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COMPUTATIONAL AND EXPERIMENTAL FORMULATION OF HYBRID NANOMATERIAL SHIELDS FOR ELECTROMAGNETIC RADIATION MITIGATION FROM MOBILE TOWERS

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Abstract: - The proposed research work focused on developing effective shielding materials to safeguard the public from electromagnetic interference (EMI) radiation emitted by mobile towers. Mathematical modelling played a critical role in understanding the physical phenomena, predicting shielding effectiveness, and optimizing design parameters. Copper and Aluminium emerged as top-performing materials, while Nickel and Carbon Nanotubes showed promise. Innovative geometric designs, such as the Wire-mesh 3D model and grid type shielding, were explored for enhanced EMI attenuation. The project's findings highlighted the importance of selecting the right material based on frequency requirements, while mathematical modelling enabled efficient decision-making and reduced the need for extensive experimentation.

Keywords: EMF Radiation, Shielding materials, Carbon Nanotubes, Reflection coefficient, Skin depth, Shielding Effectiveness.

I. INTRODUCTION

A. Background information on EMI shielding and the need for improved materials

The increasing use of mobile communication networks and the proliferation of mobile towers has raised concerns about potential health risks associated with electromagnetic radiation exposure. Mobile towers emit electromagnetic fields (EMF) as they transmit signals to and receive signals from mobile devices as shown in figure 1. There is some evidence that EMF radiation from mobile towers can cause adverse health effects, such as cancer. However, the research on this topic is still inconclusive. One way to reduce exposure to EMF radiation from mobile towers is to use shielding materials. These materials can block or absorb EMF radiation, reducing the amount of radiation that reaches the public. There are several different shielding materials that can be used, including metals, plastics, and composites. The most effective shielding materials are metals, such as copper, aluminium, and steel.

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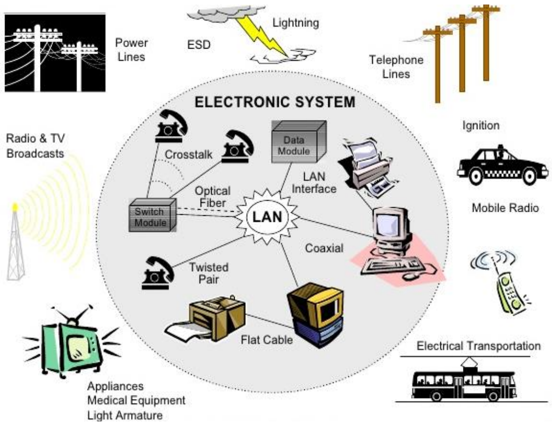

Figure 1. Different sources of Electromagnetic radiation/interference [1]

The shielding material should be designed to fit the shape of the mobile tower and to block or absorb EMF radiation from all directions. The optimal shielding material and shape for a particular mobile tower will depend on several factors, including the size and location of the tower, the amount of EMF radiation it emits, and the desired level of protection. The development of new shielding materials and shapes is an active area of research. The research work is focused on exploration of suitable shielding materials to mitigate exposure and provide optimal protection for the public.

B. Rationale for selecting Nickel, Copper, Aluminium and MWCNT coated nickel as a potential solution

Nickel, copper, and aluminium are all good conductors of electricity, which means they can effectively shield against electromagnetic radiation. MWCNT coated nickel is a newer material that has potential of shielding properties not less than these three materials. The advantages of these materials are:

(i)They have a high number of free electrons.

(ii)They have a low resistivity.

(iii)They have a high conductivity.

In addition to their shielding properties, these four metals are also relatively inexpensive and easy to work with, which makes them attractive for shielding applications.

C. The objectives of the proposed research work

(i)Perform comprehensive literature review to identify shielding effectiveness materials.

(ii)Compare shielding effectiveness of the identified materials at different frequencies.

(iii)Examine use of grid type shielding with different materials that affect the shielding effectiveness of these materials.

