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Study of RF Propagation Losses in Homogeneous Brick and Concrete Walls using Analytical Frequency Dependent Models

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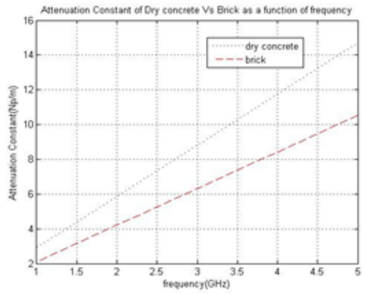
Abstract : *The prediction of wall losses is a fundamental aspect in the development of ultra-wideband through-the-wall (TTW) detection systems. Accurate ultra-wideband signal attenuation prediction has always been very difficult due to a broad variety of building materials without the support of a sophisticated model. In this paper, the attenuation of different types of concrete and brick walls are estimated using the electromagnetic characteristics of building materials for frequencies from 1 to 5 GHz by two theoretical models based on the method of general solutions of wave equations using boundary conditions and the impedance transformation method or the method of transmission line analogy. This estimation will enable in the design of any ultra wideband through-the wall radar system.*
Keywords: *brick, concrete, dielectric properties, RF propagation, through-the-wall (TTW), ultra-wideband.*

I. INTRODUCTION

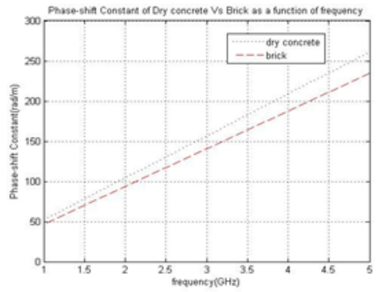
Modeling of radio frequency (RF) propagation of wave through building walls has a significant impact on the development of ultra-wideband (UWB) through-the-wall (TTW) radar systems. The construction of a building wall is usually based on the structural considerations. But the matter of the fact is that, even if the type of elements used to build the wall is known, their influence on electromagnetic waves is difficult to predict. Reflection coefficient, transmission coefficient and signal attenuation are the most dominant factors in the study of propagation of radio signals in any indoor or outdoor environments and are very closely related to the dielectric properties of building materials. This paper describes two analytical techniques such as the method of general solutions of wave equations using boundary conditions and the impedance transformation method (or the method of transmission line analogy) to study the propagation behaviors of some commonly used building wall materials: concrete and brick. Similar wall modeling has been reported in the literature [1] but by using a different approach. Several measurement techniques used to characterize the typical building materials such as brick, concrete, glass, plasterboard, plywood, wood etc. in terms of the frequency dependent dielectric properties ϵ_r, σ etc. have been reported in the literature [2-5]. Using these frequency dependent parameters, the propagation parameters can be estimated. According to the authors of [3], it is not possible to identify a particular trend in the variation of the dielectric parameters, conductivity values with frequency which can be valid for all materials. For some materials the dielectric values are found quite similar at a different frequency and this may be due to the fact that the contributions of multiple internal reflections due to large attenuation inside the wall are neglected. Also as mentioned in [3], when the thickness of the material is not very large as compared to wavelength, multiple reflections greatly impact the transmission and reflection coefficients. Hence the performance of any analytical and theoretical multilayered model in the study of attenuation to the point of its applicability and accuracy depends on whether the attenuation was evaluated including the most important effect of multiple reflections at the several interfaces comprising the model. Both of the models discussed in this paper are valid from a point of view that the effect of multiple successive internal reflections is accounted for. In a theoretical sense, even the general behavior of the dielectric constants is supposed to grow slightly with frequency; it might present some resonant frequencies which are responsible to modify this common trend. Thus, the variation of the dielectric constants with frequency does not necessarily follow the same trend for different materials and depends on the material as well as the polarization used.

II. WALL MATERIALS AND THEIR DIELECTRIC PROPERTIES

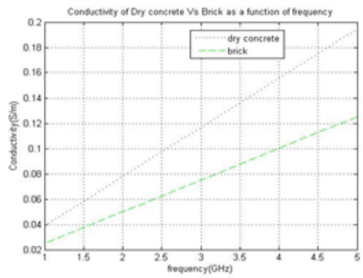
Buildings walls are commonly made up of concrete or brick and can be modeled [5] as a dielectric material having an effective permittivity, ϵ' and conductivity, $\sigma = \omega\epsilon''$ constant over the frequency range of interest so that the choice of having ϵ'' inversely proportional to the frequency could be achieved. Here, ϵ' and ϵ'' are the real and imaginary parts of the complex permittivity. The degree of dispersion of concrete depends on its water



