

Analysis of Electromagnetic Shielding Enclosure for Digital Forensics Examination

Karim Benzaoui, Youcef Amine Medjaouri, and Issam Griche.

Abstract— Shielding enclosures play a crucial role in digital forensics by providing a controlled environment that shields electronic devices from external electromagnetic interference and radio frequency interference. This paper presents an investigation into the analysis of the shielding effectiveness of rectangular conductive enclosures with various aperture configurations. The approach utilizes scattering parameters, specifically the reflection coefficient (S_{11}) and transmission coefficient (S_{21}). The Ansys HFSS simulation software is used to model the enclosure and compute the S-parameters within the frequency range of 1 GHz to 2 GHz. The numerical results of Shielding Effectiveness (SE) obtained are compared with analytical methods, such as Robinson's method based on the transmission line theory (TLM) model, and show good agreement with analytical formulas. The prediction methods presented in this paper can be used by Electromagnetic Compatibility engineers to assess the risk of failures in digital systems exposed to electromagnetic noise, particularly for forensic device testing applications.

Keywords— Conductive enclosure, Digital forensics, Electromagnetic interference, Shielding effectiveness, S-parameters.

I. INTRODUCTION

In digital forensics, safeguarding the integrity of electronic data is crucial [1]. The potential for remote wireless signal access to a device under investigation poses a significant risk, as it could alter or destroy critical data [2]–[5]. To mitigate this risk, metallic enclosures, such as Faraday cages are often employed. These enclosures block all wireless communication, ensuring that the device remains isolated from external electromagnetic (EM) signals during analysis [6], [7]. In this context, a component source of Electromagnetic Interference (EMI) refers to discrete elements that generate EMI, such as wires, cables, connectors, motors, generators, rotating devices, switches, relays, solenoids, vacuum tubes, transistors, diodes, gas lamps, and thyristors. Despite their classification as EMI sources, these components serve as emitters, transforming electrical energy into EM noise [8].

This interference can lead to data loss, degradation of signal integrity, and malfunction of devices, all of which are critical

concerns in digital forensics. The EM shielding solutions are needed to keep sensitive data and equipment safe from outside EMI and to make sure that forensic tools used in digital investigations continue to work properly. In this scenario, most of the electronic equipment, which houses forensic tools or devices during analysis, requires conductive boxes to provide both mechanical protection and electrical shielding for the subsystems and internal circuits.

In addition, for practical applications, apertures or slots of various shapes are essential features of shielding enclosures to accommodate thermal dissipation, Input/output cabling connectors, CD-ROM, and other components. However, these unavoidable discontinuities can degrade the performance of the shielding enclosures in high speed digital systems. To mitigate EMI and susceptibility risks caused by these discontinuities, shielding enclosures with apertures must be designed and an analysis of the EM coupling mechanisms through the apertures must be conducted.

However, these apertures break the enclosure's integrity and are considered to be the primary cause of EM energy leakage, which directly influences the enclosure's SE [9], [10]. The SE can be calculated using numerical simulations or analytical formulations. The analytical formulas for calculating the SE of an aperture in a rectangular box consist of representing the box by a length of rectangular wave guide that has been short-circuited at both ends and is operating above or below cut-off [11], [12]. Numerical modeling involves reproducing a design as a numerical model that can be easily manipulated for various modifications.

Numerical simulations enable system dimensioning, reducing development time, cost, and the number of tests required [13]. Additionally, transmission-line modeling is one of the numerical techniques used to compute shielding effectiveness (SE) [11]. In our study, we focus on the effect of the enclosure's geometry in providing adequate protection for cellular phones against external sources of EM interference during forensic laboratory examinations.

Additionally, to justify the selected frequency range, we focus on the interval from 1 GHz to 2 GHz, as it aligns with the resonance frequencies of the metallic enclosures studied, whose dimensions correspond to this frequency range.

In this paper, we use the Ansys HFSS simulation software to model a rectangular box with various slot shapes and dimensions. We also evaluate the S-parameters and shielding effectiveness (SE) of the enclosure at high frequencies, from 1GHz to 2GHz. The results show that the numerical model agrees well with the analytical model, indicating that the numerical model serves as an effective tool for predicting the SE of conductive enclosures, particularly in high-frequency applications.