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The scope of the present work based on comprehensive literature review reported in Section:II is as follows:

(i)Focus on investigation of shielding effectiveness for nickel, aluminium, copper, MWCNT and Nickel coated MWCNT.

(ii)Perform simulation on shielding effectiveness at different frequencies in MHz (440, 660, 840, 1000, 2000, 3000, 3700).

II. LITERATURE REVIEW

The demand for high-speed internet and signal networks has grown in recent decades. High-speed internet is essential to transform the way we live, work, learn, and play [1]. The increasing use of high-speed internet and cell phones has resulted in increase in the number of cell phone towers. The antennae positioned on these towers radiates Electromagnetic waves [2], which is mainly non-ionizing radiation (do not directly destroy the DNA inside cell), whereas radiation such as x-rays, gamma rays, and ultraviolet (UV) rays are ionizing in nature. In the coming years, use of high-speed networks may result in producing ionizing radiation, thus causing the community to suffer from variety of health problems [3].

Shielding is one of the prime protective mechanisms to be free from EM exposure. Shielding Effectiveness (SE) is the degree of isolation from EM radiations provided by a shield. When the distance between the radiation source and the shield exceeds $\lambda/2\pi$, it is regarded to be in the far field shielding zone, else in the near field shielding region [4]. In the far field, electromagnetic plane wave theory is used, while in the near field, dipole theory is used. Quality shielding materials are usually made from any metal or metallic compound, including brass, copper, aluminium, silver, and steel as they are good conductors of electricity [5, 6].

It is due to the extensive use of electronic devices and systems, electromagnetic interference (EMI) has become a growing concern, necessitating the use of efficient shielding materials. Since metal-based shields are heavier, they are being modified with other materials to address EMI and associated issues, with reflection and absorption being the primary processes in the shielding mechanism. In a study by Saini and Shukla (2020), $Ag/NiFe_2O_4/PANI$ nanocomposites were fabricated using the in-situ polymer technique, demonstrating excellent EMI shielding effectiveness [7]. The prepared carbon fiber composites demonstrated good electromagnetic interference (EMI) shielding effectiveness, and the combination of conductive and magnetic materials proved to enhance the EMI shielding performance. The research establishes a promising foundation for future advancements in EMI shielding materials [8]. Some researchers aim to address the rapid growth of electronic devices leading to radio frequency interference (RFI) and electromagnetic interference (EMI). To overcome limitations of heavy and corrosive metals used as EMI shielding materials, the study focuses on developing lightweight, thin, and environmentally friendly alternatives. Light materials such as polymer-based foams and aerogels with fillers like metal, metal oxide, and carbon demonstrate superior electrical, dielectric, thermal, mechanical, and magnetic properties for EMI shielding applications in the frequency range of 1 kHz to 1.9 GHz.[9]. The combination of carbon nanotubes and carbon nanofibers led to enhanced EMI shielding, with the composite containing

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1 wt% carbon nanotubes and 10 wt% carbon nanofibers achieving a shielding effectiveness of 20.3 dB, making it suitable for commercial EMI shielding applications due to its superior microstructure [10]. While metals serve as excellent EMI shielding agents, their heavy weight, high cost, and environmental susceptibility have led to the exploration of fiber reinforced polymeric (FRP) composite materials, especially carbon fiber, for aerospace applications, requiring the addition of filler materials to enhance electrical conductivity and shielding effectiveness (SE).

The study concludes that adding metal powders to carbon fiber reinforced polymer composites is a cost-effective method to improve shielding effectiveness, though analytical models for SE vary and lack correlation with physical testing, showing a slight improvement in SE when using metal mesh and materials with discontinuous fillers, warranting further exploration of filler materials' impact on composite processing [11]. The study also focuses on creating an innovative 3D porous heterostructure EM interference (EMI) shielding material by integrating dielectric and magnetic components. The process involves coating highly porous nickel metal foam (NF) with polyaniline (PANI) using a facile in-situ polymerization technique, resulting in the formation of Ni/PANI composite foam (NPF) with exceptional shielding effectiveness [12].

