

Investigating the Equivalent Source and the Plane Wave Spectrum Methods in Predicting the Magnetic Field Behavior in the Vicinity of Microstrip Patch Antenna for Bluetooth and Wi-Fi Applications

Mohamed Amine Benchana¹, Abdesselam Babouri^{2, *}, Zouheir Riah³,
Abderrezak Khalfallaoui¹, Abdelaziz Ladjimi², and Jamel Nebhen⁴

Abstract—Over the past few years, the continuous evolution of embedded electronic systems has increased electromagnetic interferences problems. It has also generated a new design constraint on electromagnetic compatibility. Hence, predicting the electromagnetic field behavior in the vicinity of the electronic components and systems becomes a priority to avoid the potential for unwanted coupling occurrence, as well as to ensure the electromagnetic compatibility compliance for those components and systems which are embedded in a confined space. As a result, the designers of electronics' equipment are extremely interested in radiated emission models. This paper reports a comparative study in which two different methods will be applied: the equivalent source method and plane wave spectrum method. These two methods will be used to predict the magnetic field behavior in the vicinity of a microstrip patch antenna. The latter works in ISM band for Wi-Fi and Bluetooth applications. The two applied models are constructed from the tangential magnetic fields cartographies of the antenna obtained from HFSS® at 3.5 mm and validated by comparing the HFSS® results with those of the models at a higher elevation. Furthermore, the relative error between the simulated field of the antenna and those of the equivalent source model according to the dipoles number is presented to determine the minimum number of dipoles that allow users to obtain the results with better accuracy. Subsequently, the relative error as function of different elevations along the z axis together with the two methods comparison results is presented.

1. INTRODUCTION

In recent years, with the growth and advancements in the microelectronics field, wireless communications, networking, telecommunications, and ISM (industrial, scientific and medical) applications [1], it has become essential to be able to characterize the propagation of the electromagnetic field in a complex and polluted environment in order to guarantee the quality and reliability of electronic systems. Indeed, the high integration tendency of electronic functions in confined spaces increases Electro Magnetic Interference (EMI) that can cause equipment and systems to malfunction or failure [1]. Therefore, it is important to have tools to quantify, characterize, and predict the levels of the electromagnetic fields across industries that may affect other electronic systems or human health [2].

Electromagnetic Compatibility (EMC) has become a major consideration in any project involving the design, construction, manufacture, and installation of electrical and electronic equipment and systems. Hence, engineers of embedded systems are deploying new methodologies and models [3–12]

Received 30 March 2021, Accepted 18 May 2021, Scheduled 31 May 2021

* Corresponding author: Abdesselam Babouri (abdesselam.babouri@gmail.com).

¹ LT Laboratory, Université 8 Mai 1945 Guelma, Algeria. ² LGEG Laboratory, Université 8 Mai 1945 Guelma, Algeria. ³ IRSEEM, Ecole Supérieure D'ingénieurs ESIGELEC, Rouen, France. ⁴ College of Computer Science and Engineering, Prince Sattam bin Abdulaziz University, KSA.

that allow optimal EMC design procedures to be incorporated into the design process from the start to increase safety, reduce costs, and ensure EMC compliance.

The authors in [3] used the data relating to the circuit architecture to model the radiated emission of the microcontroller. The equivalent source (ES) method based on magnetic/electric current densities distribution for near-field to far-field transformation was earlier introduced in [4, 5]. Moreover, the ES method was also reported in [6, 7]. However, this time the proposed model was based on magnetic/electric dipoles instead of magnetic/electric current densities distribution. It was applied to model a range of devices that operate in a frequency range between 400 kHz and 1 GHz. Furthermore, in [8] several mathematical improvements were conducted to the ES radiated emission model. Subsequently, a simple electromagnetic modeling procedure was proposed in [9] to integrate this model into a 3D commercial electromagnetic simulation tool. More to the point, the 3D ES model was first introduced in [10] and was enhanced in [11, 12] to take into consideration the 3-D radiated fields. Recently, an overview was effectuated in [13] by investigating various formulations of the inverse equivalent source problem and its corresponding solutions. On the other hand, other methods focus on near-field measurements to develop radiated emission models allowing near-field to far-field transformation by applying either the Plans Waves Spectrum (PWS) theory [14–16] or the neural network theory [17]. Our team, LGEG Laboratory, in collaboration with the electricity production company SONELGAZ, Annaba, Algeria, carried out several experimental studies [18–20]. These studies focus on the characterization of high voltage lines and their subsequent use as a source of disturbance applied to study the EMC of medical implants (cardiac pacemakers, hearing, etc.) [21, 22]. Other research works aim to study the professional environment and ensure the safety of people's lives and employees in the production stations of electrical energy [23, 24].

In this paper, we choose to employ the near-field/far-field transformation by using two different methods. The first is the ES method which makes it possible to represent the device to be characterized as a set of equivalent elementary sources. This network of sources radiates the same electromagnetic field as that of the device under test (DUT). The second is a post-processing method based on the plane wave spectrum technique. The two methods allow us to predict the magnetic field behavior at several elevations above the DUT for a given frequency and for a specific activity of the component. A validation and comparative study of the two methods will be carried out in this paper by applying them to predict the radiated emission of a microstrip patch antenna, operating in the ISM band, at a frequency of 2.4 GHz for Bluetooth and Wi-Fi applications. The rest of the paper is organized as follows. Section 2 presents an overview of the designed antenna. Section 3 provides a detailed description of the two applied methods. Section 4 presents the modeling results of the designed antenna and discussion. Then, Section 5 discusses the comparison results. Finally, Section 6 concludes the paper.

2. ANTENNA DESIGNING AND DESCRIPTIONS

Microstrip patch antennas are becoming increasingly useful and most widely used antennas due to their promising features like low weight, low volume and reduced thickness, low manufacturing cost, and their compatibility with integrated circuits [25, 26]. Figure 1 shows a microstrip patch antenna in its most basic form, which is fed by a microstrip transmission line [27]. The geometry consists of a patch and a microstrip transmission line on one side of a dielectric substrate of certain thickness d and a ground plane on the other side.

A high conductivity metal such as copper is used to design the patch antenna, microstrip transmission line, and ground plane [28, 29]. The device under test composed by the rectangular patch antenna is designed using the HFSS® (High Frequency Structure Simulator) software tool as illustrated in Figure 2. The HFSS® software tool depicts one of the most reliable and widely used software tools for antenna design and fabrication.

In this case, the antenna is designed for Bluetooth and Wi-Fi applications in the ISM band. Therefore, its resonating frequency is 2.4 GHz. Using the HFSS® software, the microstrip patch antenna is designed to resonate at this frequency. The ground plane length and length width are 120 mm and 100 mm, respectively, while the substrate height is 1.558 mm. The patch dimensions here are 484 mm for the length and 40.5 mm for the length width. Figure 3 shows the magnitude of the S_{11} parameter of the designed rectangular patch antenna.

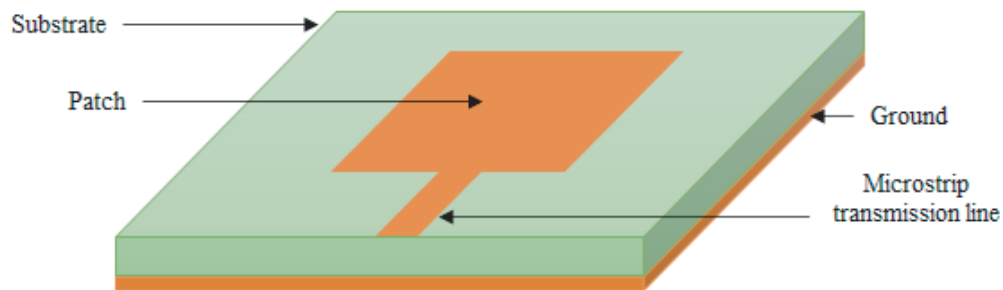


Figure 1. Microstrip patch antenna configuration.

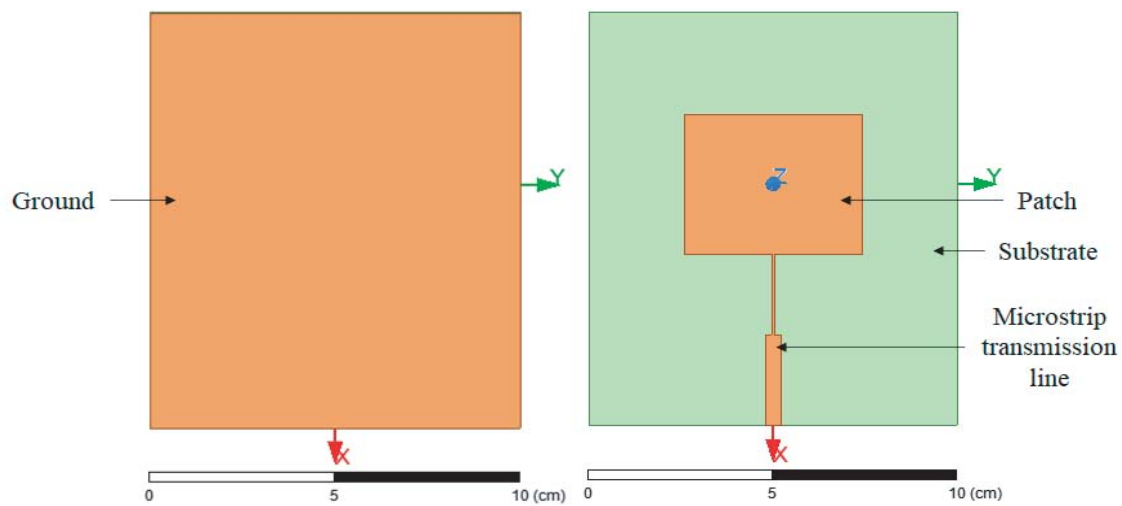


Figure 2. HFSS design of microstrip patch antenna.

