Interaction Notes
Note 624

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Modeling of Propagation Losses in Common Residential and Commercial Building Walls

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Abstract: This note reviews the wave propagation and attenuation through exterior walls of common United States residential and commercial buildings. Some of the past analyses and measured data from previously tested construction materials are also included.

1. Introduction

The construction of external walls in a building or other facility is usually determined by the structural and architectural needs. Many different building materials may be used, and their electrical characteristics $(\mu, \varepsilon, \sigma)$ might be unknown making it difficult to predict the reflection coefficient (Γ), the transmission coefficient (T) and the complex propagation constant (γ) where,

$$\gamma = j\omega\sqrt{\mu_o \mu_r \left(\varepsilon - j\frac{\sigma}{\omega}\right)} \qquad (1)$$
$$\gamma = \alpha + j\beta$$

and α and β are the real and imaginary parts of the complex propagation constant [1]. The propagation model of electromagnetic-wave travel through a wall with free space on either side (figure 1) assumes the configuration and construction materials are known in detail. Present day propagation software [2-5] can allow the user to define the electromagnetic wall parameters of a complex structure to determine the reflection and transmission coefficients [6]. In figure 1 a single uniform plane wave arrives at the boundary between the air and wall. Using the boundary connection super matrix (BCS) detailed in [7 and 8], a complex wall consisting of many different materials can be analyzed by a simple multiplication of the appropriate matrices representing each layer. At the boundary z=0 the uniform plane wave gives rise to one transmitted wave and one reflected uniform plane wave. As the transmitted wave travels through the wall it will attenuate by a factor of $e^{-\gamma z}$. One of the Maxwell's curl equations states

$$\nabla X \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \qquad (2)$$

In frequency domain the above equation can be written as

$$\nabla X \tilde{\vec{H}} = \sigma \tilde{\vec{E}} + j\omega\varepsilon \tilde{\vec{E}} \qquad (3)$$

The right had side termns are respectively the conduction and displacement currents. If the conductivity (σ) is infinity, the medium would be a perfect conductor and if $\sigma = 0$, it is a perfect dielectric. Building materials are lossy materials with finite σ and ε, with a relaxation time given by $\tau = (\varepsilon/\sigma)$. In frequency domain, a medium is a good conductor if $\sigma >> (\omega\, \varepsilon)$ or if $(\omega\tau) << 1$, with conduction current dominating over the displacement current. Building walls can be: a) stucco, b) solid concrete, c) cinder block or d) brick.

Since the wall material is lossy $(\sigma \neq 0)$, the wave will have a phase shift as well as decrease in amplitude. If the material is lossless, however, there will only be phase shift. As the wave hits the z = d boundary there will again be a reflected wave back through the wall material and transmitted wave into free space. The transmitted wave into free space will be decreased in amplitude compared to the incident wave due to reflections and attenuation. Figure 1 is also known as a bounce diagram and could go on again and again but for simplicity is kept to two bounces.

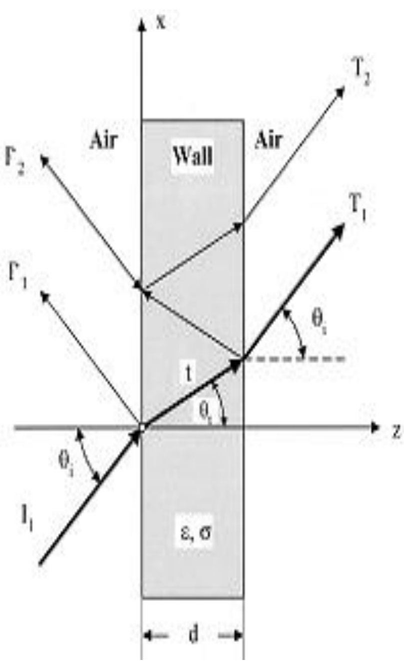

Figure 1. Through-wall propagation model

In Sections 2 through 5, we review the shielding behavior of rebar, concrete and concrete reinforced with rebar, cinder blocks, and bricks. Measured data is graphed for each construction material to show how EM fields attenuate as they propagate through each material. In the later Sections of 6 and 7, the most common U.S. residential and commercial buildings exterior wall configurations are explained. The empirical data from Sections 2 through 5 is used to describe how common residential and commercial buildings in the United States might attenuate waves from outdoor-to-indoor propagation.

