited by adding different slot shapes on the ground plane [15]-[21] in order to enhance the antenna bandwidth.

According to the previous analysis and still with the aim of improving the bandwidth of the PIFA antenna or introducing novel resonant frequencies, this study proposes the use of a semi-defected ground plane and the genetic algorithm in binary code [22]. The mobile's electronic components are normally attached to the antenna ground plane. The use of a fully defected ground plane makes the implementation of components impossible, while the use of a semi-defected ground plane is justified. The genetic algorithm remains among the most powerful algorithms to search for an optimal solution.

In this paper, we propose the use of this algorithm to determine the shape of the ground plane instead

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of the traditional method based on the parametric study. It is used to indicate the location of the slots which must be placed on the part of the ground plane. With the proposed method, we can control the desired frequency ranges without modifying or increasing the antenna volume.

The purpose of this study is to present a new method of designing a multi-band PIFA antenna to overcome the problems of a voluminous antenna and narrow band with a simple deformation of the ground plane. The proposed antenna is a very compact triple-band antenna with a semi-defected ground plane for GPS, LTE band 11 and 5G applications. The antenna dimensions are $38 \times 40 \times 1.9$ mm^3 with an FR4 epoxy substrate of $40 \times 100 \times 1.6$ mm^3. The antenna covers three bands, the first bandwidth is from 1.28 GHz to 1.38 GHz with the resonant frequency of 1.326 GHz (S11= -17.12 dB), while the second bandwidth is from 3.05 GHz to 3.17 GHz with the resonant frequency of 3.12 GHz (S11= -24.11 dB) and the third bandwidth is from 4.93 GHz to 5.44 GHz with the resonant frequency of 5.2 GHz (S11= -30.88 dB).

The developed PIFA antenna exhibits good performance in terms of reflection coefficient, gain, efficiency and 2D radiation at the three resonant frequencies. This research is composed of five sections. The first section is an introduction. An overview of the genetic algorithm, methodology and antenna parameters is clarified in Section 2. The simulated results are introduced in Section 3. In Section 4, a comparative study is presented, while the conclusion is presented in Section 5.

2. DESIGN METHODOLOGY AND ANTENNA PARAMETERS

In this section, an overview of the genetic algorithm, the PIFA antenna theory, the design method based on DGP (Defected Ground Plane) and GA (Genetic Algorithm) and the antenna parameters and their optimal form is given.

2.1 PIFA Antenna Theory

The inverted-F antenna is evolved from a quarter-wavelength monopole antenna. It is basically a modification of the inverted-F antenna (IFA) which is consisting of a short vertical monopole wire. To increase the bandwidth of the IFA, a modification is made by replacing the wires with a horizontal plate and a vertical short circuit plate to obtain a PIFA antenna [28].

The conventional PIFA is constituted by a top patch, a shorting plate and a feeding plate. The top patch is mounted above the ground plane, which is connected also to the shorting plate and the feeding plate at proper positions. They have the same length as the distance between the top patch and the ground plane. The standard design formula for a PIFA antenna is [29]:

$$f_r = \frac{C}{4(L + h)}$$

Where f_r is the resonant frequency of the main mode, C is the speed of light in the free space; h and L are the height and the length of the radiating plate, respectively.

2.2 Overview of Genetic Algorithm

In the field of antenna design, the application of metaheuristic algorithms is critical. The genetic algorithm is one of these algorithms (GA). GA is regarded as a resilient and stochastic search approach based on the concepts and principles of natural evolution and selection. This algorithm's strength stems from its capacity to use prior solutions' historical information structures in an optimization process of making future solution structures operate better.

The most important parameters of genetic algorithms which must be chosen carefully are [23]-[24], [30]:

-Population number: It represents the number of chromosomes that are considered in a generation. The bigger this number is, the more important is the calculation time, but the solution becomes better.

-Generation numbers: The genetic algorithm can evolve for the maximum number of generations or iterations before stopping.

-Selection: It is based on the evaluation of criteria to choose the best individuals in a population that will reproduce. Roulette selection and tournament selection are the two most used techniques.