II. STATEMENT OF THE PROBLEM

The forensic investigation of personal electronic mobile devices has become a significant aspect of law enforcement agencies' daily operations [14]. Mobile phones, in particular,

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K. Benzaoui, is now with the Electronic Laboratory at the Research and Development Centre (CRD-GN), Algiers, Algeria (e-mail: karim.benzaoui@yahoo.com).

Y. Medjaouri, is now with the Electromagnetic Compatibility Laboratory, Ecole Militaire Polytechnique, Algiers, Algeria (e-mail: medjaouriyoucef@gmail.com).

I. Griche, is now with the Department of Electrical Engineering; Faculty of Sciences; Bouira University; Algeria (e-mail: issam.grich@univ-bouira.dz).

have emerged as vital sources of evidence in criminal investigations, often containing essential information such as call logs, messages, photos, and location data [15]. However, this data is highly volatile and can be easily overwritten or deleted, either intentionally or accidentally, during forensic examination. To address this challenge, various tools and techniques have been developed, such as shielding boxes, which are designed to block all wireless signal noise or EM interference to safeguard mobile phone data because the preservation of data is the primary goal of digital forensics [16], [17].

In the literature, the report by the Interpol European Working Party on IT Crime (2006) provides guidelines and recommendations regarding the use of shielding devices in the context of digital forensics. According to this study, shielding devices play a critical role in maintaining the integrity of digital evidence. Among these devices are Faraday bags, which operate on the Faraday cage principal [15]. As identified by Rajendran and Gopalan [18] in their process for mobile forensics investigation life cycle, after obtaining a digital device and collecting details about the device and its environment, the initial step is to deactivate all external connections including mobile network, Internet, Bluetooth, and tethering.

Doherty [19] highlights the importance of faraday bag's effectiveness during device examination (Fig.1). Therefore, it is crucial to implement EM field measures that prevent any modification or remote destruction of the data on the device while awaiting examination. Furthermore, according to the US National Institute of Justice (NIJ) [20], it is suggested that first responders present at the scene of the crime should possess radio frequency shielding materials in case smartphones or other mobile communications devices are involved in the investigation and need to be safely confiscated.

In this context, the forensic shielding box must be specifically designed for mobile forensics experts who need to examine, evaluate, recover, and analyze data from electronic devices in a secure environment while protecting them from EMI. These enclosures are typically constructed from conductive materials such as aluminum, stainless steel, copper, or composite conductive polymers, which offer effective shielding. The choice of material for shielding is determined by the specific frequencies to be attenuated, as well as its conductivity and permeability properties. Additionally, effective methods for blocking EM radiation, such as a 'Faraday Cage,' are crucial for disconnecting a device from the network and safeguarding its data. For instance, Androulidakis et al. state that a 'Faraday Cage' is an effective method for achieving this [21]. This approach can be utilized for the forensic examination of various mobile devices [22].



Fig. 1: Using shielding enclosures (Faraday bags) to safeguard digital evidence in forensic investigations.

III. APPROACH TO CALCULATE THE (SE) OF ENCLOSURE

The (SE) in decibels (dB), is defined as the ratio of the transmitted power (P_t) of the EM wave through the shield to its incident power (P_i). This relationship is expressed by the following equation [23] :

$$SE(dB) = 10 \log_{10} \left(\frac{P_t}{P_i} \right) \quad (1)$$

The equation in (2) illustrates that the SE (dB) is the sum of three distinct terms: reflection loss (SE_R), absorption loss (SE_A), and multiple reflections (SE_{RM}). At high frequencies, the SE_{RM} is negligible [24], [25].

$$SE(dB) = SE_R(dB) + SE_A(dB) + SE_{RM}(dB) \quad (2)$$

The calculation of the SE, SE_R and SE_A sing S-parameters is presented by (03).

$$SE(dB) = 10 \log_{10} \left| \frac{1}{1-R} \right| + 10 \log_{10} \left| \frac{1-R}{T} \right| = 10 \log_{10} \left| \frac{1}{T} \right| \quad (3)$$

Where: $T = |S_{21}|^2$ is the transmission coefficient and $R = |S_{11}|^2$ is the reflection coefficient [26], [27].

A. Analytical Formulas

This section outlines the Robinson model employed to determine the SE of metallic enclosure with a central rectangular opening of dimensions " $l \times w$ " crossed by a plane wave. The enclosure is assumed to be of parallelepiped shape, with all walls perfectly conductive and of thickness " t ".