(a)



(b)



(c)

Fig.1. Comparison of the variation of (a) attenuation constant (b) phase-shift constant and (c) conductivity between dry concrete and brick with frequency.

content because complex permittivity of water varies with frequency and thus the dielectric properties are different from wet concrete to dry concrete. Being a dielectric, nonmagnetic material the relative permeability of concrete is unity. ϵ_r', the so-called dielectric constant is the quantity that measures the amount of energy stored in the material being transferred from an external electric field. Similarly, ϵ_r'' is the measure of the energy lost from the material to an external electric field and is referred as the relative loss factor. The ratio that defines the energy lost to the energy stored in a material is called as the loss tangent, $\tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{\sigma}{\omega\epsilon'}$. Solid concrete is homogeneous as ϵ_r and σ are similar for both types of polarizations. The complex permittivity values based on the empirical measurements carried out at the Office National d'Etudes et de Recherches Aerospatiales (ONERA), a French aerospace research agency were obtained as constant and equal to 6.2-j0.7 for frequencies between 1 and 5 GHz. Similarly, for brick, the constant relative permittivity equal to 5-j0.45 was obtained for the same band of frequencies. In this paper, the propagation analysis is performed for the homogeneous building wall types such as solid concrete, hollow concrete and brick using the permittivity values. The attenuation constant, phase-shift constant and conductivity are calculated and their variations are plotted as a function of frequency as shown in Fig.1. It is seen that as frequency increases, these quantities increase almost linearly [Fig. 1(a)-(c)]. In general, wall transmission coefficient depends much more on conductivity than on permittivity [3].

III. ANALYSIS TECHNIQUES

When a uniform plane wave is incident normally [Fig.2] on the interface between medium-1(air) and medium-2(wall) then it becomes interesting to compute the reflected, transmitted components of the wave energy. This problem can be analyzed using the following analytical techniques as described in [6-7].

A. Intrinsic Impedance Method

Considering three mediums of intrinsic impedances η_1, η_2 and η_3, a fraction of wave energy incident on interface-1 is transmitted into medium-2 which further propagates to its right encountering the interface between medium-2 and medium-3. At interface-2, a portion of energy is transmitted into medium-3 and the remaining is reflected back to the left in medium-2 which again encounters the interface-1. At interface-1, some of the

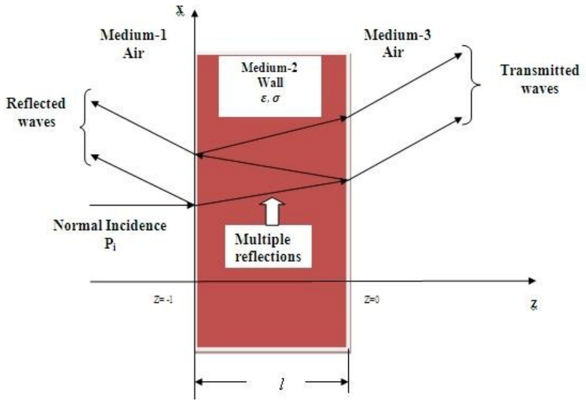


Fig.2. Through-wall propagation model

backward propagating energy is transmitted into medium-1 and the rest of the energy is reflected back into medium-2. Thus, the physical process involves a series of reflections and transmissions. The amount of reflection and transmission at every interface depends on the reflection and transmission coefficient of a boundary between mediums. The electric field strength at every interface depends on the attenuation constant, phase-shift constant of the previous medium during both forward and backward propagation. This method might analyze the transient phase of the process (the period during which a wave is incident on every interface for the first time) to some degree of accuracy. But the method might not accurately predict the propagation losses as it is not consistent with the steady state situation that arises eventually when the incident wave maintains to strike on an interface for a sufficiently long time. Moreover, the method does not account for the effect of multiple reflections. This method was used in our previous work [8] for propagation analysis of human thorax model but, as it does not include the effect of multiple reflections, a more appropriate analysis was done by utilizing the impedance transformation model described in Section III-C.

The basic determination of the reflected and transmitted components of wave energy for multiple dielectric interfaces taking multiple reflections at the interfaces into account , can be performed using the methods such as the method of general solutions of wave equations using boundary conditions and the impedance transformation method (or Method of transmission line analogy) as explained in [6-7]. These methods are discussed in the following Sections III-B and C respectively.