-Crossover: For an optimization issue, the crossover is an exchange of sub-strings signifying chromosomes. It could be a one-point crossover or a two-point crossover.

-Mutation: Mutation is the process of changing the state of a bit (gene) in the chromosomes to produce a population variation.

The optimization process can be summarized in four steps; Step 1, A random population will be generated based on the number chosen for this population. In Step 2, it is required to assess the fitness function. The fitness function is a function that can be used to determine whether a solution is excellent or bad for the problem under consideration. If the stopping criteria are satisfied, then stop, else go to Step 3. In Step 3, after evaluating the fitness function, the GA selects the individuals who will reproduce in the new population and removes the others. In Step 4, after the selection phase and to vary the population, the GA uses genetic operators, such as mutation and crossover, by selecting the number of this population. This process is repeated until the optimal solution is found.

GAs are defined by their ability to adapt to difficult problems, their ease of implementation and the fact that they can be used to find one or more variables. On the other hand, the GA has a slow convergence and a low risk of having a premature convergence, because the adjustment of these parameters is delicate.
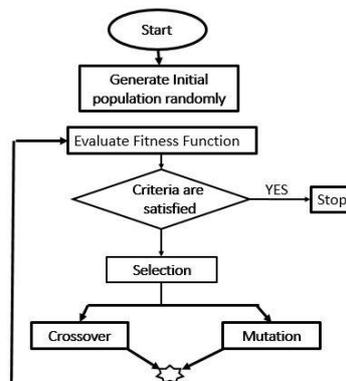
Figure 1. Genetic algorithm flowchart.

2.3 Design Methodology

According to the literature, the ground plane has a remarkable impact on the performance variation of a planar antenna (PIFA). This sub-section proposes the combination of a defected ground plane and a binary genetic algorithm for the design of a new PIFA antenna structure with multi-band option without increasing its volume. The base antenna to be improved is a single-band antenna. The use of a sub-divided ground plane instead of a continuous plane is intended to keep just the cells that will give the desired performance. These cells will be determined using the genetic algorithm in binary code while evaluating fitness functions. This method's major objective is to create a new antenna design from the conventional PIFA antenna.

Figure 2 shows the technique proposed in this study to optimize the performance of a PIFA antenna. The first step is to divide the ground plane of the base antenna into 260 small cells of the size of 2×2 mm^2, according to the X-axis (Figure 2 a). The adjacent cells and the parallel cells are separated by a width of 1 mm called overlap to ensure physique support of the antenna and to find a better solution for conductive cells. The second step is the use of the binary genetic algorithm (BGA). The choice of the algorithm is justified by the fact that only two cases exist; existing cells and non-existing cells; The conductivity qualities of each cell are determined by the usage of "0" or "1" in the chromosome. A gene with the value "1" defines the existing cell, while a gene with "0," often known as a slot, defines the non-existent cell. Figure 2b shows how the binary genetic algorithm was used to create a design that could produce the desired and anticipated antenna performances. The non-existing cells shape the slots, while the existing cells create the new ground-plane shape.

The parameters of the genetic algorithm used in this study to obtain the final solution are 40 individuals in the population, while the single-point crossover approach is utilized with a 100% probability of

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crossover. Considering tournament selection type and mutation probability of 0.8% the generation number is set to 100 iterations or generations.

The genetic algorithm has two options; either it minimizes a function or it maximizes it. With the function F described below whose value is negative because S11 is less than zero, the genetic algorithm will minimize it. If we want to maximize it, we must use the F function in absolute value. However, in the desired bands, we wanted to obtain a reflection coefficient of less than -10 dB. To discover the optimum design, the F function proposed in this study is represented as:

$$F = \frac{\sum_{i=1}^{N} S11(f(i))}{N}$$

In this equation, the variable *f(i)* represents the sampling frequency and *N* represents the number of samples. The fitness function *F* is defined as having an impedance bandwidth of less than -10 in the desired range of frequencies. The minimum value of *F* is used as the iteration's end condition to determine when the algorithm should be stopped.