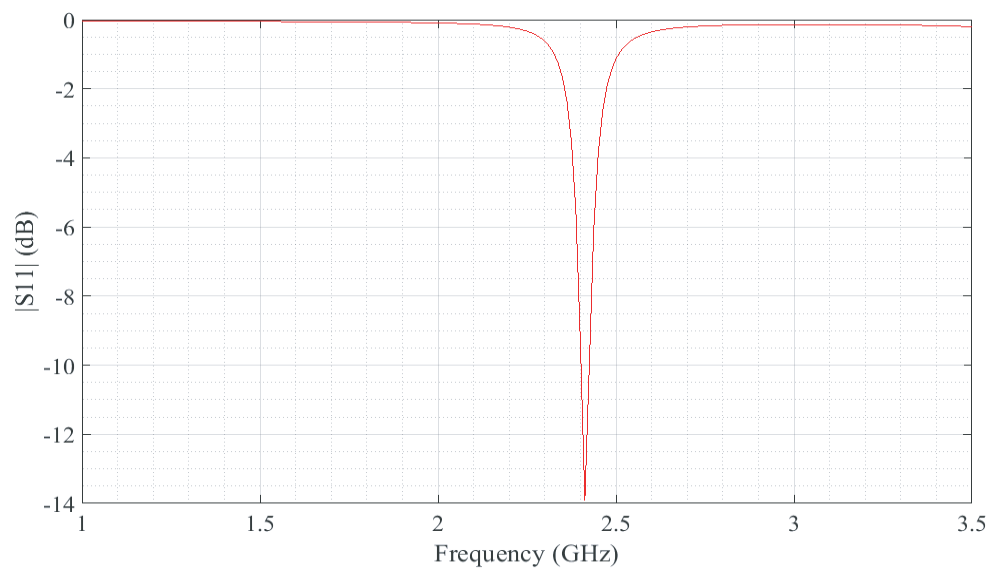


Figure 3. Magnitude of S_{11} versus frequency for square patch antenna.

3. RADIATED EMISSION MODELING: ANALYTICAL MODEL

3.1. Equivalent Source Method

In this approach, the microstrip patch antenna or the DUT is replaced by a network of electric dipoles uniformly distributed in the same area as that of the DUT. This set of electric dipoles are supposed to radiate the same magnetic field as that of the DUT. Each electrical dipole of this network is arranged in the XY plane and is characterized by an orientation θ and a current I . Compared to the wavelength, its length and width are negligible. From Maxwell's equations, the radiated magnetic field of a single dipole is given as follows [6, 28]:

$$\vec{H}_x = \frac{I_0}{4\pi} \cdot \frac{e^{-jkR}}{R^3} \cdot dl \cdot \sin \theta \cdot (1 + jkR) \cdot (z - z_0) \vec{a}_x \quad (1)$$

$$\vec{H}_y = \frac{I_0}{4\pi} \cdot \frac{e^{-jkR}}{R^3} \cdot dl \cdot \sin \theta \cdot (1 + jkR) \cdot (z - z_0) \vec{a}_y \quad (2)$$

$$\vec{H}_z = \frac{I_0}{4\pi} \cdot \frac{e^{-jkR}}{R^3} \cdot dl \cdot (1 + jkR) \cdot (\cos \theta \cdot (y - y_0) - \sin \theta \cdot (x - x_0)) \vec{a}_z \quad (3)$$

By calculating the magnetic field radiation by one electric dipole, it is possible to calculate the total magnetic field radiation at a point M in space by the dipoles network that compose the ES model. The total magnetic field radiation is the vector sum of the magnetic field radiation generated by each dipole. Thus, the problem can be summarized in the following matrix form [6]:

$$[H_x]_{m \times 1} = [\alpha_x \cdot \sin \theta]_{m \times p} \cdot [I_0]_{p \times 1} \quad (4)$$

$$[H_y]_{m \times 1} = [\alpha_y \cdot \cos \theta]_{m \times p} \cdot [I_0]_{p \times 1} \quad (5)$$

where $[\alpha_x]$ and $[\alpha_y]$ are a matrix whose elements are equations connecting all the fixed parameters (number, position, length, and frequency). $[H_x]$ and $[H_y]$ are the maps of the near tangential fields in a plane parallel to the XY plane and located at a distance $d1$. (m) is twice the number of simulation points in the plane in which the radiated fields are evaluated, and (p) is twice the number of dipoles utilized for the modeling process.

The parameters to be determined for this model are the orientations and currents flowing through each electric dipole. By applying a least-squares matrix inversion and element-by-element division, it is possible to determine the orientations as indicated in the following formula:

$$\theta_i = \arctan \left(\frac{A_i}{B_i} \right) \quad (6)$$

After having all the orientations computed, the current intensities are obtained in the same way, but beforehand, the determined orientations must be inserted in Eqs. (4) and (5). In this case, only

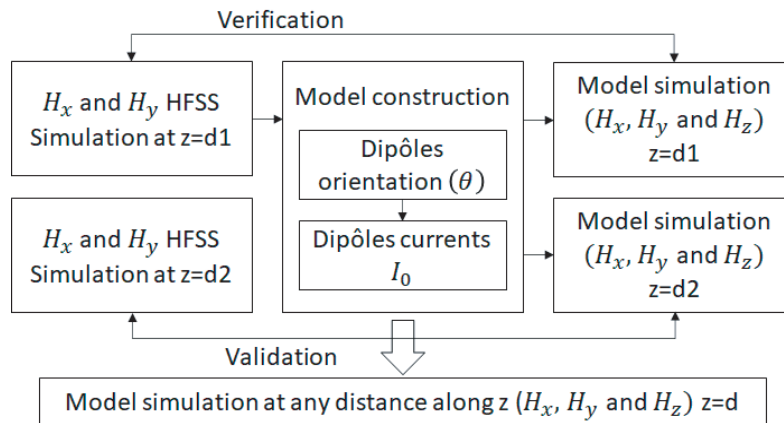


Figure 4. The ES method modeling process.

one component of the field can be used.

$$\begin{bmatrix} H_x \\ H_y \end{bmatrix} = \begin{bmatrix} \alpha_x \cdot \sin \theta_i \\ \alpha_y \cdot \cos \theta_i \end{bmatrix} [I_0] \quad (7)$$

Once the currents and orientations of each electric dipole are defined and the ES model is built, a verification of the ES model is carried out by simulating its radiation at the same distance as that used for its construction ($d1$). Then, the obtained results at $d1$ above the ES model will be compared to the ones obtained with HFSS® at $d1$ above the designed antenna as seen in Figure 4. This is followed by a validation of the ES model at a higher elevation than $d1$ ($d2$) (see Figure 4). Therefore, it is possible to simulate the radiation of the ES model at any distance along the z axis.

3.2. Plane Wave Spectrum Theory

In a source-free free-space region, the time-harmonic Maxwell equations can be transformed into the following vector wave equations [15, 30]:

$$\begin{cases} \nabla^2 E + k^2 E = 0 \\ \nabla^2 H + k^2 H = 0 \end{cases} \quad (8)$$

$$\nabla \cdot E = \nabla \cdot H = 0 \quad (9)$$

The general solution of Equation (8) for $z \geq 0$ can be represented as a superposition of plane waves with the same frequency propagating in different directions of space.

$$\vec{H}(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \vec{F}(k_x, k_y) \exp(-j\vec{k} \cdot \vec{r}) dk_x dk_y \quad (10)$$

$$\vec{H}(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [\vec{F}(k_x, k_y) e^{-jk_z z}] \exp(-j(k_x x + k_y y)) dk_x dk_y \quad (11)$$

From (11) the following inverse Fourier transform can be derived:

$$\vec{F}(k_x, k_y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \vec{H}(x, y, z) \cdot \exp(j(k_x x + k_y y)) dx dy \quad (12)$$

with $\vec{k} = k_x \vec{u}_x + k_y \vec{u}_y + k_z \vec{u}_z$ and $\vec{r} = x \vec{u}_x + y \vec{u}_y + z \vec{u}_z$. $\vec{k}$ is the wave vector, and $\vec{r}$ is the position vector.

In Equations (10) and (11), F represents a uniform plane wave spectrum of the magnetic field that propagates in the direction k .

$$\vec{H}(x, y, z) = \vec{F}(\vec{k}) \exp(-j\vec{k} \cdot \vec{r}) \quad (13)$$

Inserting Equation (13) in (9) leads to Equation (14).

$$F_z(k) = \frac{-(F_x(k) k_x + F_y(k) k_y)}{k_z} \quad (14)$$

Equation (11) shows that to calculate the magnetic field at any height along z , the spectrum at the same height must be known. Moreover, the spectrum at any distance along z can be found from the spectrum at $z = z_1$ by using Eq. (15).

From Eq. (12) we note that the PWS calculation from the field corresponds to two-dimensional inverse Fourier transform, and Eq. (11) shows that the field calculation from the PWS corresponds to a two-dimensional direct Fourier transform [30].

$$\vec{F}(\vec{k}) \Big|_{z=z_2} = \vec{F}(\vec{k}) \Big|_{z=z_1} \exp(-jk_z(z_2 - z_1)) \quad (15)$$

The modeling process is presented in Figure 5, where the radiated source is placed in $z = 0$, and the planar scanning used for H_x , H_y and H_z simulation is conducted to a plane defined at $z = z_1$ near the source. Then the calculation process will be implemented in MATLAB to obtain the field at any height $z > z_1$.

