

# Characterization of Radio Wave Propagation through Metallic Materials

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## ABSTRACT

The propagation of radio wave through metallic structures which often suffers signal attenuation has been a major concern to both the network engineers and the subscribers. In particular, the loss of electromagnetic (EM) signal when propagated through metals has been attributed to the conductivity ( $\sigma$ ) of the material as reported in the literature. However, the significance of the effect of conductivity and other parameters of specific metals on radio wave signal has not received much research attention. Consequently, this paper seeks to characterize the radio wave propagation through metallic materials. Specifically, Copper and Iron are chosen due to their relative availability and the rate of deployment in almost every constructions and installations; such that when an incident wave impinges on the interface between the air and the metal, the reflection coefficient and transmission coefficient of the metals are computed. The general solutions of wave equation (SWE) using boundary conditions method is used in the analyses. The outcome of the analyses is presented in graphical form showing the separate contributions of each of the metals on radio wave. The simulation results show that different metallic materials have separate effects on radio wave even though the frequency of propagation and materials' thickness are constant; because, the conductivities of the materials (metallic materials) vary. This paper has been able to establish through simulation that, as the width of the metal is increased from 1mm to 10mm, the transmission coefficient decreases even to zero (0dB) decibel; whereas, the reflection coefficient continues to rise. Therefore, in order to achieve a reasonable level of radio wave transmission through metals, proper attention must be paid to the width of the metal(s) chosen as revealed in this research which has not been reported in the literature. This research has not addressed the computation of electromagnetic field power transfer and intrinsic impedance through metallic materials; it is hereby recommended for future work.

## 1. INTRODUCTION

Electromagnetic (EM) fields experience variations in their directions and amplitudes and exhibit different characteristics as they are transmitted across various materials as a result of the propagation through the interfaces between the materials. The various properties exhibited by radio wave are determined by the type of material, the direction in which the signal is propagated, the frequency of propagation and the orientation (polarization) of the waves. Perpendicular incidence and oblique incidence are the main conditions often

encountered in applications by waves as they propagate different materials on both the dielectric interface and conducting interface (Ida, 2000; Seybold, 2005).

Usually, EM waves penetrate through different materials with different interfaces, and these may include; the interface between a pair of optical fibers, Air-Lossy Dielectric Interface, Air-lossless Dielectric Interface and Air-Conductor or Metal Interface; which this research focuses on. Throughout years of research, engineers have endeavoured to overcome the challenges associated with propagating radio wave through conductive materials (composite and metallic materials), including graphite/epoxy fibre, copper, iron, steel etc. This has allowed communication through structures constructed with such materials but with some measure of signal attenuation. Despite the successes as obvious in the open literature, ever greater demands are placed on performance, which continually presents new challenges; because oil, gas, military, ship decks, chemical processing and even civil nuclear sectors make extensive use of metallic structures or 'conductive armours', which RF transmissions cannot penetrate easily due to their properties (Graham, 2011). Hence, proper characterization of radio wave through the conductive materials is of utmost necessity.

There are few publications which are analytical in nature that are available on the radio wave propagation and they are either based on the radio wave propagation through building walls (Savov and Herben, 2002), periodic inhomogeneous walls (Lin *et al.*, 1993), multilayer dielectric periodic structures (Jao *et al.*, 1993), multilayer periodic building structures (Savov and Herben, 2003) and so on. Others are radio wave propagation through composite structures (Allen *et al.*, 1976; Chu *et al.*, 1996). The method of modal transmission line was used in almost all the papers cited in this paragraph, where the authors concluded that the method is efficient in terms of computational time, but the process of analysis seems cumbersome. References (Jao *et al.*, 1993; Chu *et al.*, 1996) however used different approaches and they were as follows; an extension of previous analysis by introducing additional dielectric layers and periodic surface integral formulation respectively.

There are also quite a number of experimental investigations on radio wave propagation. Following the land mark achievement by the renowned scientist, Clerk Maxwell in 1864, where he pioneered the idea of dielectric current to satisfy the continuity equation; Maxwell then came up with a conclusion that there exist EM waves that could be propagated with the speed of light (Maxwell, 1864). Heinrich Hertz through his various experiments conducted in the 1880s using the spark produced from a Leyden jar, said in order to produce a spark at the terminal of a receiving antenna, the effect produced from the spark must be propagated at a reasonable distance. Meanwhile, EM waves were generated as predicted by Maxwell using waves' properties such as; reflection, refraction, polarization and rectilinear propagation concepts (Hertz, 1887 and Tissot, 1906) investigated the work done by (Blondel, 1898) where he pointed out that, the earth's effect on a vertical antenna has a tendency of producing the antenna's image, and he claimed the approximation is appropriate for long waves.