III. METHODOLOGY

The methodology for performing a shielding effectiveness study using COMSOL Multiphysics:

1. Setup: The first step is to set up the model in COMSOL Multiphysics. This involves creating the geometry of the shield and the source of the electromagnetic radiation. The materials of the shield and the source must also be specified.

2. Meshing: The next step is to mesh the model. This involves dividing the geometry into a grid of small elements. The size of the elements must be small enough to accurately capture the behaviour of the electromagnetic waves.

3. Boundary conditions: The boundary conditions must then be specified. These conditions define how the electromagnetic waves interact with the boundaries of the model.

4. Simulation: The model is then simulated. This involves solving the Maxwell equations for the electromagnetic waves in the model. The results of the simulation will be a set of electric and magnetic field values at each point in the model.

5. Post-processing: The results of the simulation must then be post-processed. This involves calculating the shielding effectiveness of the shield.

Here are the specific steps to perform a shielding effectiveness study using COMSOL Multiphysics for the study parameters Electromagnetic Waves, Frequency Domain Frequency (MHz): 440, 660, 840, 1000, 2000, 3000, 3700.

The results of the shielding effectiveness study can be used to compare the shielding effectiveness of different materials and to determine the factors that affect the shielding effectiveness of a material. The results can also be used to design new shielding materials and products. The Flow chart for the computational analysis on COMSOL is presented in Figure 2.

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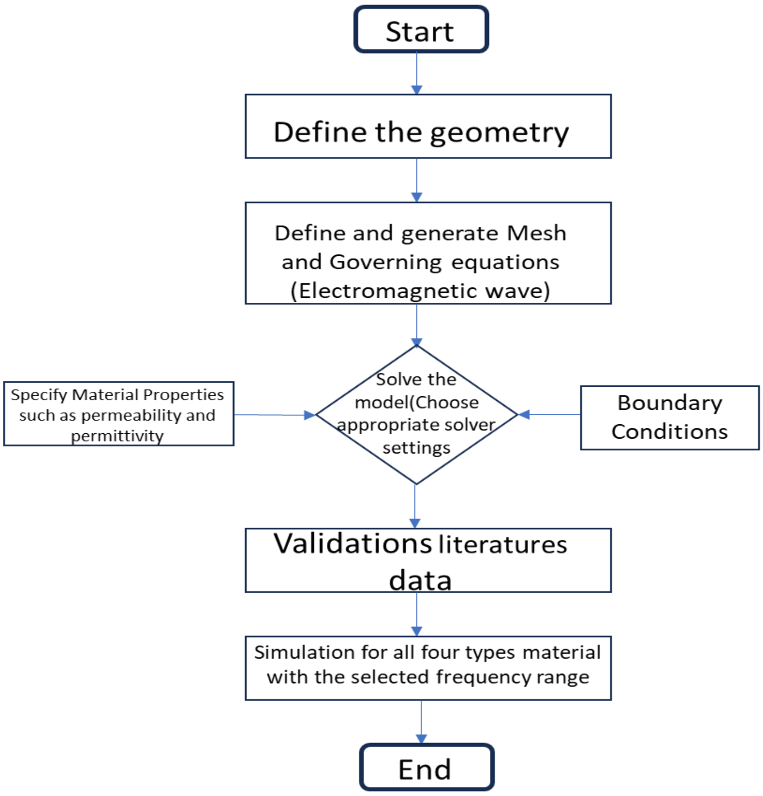

Figure 2. Flow chart for the computational analysis on COMSOL

A.Materials properties used in this study are as follows:

Materials: MWCNT, Nickel, Copper, and Aluminium for comparative study.