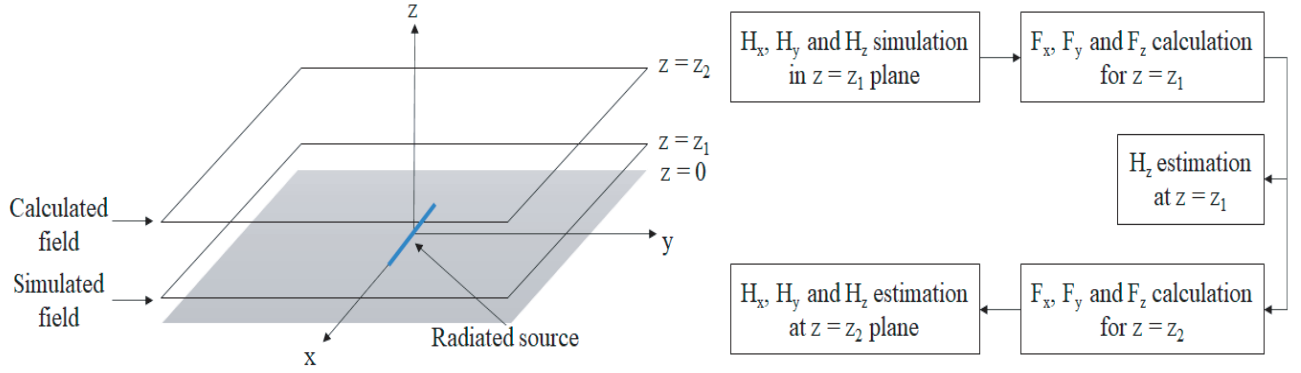


Figure 5. The plane wave spectrum modeling process.

For $z > 0$, the radiation condition requires

$$k_z = \begin{cases} \sqrt{k^2 - k_x^2 - k_y^2}, & \text{if } k_x^2 + k_y^2 \leq k^2 \\ -j\sqrt{k_x^2 + k_y^2 - k^2}, & \text{otherwise} \end{cases} \quad (16)$$

Imaginary k_z corresponds to an evanescent PWS which is rapidly attenuated away from the $z = 0$ plane.

4. RESULTS

In order to obtain the magnetic fields components required for the ES method modeling process and also for the PWS modeling process, we perform a full-wave simulation of the designed antenna using the finite element analysis of HFSS®. The required H_x and H_y cartographies are obtained at a height of 3.558 mm from the ground plane of the antenna which is 2 mm above the patch. The cartographies have an area of 150×100 mm with 75×75 simulation points used to export the magnetic field data from HFSS®.

4.1. Equivalent Source Method

The modeling process presented in Figure 4 is applied to model the radiated emission of the microstrip patch antenna. The analytical model presented in Section 3.1 will be implemented in MATLAB to calculate the orientation and the current of each electric dipole included in the ES model, as well as the magnetic field pattern above it. The model verification is shown in Figure 6 at $z = 3.558$ mm, while the model validation is carried out at a height of 13.558 mm, as shown in Figure 8. Furthermore, a cross section of the three magnetic fields components calculated with the ES model and that of the ones obtained with HFSS® are plotted along the X axis in Figure 9(a) and Figure 9(b), for $z = 3.558$ mm and $z = 13.558$ mm, respectively. However, in advance of model validation, an error criterion between the cartographies of the simulated field obtained with HFSS® above the microstrip patch antenna and those calculated above the ES model at $z = 3.558$ mm is presented in Figure 7 as a function of the number of electric dipoles used in the network. The latter helps to determine the minimum number of dipoles used in the ES model. The relative error is obtained from the following formula:

$$Error_x = \sum_{i=1}^n \frac{1}{\alpha} |(H_{xsimu}(M_i) - H_{xmod}(M_i))|^2 \quad (17)$$

$$Error_y = \sum_{i=1}^n \frac{1}{\beta} |(H_{ysimu}(M_i) - H_{ymod}(M_i))|^2 \quad (18)$$

$$Error_z = \sum_{i=1}^n \frac{1}{\gamma} |(H_{zsimu}(M_i) - H_{zmod}(M_i))|^2 \quad (19)$$

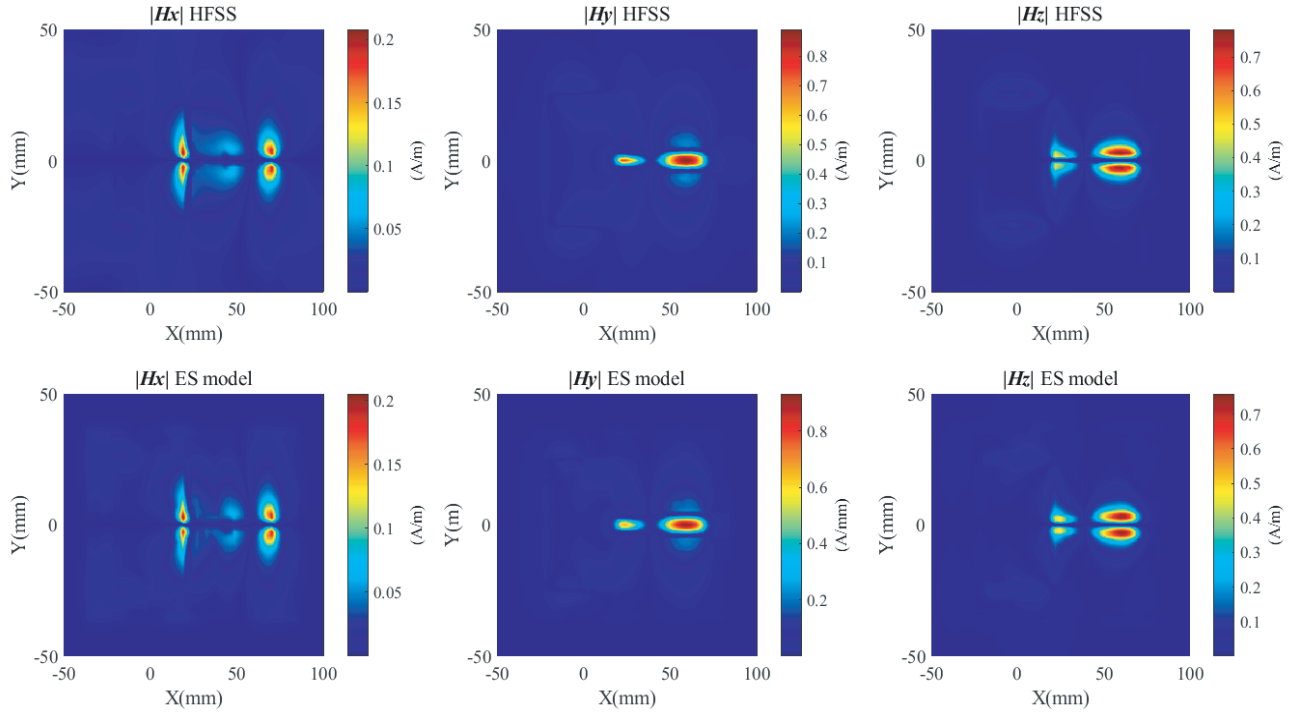


Figure 6. Comparison between the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained above the ES model using Matlab at $f = 2.4$ GHz, and at $z = 3.558$ mm.

with

$$\alpha = \sum_{i=1}^n |(H_{xsimu}(M_i))|^2 \quad (20)$$

$$\beta = \sum_{i=1}^n |(H_{ysimu}(M_i))|^2 \quad (21)$$

$$\gamma = \sum_{i=1}^n |(H_{zsimu}(M_i))|^2 \quad (22)$$

where M_i is the point where the magnetic field is calculated, and n is the number of simulation points.

Figure 7 shows that the greater the number of dipoles placed in the network is, the more the error decreases especially for the x and y components. In accordance to Figure 7, an ES model that contains 800 dipoles is enough to obtain the results with the same precision as that which contains 1444 dipoles. However, here we chose 1444 dipoles to avoid confusion in the field mapping at $z = 3.558$ mm, because at this height the magnetic field distribution is very narrow, which makes the mapping of the field intermittent. It is important to note that this will be no longer a problem since the field will be expanded at higher distances such as for $z = 13.558$ mm. The 1444 electric dipoles are distributed uniformly inside the red perimeter area delineated in the Hx mapping of Figure 6. According to Figure 6 and Figure 9(a), it is clear that the profiles of the three magnetic fields components calculated at $z = 3.558$ mm above the constructed ES model are identical to the simulated ones obtained from HFSS® at the same elevation above the microstrip patch antenna. Moreover, the magnetic fields amplitudes levels of the antenna and that of the ES model are coherent except for the z component (see Figure 9(a)), which is slightly different. This last has an error estimated by 0.049 (see Figure 7), while the errors in the x and y components are 0.0082 and 0.016, respectively (see Figure 7).