2. Rebar Enforced Structures

Two different rebar meshes were tested [9] for how EM waves attenuate as they pass through. These cases have been identified as RE1 and RE2 as shown in figure 2. The dimensions of each shield are shown below and the wire diameter $d_w = 2r_w = 19mm$. A good electrical contact at the joints of the rebar was maintained.

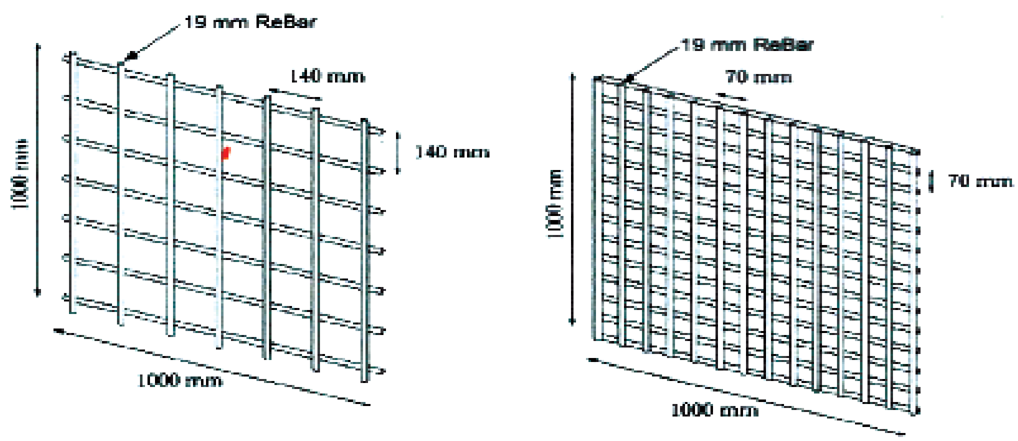

Figure 2. Rebar structures RE1 and RE2 respectively

Two bands of frequency were tested to study the propagation of electric fields. The low frequency band ran from 0.5 to 2 GHz and the high frequency band from 3 to 8 GHz. The results are shown below in figures 3 and 4.

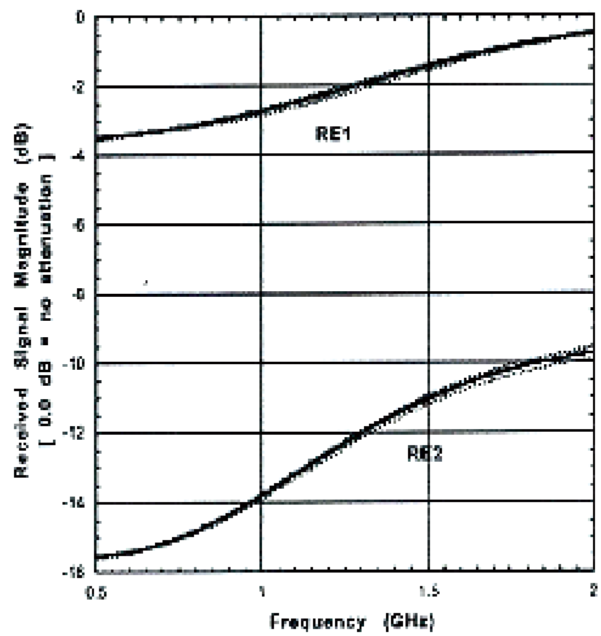

Figure 3. Plots of the measured E-field transmission coefficients for RE1 and RE2 in the low frequency band of 0.5 to 2 GHz.