The parameters of the genetic algorithm used for this obtained solution are:
Population size: 40, Crossover: Two-point, Mutation: 100%, Selection: tournament selection and Number of generations: 50.
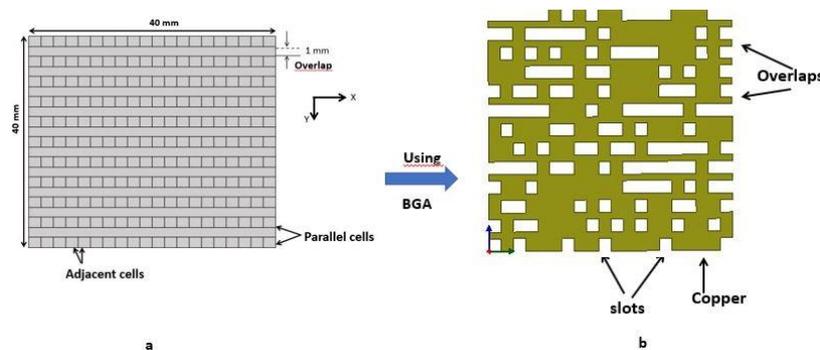

Figure 2. Ground plane: a. Conventional ground plane, b. Obtained ground plane by BGA.

The reflection coefficient of the conventional antenna (Fig 2a) and the proposed antenna (Figure 2b) are shown in Figure 3. The conventional antenna is a single-band antenna with a resonance frequency of 3.56 GHz and a reflection coefficient of -28.29 dB at this frequency. It has a bandwidth of -10 dB at 130 MHz. The proposed antenna has three resonant frequencies; the main frequency of the conventional antenna with two other frequencies that have appeared at 1.32 GHz and 5.2 GHz, the reason why two new bandwidths appear. The use of a slotted ground plane not only improves the main bandwidth but also makes new resonances appear and thus new operating bands appear. This miniature antenna is designed for mobile-phone applications to cover the following frequency bands: LTE Band 11 (1427.9-1495.9 MHz), HIPERLAN/2 (5.15-5.35 GHz), WLAN (5.15-5.35 GHz) and 5G Sub-6GHz applications. Table 1 summarizes the evolution of the bandwidth from the conventional antenna to the proposed antenna.

Table 1. Bandwidth of the antenna without/with the slots.

Characteristics	Conventionnal antenna	Proposed antenna
Frequency (GHz)	3.56	1.32
		3.12
		5.2
Bandwidth (GHz)	0.13 (3.5 to 3.63)	0.17 (1.28 to 1.45)
		0.12 (3.05 to 3.17)
		0.61 (4.83 to 5.44)
S11 (dB)	-28.29	-17.12
		-24.11
		-30.88

Results across Table 1 show that the single-band antenna features have been improved to have a triple-band antenna. The first band at the 1.53 GHz resonance frequency is enhanced from 0 to 20%. The

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second band that has been improved at the 5.45 GHz resonance band; its value was 0 and changed to 30 %. The main band is improved by 35%. The objective of this technique is to increase the bandwidth of the PIFA antenna at low and high frequencies f1 and f3 to reach triple frequency bands.

During this study, we have used two principal software. The first one is a programming platform to use the genetic algorithm and the second is an electromagnetic simulation software which is used to model and design the antenna.

To implement the genetic algorithm in electromagnetic software, we checked the electromagnetic software from the programming platform. This technique is compiled by the programming platform and VbScript of the electromagnetic software. The idea is to introduce some parameters of design into the electromagnetic software from the programming platform and use the electromagnetic software for simulation, exporting the reflection coefficient from the electromagnetic software using the programming platform and drawing data by the programming platform. The flowchart boxes contain the operations to be performed, while the software package that operates. Figure 4 shows a flowchart of the programming platform- electromagnetic software configuration.

In the programming platform, we create the antenna design and the VBScript file through an interface that allows us to pass the communication between electromagnetic software and the programming platform. Then, the electromagnetic software is triggered. In electromagnetic software, the antenna will be modelled and simulated and finally, the simulated results will be imported from the programming platform to plot them. The programming platform can directly call the electromagnetic software to calculate the reflection coefficient (S11) in dB.