Many years later, a crucial experiment was conducted by the duo of Hunt and Decino which confirmed that the formulation by Weyl was correct and that Sommerfield's surface wave never existed (Burrows, 1937). Other measurements were carried out by Austin several years later where he demonstrated and confirmed that wave propagated at night time was always irregular as established by Marconi in 1902 (Austin, 1911). After deep and comprehensive observation of the variation of radio wave propagation between the night time and day time by Marconi, Austin formulated the first expression for the radio wave propagation that represents the summary of all the experimental data used for the wave's propagation over the sea during the day in the kilometre range of wavelengths. It was however regarded as empirical formula (Burrows and Gray, 1941). This was given as;

$$I_r = 4.25 \frac{I_s h_1 h_2}{\lambda d} \exp\left(\frac{-0.015d}{\sqrt{\lambda}}\right) \text{ (Burrows and Gray)}$$

where all the symbols bear their usual meanings and standard units and they are defined as;  $I_r$  is the current in the vertical antenna of height  $h_2$  resulting from a current  $I_s$  in an antenna of height  $h_1$  separated by a distance  $d$  on a wavelength  $\lambda$

Hogan later performed experiments to confirm Austin's formula and demonstrated that, the formula by Austin was valid over a wider range of distances. Quite a number of experimental works are available on radio wave propagation through metallic materials; prominent among them is the "measurements of 800 MHz radio transmission into buildings with metallic walls" conducted by (Cox *et al.*, 1983). "The information gathered from the measurements will assist in redefining and reconfiguring the portable radiotelephone systems that will allow low-power movable systems". Other experimental investigations include the work by the duo of Deepak Gupta and Sunil Joshi, where inside the building, radio propagation at 900MHz on a multi-storied building was measured to develop a model that will rely on the computation of median path loss for a link under a certain prediction that the considered situation will occur (Gupta and Joshi, 2011).

Determination of attenuation of radio waves propagating into buildings is a very critical factor in the feasibility and design of radiotelephone systems. For the characterization of signals around steel shielded buildings, signal levels were measured at 900MHz (Harold and Cox, 1982). As reported in the foregoing and other literature, strong signal attenuations and variations are experienced by radio waves inside and around building structures as a result of scattering and losses posed by the components of the structure, especially the metallic segment. The effect of multipath fading on the structures cannot also be underestimated (William, 2010). International Telecommunication Union (ITU) in a research conducted between 2013 and 2015 has given some fundamental recommendations (ITU, 2015). Another research sponsored by Ofcom and carried out in 2014 on building materials and propagation (Rudd *et al.*, 2014) and was based on the review of electrical properties of building materials and measurements of building entry loss. In this research, a 'simpler and accurate' analytical method known as General Solutions of Wave Equations using Boundary Conditions (SWE) (Sahu *et al.*, 2014) is used. The effects of frequency and material's thickness on metals as radio wave propagates through metals are investigated through simulation with particular attention on both transmission and reflection coefficients.

## 2. MATERIALS AND METHODS

As stated in the foregoing, the method used for the analysis is SWE. Following the analysis is the simulation process, where it will be established in detail the behaviour of radio wave as it is being propagated through two different metals (Copper and Iron). The variables used are Frequency (GHz), Width (mm) and Polarization (Vertical and Horizontal). Matlab 2015 edition simulation software is used in this work, due to its ability to offer better graphical results than the earlier versions.

### Analysis Techniques

When a uniform plane wave is incident normally (Figure 1) on the interface between region-1 (air) and region-2 (metallic material), then it becomes interesting to compute the reflected, transmitted components of the wave energy.

### Method of General Solutions of Wave Equations using Boundary Conditions

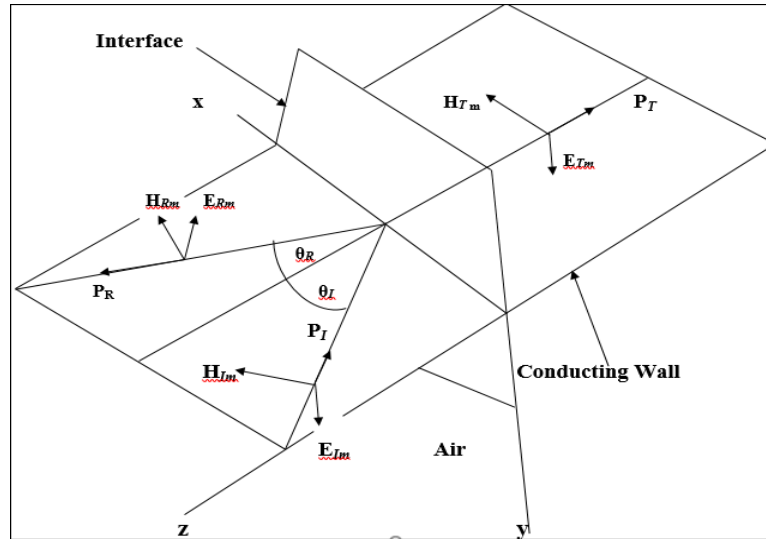
As earlier mentioned and recorded in several literatures, the wave is usually taken to be travelling along the positive z-direction. Therefore, the incident electric field intensity of the wave on the metal is given as;

$$E_i = E_{i1} e^{-\gamma_{1z}} \quad (1)$$

where  $E_{il}$  represents the incident wave's amplitude on the metal,  $\gamma_1$  represents the propagation constant of the propagating wave through metal and it is expressed as follows

$$\gamma_1 = \alpha_1 + j\beta_1 \quad (2)$$

$\alpha_1$  and  $\beta_1$  are attenuation and phase constants of the propagating wave through metal and the implication of these is that, whenever a wave is propagated within a conductor, it will experience attenuation and phase shift.