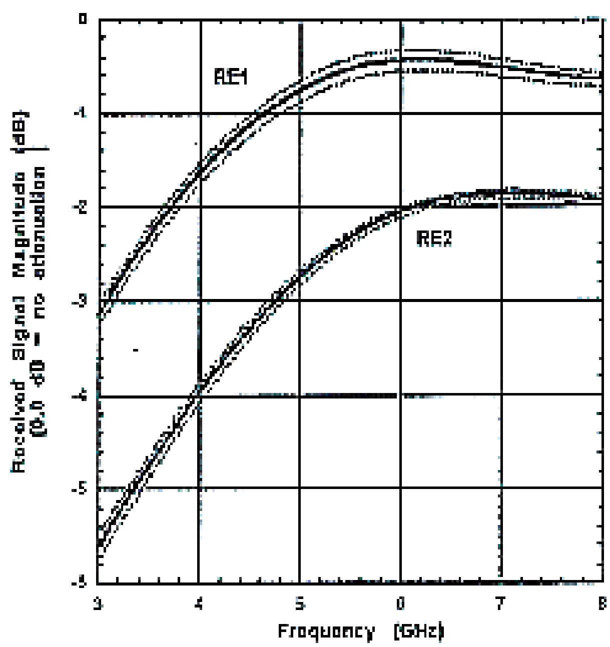

Figure 4. Plots of the measured E-field transmission coefficients for RE1 and RE2 in the high frequency band of 3 to 8 GHz.

It is easily observed that, at low frequencies the rebar mesh looks like a thin plate of lossy material. This causes the EM wave to attenuate (via reflection) as it passes through. However, at higher frequencies, the incident wave has a smaller wavelength and thus the incident EM field sees larger spacing in the rebar mesh and is able to penetrate more. Also noted about this experiment is the rebar with greater coverage (RE2) has lower transmission compared with the RE1 data. This shows that the mesh with more conducting material acts as a better shield.

3. Concrete and Concrete/Rebar Structures

In [9] three different concrete wall slabs were tested for various transmission properties. The concrete used had an approximate water cement ratio of 0.36, a slump of 165 mm ("high"), a nominal maximum crushed aggregate size of 25.4 mm ("large"), a cement content (by weight) of 14%, and an average density of 2.38 g/cc. For this mixture three different thicknesses were considered: sample C84 with a thickness of 102 mm, sample C88 with a thickness of 203 mm, and sample C812 with a thickness of 305 mm. The E-field coefficient (in dB) for the three different thicknesses of a concrete only slab in the frequency range of 0.5 to 2 GHz is graphed in figure 5 and for a frequency range of 3 to 8 GHz is graphed in figure 6.

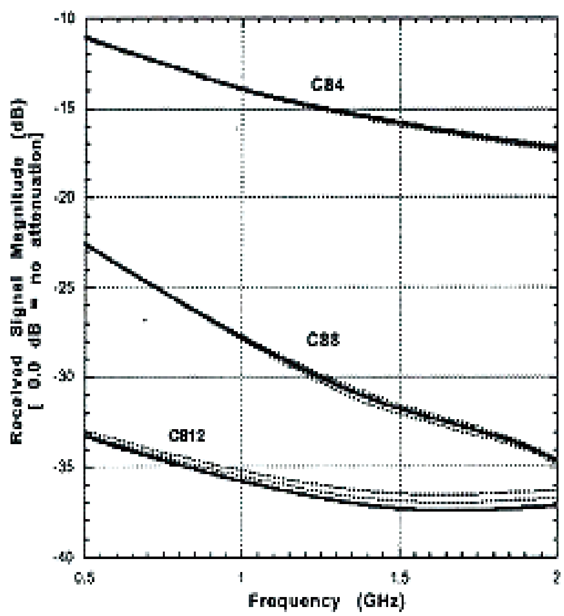

Figure 5. 0.5 to 2 GHz frequency band

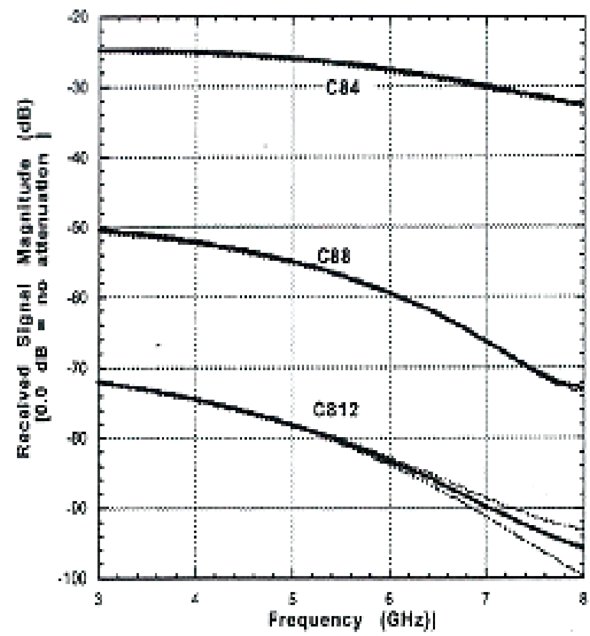

Figure 6. 3 to 8 GHz frequency band

To calculate the transmission coefficients from figures 5 and 6, it is necessary to determine the proper electrical parameters of the concrete, σ, μ_r and ε_r. These parameters are at first unknown but it is possible to infer their values by "fitting" the calculated results to the measured ones. Doing this results in the set of parameters $\sigma = 0.1S/m$, $\mu_r = 1$ and $\varepsilon_r = 1$.