Table 1. Material Property of different material used for this study

S. No	**Property**		**Values**		
		Nickel	**Aluminium**	**Copper**	**MWCNT**
1	Relative permeability	1	1	1	1
2	Electrical conductivity (S/m)	13.8×10^{6}	3.774×10^{7}	5.998×10^{7}	1×10^{7}
3	Coefficient of thermal expansion (1/K)	13.4×10^{-6}	23×10^{-6}	17×10^{-6}	2×10^{-6}
4	Heat capacity at constant pressure (J/ (kg. K))	445	900	385	845

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5	Relative permittivity	1	1	1	1
6	Density (kg/m^3)	8900	2700	8960	2200
7	Thermal conductivity (W / (m. K))	90.7	238	400	3000

The formulae used for COMSOL simulation of attenuation/shielding effectiveness consisting the values of permeability, permittivity of material used, thickness of the grid, size of the grid, frequency of operation.

B.Governing equation to calculate the shielding effectiveness using the wave equation for electric fields:

The governing equation can be written in the form

$$\nabla \times (\mu_r^{-1} \nabla \times \boldsymbol{E}) - k_0^2 \varepsilon_{rc} \boldsymbol{E} = 0$$

where ***n***=refractive index, ***E*** = electric field intensity, ε_r=Relative permittivity

The Wave Number (k_o) of free space

$$k_o = \omega\sqrt{\varepsilon_0 \mu_0} = \frac{\omega}{c_0}$$

where c_0 is the speed of light in vacuum.

Note: When Relative permittivity is selected, the default Relative permittivity ε_r takes values from material.

C.Geometry:

(i)Length Unit: meter

(ii)Wire-mesh 3D model

(iii)One grid dimension: 115 mm×115 mm×1 mm

The "Wire-mesh 3D model" and "grid type shielding design with variable distance between radiation source and shielding" are related to the geometry and design of shielding materials for electromagnetic interference (EMI) applications. These designs aim to enhance the EMI shielding effectiveness by providing unique geometries and structures. Figure 3: shows grid type shielding design with variable distance between radiation source and shielding.

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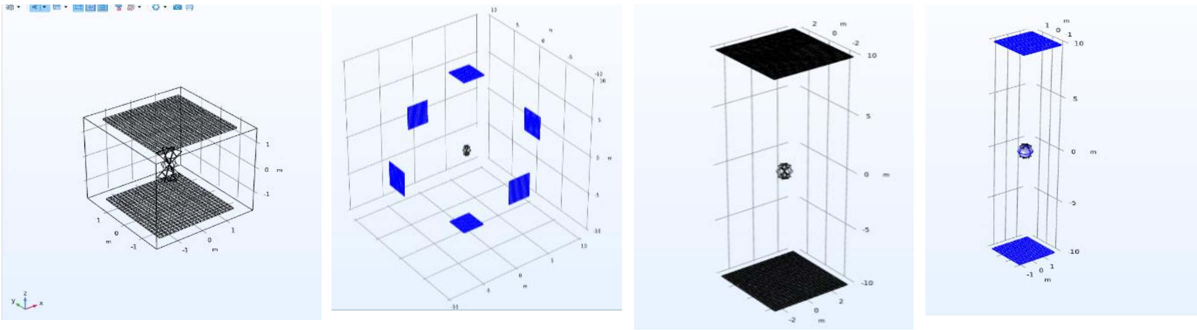

(a) (b) (c) (d)

Figure 3. Grid type shielding design with variable distance between radiation source and shielding (a) Grid Design (b) isometric view of design for all four directions (c) Design taken for this investigation with increased distance (d) Generated mesh.

IV. Mathematical Modelling

Mathematical modeling plays a crucial role in the proposed work focused on the development of suitable shielding materials for optimal protection against EMF radiation from mobile towers. It provides a theoretical framework to analyze how different factors, such as material properties, geometry, and frequency, affect the shielding effectiveness. The mathematical model allows for quick design validation and comparison of different shielding materials and configurations. It helps in identifying the most promising materials for subsequent experimental validation.