The observation point is located a distance " P " away from the aperture within the enclosure, positioned on a line perpendicular to the aperture passing through the center of the enclosure. The SE is the ratio of the E_y or E_x components at the observation point with and without the enclosure, or by the voltage and current at point " P " (Fig.2).

Robinson's model is based on the theory of transmission lines and wave-guides [11]. It entails converting the metal enclosure into an electrical circuit equivalent to Fig.3, where the incident signal is replaced by a source of tension " V_0 " in series with a vacuum impedance $Z_0 = 377 (\Omega)$, and the enclosure is a short-circuited guide with a characteristic impedance " Z_g " and a propagation constants K_g .

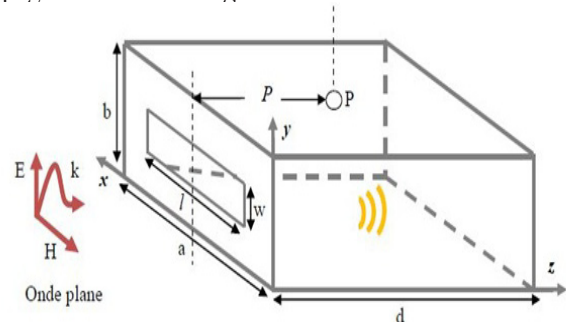


Fig. 2: Rectangular metal enclosure excited through its aperture.

This modeling approach relies on Kirchhoff's laws applied to the equivalent electrical circuit. It enables a simple and rapid resolution of the problem and allows the studied structure to be represented using electrical equations. The principle of this model is based on dividing the geometry of the problem into three parts, corresponding to three different sub-models, namely:

- The incident wave model (the source of interference).
- The aperture model (the slot).
- The cavity model (the enclosed waveguide).

• Disturbance source model:

Every EM system requires an excitation that generates its response. The excitation is a vertically polarized plane wave, represented by a voltage generator “ $V_0=1V$ ” in series with its internal impedance (the impedance of free space $Z_0=377 \Omega$), as shown in Fig. 3.

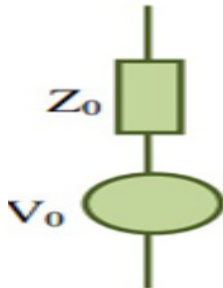


Fig.3: Electrical model of the interference source.

• The aperture model

The aperture is represented by a transmission line in the form of two stubs of length $l/2$ (where l is the length of the slot), connected to each other and short-circuited at both ends (Fig.4).

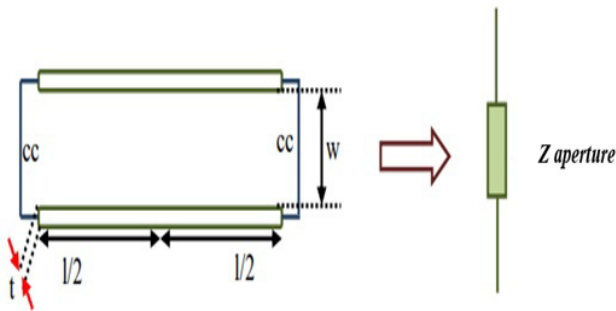


Fig.4: Geometric and electrical model of the aperture.

The localized impedance of the slot is given by Gupta's formulas.

$$Z_{ap} = \frac{1}{2} \frac{l}{a} j Z_{0s} \tan \frac{k_0 l}{2} \quad (4)$$

The characteristic impedance is given by the following formula:

$$Z_{0s} = 120\pi^2 \left[\ln \left(2 \frac{1 + \sqrt{1 - (w_e/b)^2}}{1 - \sqrt{1 - (w_e/b)^2}} \right) \right]^{-1} \frac{k_0 l}{2} \quad (5)$$

The effective width of the aperture is given by the following formula:

$$Z_e = w - \frac{5t}{4\pi} \left(1 + \ln \frac{4\pi w}{t} \right) \quad (6)$$

With:

$k_0=2\pi/\lambda$: The propagation constant.

l : the length of the aperture.

a : the width of the enclosure.

b : the height of the enclosure.

t : the thickness of the enclosure walls.

w : the width of the aperture.

• Model of the enclosure without an aperture

The metallic cavity without an opening can be represented as a waveguide with length “ d ” and its geometric height “ b ” along the (oy) axis, short-circuited at both ends, as shown in Fig. 5.

In this representation, only the existence of the fundamental TE_{10} mode is considered.