In construction today concrete structures are rarely used by themselves. Often rebar is embedded in concrete, which itself attenuates the passing EM field. When examining the shielding behavior of conducting materials, such as concrete, attenuation increases as the frequency of the propagating EM field increases.

It is assumed that the building is made up of concrete material in which a square shaped rebar is embedded. The geometrical (thickness) and electrical parameters of the concrete are designated as the input parameters. Observe that in figure 7, the concrete has a thickness of (d/2) on both sides of the rebar and the total concrete thickness is "d". The rebar is assumed to be sandwiched between these two layers of concrete. For typical building structures and materials, roughly speaking, it is well known that:

i) Concrete offers little attenuation and rebar dominates ---- at frequencies < 500 MHz,

Low frequencies go thru concrete

ii) Rebar offers little attenuation and concrete dominates ---- at frequencies > 500 MHz

High frequencies go thru the metallic rebar.

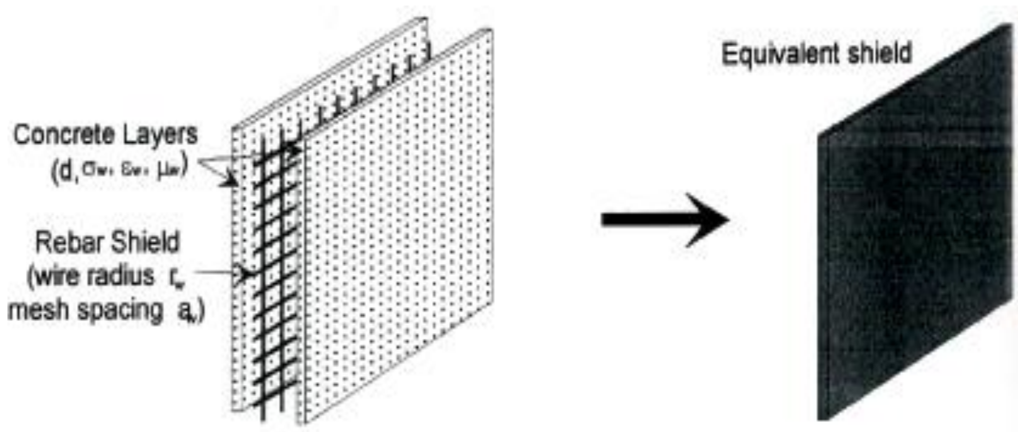

Figure 7. A square shaped rebar embedded in concrete

The approach used here is to relate the fields on either side of the concrete half slabs, and the rebar and cascade the effects in matrix form to get the resulting propagation loss due to the composite shield.

The electromagnetic fields on the two sides of the concrete layer can be related by a boundary connection super matrix (BCS) as described in [7 and 8].

$$\begin{aligned}\begin{bmatrix} E_1^{\tan} \\ H_1^{\tan} \end{bmatrix} &= \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} E_2^{\tan} \\ H_2^{\tan} \end{bmatrix} \\ &= \begin{bmatrix} \cosh(\gamma\, d/2) & Z\sinh(\gamma\, d/2) \\ Z^{-1}\sinh(\gamma\, d/2) & \cosh(\gamma\, d/2) \end{bmatrix} \begin{bmatrix} E_2^{\tan} \\ H_2^{\tan} \end{bmatrix}\end{aligned} \tag{4}$$

where the term γ is the complex wave propagation constant in the concrete, given by

$$\gamma = \sqrt{j\omega\mu_w\left(j\omega\varepsilon_w(f) + \sigma_w(f)\right)} \tag{5}$$

and Z is the wave impedance in concrete:

$$Z = \sqrt{\frac{j\omega\mu_w}{j\omega\varepsilon_w(f) + \sigma_w(f)}}\,. \tag{6}$$