This could be explained by the fact that the ES model is built from the Hx and Hy components,

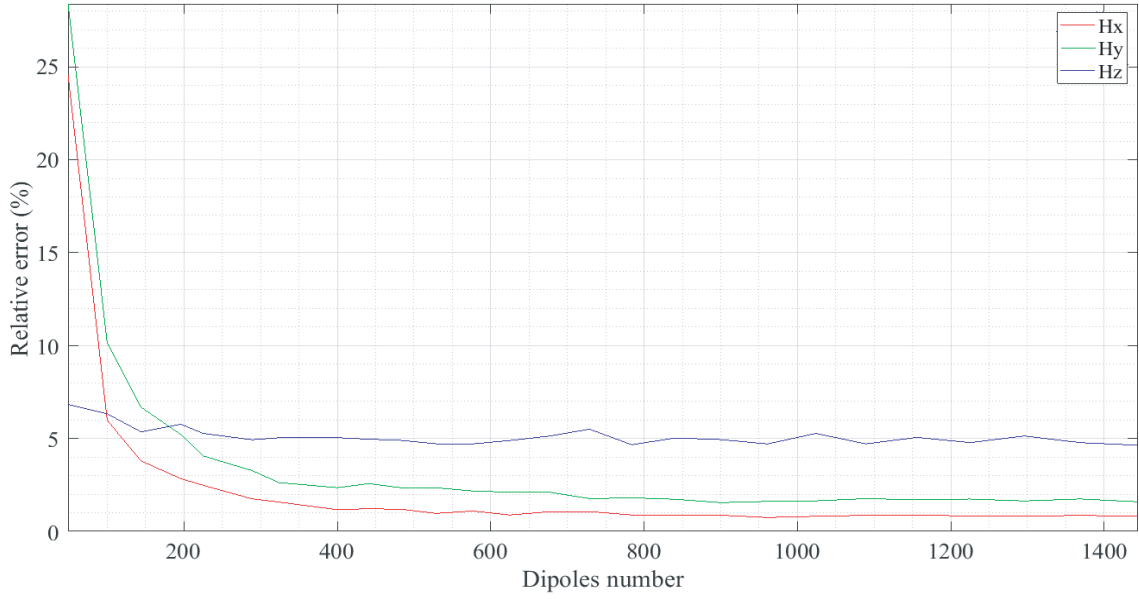


Figure 7. The relative error between the cartographies of the simulated field of the microstrip patch antenna and those of the ES model as function of the dipoles number.

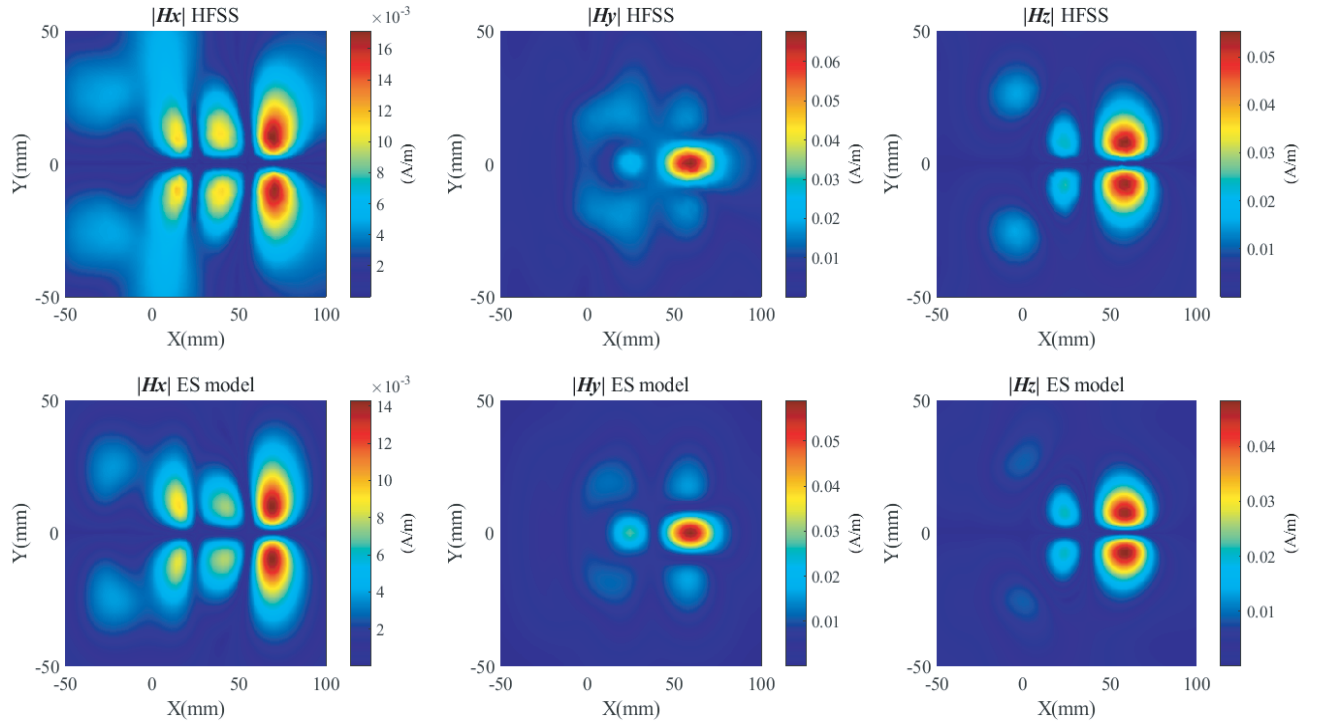


Figure 8. Comparison between the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained above the ES model using Matlab at $f = 2.4$ GHz, and at $z = 13.558$ mm.

and the determination of H_z is obtained directly from the ES model. Nevertheless, after analyzing the results shown in Figure 6 and Figure 9(a), it is decided that these differences are not excessive and that the model is reliable and gives good results. Therefore, we can proceed to the validation setup which is carried out at a height of 13.558 mm, as shown in Figure 8.

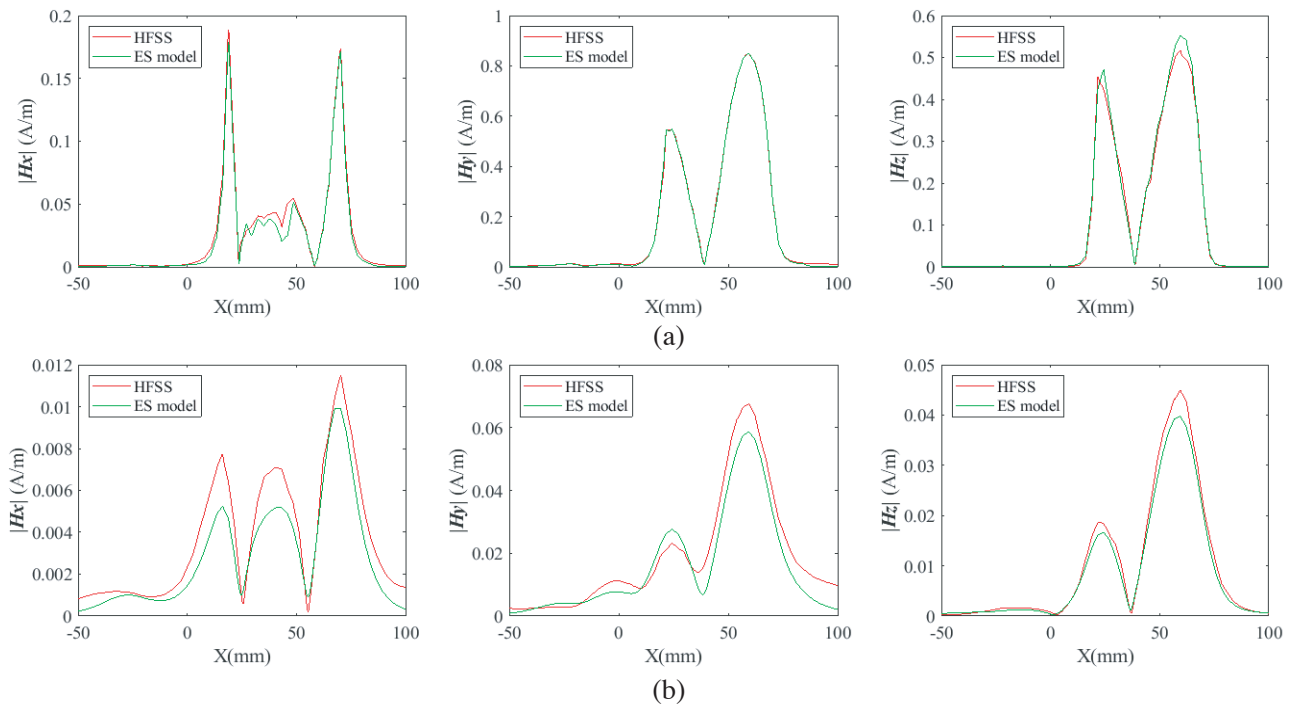


Figure 9. A cross section along the x axis of the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained above the ES model using Matlab at $f = 2.4$ GHz, and at (a) $z = 3.558$ mm, (b) $z = 13.558$ mm.

At $z = 13.558$ mm, the magnetic fields cartographies of the ES model still show a good agreement compared to the simulated ones with HFSS®, although there is a small contrast occurring in the field amplitude levels as it is clear in Figure 9(b). To substantiate the practicability of the ES model, the relative error is plotted in Figure 10 as a function of different elevations along z axis.

Figure 10 indicates that the small contrasts observed in Figure 9(b) in the field amplitude levels are amplified when the magnetic field is characterized at a higher elevation above the ES model. These differences reach 0.0453, 0.0599, and 0.0656 for x , y , and z components, respectively at $z = 43.558$ mm (see Figure 10 and Table 1). The comparison between the cartographies of the three magnetic fields

Table 1. Evolution of the relative error between the cartographies of the field simulated with HFSS and those of the field calculated either with the PWS method or the with ES model as function of the different elevations along the z axis.