Figure 5 presents the implementation of the genetic-algorithm optimization with the electromagnetic software. As indicated in Figure 5, the optimization procedure is carried out. The programming platform and the electromagnetic software are two software applications that are linked. The electromagnetic software gives the modeling of the PIFA antenna in terms of its characteristics, while the programming platform contains the genetic algorithm and allows the calculation of the fitness value. This function is the physical link with the GA to obtain the optimal solution.

By comparing the design of the PIFA-antenna ground plane to the evaluation of a fitness function, the design of the PIFA-antenna ground plane is justified. The method is finished if the fitness meets the parameters. Otherwise, a GA technique is used to create new structures. To justify their performances, those new structures are utilized in the following generation of electromagnetic-software analysis. Figure 2 shows the optimized ground plane obtained by the proposed method in retrieving the objectives.
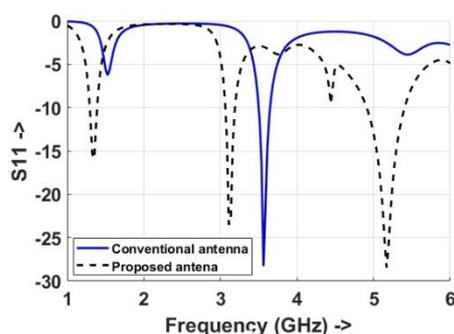
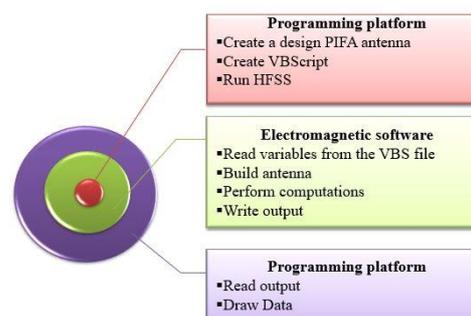Figure 3. Reflection coefficients of the conventional and proposed antennas.

Figure 4. Interfacing the programming platform and electromagnetic software for PIFA-antenna design.

2.4 Antenna Parameters

The proposed antenna was developed from the conventional PIFA antenna by modifying its ground plane. The dielectric type FR4-epoxy is placed on the ground plane with a relative permittivity value of 4.4 and a thickness t1 of 0.5 mm. The radiating plate is composed of a continuous plane of dimensions $Lp \times Wp \times 0.2$ mm^3. The overall dimensions of the proposed antenna is $Wp \times Lp \times h$. The dimensions of the ground plane were $Wg \times Lg \times t1$. The distance between the radiating plate and the ground plane represents the height h of the antenna filled with air. The dimensions of the feeding and shorting plates were $W1 \times L1$ and $W2 \times L2$, respectively.

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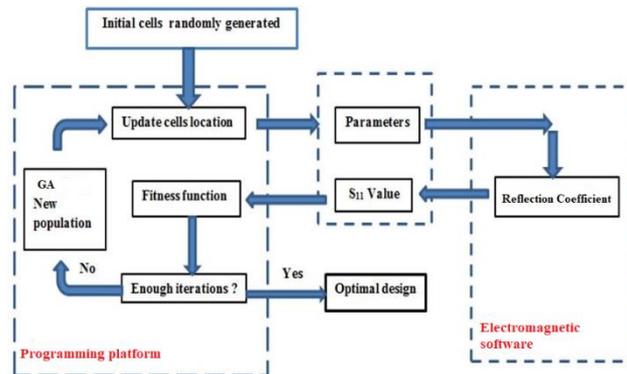

Figure 5. Implementation of the genetic-algorithm optimization with electromagnetic software.