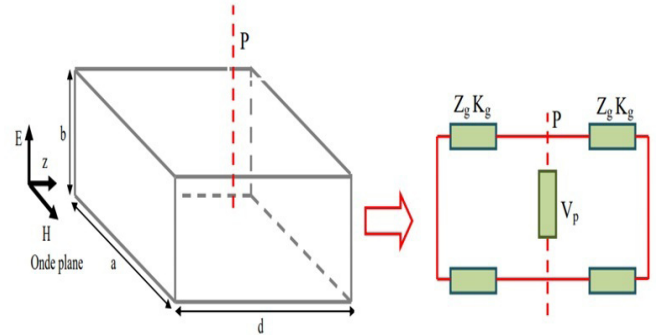


Fig.5: Electrical model of a waveguide.

“ Z_g ”: The characteristic impedance of the waveguide is given by:

$$Z_g = Z_0 / \sqrt{1 - (\lambda/2a)^2} \quad (7)$$

“ k_g ”: The propagation constant is expressed as follows :

$$k_g = k_0 / \sqrt{1 - (\lambda/2a)^2} \quad (8)$$

Based on the analytical models developed above, we construct the equivalent electrical model of Robinson, which corresponds to a perfectly conductive rectangular enclosure with a centered rectangular aperture, illuminated by a normally incident plane wave.

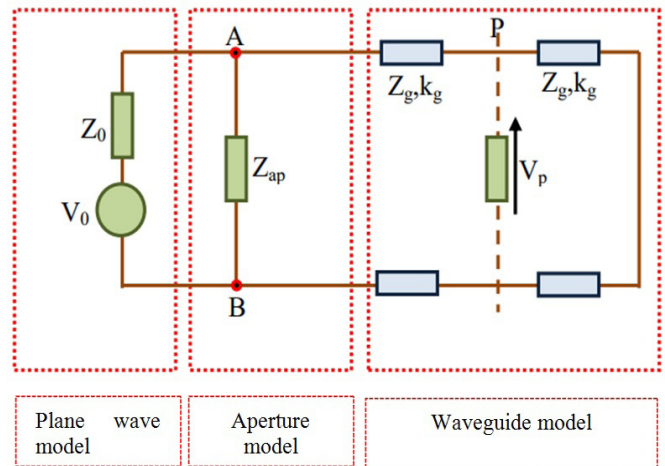


Fig.6: Equivalent electrical circuit model of the complete system.

The electromagnetic energy penetrating inside the enclosure is expressed at a point P (x, y, z) by a voltage “ V_p ” along the equivalent electrical circuit.

This approximation constitutes the first step leading to the evaluation of the electrical (SEE) and magnetic (SEH) shielding efficiencies.

The calculation of the SEE and SEH is carried out from the equivalent electrical circuit of the Robinson model (Fig.7).

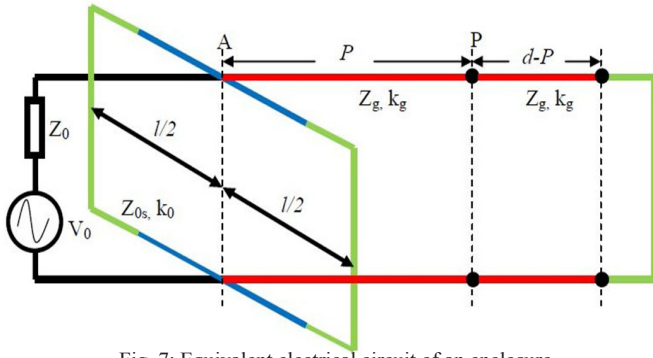


Fig. 7: Equivalent electrical circuit of an enclosure.

We can calculate the voltage " v_p " and the current " i_p ", which represent the electric and magnetic fields at the calculation point P in the presence of the metallic enclosure. Now, we will calculate these quantities in the absence of the metallic enclosure. The load impedance at point P is equal to Z_0 ; in this case, the voltage and current are expressed as follows:

$$V_p' = V_0 / 2 \quad (9)$$

$$i_p' = V_0 / 2Z_0 \quad (10)$$

Equation (4) and (5) express the SEE and SHE respectively [12].

$$SE(dB) = -20 \log_{10} \left| \frac{v_p}{v_p'} \right| = -20 \log_{10} \left| \frac{2v_p}{v_0} \right| \quad (11)$$

$$SE(dB) = -20 \log_{10} \left| \frac{i_p}{i_p'} \right| = -20 \log_{10} \left| \frac{2i_p}{i_0} \right| \quad (12)$$

B. Numerical Analysis

In this section, we will use the Ansys HFSS simulation software, which is a good high-frequency simulator based on the finite element method (FEM). It will be utilized to simulate an enclosure with apertures. The enclosure is made of conductive material, with dimensions of 230mm × 60mm × 150mm and includes an aperture of 100mm × 5mm.