B. Method of General Solutions of Wave Equations using Boundary Conditions

In this method, the reflected and transmitted waves are determined by solving the general wave equations. Solution of the wave equations means obtaining the two unknown electric field amplitudes of the forward and backward propagating waves by the application of the boundary conditions. Assuming E_{2_0} and E_{i_0} as the initial amplitudes of electric field waves in medium-1 and medium-2 respectively, the total electromagnetic field waves in every medium [Fig.2] can be given as below.

Medium-1:

$$E_1(z)=E_{1i}^{+}+E_{1r}^{-}=E_{i_0}\left[e^{-j\gamma_1(z+l)}+\Gamma_{eff}\,e^{+j\gamma_1(z+l)}\right] \quad 1(a)$$

$$H_1(z)=H_{1i}^{+}+H_{1r}^{-}=\frac{E_{i_0}}{\eta_1}\left[e^{-j\gamma_1(z+l)}-\Gamma_{eff}\,e^{+j\gamma_1(z+l)}\right] \quad 1(b)$$

Medium-2:

$$E_2(z) = E_2^+ + E_2^- = E_{20}\left[e^{-j\gamma 2z} + \Gamma_{23}e^{+j\gamma 2z}\right] \quad 1(c)$$

$$H_2(z) = H_2^+ + H_2^- = \frac{E_{20}}{\eta_2}\left[e^{-j\gamma 2z} - \Gamma_{23}e^{+j\gamma 2z}\right] \quad 1(d)$$

Medium-3:

$$E_3(z) = E_3^+ = \tau_{eff}\, E_{i0}\, e^{-j\gamma 3z} \quad 1(e)$$

$$H_3(z) = H_3^+ = \frac{\tau_{eff}\, E_{i0}}{\eta_3} e^{-j\gamma 3z} \quad 1(f)$$

where E_2^+ and E_2^- represent the forward and reverse wave propagation, Γ_{23} is the reflection coefficient at the interface between medium-2 and medium-3. γ_1, γ_2 *and* γ_3 are the propagation constants of mediums 1,2 and 3 respectively. Γ_{eff}, τ_{eff} in general are the complex reflection and transmission coefficients at the interface-1which accounts for the loading effect of medium-3.

Electromagnetic boundary conditions and their applications: The sum of the tangential components of electric and magnetic field vectors on either side of an interface is continuous about the interface.

Applying this boundary condition at interface-1 for which $z = -l$ we can have,

$$E_1\big|_{z=-l} = E_2\big|_{z=-l}$$
$$E_{i_0}\left(1 + \Gamma_{eff}\right) = E_{2_0}\left(e^{j\gamma_2 l} + \Gamma_{23}e^{-j\gamma_2 l}\right) \quad 2(a)$$

Similarly, $H_1\big|_{z=-l} = H_2\big|_{z=-l}$

That is, $$\frac{E_{i_0}}{\eta_1}\left(1 - \Gamma_{eff}\right) = \frac{E_{2_0}}{\eta_2}\left(e^{j\gamma_2 l} - \Gamma_{23}e^{-j\gamma_2 l}\right) \quad 2(b)$$

Now applying the boundary condition at interface-2 i.e. $z = 0$ we get,

$$E_2\big|_{z=0} = E_3\big|_{z=0}$$
$$\Rightarrow E_{2_0}\left(1 + \Gamma_{23}\right) = \tau_{eff}E \quad (2c)$$

Similarly, $H_2\big|_{z=0} = H_3\big|_{z=0}$

$$\Rightarrow \frac{E_{2_0}}{\eta_2}\left(1 - \Gamma_{23}\right) = \frac{\tau_{eff}E_{i_0}}{\eta_3} \quad (2d)$$

where Γ_{eff} , τ_{eff} , Γ_{23} and E_{2_0} are the unknown quantities and E_{i_0} , η_1 , η_2 and η_3 are the known quantities.

Multiplying equation 2(d) by η_3 and then subtracting the result from equation 2(c) we get,

$$\Gamma_{23} = \frac{\eta_3 - \eta_2}{\eta_3 + \eta_2} \quad (3)$$

Substituting for Γ_{23} in equations 2(a) and 2(b) and solving them further for Γ_{eff} and τ_{eff} we get,

$$\Gamma_{eff} = \frac{(\eta_2 - \eta_1)(\eta_3 + \eta_2) + (\eta_2 + \eta_1)(\eta_3 - \eta_2)\, e^{-2j\gamma_2 l}}{(\eta_2 + \eta_1)(\eta_3 + \eta_2) + (\eta_2 - \eta_1)(\eta_3 - \eta_2)\, e^{-2j\gamma_2 l}} \quad (4)$$