In considering the concrete material, it is important to include the frequency dependence of the conductivity and dielectric constant, in order to get accurate results at higher frequencies. For the frequency dependent model, we have elected to use the causal fit to the parametric variations with frequency in accordance with the Debye model [10]. In this context, the frequency variation is given as

$$\varepsilon_w(\omega) = \varepsilon_\infty + \sqrt{\frac{2\sigma_o\varepsilon_\infty}{\omega}} \tag{7}$$

and

$$\sigma_w(\omega) = \sigma_o + \sqrt{2\sigma_o\varepsilon_\infty\omega}\,. \tag{8}$$

In these expressions, σ_o is the dc conductivity, and ε_∞ is the high frequency permittivity, which is related to the permittivity of free space by the *relative* permittivity ε , as $\varepsilon_\infty = \varepsilon\varepsilon_o$. Note that if the two scalar quantities σ_o and $\varepsilon_\infty = \varepsilon\varepsilon_o$ are known, the frequency dependence of the concrete parameters is fully characterized.

With regards to the rebar, Casey [11] has developed a theory for mesh shields characterized by equivalent impedance, of the form

$$Z_s = R_s + j\omega L_s\,, \tag{9}$$

Let us assume that the conductivity of the rebar wires is high enough to neglect the resistance part in above. For a wire diameter $d_w = 2r_w$ and spacing a_w, the inductance is given by

$$L_s = \frac{\mu_o a_w}{2\pi} \ln\left(\frac{1}{1 - e^{-2\pi r_w / a_w}} \right) \tag{10}$$

For such a rebar shield, the BCS is given in terms of the sheet impedance by the following expression

$$\begin{aligned} \begin{bmatrix} E_1^{\tan} \\ H_1^{\tan} \end{bmatrix} &= \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} E_2^{\tan} \\ H_2^{\tan} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ (Z_s)^{-1} & 1 \end{bmatrix} \begin{bmatrix} E_2^{\tan} \\ H_2^{\tan} \end{bmatrix} \end{aligned} \tag{11}$$

The total cascaded matrix for the concrete and rebar is then given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \cdot \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \cdot \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \tag{12}$$

Relating the electric field on the outside and inside of the building, and then casting it in terms of attenuation factor for power densities on both sided of the building, we get,

$$\text{A (dB)} = -20 \log \left[\left| \frac{2 Z_0}{Z_0 (A + Z_0 C) + (B + Z_0 D)} \right| \right] \tag{13}$$

The values of A, B, C and D in the above equation (12) may be specialized in close form, as follows:

$$A = D = 1, \quad B = 0 \text{ and } D = C_2 \quad \text{(rebar only, neglecting concrete)} \tag{14}$$

$$\begin{aligned} A &= \cosh(\gamma\, d/2) & B &= Z\sinh(\gamma\, d/2) \\ C &= Z^{-1}\sinh(\gamma\, d/2) & D &= \cosh(\gamma\, d/2) \end{aligned} \qquad \text{(concrete only, neglecting rebar) (15)}$$

For the composite case of concrete and rebar, one needs to use equations (12) and (13).

Concrete is known to have an electrical conductivity that depends both on frequency and water content. Reference [12], states that the electrical conductivity of concrete typically varies within the range of 0.001 to 0.01 S/m, and the relative dielectric constant ranges from 5 to 10, depending on the water content.

To illustrate the effect of this variation on the attenuation of RF signals through a slab of reinforced concrete, Carron [13] plot the RF attenuation through a 20 cm thick concrete slab having a rebar structure with 20 cm spacing and a wire diameter of ¼ inch (0.635 cm). Considering only the case of normal incidence on the slab, figure 8 from [13] illustrates the reported variation of the attenuation as a function of frequency for different water contents. In this reference, it is not clear what the basis of water content is? – whether by weight of by volume.

Another useful piece of information on the conductivity of concrete has been provided by Flanagan [12], who has measured the conductivity of concrete as a function of water content. In this study, a transient EM field was applied to a concrete sample, and the conductivity was inferred from an examination of the transmitted field through the sample. The reported conductivity of the concrete is shown in Figure 9, and the values are similar to those suggested in [12].