Distances (mm)	H_x		H_y		H_z	
	PWS	ES	PWS	ES	PWS	ES
8.558	0.0354	0.0319	0.0128	0.0143	0.0340	0.0651
13.558	0.0445	0.0387	0.0170	0.0226	0.0461	0.0569
18.558	0.0498	0.0481	0.0241	0.0284	0.0592	0.0589
23.558	0.0563	0.0438	0.0403	0.0399	0.0711	0.0606
28.558	0.0601	0.0463	0.0420	0.0345	0.0814	0.0608
33.558	0.0595	0.0494	0.0459	0.0344	0.0746	0.0563
38.558	0.0565	0.0477	0.0592	0.0408	0.0696	0.0577
43.558	0.0602	0.0453	0.0921	0.0599	0.0670	0.0656

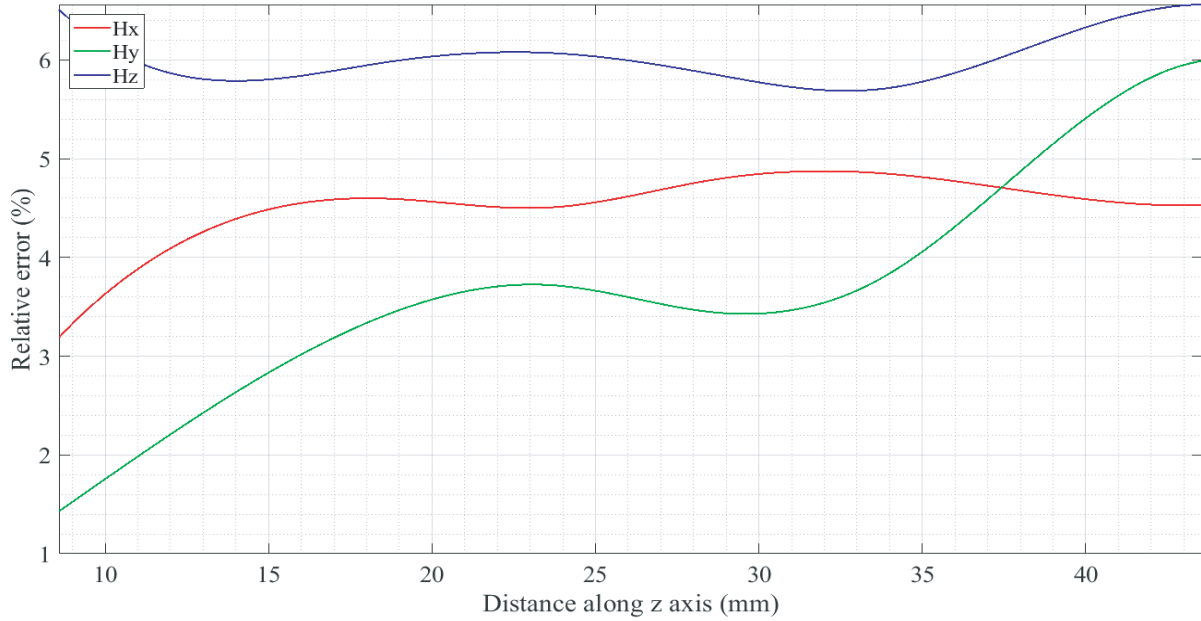


Figure 10. Evolution of the relative error between the cartographies of the simulated field of the microstrip patch antenna and those of the ES model as function of different elevations along the z axis.

components at this elevation is presented in Figure 11. A dispersion was observed in the magnetic field profile obtained above the ES model at this altitude. This is because the ES model was constructed at $z = 3.558$ mm. Therefore, it can be concluded that the differences in the field amplitude levels are growing, whenever the magnetic field is evaluated at higher plans above the ES model. Even though these differences rise significantly, they are still reasonable, and we can state that the model still gives good results.

4.2. Plane Wave Spectrum Method

The modeling process presented in Figure 5 is applied to model the radiated emission of the antenna under test. The analytical model presented in Section 3.2 will be implemented in MATLAB to calculate the magnetic field pattern at any elevation along the z axis. However, first an estimation of H_z component at 3.558 mm is presented in Figure 12 by using Equation (14).

According to Figure 12 that represents a comparison between the H_z component of the magnetic field obtained from HFSS® and the one calculated with the PWS method, it is clear that they are identical in profile and field amplitude levels.

From the near field cartographies and by applying the PWS theory, the magnetic field can be calculated at several heights $z > 3.558$ mm above the antenna. The results are presented in Figure 13 and Figure 15 for $z = 13.558$ mm and 43.558 mm, respectively. Furthermore, the relative error between the cartographies of the simulated field obtained from HFSS® and those obtained with the PWS method as function of different elevations above the microstrip patch antenna is presented in Figure 14.

Figure 13 shows that the magnetic fields components calculated by the PWS at 10 mm are coherent in profile and amplitude with the ones simulated by HFSS® at the same height, with acceptable differences as reported in Table 1 and Figure 14.

For $z = 43.558$ mm, we observe a dispersion in the field cartographies calculated with the PWS method compared to the simulated ones with HFSS®. Moreover, the differences in the field amplitude levels are also amplified as can be seen in Figure 14 and Table 1. These differences occur especially in the extremities for lower-field values (see Figure 15). We find that they are almost of the same order of magnitude at 43.558 mm, and they are higher than their values at 13.558 mm; however in the mean time, they remain quite reasonable.

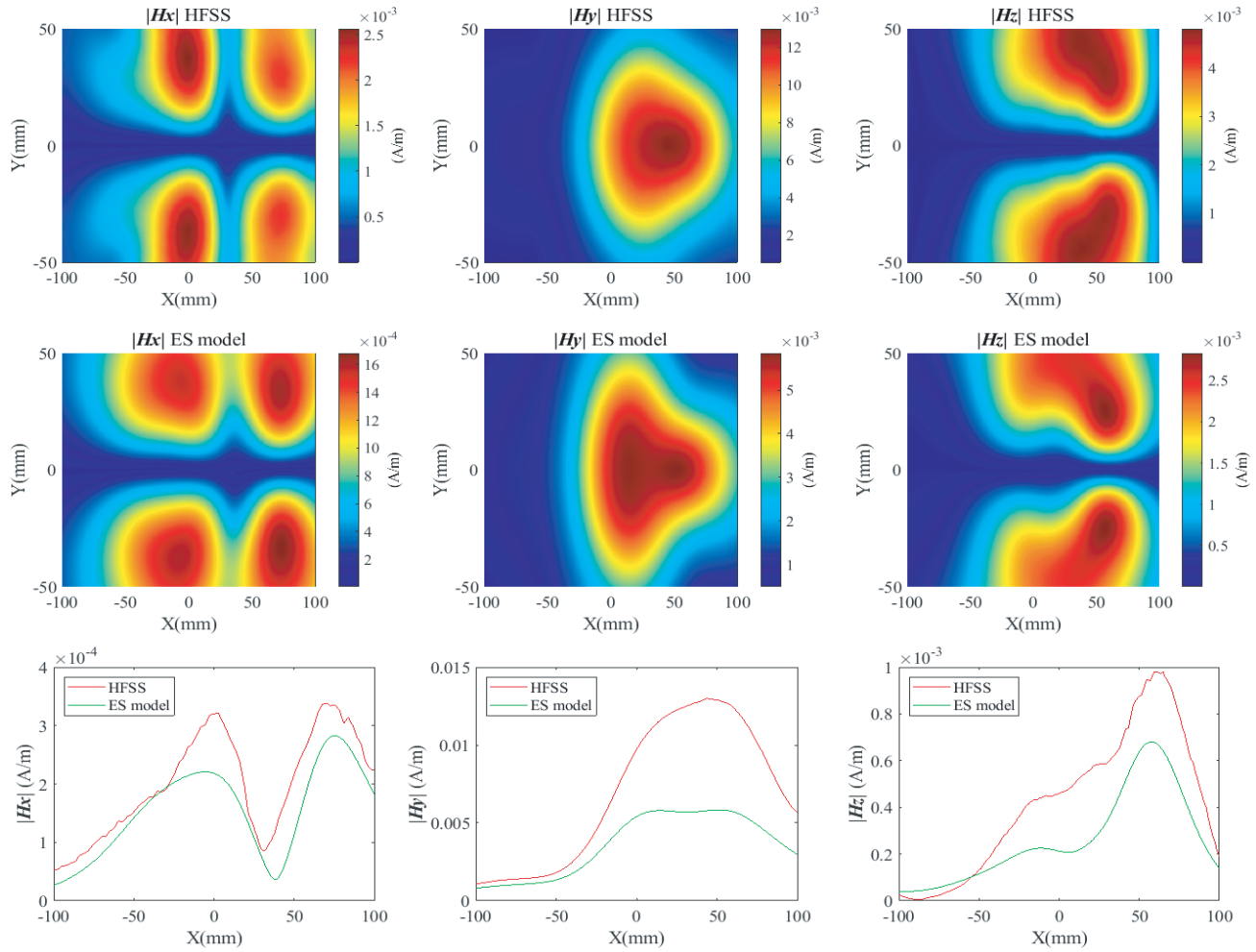


Figure 11. Comparison between the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained above the ES model using Matlab at $f = 2.4$ GHz, and at $z = 43.558$ mm.