**Fig. 1:** Geometry of an electromagnetic wave incident on a metal (Adapted from Graham, 2011)

In the same vein, the reflected wave from the metal is given as:

$$E_r = E_{r1} e^{+\gamma_{1z}} \quad (3)$$

The negative and positive signs of the exponential are the forward and backward waves respectively.

As the wave is propagating, the reflected electric field intensity is assumed to be in the same direction as the incident wave's electric field intensity. Applying the boundary conditions at the interface of Figure 1, the actual direction can be found. The total wave in region 1 is given as;

$$E_1 = E_{i1} e^{-\gamma_{1z}} + E_{r1} e^{+\gamma_{1z}} \quad (4)$$

In like manner, the magnetic field can be expressed as;

$$H_{i1(z)} = \frac{E_{i1}}{\eta_1} e^{-\gamma_{1z}} \quad (5)$$

and

$$H_{r1(z)} = -\frac{E_{r1}}{\eta_1} e^{+\gamma_{1z}} \quad (6)$$

Therefore, the total magnetic field in region 1 is expressed as:

$$H_{1(z)} = \frac{E_{i1}}{\eta_1} e^{-\gamma_{1z}} - \frac{E_{r1}}{\eta_1} e^{+\gamma_{1z}} \quad (7)$$

Now for the transmitted wave,

For the transmitted wave through the metal (region 2), as seen in Figure 1, it is assumed that, both the electric field intensity (E) and magnetic field strength (H) have the same form when the wave was incident on the interface between the air and the metal, except that the reflected wave is absent. It is clear from the Figure that, the transmitted wave is infinitely directed and therefore, no mechanism for a reflected wave as the wave is transmitted. Thus,

$$E_{t(z)} = E_{t2} = E_{t2} e^{-\gamma_{2z}} \quad (8)$$

and

$$H_{t(z)} = H_{t2} = \frac{E_2}{\eta_2} e^{-\gamma_{2z}} \quad (9)$$

Having written the fields for the propagating wave through metallic structure, an expression for the reflection coefficient which is defined as the ratio between the amplitudes of the reflected wave and that of the incident wave as they act on the interface can be shown mathematically as:

$$\Gamma = \frac{E_{r1}}{E_{i1}} \quad (10)$$

In the same vein, the ratio between the amplitude of the transmitted wave and the amplitude of incident wave gives the transmission coefficient.

$$T = \frac{E_t}{E_{i1}} \quad (11)$$

According to Fresnel's equations, for a wave polarised with **E** normal to the plane of incidence, the approximations in (12) and (13) are valid for any angle of incidence.

$$\left( \frac{E_{rm}}{E_{im}} \right)_{\perp} = \frac{\frac{n_1 \cos \theta_i - \cos \theta_t}{n_2}}{\frac{n_1 \cos \theta_i + \cos \theta_t}{n_2}} \approx -1 \quad (12)$$

$$\left( \frac{E_{tm}}{E_{im}} \right)_{\perp} = \frac{2 \frac{n_1 \cos \theta_i}{n_2}}{\frac{n_1 \cos \theta_i + \cos \theta_t}{n_2}} \approx 0 \quad (13)$$

Horizontal

Similarly, the approximations in (14) and (15) are valid for angles of incidence when the waves are polarised with **E** parallel to the plane of incidence.

$$\left( \frac{E_{rm}}{E_{im}} \right)_{\parallel} = \frac{\frac{n_1 \cos \theta_t - \cos \theta_i}{n_2}}{\frac{n_1 \cos \theta_t + \cos \theta_i}{n_2}} \approx -1 \quad (14)$$

$$\left( \frac{E_{tm}}{E_{im}} \right)_{\parallel} = \frac{2 \frac{n_1 \cos \theta_i}{n_2}}{\cos \theta_i + \frac{n_1 \cos \theta_t}{n_2}} \approx 0 \quad (15)$$

Vertical

where  $n_1$  and  $n_2$  are the refractive indexes of region 1 and region 2 respectively

Based on (12), (13), (14) and (15), Fresnel's equations show that normal or parallel polarised waves, incident at almost any angle on a good conductor, will experience almost perfect reflection.

The relative amplitudes of the transmitted and reflected waves could also be determined using the expressions in (12), (13), (14) and (15).

The reflected wave can be written in terms of the incident wave by applying the definition of the reflection coefficient given in (9) and substitutes in (3);

$$E_r = \Gamma E_{i1} e^{\gamma_{1z}} \quad (16)$$

Also, using (8) and (10) the transmitted wave can be expressed as a function of the incident wave:

$$E_{t2} = T E_{i1} e^{-\gamma_{2z}} \quad (17)$$

Given the incident magnetic field in region 1 as in (5),

By using (6) and (9), the reflected magnetic field can be written as a function of incident electric field as:

$$H_r = -\Gamma \frac{E_{i1}}{\eta_1} e^{+\gamma_{1z}} \quad (18)$$

Also applying (9) and (11), the transmitted magnetic field is obtained as:

$$H_{t2} = T \frac{E_{i1}}{\eta_2} e^{-\gamma_{2z}} \quad (19)$$

### Applying Boundary Conditions

Based on the analysis overleaf, both the transmission coefficient and reflection coefficient can be evaluated from the relations at the interface. To achieve this, the interface is placed at  $z = 0$ , the total electric and magnetic fields are written on each side of the interface, and finally we equate the tangential components which are continuous across the interface.