The process using HFSS software to calculate the SE of enclosure is detailed below:

- Define the analysis domain including the electrical properties of enclosure (conductivity, permittivity, and permeability).
- Construct the 3D geometry of the enclosure, incorporating its apertures, dimensions, and wall thickness.
- Set the frequency range for the analysis, the simulation parameters of the model are performed in the frequency range from 1GHz to 2GHz.
- Surround the enclosure with free-space regions to simulate accurate wave propagation.
- Plane wave sources (ports) are placed both inside and outside the enclosure to be exposed to a guided plane wave and configure the excitation parameters, including the frequency range and center frequency.
- Select the frequency domain solver in HFSS and execute the simulation to compute the S-parameters over the specified frequency range.
- Extract the S-parameters to determine the reflection and transmission values in (dB) and calculate the SE.
- The SE is derived by subtracting two measurements: the

reference measurement (SE_{ref}) taken without the enclosure (two ports only) and the load measurement (SE_{load}), taken with the enclosure placed between the source and receiver. These measurements are conducted according to the model designs shown in Fig. 8b and Fig. 8a, respectively. The signal level from the source is kept constant in both cases to ensure consistency.

The SE can be also obtained from the numerical simulations of the scattering parameters according to equation (3).

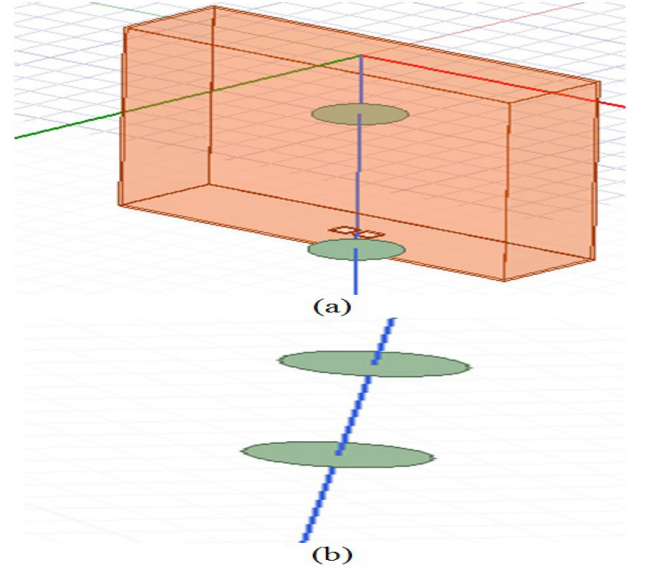


Fig. 8: 3D simulation model in Ansys HFSS: (a) material load, and (b) reference case.

IV. RESULTS AND DISCUSSION

In this section, we compute the (SE) of an enclosure with apertures, taking into account the general factors that influence SE (dimensions, form, and number of apertures).

Initially, we will analyze the fundamental concepts of the shielding enclosure with aperture. Next, we will discuss the results from the computational simulations for three different shapes of apertures (rectangular, square, and circular) in both the cases of a single aperture and multiple apertures.

Afterward, a comparison of the obtained results from the analytical model and numerical model will be performed to validate the proposed approach.

Figures 9, 10 and 11 illustrate the (SE) coefficient calculated using analytical model of Robinson's approach and numerical simulations performed in HFSS for metallic enclosure with dimensions of 230mm × 60mm × 150mm including three types of the same surface aperture shapes: a rectangular aperture of 100mm × 5mm, circular aperture with a radius of 12.62mm, and a square aperture of 22.36mm.

According to the plots, the enclosure exhibits resonance at approximately 1.2 GHz, resulting in negative shielding in this frequency range.

Despite the different shapes of the apertures, all the curves demonstrate the same resonant frequency, which corresponds to the dimensions of the enclosure. This consistency in the resonant frequency is due to the fact that the resonant frequency is primarily determined by the geometric dimensions of the enclosure, such as its length, width, and height. When the incident EM frequency aligns with the resonant frequency of the enclosure, the interaction between the EM wave and the aperture is enhanced, leading to potential resonance effects that can reduce the SE.