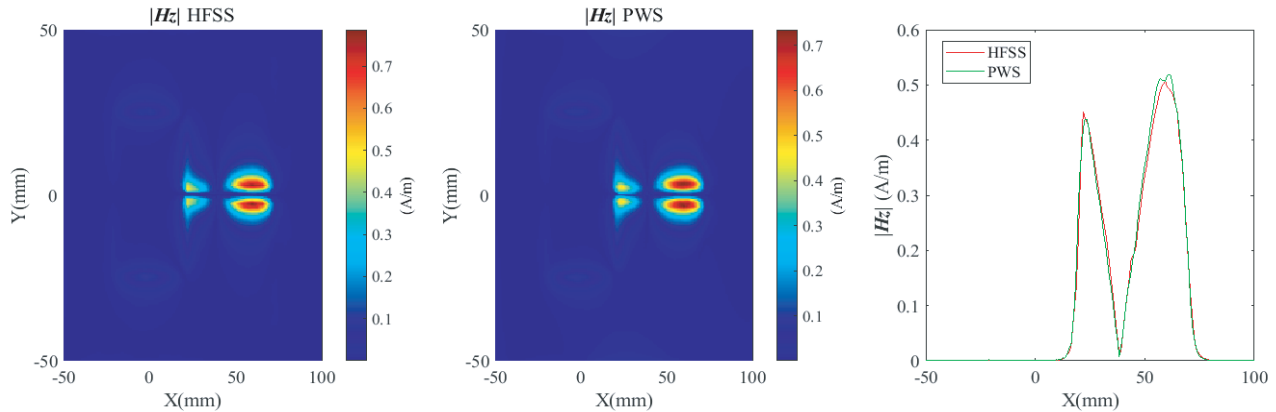


Figure 12. H_z components obtained in simulation and with PWS at $z = 3.558$ mm.

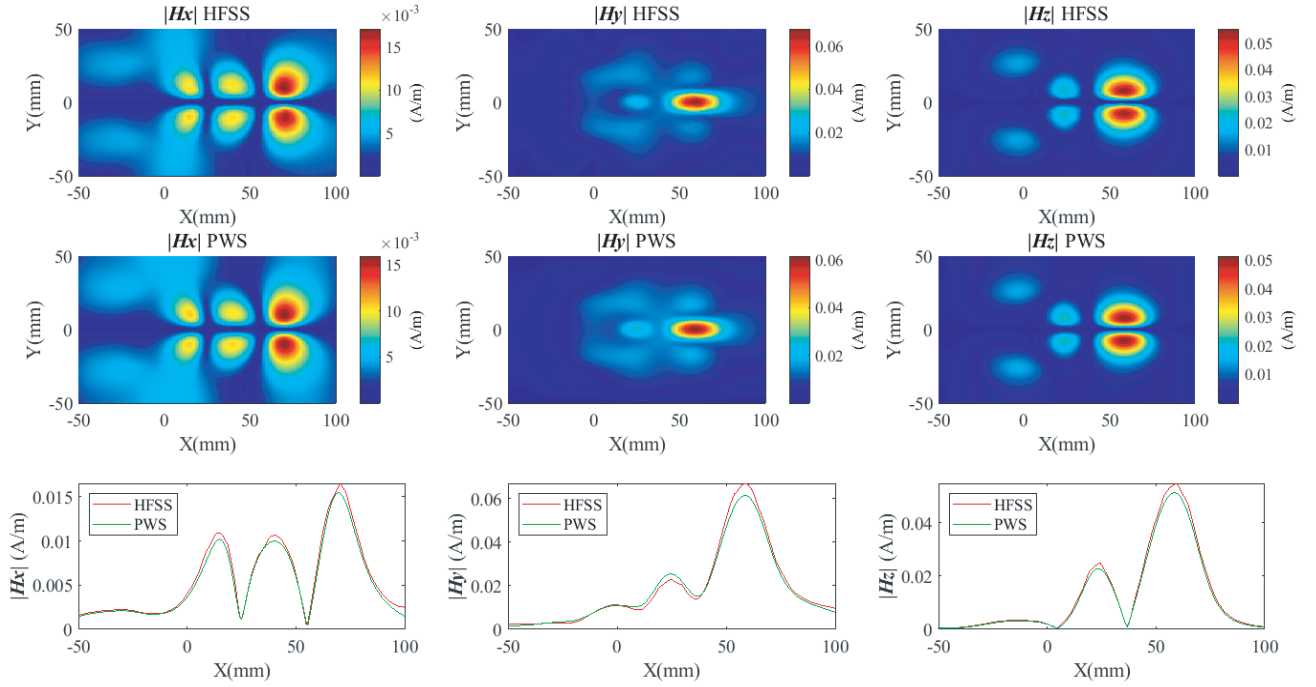


Figure 13. Comparison between the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained with the PWS method using Matlab at $f = 2.4$ GHz, and at $z = 13.558$ mm.

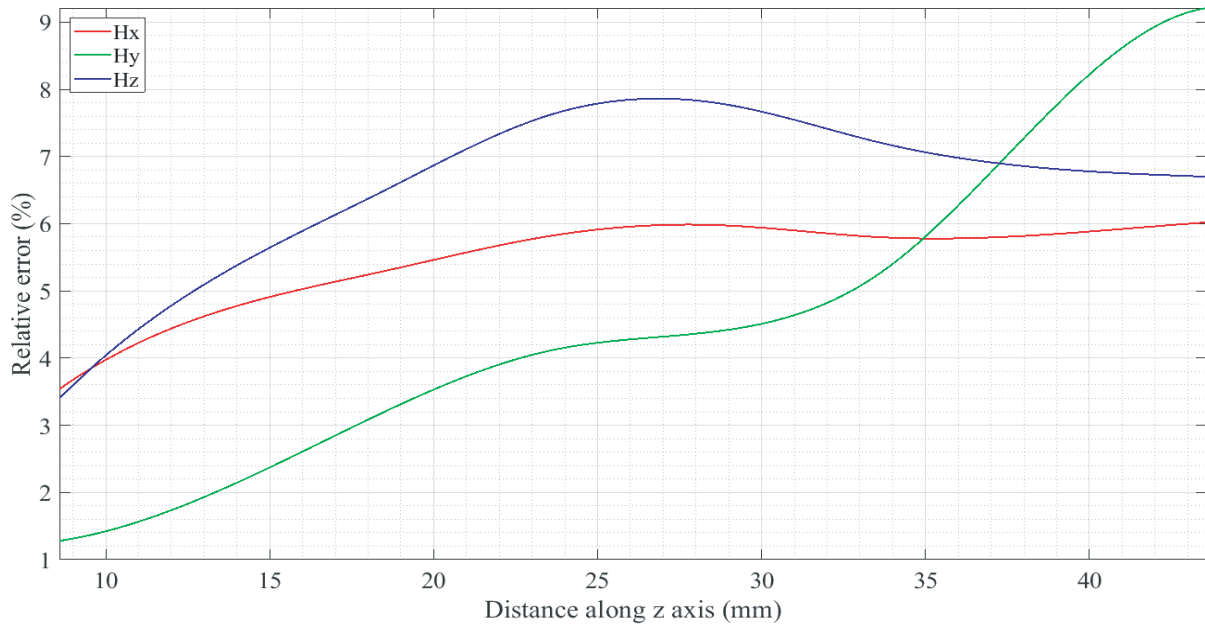


Figure 14. Evolution of the relative error between the cartographies of the simulated field of the microstrip patch antenna and those of the PWS method as function of different elevations along the z axis.

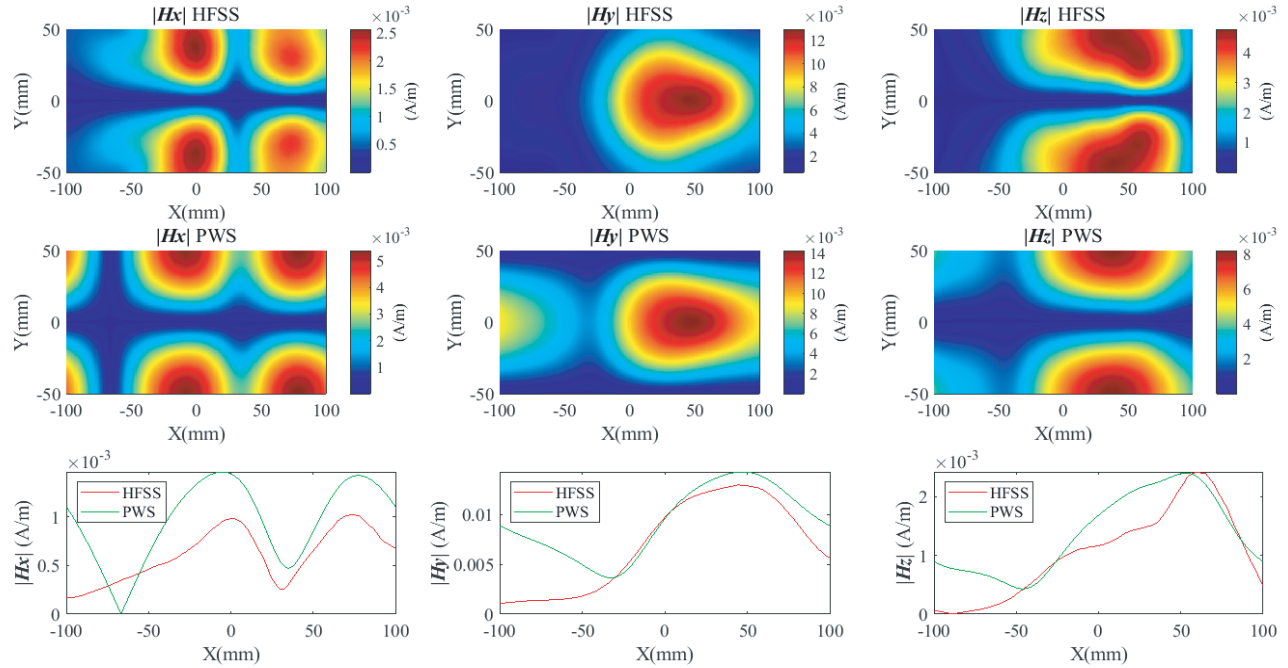


Figure 15. Comparison between the three magnetic fields components obtained above the microstrip patch antenna using HFSS and those obtained with the PWS method using Matlab at $f = 2.4$ GHz, and at $z = 43.558$ mm.