MATLAB Programming M Files are used for Mathematical Modelling; the procedure is as follows:

Step1: Calculate impedance of the materials MWCNT, Nickel, Copper, and Aluminum at selected frequency

Step2: Calculate degree of penetration in terms of skin depth for SE calculation

Step3: Calculate the Shielding Effectiveness for the material at a given frequency, i.e absorption loss (SA)

Step4: Calculate reflection coefficient

Step5: Calculate the Shielding Effectiveness for the material at the given frequency i.e reflection loss (SRe)

Step6: Total shielding effectiveness is (SA + SRe)

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Calculate impedance of the materials Nickel, Aluminium. Copper and MWCNT at 3700 MHz frequency

To calculate the impedance (Z) of the materials at a specific frequency (in this case, 3700 MHz) and to consider their complex impedance. The complex impedance includes both the resistance (R) and reactance (X). The formula for complex impedance is:

$Z = R + jX$

where

Z is the complex impedance (in Ohms).

R is the resistance (in Ohms).

X is the reactance (in Ohms).

For simplicity, we have assumed that the reactance of these materials is negligible at the given frequency.

Table 2. Impedance of materials Nickel, Aluminium, Copper and MWCNT at 3700 MHz.

S. No	Parameter	Nickel	Aluminium	Copper	MWCNT
1	Resistance (ρ)	Approx 6.99×10^{-8} Ω·m (at 20°C)	Approx 2.65×10^{-8} Ω·m (at 20°C)	Approx 1.68×10^{-8} Ω·m (at 20°C)	Approx 10^{-4} Ω·m (as before)
2	Frequency (f)	3700 MHz (3.7×10^9 Hz)	3700 MHz (3.7×10^9 Hz)	3700 MHz (3.7×10^9 Hz)	3700 MHz (3.7×10^9 Hz)
3	Reactance (X)	Negligible (assumed)	Negligible (assumed)	Negligible (assumed)	Negligible (assumed)
4	Impedance (Z)	$Z=R=6.99\text{x}10^{-8}\Omega$	$Z=R=2.65\times10^{-8}\ \Omega$	$Z=R=1.68\times10^{-8}\ \Omega$	$Z=R=10^{-4}\ \Omega$

Calculate the shielding effectiveness for copper (absorption loss)

frequency = 3.7e9; % 3.7 GHz (high-frequency scenario)
thickness = 0.000001; % 1 micron (thickness of the copper shielding material)
mu0 = 4 * pi * e-7; % Permeability of free space in H/m
conductivity_copper = 5.998e7; % Electrical conductivity of copper in S/m

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Calculate the angular frequency
angular_frequency = 2 * pi * frequency;
Calculate the skin depth
skin_depth = sqrt (2 / (angular_frequency * mu0 * conductivity_copper))
SA (absorption loss) = 20 * log10(exp (thickness / skin_depth)) = 8.1043dB
Calculate the Shielding effectiveness for Copper (Reflection Loss)
Permittivity of air ($\mathcal{E}_{air}$) = 8.854e-12;
Permittivity of the shielding material (F/m) ($\mathcal{E}_{copper}$)=1.013* $\mathcal{E}_{air}$=8.9691e-12
Conductivity of copper material (S/m) = 5.998e7;
Incident electric field strength
Incident electric field strength (V/m) = 1;
Calculate the wave impedance
Wave impedance of air (ohms) (Z_{air}) = $\sqrt{\frac{\mu_0}{\varepsilon_0}}$ =376.730313
Impedance of air = 376.730313 **Ω**
The wave impedance of copper at 3700 MHz is approximately 125 **Ω** . This can be calculated using the formula

$Z_{copper} = \sqrt{\frac{\mu}{\varepsilon}}$ =125 **Ω**

Calculate the reflection co-efficient

Gamma (γ) = $\sqrt{\frac{(z_{copper}+1i*z_{air}*\text{conductivity of copper})}{(z_{air}+1i*z_{copper}*\text{conductivity of copper})}}$

Reflection_coefficient = (γ-1)/(γ+1);
Reflection_coefficient = 0.0016 + 0.0000i
SRe(Reflection) = 20*log 10 (1/abs (reflection_coefficient) = 55.84 dB