$$E_i + E_r = E_2 \rightarrow E_{i1} + \Gamma E_{i1} = T E_{i1} \quad (20)$$

In the same vein, from the continuity of the tangential components of the magnetic field strength,

$$H_i + H_r = H_2 \rightarrow \frac{E_{i1}}{\eta_1} - \frac{\Gamma E_{i1}}{\eta_1} = \frac{T E_{i1}}{\eta_2} \quad (21)$$

$$\text{from (20);} \quad 1 + \Gamma = T \quad (22)$$

$$\text{and from (21);} \quad \frac{1}{\eta_1} - \frac{\Gamma}{\eta_1} = \frac{T}{\eta_2} \quad (23)$$

solving for  $\Gamma$  and  $T$ ,

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} \quad (24)$$

$$\text{and} \quad T = \frac{2\eta_2}{\eta_1 + \eta_2} \quad (25)$$

Reflection coefficient ( $\Gamma$ ) based on (24), can be negative (depending on the relative values of the intrinsic impedances), but Transmission coefficient ( $T$ ) is always positive based on (25).

In view of the above, the electric field intensity in region 1 can be expressed as the sum of the incident and reflected waves as seen in (4):

$$E_{1(z)} = E_{i(z)} + E_{r(z)} = E_{i1}(e^{-\gamma_{1z}} + \Gamma e^{+\gamma_{1z}}) \quad (26)$$

Adding and subtracting the term  $\Gamma e^{-\gamma_1 z}$  on the right-hand side (R.H.S) of (20), it can be written as;

$$E_{1(z)} = E_{i1} [(1 + \Gamma) e^{-\gamma_1 z} + \Gamma (e^{+\gamma_1 z} - e^{-\gamma_1 z})] \quad (27)$$

In the same manner, the magnetic field strength in region 1 is the sum of the incident and reflected fields:

$$H_{1(z)} = \frac{E_{i1}}{\eta_1} (e^{-\gamma_1 z} - \Gamma e^{+\gamma_1 z}) \quad (28)$$

Again adding and subtracting  $\Gamma e^{-\gamma_1 z}$  on the RHS of (22) we get

$$\begin{aligned} H_{1(z)} &= \frac{E_{i1}}{\eta_1} (e^{-\gamma_1 z} - \Gamma e^{+\gamma_1 z} + \Gamma e^{-\gamma_1 z} - \Gamma e^{-\gamma_1 z}) \\ &= \frac{E_{i1}}{\eta_1} [(1 + \Gamma) e^{-\gamma_1 z} - \Gamma (e^{+\gamma_1 z} + e^{-\gamma_1 z})] \end{aligned} \quad (29)$$

As earlier stated, the fields in region (2) are;

$$E_2 = TE_{i1} e^{-\gamma_2 z} \quad (30)$$

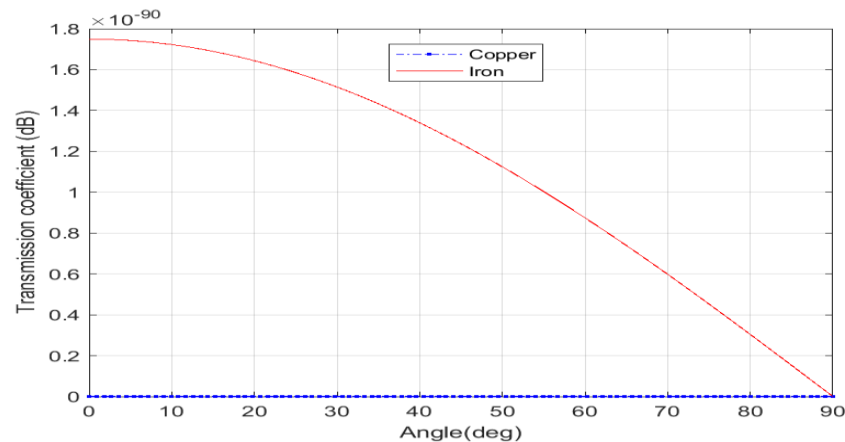
and

$$H_2 = T \frac{E_{i1}}{\eta_2} e^{-\gamma_2 z} \quad (31)$$

The case study to this work is a good conductor, through which EM signal is capable of being transmitted, whereas in a perfect conductor, the entire incident wave is reflected but has its areas of application. Although the transmitted wave in a good conductor is a little fraction of the incident wave, yet, it is of significant interest in the study of radio wave propagation through metals.