5. DISCUSSION

The obtained results show a good similarity in profile and amplitude between the magnetic fields cartographies obtained by radiated emission modeling and those obtained by HFSS simulation. These results which are shown in the precedent section indicate that both methods are effective for predicting the magnetic field behavior of the antenna. In this section, we will discuss the practicability of each method presented in this paper along with a comparative study of the two methods. The MATLAB simulation takes a short period of time for both methods. It took 60 seconds for the PWS method and 79 seconds for the ES method. Figure 16 presents the comparison between the H_z component calculated from H_x and H_y cartographies with the PWS method and the ES method at $z = 3.558$ mm.

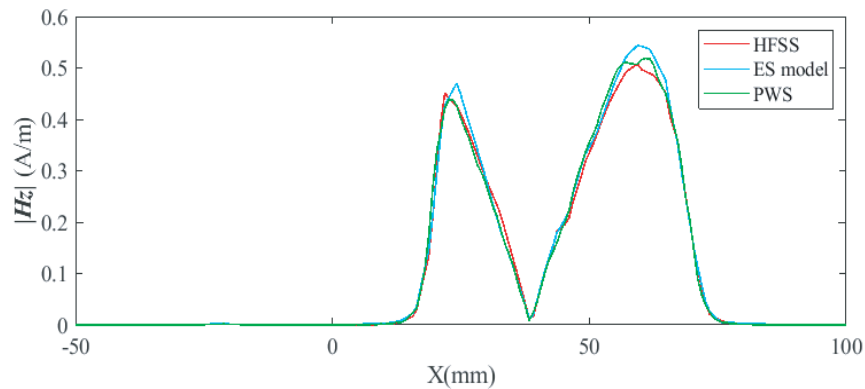


Figure 16. A cross section along the x axis of the H_z component obtained above the microstrip patch antenna using HFSS together with those obtained with the PWS method and with the ES method using Matlab at $f = 2.4$ GHz, and at $z = 3.558$ mm.

According to Figure 6, Figure 12, and Figure 16, the magnetic field amplitude and profile calculated by both methods are identical with the one obtained from HFSS®. The comparison between the two methods for $z = 13.558$ mm and $z = 43.558$ mm is presented in Figure 17(a) and Figure 17(b), respectively. Moreover, the relative error evolution of the two methods as a function of the different distances along the z axis is presented in Table 1 and Figure 18.

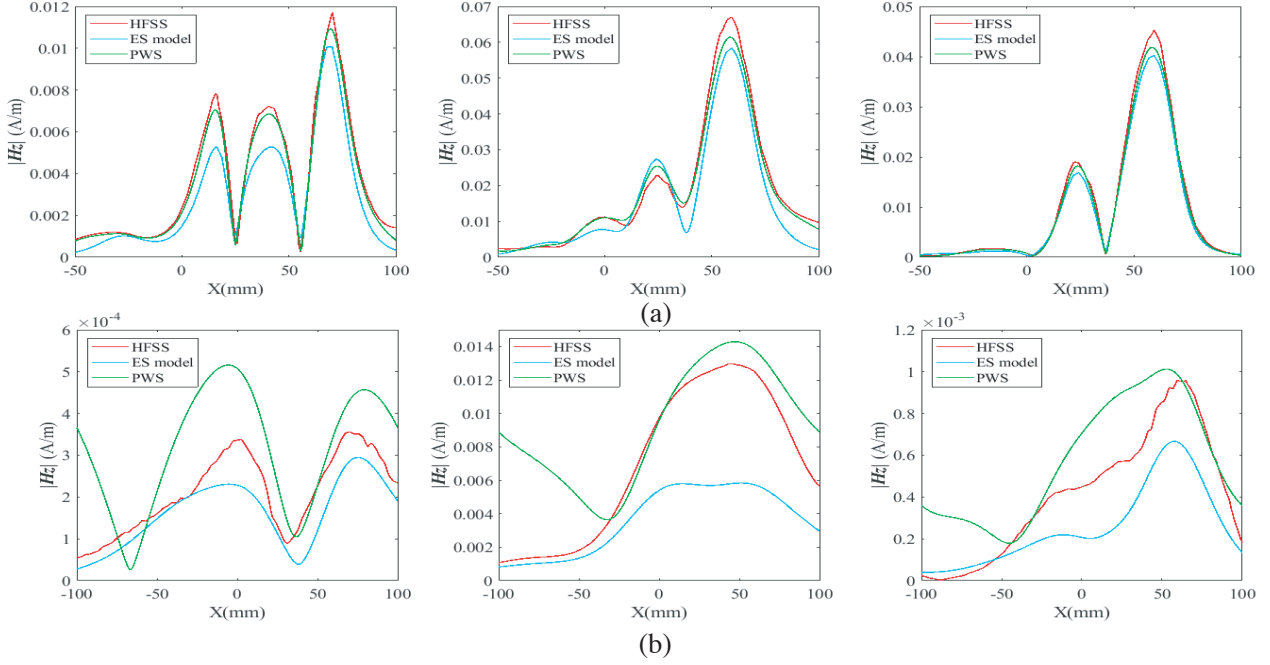


Figure 17. A cross section along the x axis of the three magnetic fields components obtained above the microstrip patch antenna using HFSS together with those obtained with the PWS method and with the ES method using Matlab at $f = 2.4$ GHz, and at (a) $z = 13.558$ mm, (b) $z = 43.558$ mm.

The presented results show that the PWS method is more effective and reliable in the near distances above the antenna than the ES method especially in the middle where the magnetic field is concentrated as shown in Figure 17(a). Furthermore, the differences in the field values calculated with PWS method are almost the same as the ones calculated with the ES model (see Table 1 and Figure 18), although the cross sections of the magnetic fields components calculated with the PWS method are more coherent than those calculated with the ES model as can be seen in Figure 17(a). This could be explained by the fact that in the PWS method the differences in the field values occur more in the extremities for lower-field values, and this becomes very evident when the magnetic field is characterized at higher plans above the antenna as indicated in Figure 17(b). At these plans, we observe a dispersion in the magnetic field profile for the two methods, particularly for the one calculated with the PWS method as shown in Figure 11 and Figure 15. Despite that, the results obtained with the PWS method still show a better agreement in the field amplitude levels (only in the middle of the field) than those of the ES model as it is clear in Figure 17(b). Thus, one can conclude that at near plans (from 3.558 mm till less than 23.558 mm (see Table 1 and Figure 18)), the PWS is more reliable than the ES method, while at far plans (from 23.558 mm and higher (see Table 1 and Figure 18)) from the antenna, the ES method becomes more reliable, especially when their evaluation relies on the magnetic field distribution at these plans.

Table 2 summarizes the investigation results of the two presented methods according to the few criteria that we have defined: minimum relative error, maximum relative error, simulation time, input data, modeled fields, model parameters, practicability, advantages and limitation of each method.

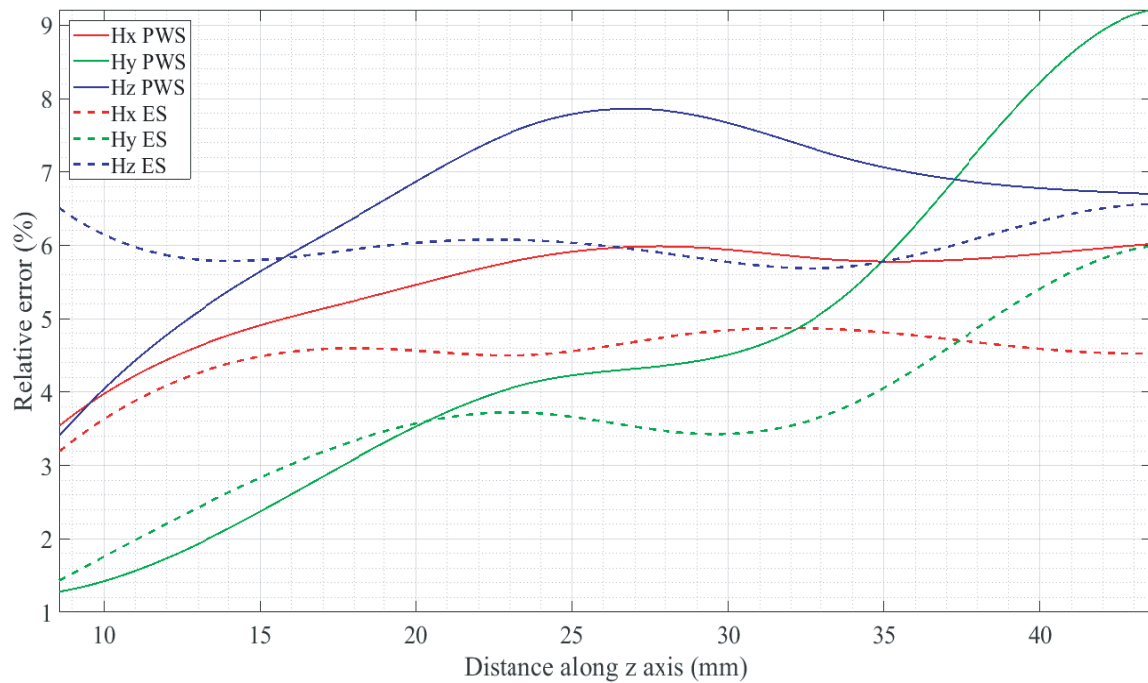


Figure 18. Evolution of the relative error between the cartographies of the field simulated with HFSS and those of the field calculated with the PWS method or with the ES model as function of the different elevations along the z axis.