$$\tau_{eff} = \frac{4\eta_2\eta_3\, e^{-j\gamma_2 l}}{(\eta_2 + \eta_1)(\eta_3 + \eta_2) + (\eta_2 - \eta_1)(\eta_3 - \eta_2)\, e^{-2j\gamma_2 l}} \quad (5)$$

where γ_2 , the propagation constant $= \alpha_2 + j\beta_2$

C. Impedance Transformation Method (or Method of Transmission Line Analogy)

The underlying principle of dealing with multiple interfaces in layered models is identical to that in case of the impedance matching of transmission lines. This is a powerful method to deal with multiple dielectric layered mediums and determination of effective input impedance is based on the successive impedance transformation of cascaded transmission lines. In this method every layer is considered as a transmission line equivalent and the complete layered medium is considered as a cascaded transmission line. Considering the two-interface, three layer medium [Fig.2], medium-1 is analogous to a transmission line of characteristic impedance z_1 and is terminated at the load i.e. medium-3 of characteristic impedance z_3 by means of another transmission line i.e. medium-2 of characteristic impedance z_2. The wave equations are identical to transmission line equations and the electromagnetic boundary conditions here are equivalent to those for the continuity of voltage and current at a line termination.

In this method the effective input impedance as seen from the transmission line to the load is calculated as explained in [6-7]. The input impedance is calculated at interface-1 whereas the input impedance at interface-2 is equal to the input seen at this interface towards medium-3 and is equal to the intrinsic impedance of medium-3. The effective input impedance at interface-1 as obtained in [6-7] is as given below.

At interface-1, the effective input impedance, $$\eta_{in,1} = \eta_2 \frac{\eta_3 + j\eta_2 \tan\beta_2 l_2}{\eta_2 + j\eta_3 \tan\beta_2 l_2} \qquad (6)$$

and effective reflection coefficient, $$\Gamma_{eff} = \frac{\eta_{in,1} - \eta_1}{\eta_{in,1} + \eta_1} \qquad (7)$$

IV. ELECTROMAGNETIC POWER FLOW ACROSS INTERFACES

The effective reflection coefficient and transmission coefficient obtained in the previous sections can be used to determine the power transfer across the interfaces as mentioned below.

Fraction of total incident power (P_i) reflected back in medium-1(during backward propagation),

$$P_{r_1}^{-} = \left|\Gamma_{eff}\right|^2 P_i \qquad (8)$$

Fraction of total power transmitted to the right of interface-1(during forward propagation),

$$P_t^{+} = \left(1 - \left|\Gamma_{eff}\right|^2\right) P_i \qquad (9)$$

If medium-2 is lossy then out of the total $P_t^{+} = 1 - \left|\Gamma_{eff}\right|^2$ some power $= \frac{\eta_1}{\eta_3}\left|\tau_{eff}\right|^2$ will be able to transmit into medium-3 $(P_{t_3}^{+})$ and the remaining of P_t^{+} after subtracting $P_{t_3}^{+}$ will be absorbed by medium-2 $(i.e. P_{a_2})$. Thus we can have,

$$P_{t_3}^{+} = \frac{\eta_1}{\eta_3}\left|\tau_{eff}\right|^2 \qquad (10)$$

$$P_{a_2} = P_t^{+} - P_{t_3}^{+} = \left(1 - \left|\Gamma_{eff}\right|^2\right) - \left(\frac{\eta_1}{\eta_3}\left|\tau_{eff}\right|^2\right) \qquad (11)$$

and $$P_t^{+} = P_{a_2} + P_{t_3}^{+} \qquad (12)$$

From the foregoing discussion as reported in [6-7] it can be outlined that in any dual interface configuration of layered dielectric systems, the complex reflection coefficient, Γ_{eff} can be obtained by using equation (4) of the method discussed in 3.2 and/or equation (7) of the impedance transformation approach discussed in section 3.3. The complex transmission coefficient, τ_{eff} can be obtained by using equation (5). The reflected component of power in medium-1, the transmitted component of power in medium-3 and the absorbed component of power in medium-2 can be obtained from the equations (8), (10) and (11) respectively.

V. MODELING RESULTS OF BRICK AND CONCRETE WALLS

As the building construction materials such as concrete, brick etc. are lossy media, from an electromagnetic point of view they are characterized in terms of the frequency dependent propagation parameters. For the determination of propagation losses, every material is modeled as a multilayered system of multiple interfaces and then the reflected, transmitted and absorbed power in the mediums are calculated over the ultra wide-band range from 1 to 5 GHz using the power relations obtained in equations (8), (9) and (11) respectively. In the event of more than two interfaces as in the case of propagation in a hollow concrete (air-concrete-air-concrete-air), the impedance transformation approach is used to reduce it until a dual interface configuration is obtained with medium-3 having impedance equal to the effective input impedance of all the successive layers loaded to the right of medium-2. Then the analysis could be performed further following the same treatment as for any dual interface system.