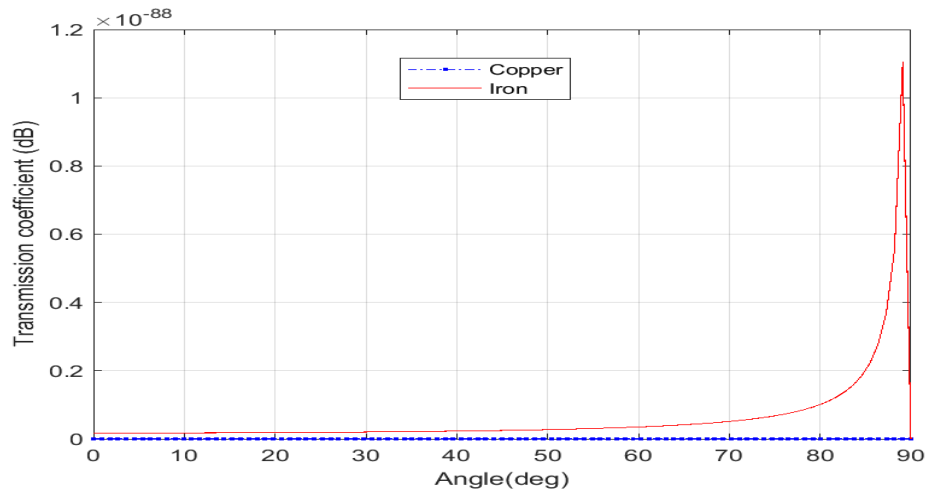
### 3. RESULTS AND DISCUSSION

The investigation continues with the determination of transmission coefficients, reflection coefficients of propagation of radio wave through metals with specific attention on copper and iron. The frequency of choice ranges between 1GHz and 5GHz with the metals' thickness between 1mm and 10mm. Both vertical and horizontal polarizations are plotted. In the plots, comparisons are made between the chosen metals using the parameters aforementioned as radio wave propagates through them.



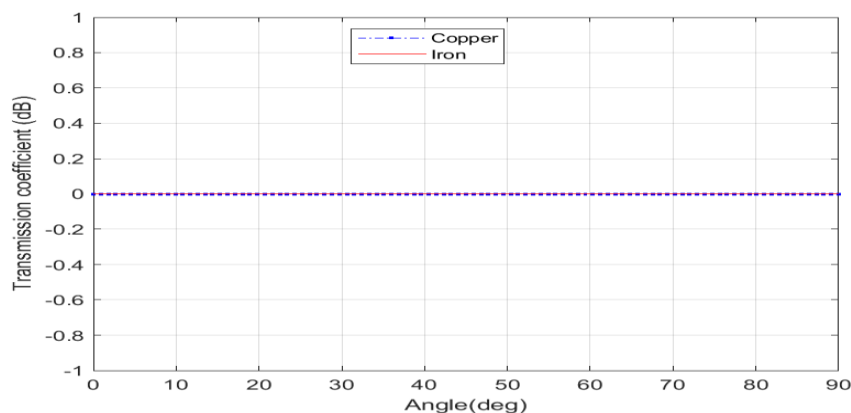
**Fig. 2:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width = 1.0mm, vertically polarized)

In Figure 2, the transmission coefficient of copper is represented with dashed lines and is 0dB, while that of the Iron is represented with solid line and is a little above 0dB. Though all the parameters are the same but clearly the conductivities vary. The transmission coefficient of iron is similar to another work which was based on reinforced concrete as reported by Chu *et al.* (1996).



**Fig. 3:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width = 1.0mm, horizontal polarization)

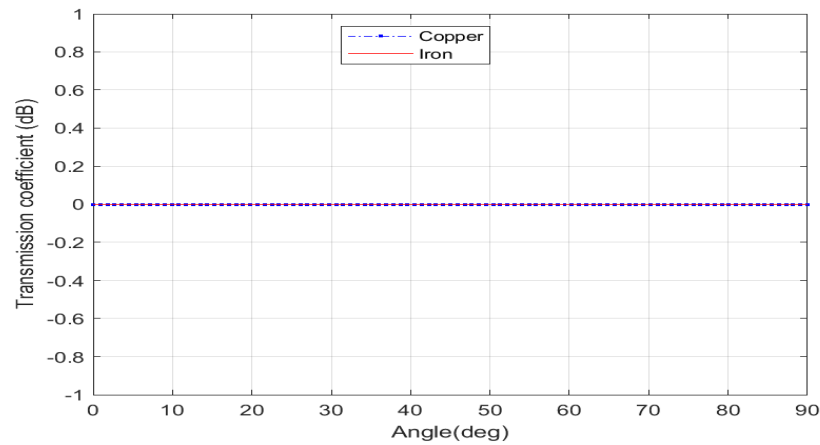
The transmission coefficients of both copper and iron in Figure 3 are almost the same until the angle of incidence is  $40^\circ$  where the transmission coefficient of iron increases steadily to about 1.2dB before it declines to 0dB.



**Fig. 4:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width = 10mm, vertical polarization)

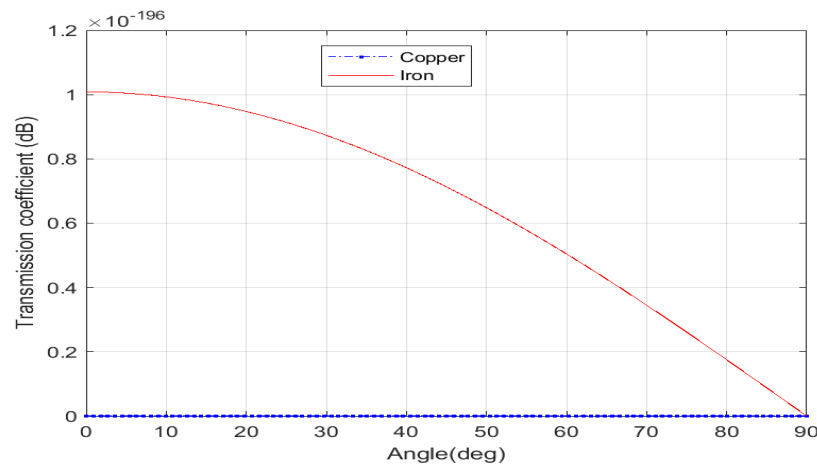
It is shown in Figure 4 that both copper and iron will not allow radio wave propagation because the thickness of both copper and iron in this case is 10mm, hence, the two graphs overlap. The frequency of propagation does not really matter at this point. Therefore, proper choice of materials' thickness is germane for a reasonable measure of radio wave propagation. It will be assumed that, the metals of such thickness (10mm) are exhibiting the characteristics of perfect conductors which will never allow radio wave transmission but