Therefore,
Total Shielding Effectiveness (SEe)=SRe+SA= 55.84 dB+8.1043 dB=63.94 dB

% Program : SE Calculator for Copper Material

```
clc
clear all
sigmar = 1;
mur=1;
mu0 = 4 * pi * 1e-7;
```


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```
conductivity_Copper = 5.998e7;
t=0.000001
finax = 3.7e9;
angular_frequency = 2 * pi * finax;
skin_depth = sqrt (2 / (angular_frequency * mu0 * conductivity_Copper));
  SA =  20 * log10(exp(t / skin_depth))
% Material properties
epsilon_air = 8.854e-12; % Permittivity of air or vacuum (F/m)
epsilon_material = 1.013 * epsilon_air; % Permittivity of the shielding material (F/m)
conductivity_material =5.998e7; % Conductivity of the shielding material (S/m)

% Incident electric field strength
E_incident = 1; % Incident electric field strength (V/m)

% Calculate the wave impedance
eta_air = 1 / (sqrt(epsilon_air)); % Wave impedance of air or vacuum (ohms)
eta_material = 1 / (sqrt(epsilon_material)); % Wave impedance of the shielding material (ohms)

% Calculate the reflection coefficient
gamma = sqrt ((eta_material + 1i * eta_air * conductivity_material) / (eta_air + 1i * eta_material * conductivity_material));
reflection_coefficient = (gamma - 1) / (gamma + 1);