In order to evaluate the propagation characteristics of a building wall such as transmission coefficient, reflection coefficient, signal attenuation and absorption, knowledge of accurate dispersive behavior of building construction materials is a must. As reported in [2], TTW radars operate from UHF to S-band for better

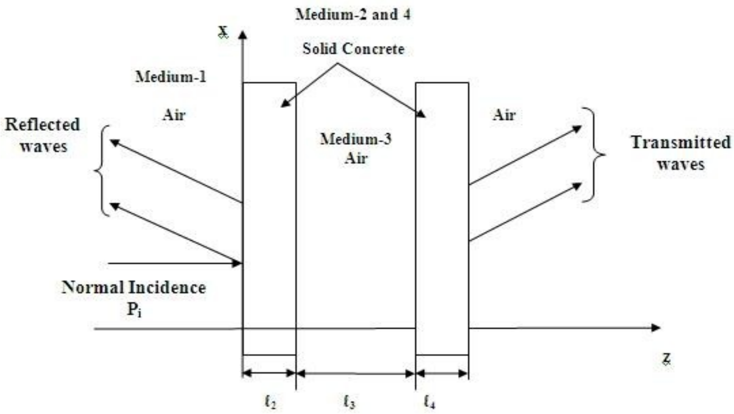
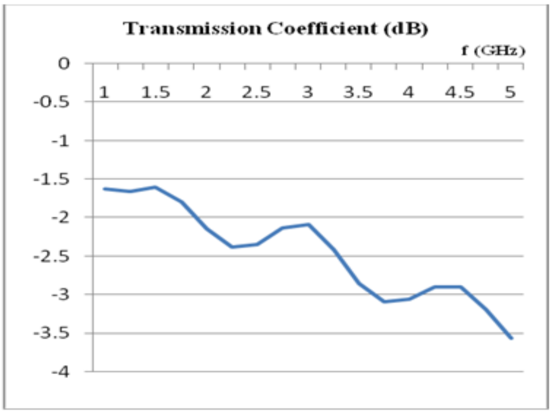


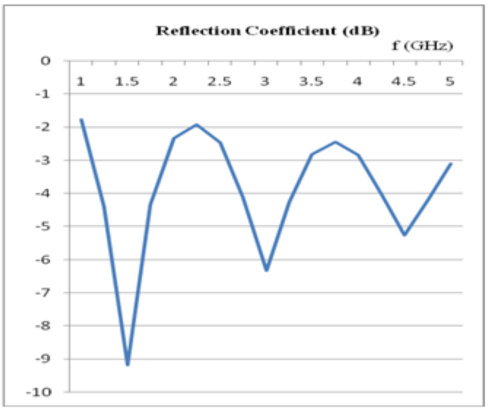
Fig.3. Through-wall wave propagation model for 20 cm thick hollow concrete

penetration into any kind of wall. Therefore, in this work, the change of wall responses are studied over an ultra-wideband frequency of 1 to 5 GHz for three different types of walls each of thickness 20 cm such as (i) a hollow concrete wall, (ii) a solid concrete wall and (iii) a brick wall as presented below.

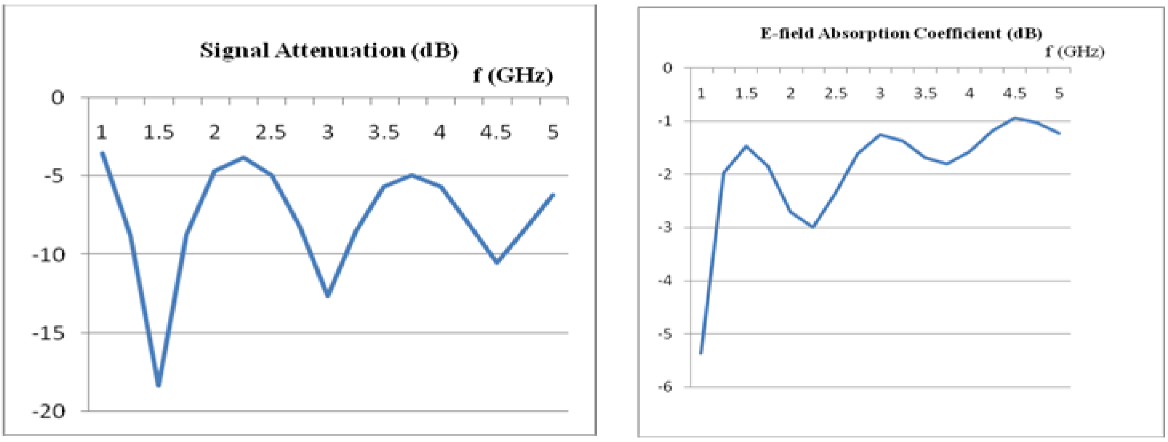
(i) Hollow Concrete Wall: This is a 20 cm thick wall and consists of two solid concrete portions each 4 cm thick with a 12cm thick air gap between them as shown in Fig.3.