are useful for other applications where total reflection of radio wave is required, such as parabolic dish the antenna.



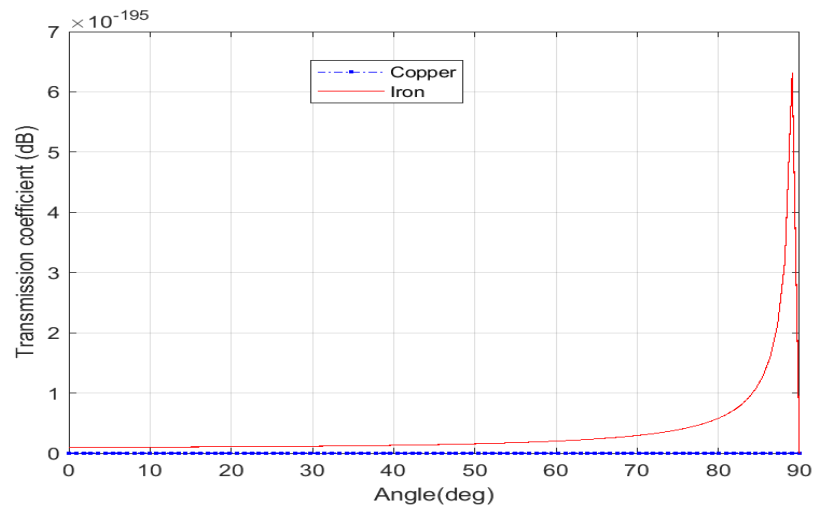
**Fig. 5:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width =  $10.0\text{mm}$ , horizontal polarization)

It is obvious here that, whether the radio wave is propagated by vertical polarization or horizontal polarization, the metals' width plays significant role in determining the presence or absence of transmission of the signal. Figures 4 and 5 are closely the same even though they are differently polarized because there is overlapping of the graph of transmission coefficient for copper and that of iron. Based on the selected metals in this research, every good conductor will behave like a perfect conductor whenever the thickness reaches  $10\text{mm}$ , irrespective of the metal's conductivity.



**Fig. 6:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 5.0\text{GHz}$ , Width =  $1.0\text{mm}$ , vertical polarization)

Figure 6 shows that, iron gives better radio wave transmission than copper at high frequency even though the metals' thickness is the same. The difference in their conductivities is responsible for the variation in the wave patterns. Although, the transmission coefficient decreases as the angle of incidence increases towards  $90^\circ$ .

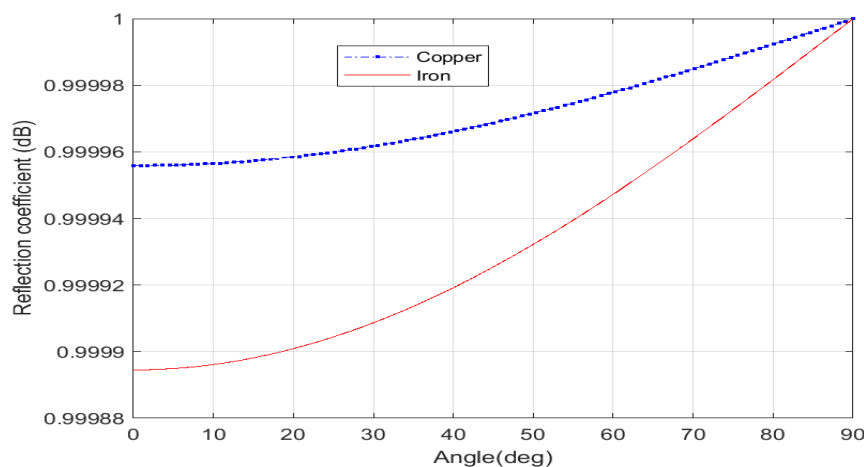


**Fig. 7:** Transmission coefficient of Copper and Iron against Angle of incidence for ( $f = 5.0\text{GHz}$ , Width = 1.0mm, horizontal polarization)