% Calculate the shielding effectiveness
SRe = 20 * log10(1 / abs(reflection_coefficient))
SEe = SRe + SA
```

Figure 4. MATLAB Script for Shielding Effectiveness calculations

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V. RESULTS

Table 2 depicts the values of Shielding Effectiveness at different frequencies ranging from 440 MHz to 3700 MHz for each of the chosen material; Nickel, Aluminium, Copper, MWCNT (without coating), MWCNT (with Nickel coating). The table also provides the comparison of these values with respective values through COMSOL simulation and corresponding Mathematical Modelling using MATLAB. An improved visualization of the findings of this research summarised in the table is also being represented via a 2-D Graph as Figure 5(a) and 4(b).

The results simulation and mathematical results were compared and validated and found similar trend. The results of the literature 13 presented only two materials such as copper and mu-metal. In literature 14, SE varies in between 53 to 67 dBs for the 1G- 4G range for the Copper materials and 37 to 53 dBs for Aluminium for same frequency range. Whereas in this study, the SE varies in between 51.4 to 55.7 dBs for Copper, and SE varies in between 49.4 to 54.6 for Aluminium for the frequency range 0.44 GHz to 3.7 GHz.

Table 3. Shielding Effectiveness values for all the materials at different frequencies taken into consideration

Material	**Nickel**		**Aluminum**		**Copper**		**MWCNT**		**Coated MWCNT**	
Frequency(MHz)	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Matical**
440	48.1	57.18	49.4	58.06	51.4	58.63	47.6	56.64	50.5	58.12
660	48.6	57.48	51.2	58.56	52.6	59.26	48.4	56.83	52.1	58.64
840	49	57.69	52	58.91	52.7	59.70	48.8	56.95	52.5	59
1000	50.9	57.86	52.8	59.19	52.9	60.05	50.6	57.05	52.8	59.29
2000	51.5	58.70	53.2	60.57	53.1	61.79	51	57.56	53	60.72
3000	52.6	59.35	54.1	61.64	53.6	63.13	52	57.95	53.4	61.81

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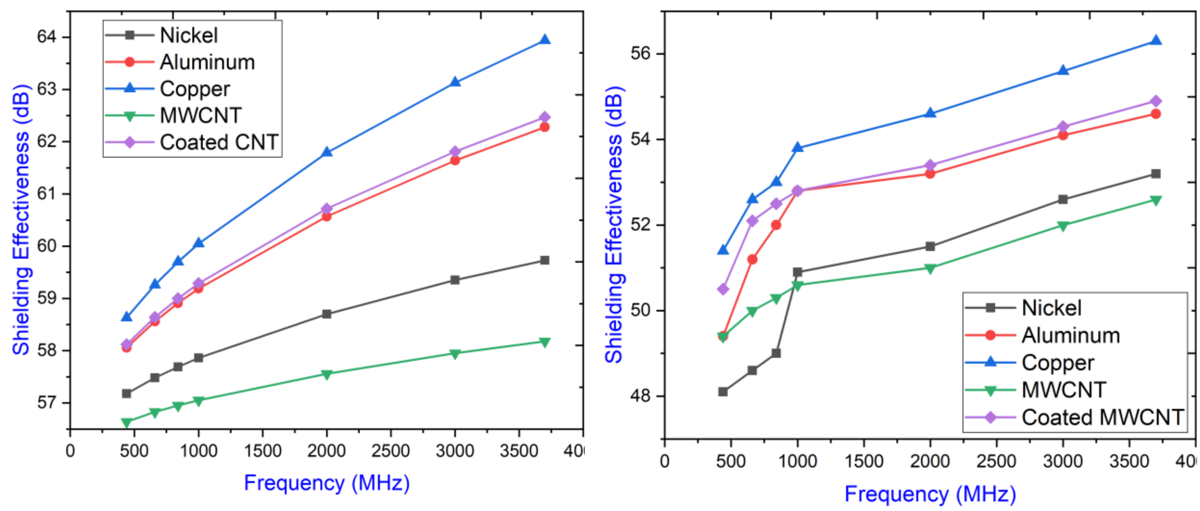
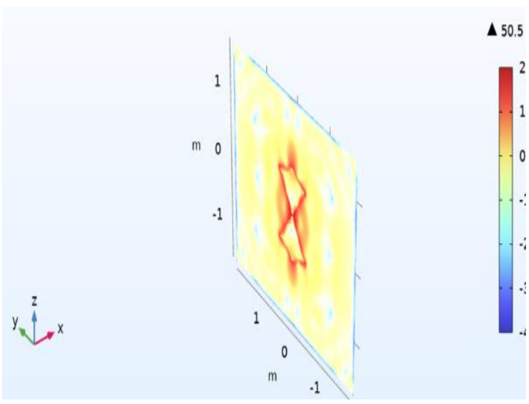
Material	**Nickel**		**Aluminum**		**Copper**		**MWCNT**		**Coated MWCNT**	
Frequency(MHz)	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**	**COMSOL**	**Mathematical**
3700	53.2	59.73	54.6	62.28	55.7	63.94	52.6	58.18	54.2	62.47



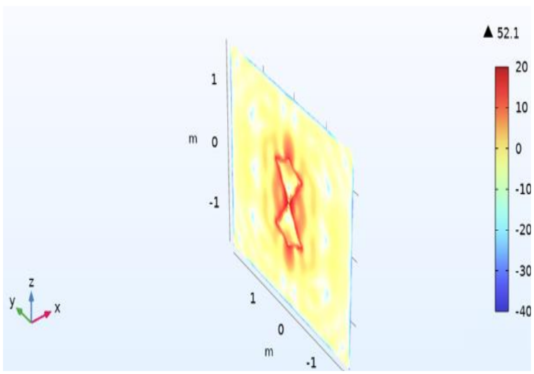
(a) SE values_Mathematical Modelling **(b) SE values_COMSOL Simulation**

Figure 5 (a) &(b). Effects of frequencies on the Shielding Effectiveness for Nickel, Aluminium, Copper, MWCNT and coated MWCNT

(a)



(b)



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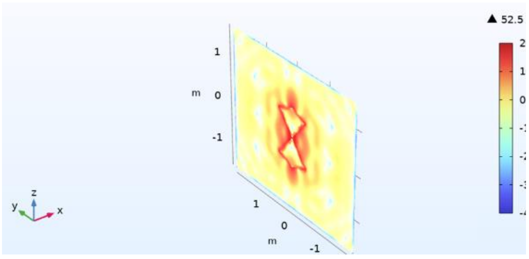
(c)