As seen in Fig.4 (a), the transmission coefficient varies between -1.6 dB and -3.6 dB and thus shows a transmission loss of about 2 dB. The electric field (E-field) reflection coefficient of the plane wave as a function of frequency is obtained as shown in Fig.4 (b) and the average reflection coefficient is around -3.87 dB over the whole band of frequency. This shows that the lower the frequency, the lesser is the wall attenuation and is clear from Fig.4(c). It is also observed from Fig.4 (d) that the mean electric field absorption coefficient decreases with frequency.





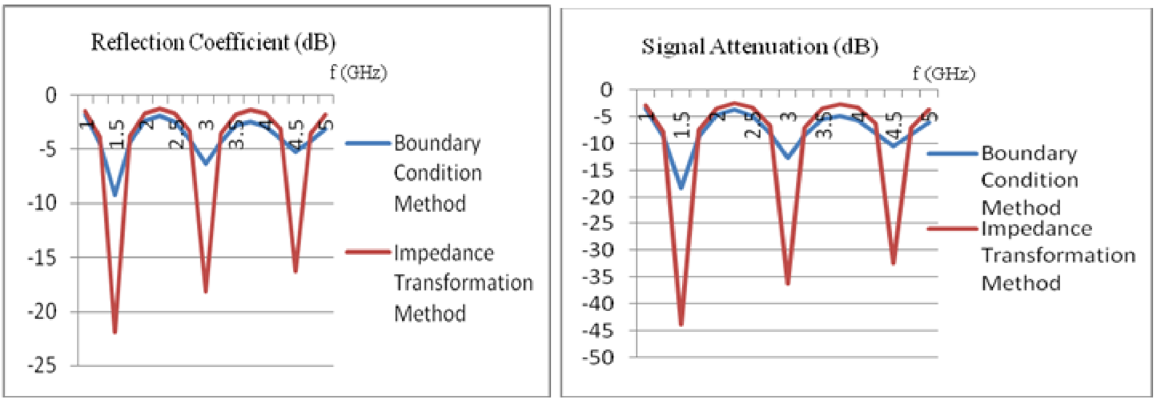
(a) (b)



(c) (d)

Fig.4. Propagation behavior of hollow concrete wall (a) transmission (b) reflection (c) signal attenuation (d) absorption coefficients by using the method of general solutions of wave equations using boundary conditions.

The reflection coefficient and the signal attenuation determined by using both the method of general solutions of wave equations using boundary conditions and the impedance transformation method or the method of transmission line analogy are shown together in Fig. 5(a) and (b) respectively. It is seen that both of the methods provide almost matching results. Both the maximum reflection as well as the peak signal attenuation prediction corresponds to the same frequency.



(a) (b)

Fig.5. (a) reflection coefficient (b) signal attenuation of hollow concrete wall predicted by both the method of general solutions of wave equations using boundary conditions and the impedance transformation method.

(ii) Solid Concrete Wall:

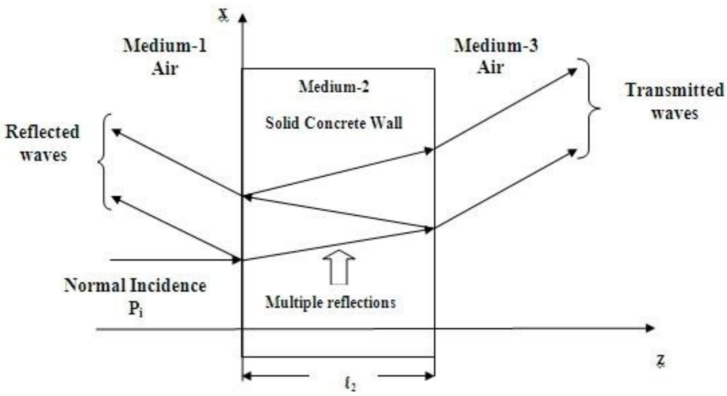


Fig.6. Through-wall propagation model for 20 cm thick solid concrete

A 20 cm thick dry and solid concrete wall as shown in Fig.6 is now considered for the RF attenuation analysis. The transmission coefficient decreases from -3.6 dB to -13.6 dB and thus shows a high transmission loss of about 10 dB as given in Fig.7 (a). The reflection coefficient of the normally incident plane wave is obtained as shown in Fig.7(b) and the average reflection coefficient is around -3.7 dB over the entire frequency range from 1 to 5 GHz. This also shows that the wall attenuation is lesser at lower values of frequency as is seen in Fig.7(c). The mean electric field absorption coefficient decreases with frequency as found in Fig.7 (d).

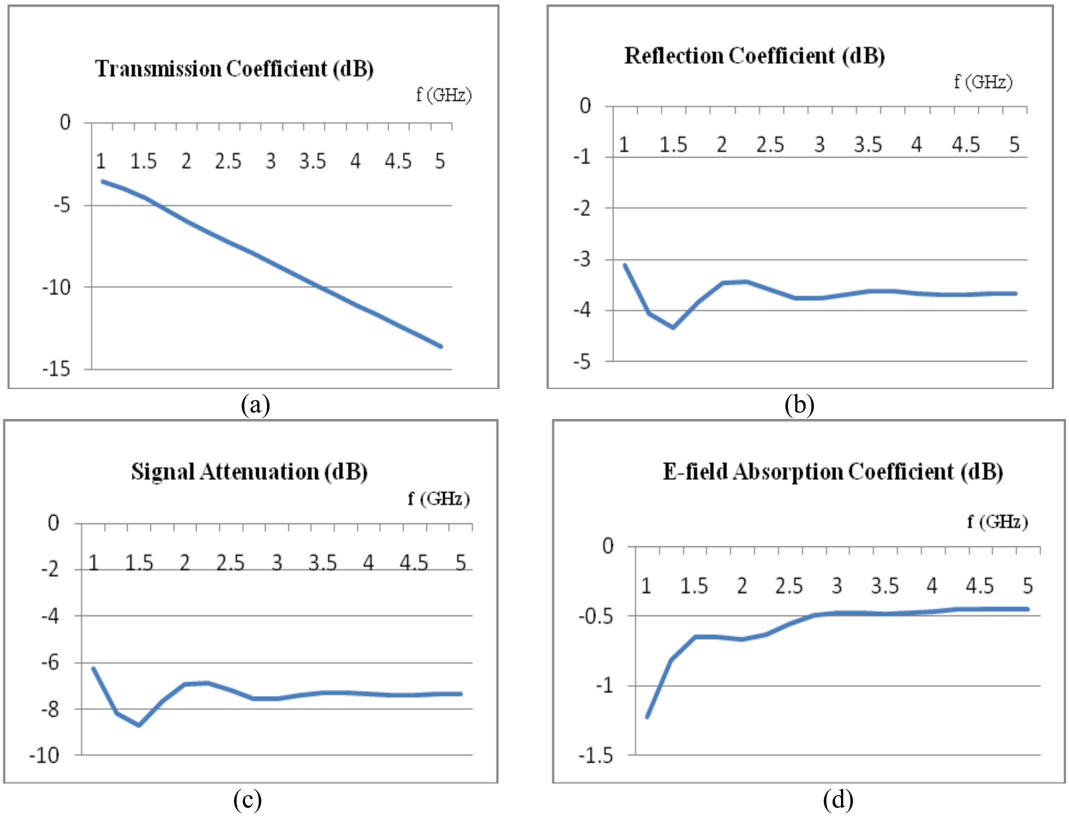
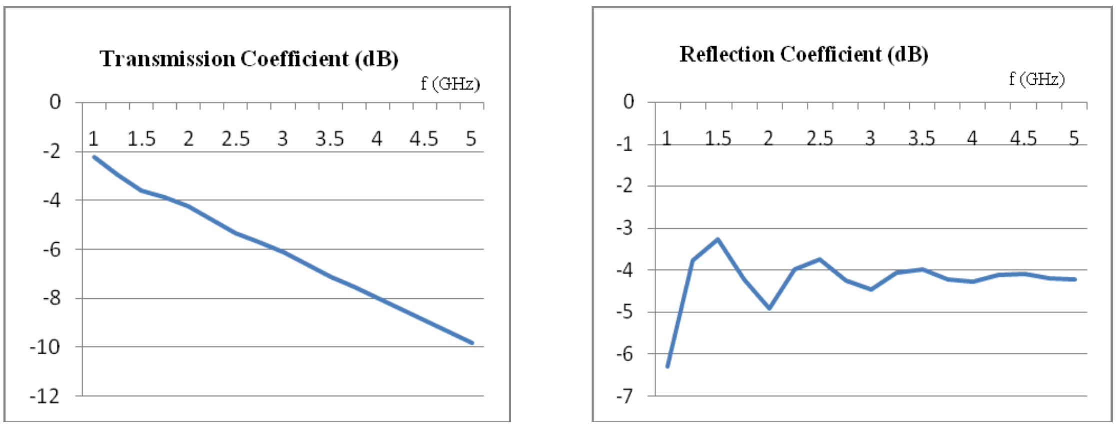