The results show good agreement between the analytical and numerical models, both above and below the 1.2 GHz resonant frequency.

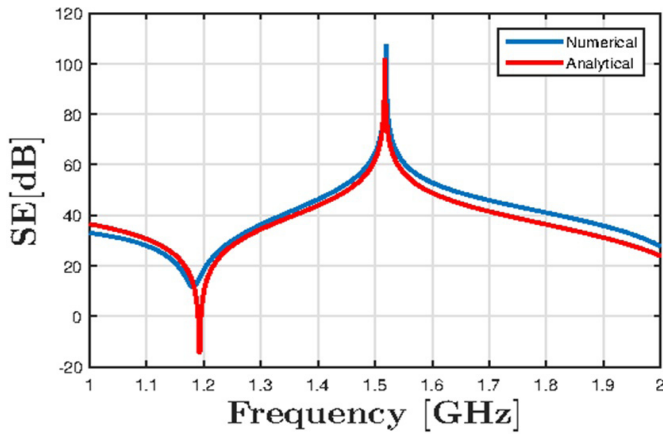


Fig.9: Evolution of the SE of the metallic enclosure with a rectangular aperture as a function of frequency

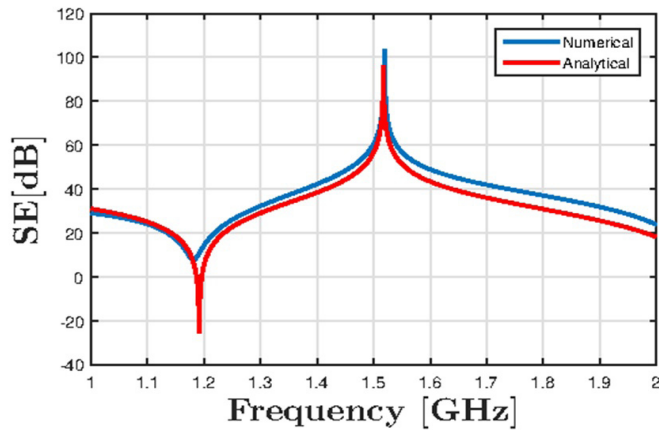


Fig.10: Evolution of the SE of the metallic enclosure with a square aperture as a function of frequency.

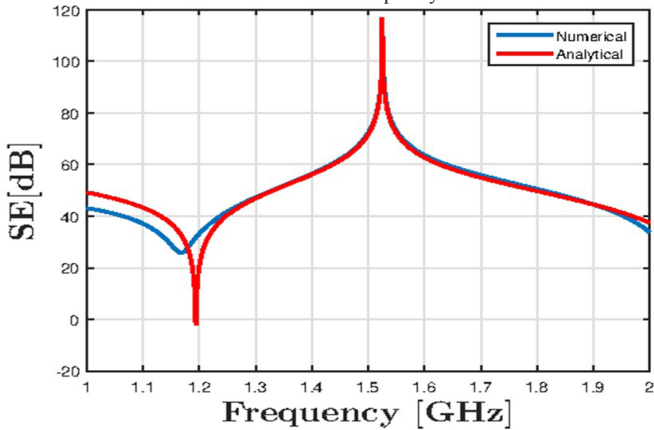


Fig.11: Evolution of the SE of the metallic enclosure with a circular aperture as a function of frequency.

As shown in Fig.12, Fig.13, and Fig.14, we simulated three types of enclosures, each with two apertures. The apertures were of the same size for all three types: rectangular, square, and circular.

This simulation was led to study the effect of number apertures on the SE. The enclosure dimensions were fixed at 230 mm × 60 mm × 150 mm. The number of apertures does not influence the resonant frequency, which remains consistent across all three plots.