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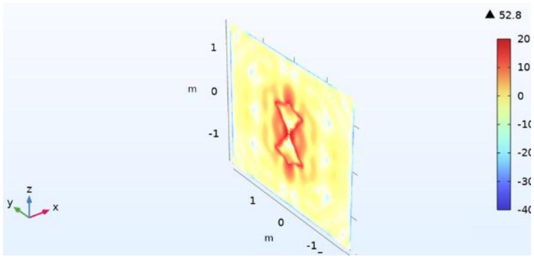
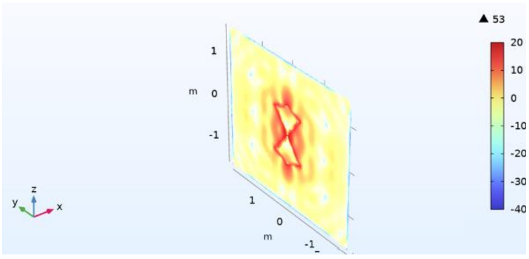
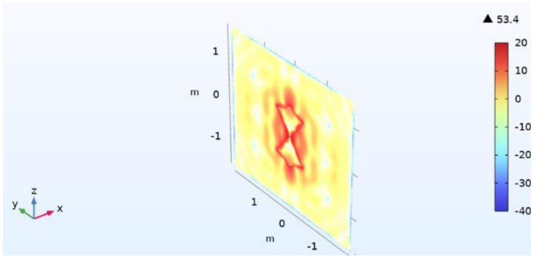


(e)



(f)



(g)

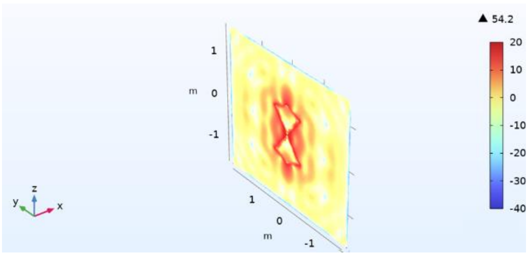


Figure 6. represents Shielding Effectiveness for Nickel coated MWCNT at (a) 440 MHz(b) 660 MHz (c) 840 MHz (d) 1000 MHz (e) 2000 MHz (f) 3000 MHz (g) 3700 MHz

VI. CONCLUSIONS

The numerical and simulation results suggest that copper provides high shielding effectiveness against electromagnetic radiation as compared to all other materials selected for the study as shown in figure 5. Copper exhibits high shielding effectiveness, especially at higher frequencies. At low frequencies, the impedance of the copper dominates the shielding effectiveness. As the frequency increases, the skin depth becomes more critical, and the shielding effectiveness is enhanced.

Open-cell metal foam with a grid geometry offers a promising alternative for EMI shielding in certain applications. Open-cell metal foams are a type of cellular material that consist of a network of interconnected metal struts or cells, resulting in a porous and lightweight structure. The grid geometry, characterized by regularly spaced and aligned cells, are found to be advantageous for EMI shielding. A special category of open-cell metal foam developed recently such as CNTs and CNTs with appropriate selected material composition, is experimented as part of current study. It is found to offer shielding effectiveness comparable to copper. Interestingly meeting the objective of current research, as in this paper, the Shielding Effectiveness of MWCNT with carefully selected Nickel coating composition is observed to be better from the offered Shielding Effectiveness of metals other than copper. Nonetheless

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MWCNT (as compared with copper) with coating has been found optimal in view of the results found via COMSOL Simulation performance characteristics as shown in figure 5. Other characteristics such as exceptional strength to weight ratio, malleability, corrosion resistance, excellent electrical conductivity indicate their closeness to those of copper. However, the challenge lies in arriving at the thickness of coating material duly optimizing with several other favourable factors of MWCNT (including cost), plays a vital role in achieving overall shielding performance.. After all there is a dire need for such a shielding solution with huge potential for high usage by the public as compared to conventional shields.

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