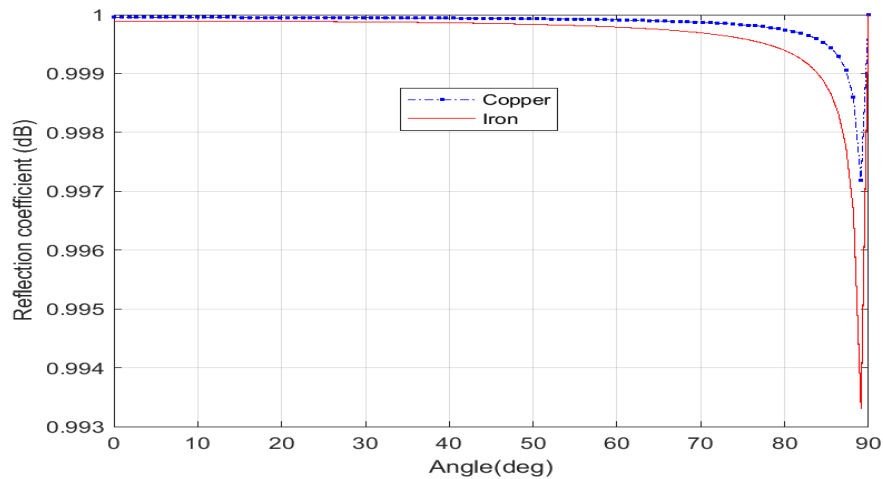
Figure 7, shows a similar wave pattern as revealed in Figure 2; it is observed that the transmission coefficient of iron in Figure 7 is slightly higher than what was received in Figure 2. The variation in frequency of propagation is the reason behind the difference obtained. However, the transmission coefficient for copper is typically the same in both cases.

### Reflection Coefficient

Figure 8 shows the reflection coefficient against angle of incidence for both copper and iron. Copper has higher reflection coefficient than iron; this is much expected because reverse is the case with transmission coefficient. Although, the reflection coefficient increases as the angle of incidence increases for the two metals. However, there is a marginal increase in reflection coefficient of metal with respect to the angle of incidence.

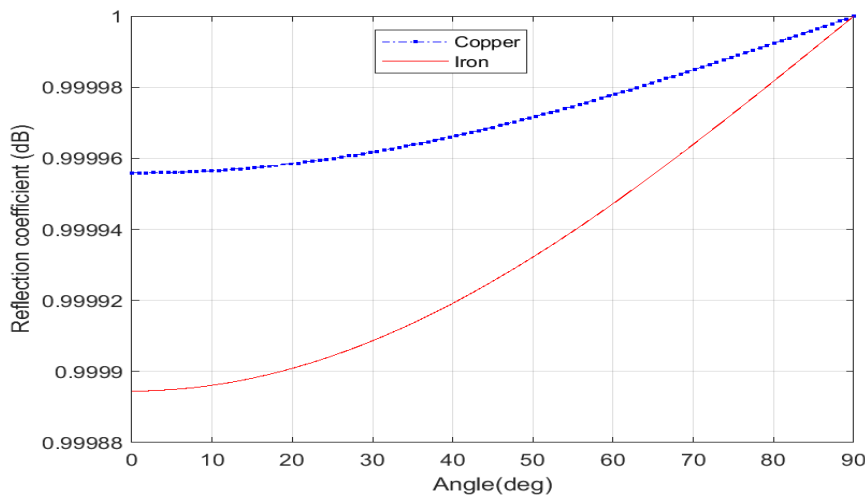


**Fig. 8:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width = 1.0mm, vertical polarization)



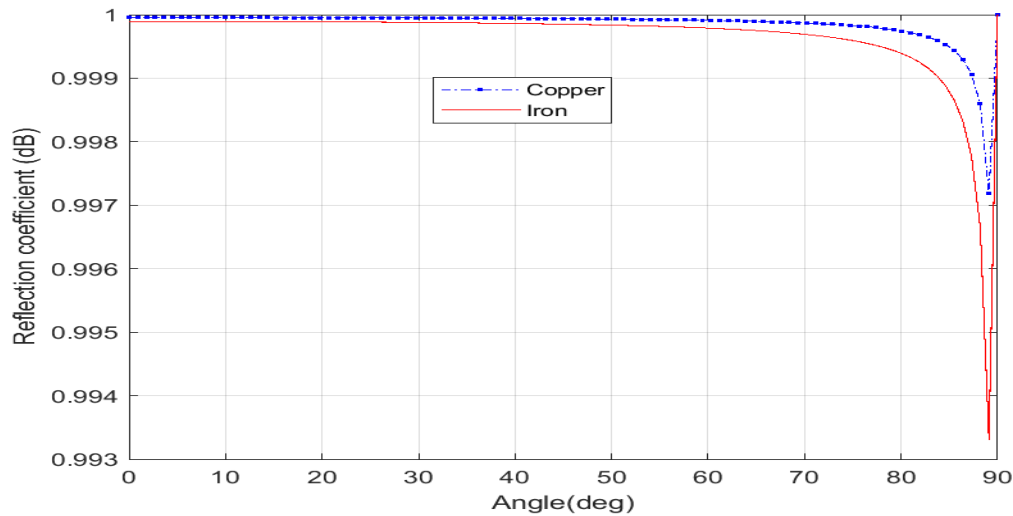
**Fig. 9:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width =  $1.0\text{mm}$ , horizontal polarization)

Both copper and iron have the same reflection coefficient of  $1\text{dB}$ , up to  $40^\circ$  angle of incidence as seen in Figure 9. However, at about  $90^\circ$ , the reflection coefficient of iron is lower than copper. Also, this is why iron will permit more radio wave transmission than copper.