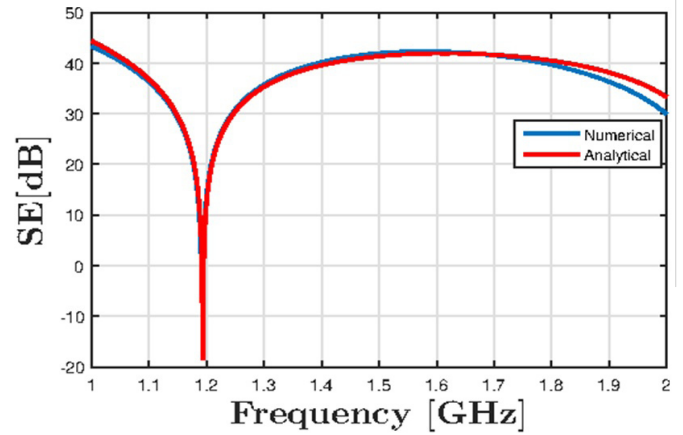


Fig. 12: Evolution of the SE of enclosure with two rectangular apertures as a function of frequency

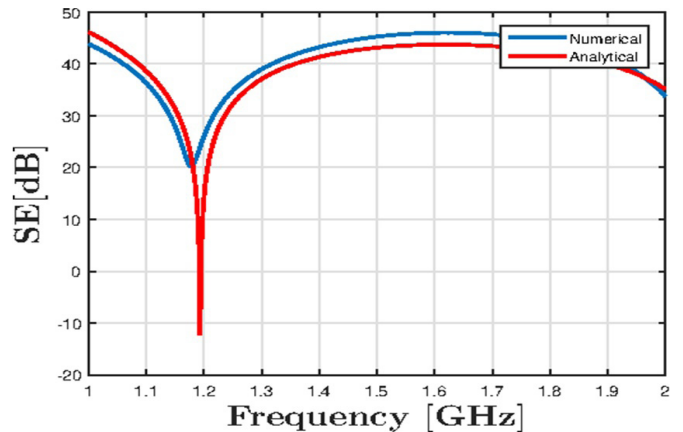


Fig. 13: Evolution of the SE of enclosure with two circular apertures as a function of frequency.

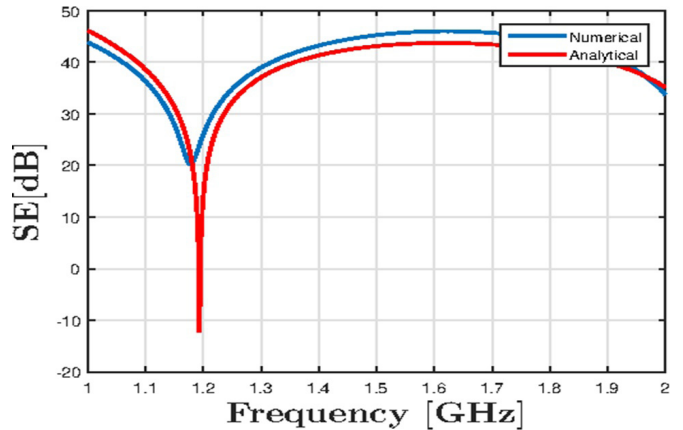


Fig. 14: Evolution of the SE of enclosure with two square apertures as a function of frequency.

Both the analytical model and the numerical simulation indicate that SE decreases with more apertures when the number of apertures increases, as long as the total aperture area stays the same. The results show good agreement between the analytical and numerical models, across frequencies above and below 1.2GHz.

Given the complexity of the shielding structure, the calculation of the SE is particularly sensitive, and in some cases, numerical methods are essential for accurate results.

In this paper, we presented the results of EM simulations of metallic enclosures with various geometric shapes, excited by a plane wave, focusing on the impact of aperture characteristics (such as shape, number, and spacing) on the SE. Overall, SE improves when a larger number of openings is concentrated in

a single location on the enclosure, where the shielding is more effectively compromised. The results presented here offer an efficient method for evaluating how design parameters influence the SE of an enclosure. Numerical simulations indicate that doubling the number of openings, while maintaining the same total aperture area, leads to an increase in SE.

V. CONCLUSION

The use of Faraday bags and metallic enclosures to protect electronic equipment from electromagnetic interference has become essential in forensic science, safeguarding the integrity of digital evidence and preventing any remote manipulation of seized devices. This study presents a quick numerical method for determining the SE of conductive enclosures with different aperture sizes and compares it with an analytical approach. Numerical simulations were used to extract the S11 and S12 parameters for evaluating the SE. To achieve optimal results, it is important that the aperture size is much smaller than the enclosure dimensions. The results show a strong correlation between the numerical and analytical models across the frequency range of 1GHz to 2GHz. Overall, this study provides significant insights into the effect of various aperture on the SE of conductive enclosures, and offering useful for guidance for the optimization of enclosure designs, improving shielding performance, and ensuring the protection of equipment against EMI, particularly in digital forensics applications.

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