Table 2. Comparison between the two applied methods.

Methods		Equivalent Source			Plane wave spectrum		
Magnetic fields components		H_x	H_y	H_z	H_x	H_y	H_z
Relative error	Min	3.19%	1.43%	5.63%	3.54%	1.28%	3.4%
	Max	4.94%	5.99%	6.56%	6.02%	9.21%	8.14 %
Simulation time		Short period of time			Short period of time		
Input data		H_x and H_y			H_x and H_y		
Modeled fields		H_x , H_y and H_z			H_x , H_y and H_z		
Model parameters		- Orientation and current of each dipole			- Mathematical expression between two fields at different distances from the source		
Practicability		- At far plans from the antenna			- At near plans from the antenna		
Advantage		- Establish an optimal arrangement of the devices within the final product - Reduce the number of measurements which usually take a lot of time - Integrable in 3D commercial electromagnetic simulation tool			- Establish an optimal arrangement of the devices within the final product - Reduce the number of measurements which usually take a lot of time		
Limitation		- Excessive number of dipoles			- Divergence of results		

6. CONCLUSION

In this paper, two different methods were applied to predict the magnetic field behavior of a microstrip patch antenna. This antenna operates in the ISM band for Wi-Fi and Bluetooth applications at a frequency of 2.4 GHz. A comparative study was conducted wherein each method was analyzed in order to define the most effective method for the radiated emission modeling. The obtained results show a comparison between the magnetic fields cartographies exported from HFSS® above the microstrip patch antenna and those obtained with the ES model or with the PWS method. The results are in a very good agreement, especially at near distances. The evolution of the relative error between the cartographies of the simulated field of the microstrip patch antenna and those of the ES model with different numbers of dipoles was carried out to determine the minimum number of dipoles that allow users to take the results with a better accuracy. At the end, it is found that the applied approach is very effective for studying, characterizing, and predicting electromagnetic interference and ensuring EMC compliance for ISM applications. In future work, along with the ES and PWS methods we plan to investigate the effectiveness of other methods reported in the literature such as the neural network method. These methods will be carefully studied in order to define the most effective method to achieve our objective of predicting the magnetic field behavior at the farthest possible elevation above a DUT. Furthermore, we also plan to study the possibility of using these methods cooperatively.

ACKNOWLEDGMENT

This work is supported by the Directorate General for Scientific Research and Technological Development (DG-RSDT) of Algeria, as part of research project (PRFU No, A01L07UN2401201 90001). I would like to express my deepest appreciation to Mrs. Benchana Samiha (Université Des Frères Mentouri Constantine) for her diligent proofreading of this paper.

REFERENCES

1. The McClean Report IC Insights 2020, [Online], Available: <https://www.icinsights.com/news/bulletins/Total-Microprocessor-Sales-To-Edge-Slightly-Higher-In-2020/>.
2. Martin, L. P., "Wi-Fi is an important threat to human health," *Environmental Research*, Vol. 164, 405–416, Mar. 2018.
3. Labussiere, D. C., S. Bekndhia, E. Sicard, J. Tao, H. J. Quaresma, C. Lochot, and B. Virgnon, "Modeling the electromagnetic emission of a microcontroller using a single model," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 50, No. 1, 22–34, Feb. 2008.
4. Petre, P. and T. Sarkar, "Planar near-field to far-field transformation using an equivalent magnetic current approach," *IEEE Transactions on Antennas and Propagation*, Vol. 40, No. 11, 1348–1356, Nov. 1992.
5. Alvarez, Y., F. Las-Heras, and M. R. Pino, "Reconstruction of equivalent currents distribution over arbitrary three-dimensional surfaces based on integral equation algorithms," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 12, 3460–3468, Dec. 2007.
6. Vives, G. Y., "Modélisation des émissions rayonnées de composants électroniques," Université de Rouen, Rouen, FR, 2007.
7. Vives, G. Y., C. Arcambal, A. Louis, F. de Daran, P. Eudeline, and B. Mazari, "Modeling magnetic radiations of electronic circuits using near-field scanning method," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 49, No. 2, 391–400, May 2007.
8. Ramanujan, A., Z. Riah, A. Louis, and B. Mazari, "Computational optimizations towards an accurate and rapid electromagnetic emission modeling," *Progress In Electromagnetics Research B*, Vol. 27, 365–384, Jan. 2011.
9. Fernandez, L. P., C. Arcambal, D. Baudry, and S. Verdeyme, "Simple electromagnetic modeling procedure: From near-field measurements to commercial electromagnetic simulation Tool," *IEEE Transactions on Instrumentation and Measurement*, Vol. 59, No. 12, 3111–3121, Dec. 2010.

10. Fernandez, P. L., C. Arcambal, and D. Baudry, "3D modeling of radiated emission of electronic components," *3th Workshop Embedded EMC 2EMC*, Nov. 2010.
11. Shall, H., Z. Riah, and M. Kadi, "A 3-D near-field modeling approach for electromagnetic interference prediction," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 56, No. 1, 102–112, Feb. 2014.
12. Shall, H., Z. Riah, and M. Kadi, "Prediction of 3D-near field coupling between a toroidal inductor and a transmission line," *IEEE International Symposium on Electromagnetic Compatibility*, 651–656, Denver, CO, USA, 2013.
13. Jonas, K., R. A. M. Mauermayer, O. Neitz, J. Knapp, and T. F. Eibert, "On the solution of inverse equivalent surface-source problems," *Progress In Electromagnetics Research*, Vol. 165, 47–65, 2019.
14. Riah, Z., "Caractérisation et Modélisation des Phénomènes Radiatifs en Champ Proche des Composants et des Dispositifs Electroniques, Rapport HDR," Université de Rouen, FR, 2015.
15. Baudry, D., M. Kadi, Z. Riah, C. Arcambal, Y. V. Gilabert, A. Louis, and B. Mazari, "Plane wave spectrum theory applied to near-field measurements for electromagnetic compatibility investigations," *IET Science Measurement and Technology*, Vol. 3, No. 1, 72–83, Jun. 2008.
16. Volski, V., B. Ravelo, V. A. E. Vandenbosch, and D. Pissort, "Investigation on planar near-to-far-field transformations for EMC applications," *European Conference on Antennas and Propagation*, Lisbon, Portugal, 2015.
17. Brahimi, R., A. Kornaga, M. Bensetti, D. Baudry, Z. Riah, A. Louis, B. Mazari, "Postprocessing of near-field measurement based on neural networks," *IEEE Transactions on Instrumentation and Measurement*, Vol. 60, No. 2, 539–546, Feb. 2011.
18. Tourab, W., A. Babouri, and M. Nemamcha "Experimental study of electromagnetic environment in the vicinity of high voltage lines," *American Journal of Engineering and Applied Sciences*, Vol. 4, 209–213, Jan. 2011.
19. Tourab, W., A. Babouri, and M. Nemamcha, "Characterization of the electromagnetic environment at the vicinity of power lines," *International Conference on Electricity Distribution*, Frankfurt, Germany, Jun. 2011.
20. Tourab, W., A. Babouri, and M. Nemamcha, "Characterization of high voltage power lines as source of electromagnetic disturbance," *International Conference and Exhibition on Electromagnetic Compatibility*, Rouen, France, Apr. 2012.
21. Babouri, A., A. Hedjiedj, and L. Guendouz, "Experimental and theoretical investigation of implantable cardiac pacemaker exposed to low frequency magnetic field," *Journal of Clinical Monitoring and Computing*, Vol. 23, No. 2, 63–73, Apr. 2009.
22. Babouri, A. and A. Hedjiedj, "In vitro investigation of eddy current effect on pacemaker operation generated by low frequency magnetic field," *International Conference of the IEEE Engineering in Medicine and Biology Society*, 23–26, Lyon, France, 2007.
23. Tourab, W. and A. Babouri, "Measurement and modeling of personal exposure to the electric and magnetic fields in the vicinity of high voltage power lines," *Safety and Health at Work*, Vol. 7, No. 2, 102–110, Jun. 2016.
24. Rachedi, A. B., A. Babouri, and X. Zhang, "Electromagnetic pollution inside high-voltage substation," *Revue Roumaine de Sciences Techniques*, Vol. 61, No. 2, 178–182, Jul. 2016.
25. Coccioni, R., F.-R. Yang, K.-P. Ma, and T. Itoh, "Aperture-coupled patch antenna on UC-PBG substrate," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 11, 2123–2130, Nov. 1999.
26. Chouksey, V. and G. Puran, "Review of micro strip patch antenna characteristics analysis and bandwidth enhancement by using U slot microstrip patch antenna," *Communications on Applied Electronics*, Vol. 7, 37–41, Nov. 2017.
27. Irfan, N., C. E. Y. Mustapha, and K. Hettak, "Design of a microstrip-line-fed inset patch antenna for RFID applications," *International Journal of Engineering and Technology*, Vol. 4, No. 5, 558–561, Oct. 2012.

28. Constantine, A. B., *Antennas Theory: Analysis and Design*, 4th Edition, John Wiley&Sons, New Jersey, 2016.
29. Achmad, M., R. Rina, and Rachmansyah, “Design of microstrip antenna for wireless communication at 2.4 GHz,” *Journal of Theoretical and Applied Information Technology*, Vol. 33, 184–192, Nov. 2011.
30. Wang, J. J. H., “An examination of the theory and practices of planar near-field measurement,” *IEEE Transactions on Antennas and Propagation*, Vol. 36, No. 6, 746–753, Jun. 1988.