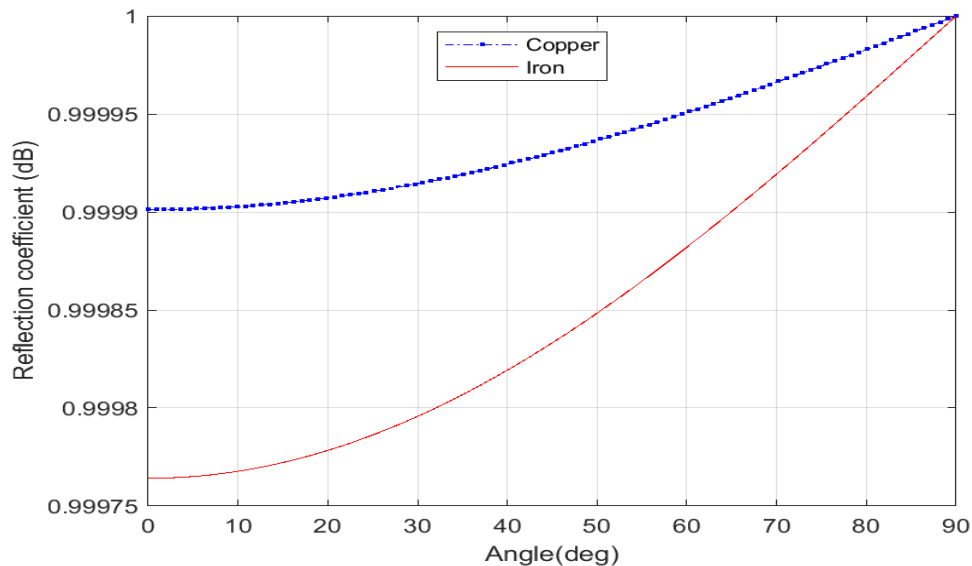


**Fig. 10:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width =  $10.0\text{mm}$ , vertical polarization)

Figures 8 and 10 look quite similar, despite the change in the metals' width from  $1.0\text{mm}$  to  $10.0\text{mm}$ . Therefore, as the reflection coefficient increases, the angle of incidence also increases. Figure 11 shows close similarities with Figure 9, despite the change in the metals' width from  $1.0\text{mm}$  to  $10\text{mm}$ . The implication of this is that, since the thickness of the metals play significant role in determining whether there will be transmission or not, it will also determine to a very large extent, the amount of signal that will be reflected during propagation.

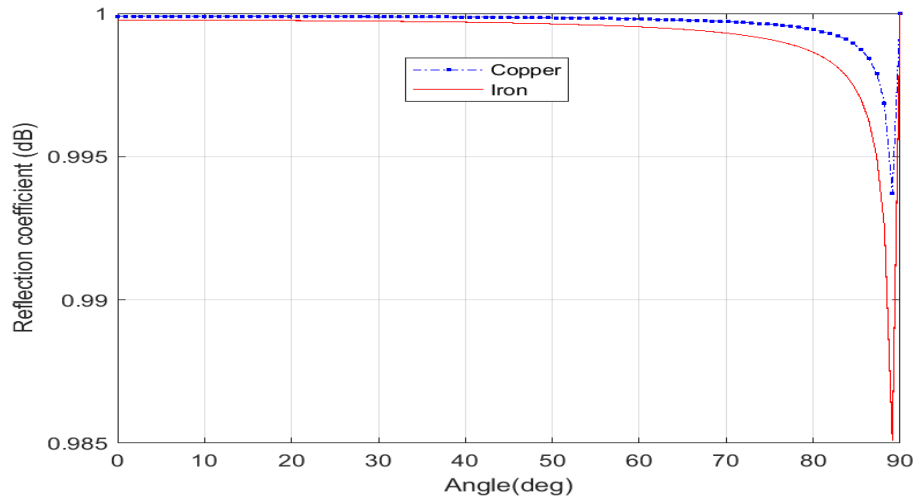


**Fig. 11:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 1.0\text{GHz}$ , Width =  $10.0\text{mm}$ , horizontal polarization)



**Fig. 12:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 5.0\text{GHz}$ , Width =  $1.0\text{mm}$ , vertical polarization)

Figure 12 shows higher reflection coefficient than Figure 10 because the former has higher frequency of propagation than the latter. This means that, as the frequency increases, the reflection coefficient also increases.



**Fig. 13:** Reflection coefficient of Copper and Iron against Angle of incidence for ( $f = 5.0\text{GHz}$ , Width =  $10.0\text{mm}$ , horizontal polarization)

The reflection coefficient after being constant for both copper and iron at  $1\text{dB}$ , drops drastically at  $80^\circ$ . While the reflection coefficient of iron continues to decrease towards  $0.985\text{dB}$ , the reflection coefficient of copper couldn't decrease below  $0.9925\text{dB}$ .

#### 4. CONCLUSION

The General Solutions of Wave Equation (SWE) using Boundary Conditions method have been used to analyze the characterization of radio wave propagation through metallic materials. Both transmission and reflection coefficients are computed and later simulated. The simulation results show that different metallic materials have separate effects on radio wave even though the frequency of propagation and materials' thickness are constant; because, the conductivities of the materials (metallic materials) vary. By this result, proper and adequate attentions need to be paid when choosing metals for constructions for the purpose of radio wave transmission

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