Figure 6 exhibits the configuration of the proposed PIFA antenna. Figure 6a presents the geometry of the antenna and its parameters. Table 2 summarizes the parameters and their corresponding coordinates. Figure 6b exposes the geometry of the ground plane obtained by the genetic algorithm. The ground plane contains 134 slots of size 2×2 mm^2 which are distributed on its surface, being reduced to 53.54% by adding slots using the genetic algorithm. This technique results in seven forms of slots that have the same width of 2 mm, but with different lengths.
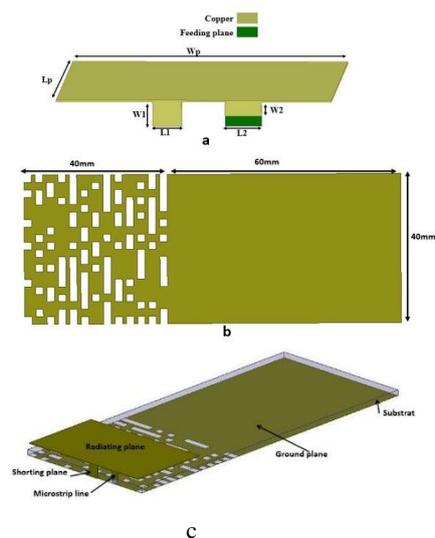

Table 2. Antenna parameters.

Parameters	Dimensions in mm
Lp	38
Wp	24
Lg	40
Wg	100
h	1.9
W1	3.5
L1	3
W2	1.9
L2	2
t1	1.6

Figure 6. Configuration of the proposed PIFA antenna: (a) Antenna, (b) Semi-defected ground plane and (c) Global view of the proposed antenna.

3. RESULTS AND DISCUSSION

In this section, we studied the proposed-antenna performances in terms of reflection coefficient S11, gain, efficiency, radiation pattern and current distribution.

3.1 Refection Coefficient

We used another electromagnetic software to verify the reflection-coefficient result that was generated by the first electromagnetic software. The reflection coefficients from the first and second electromagnetic software are compared in Figure 7. From this figure, we see that the two simulated S11 variations are correlated and represent a good agreement between the results given by the two electromagnetics software.

Based on the analysis of the results, the proposed antenna is qualified to operate in three bands (S11<-10 dB), such as LTE Band 11, HIPERLAN/2, WLAN and 5G Sub-6GHz applications. The antenna covers three bands; the first bandwidth is from 1.28 GHz to 1.45 GHz with the resonant frequency of 1.326 GHz, while the second bandwidth is from 3.05 GHz to 3.17 GHz with the resonant frequency of

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3.12 GHz and the third bandwidth is from 4.83 GHz to 5.44 GHz with the resonant frequency of 5.2 GHz.

The slots on the ground plane are responsible for attaining the new resonant frequencies at 1.32 GHz and 5.2 GHz, because of using a semi-defected ground plane. The slots on the ground plane are formed as part of the GA optimization technique to get the desired bands. They provide several resonant current paths, allowing the antenna to resonate at many frequencies. The simulation results demonstrate the importance of the optimization method adopted.

3.2 Gain and Efficiency

Figure 8 displays the gain- and efficiency-simulation results for the operating bands. The gain varies in growth: the lower frequency gain is 2.5 dB, the middle-frequency gain is 4.5 dB and the higher-frequency gain is 6 dB. We can notice that the suggested antenna has a good gain across all bands. At 1.32 GHz, 3.12 GHz and 5.2 GHz, respectively, the antenna's radiation efficiency displays respectable values in all three bands: 96%, 90% and 95%.
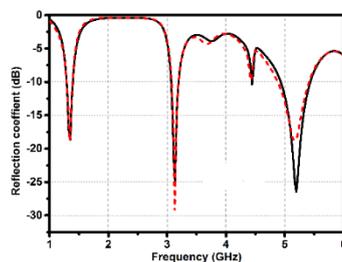

Figure 7. Reflection coefficients of the PIFA antenna extracted from different electromagnetic software.
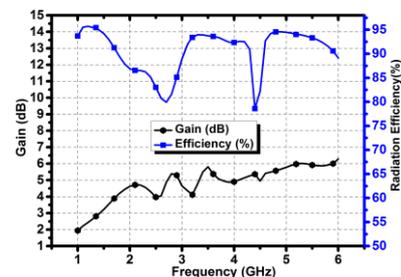

Figure 8. Gain and efficiency of the suggested antenna.