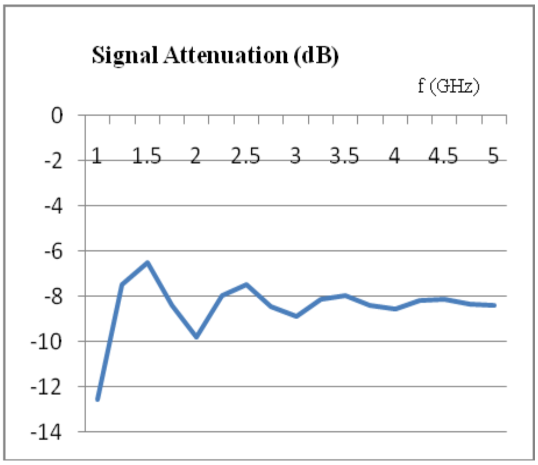
Fig.7. Propagation behavior of dry concrete wall (a) transmission (b) reflection (c) signal attenuation (d) absorption coefficient by utilizing the method of general solutions of wave equations using boundary conditions.

(iii) Brick Wall

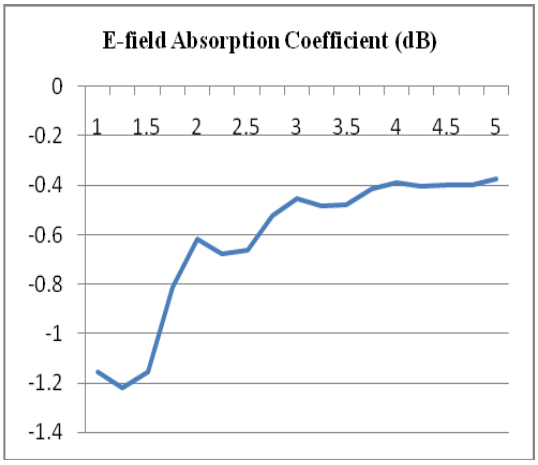
RF attenuation analysis is also carried out for a 20 cm thick brick wall. It is observed that the brick slab exhibits a different electromagnetic behavior. The transmission coefficient decreases from -2 dB to -10 dB and thus shows a transmission loss of about 8 dB [Fig.8 (a)]. The reflection coefficient is obtained as shown in Fig.8 (b) and the average reflection coefficient is around -4.24 dB over the complete frequency band. The wall attenuation is lesser at lower values of frequency as is seen in Fig.8(c). The mean absorption coefficient has a decreasing trend with frequency as found in Fig.8 (d).



(a) (b)



(c)



(d)

Fig.8. Propagation behavior of brick wall (a) transmission (b) reflection (c) signal attenuation (d) absorption coefficients by utilizing the method of general solutions of wave equations using boundary conditions.

VI. CONCLUSIONS

The RF propagation parameters such as the reflection, transmission, signal attenuation and absorption for a plane wave impinging orthogonally on the multilayered models of concrete and brick as a function of frequency are calculated. The reflected pulses show an inversion with respect to the incident pulses caused by a negative value of the reflection coefficient. This is due to the lower value of the effective input impedance of the material with respect to the free space impedance.

Since the result curves produced by both of the theoretical models are virtually overlapping, only the curves corresponding to the method of general solutions of wave equations using boundary conditions are shown in each case for solid concrete and brick. It is also worth noting that both of the theoretical models provide similar results over the whole band of frequencies from 1 to 5 GHz. The characteristic curves for various parameters obtained using the analytical techniques agree well with those reported by other authors. It can be concluded that the model based prediction essentially depends on the accuracy of the data about permittivity, conductivity of the wall material. This study of RF propagation through commonly used building materials can be used to study the performance of cardiac activity of persons behind a wall or persons buried under the rubbles of the debris of a collapsed building.

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