3.3 Radiation Pattern

The 2D radiation pattern determined in the far-field region for $\Phi = 0°$ and $\Phi = 90°$ at the three resonant frequencies 1.32 GHz, 3.12 GHz and 5.2 GHz was simulated. We present in Figure 9 the simulated 2D radiation pattern. We can see that the proposed PIFA antenna offers an approximately omnidirectional radiation pattern.
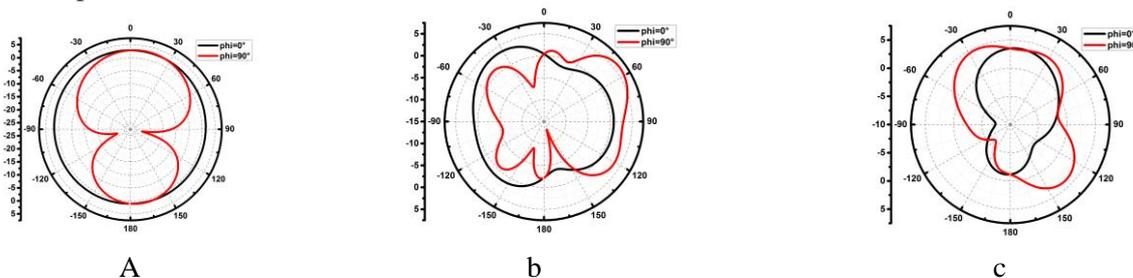

A

b

c

Figure 9. 2D Radiation pattern: (a) at 1.32 GHz, (b) at 3.12 GHz and (c) at 5.2 GHz.

3.4 Current Distributions

Figure 10 displays the simulated surface current distributions at the three resonances of the PIFA-antenna. The radiating plate and ground plane's current patterns at 1.32 GHz, 3.12 GHz and 5.2 GHz are shown in this figure. We can observe that the current is distributed on the ground plane and the radiating plane and concentrated on the shorting plane at the resonant frequencies.

4. COMPARATIVE STUDY

In the literature, the impact of the slots on the ground plane of the PIFA antenna has been researched by numerous researchers. In [25], the totally defected ground plane is used to minimize the PIFA antenna size and to convert the single-band antenna to a dual-band antenna with an important bandwidth. The authors have proposed two types of metaheuristic algorithms: the first one is the binary genetic algorithm and the second one is particle-swarm optimization to have a multi-band antenna. The ground plane was

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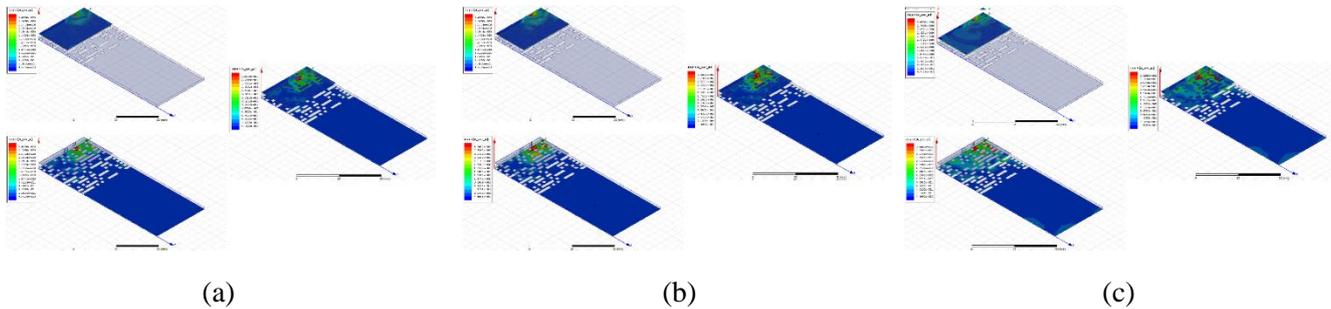(a)　　　　　　　　　　　　(b)　　　　　　　　　　　　(c)

Figure 10. Current distribution of the radiating and ground planes, (a) at 1.32 GHz, (b) at 3.12 GHz, (c) at 5.2 GHz.

divided into 56 cells with the same dimensions of 5×5 mm^2. Both algorithms were used to determine which of these cells will be removed to construct the slots and the cells will be kept forming the ground-plane shape. The simulation results were successful in finding two dual-band antennas with good performance in terms of bandwidth, reflection coefficient and radiation pattern.

In [26], the authors used a ground plane with multiple slots on the ground plane combined with PIFA antenna. In this case, the ground plane has two effects; the first one is to adjust the lower frequency and the second effect is to react as a parasitic element at the higher frequency. The antenna is a dual PIFA antenna for GSM and Bluetooth applications. In [27], the authors considered the use of a partial ground plane for the PIFA antenna to operate at 2.3 GHz. The motivation behind that research is to enhance the bandwidth to be useful for several applications. In this work, the semi-defected ground plane is used for PIFA antenna. The motivation behind this research is to achieve a triple band without modifying the PIFA antenna or increasing its volume. The simulation results present a very compact PIFA antenna compared to the works illustrated in Table 3.

Table 3. PIFA performances comparison with published papers in literature.

References	Used method	Antenna dimensions (mm^3)	Frequency	Gain & Efficiency	Type
Proposed work	Semi-defected ground plane	38×40×1.9	1.32 3.12 5.2	2.5 dB (96%) 4.5 dB (90%) 6 dB (95%)	Triple-band PIFA
[25]	Totally defected ground plane	24×38×3	3.5 5.78	- -	Dual-band PIFA
[26]	Slots on the ground plane+ slots on radiating plane	40×15×6	0.9 1.8	- -	Double-band PIFA
[27]	Partial ground plane	20×10×4	2.3	4.98 dB	Mono-band PIFA

5. CONCLUSION

A very compact tripe-band PIFA antenna with semi-defected ground plane suitable for 5G applications is proposed in this paper. This antenna has dimensions of 38×40×1.9 mm^3 with FR4-epoxy substrate. By using semi-defected ground plane and the genetic algorithm, the size is reduced by about 40%. This method presents a simple way that does not need changing the PIFA antenna's design or increasing its volume to have multi-band operation. This antenna can cover LTE Band 11 (1427.9-1495.9 MHz), HIPERLAN/2 (5.15-5.35 GHz), WLAN (5.15-5.35 GHz) and 5G Sub-6GHz applications. This antenna gives a maximum gain value of 2.5 dB, 4.5 dB and 6 dB and a radiation efficiency of 96%, 90% and 95%, at the resonant frequencies. Good radiation characteristics are shown in the operating frequency ranges.

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ملخص البحث:

في هـذه الورقــة، نقتــرح هوائيــاً مُــدْمَجاً ثلاثـي النّطاقـات علــى شــكل F مقلــوب (PIFA) للتّطبيقـات المتنقّلــة واللاســلكية باســتخدام خوارزميــة جينيــة ثنائيــة مــع الإبطــال الجزئــي للمســتوى الأرضــي. تبلــغ أبعــاد الهــوائي المقتــرح (38*40*1.9) مــم3، وهــو مخصّــص للتطبيقــات المتعلّقــة بالنّطاقــات التردديــة LTE11 و HIPERLAN/2، و WLAN، والنّطــاق الفرعــي للجيـل الخــامس (6 جيجــاهيرتز). ولضــمان الحصــول علــى هــوائي ثلاثــي النّطاقــات يعمــل بــأداءٍ مقبــول، اســتُخدمت الخوارزميــة الجينيــة لتحديــد شــكل المســتوى الأرضــي للهــوائي. وأثبتــت النتــائج أنّ الهــوائي المقتــرح مثــالي مــن حيــث الأداء عنــد ثلاثــة تــرددات 1.32 و 3.12 و 5.2 جيجــاهيرتز، علــى الترتيــب، وبمقارنــة التّصــميم المقتــرح مــع تصــاميم ســابقة لهوائيــات مماثلــة، أثبتــت المقارنــة نجاعــة التّصــميم المقترح.