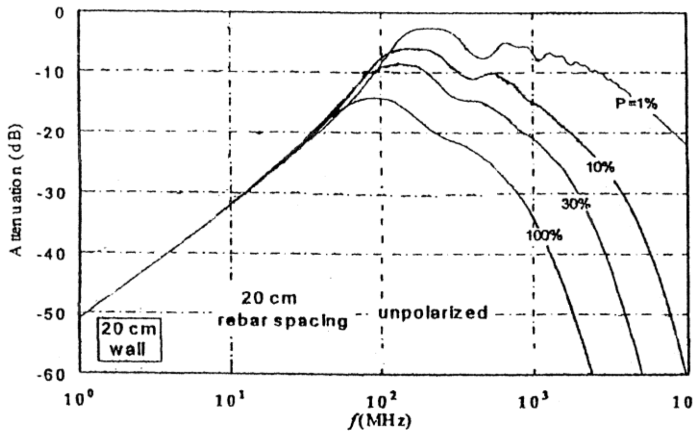

Figure 8. Reported transmission of a 20 cm thick concrete slab containing rebar with 20 cm spacing and wire diameter ***d*** **= 0.635 cm (1/4 in) for normal incidence, shown as a function of frequency for 4 different water percentages (reproduced from [13])**

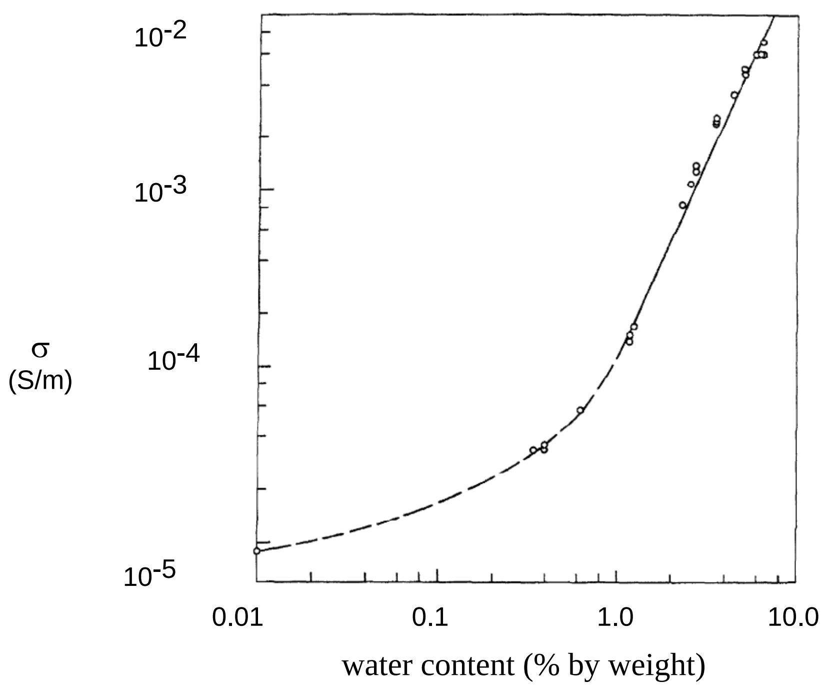

Figure 9. Plot of the electrical conductivity of concrete, shown as a function of water content (% by weight), as reported in [12]

Using the above described model, a series of calculations were performed to try to infer the proper frequency-dependent, electrical parameters of the concrete slab used for the data in Figure 7. In doing this, the analytical model (the present BCS model) was run for various values of conductivity, and the “best” fit for particular water content was selected. In this study, it was found that the dependence on the relative permittivity was relatively weak compared with the dependence on conductivity.

For an assumed permittivity of ε = 5, Figure 10 plots the family of curves that best replicate the data of Figure 8 for the reported water contents of 1%, 10%, 30% and 100%. For these curves, conductivities of σ = 0.003, 0.01, 0.02 and 0.05 S/m, respectively, were found to provide reasonable fits. Note that these values of conductivities are reasonably consistent with the measured conductivities reported by Flanagan [12] (see figure 9).

Similar plots for ε = 7.5 and 10 are shown in figures 11 and figure 12, with only a minor change in the transmission function as ε is varied.

Note that all of these curves provide reasonable fits to figure 8. There are minor differences between the present model and the curves in figure 8 at the high frequencies (> 2 GHz), which may be attributed to differences in the assumed frequency dependence of the material parameters in [12]. These differences, however, are not very important in a practical sense, since the attenuation is so high at these frequencies.

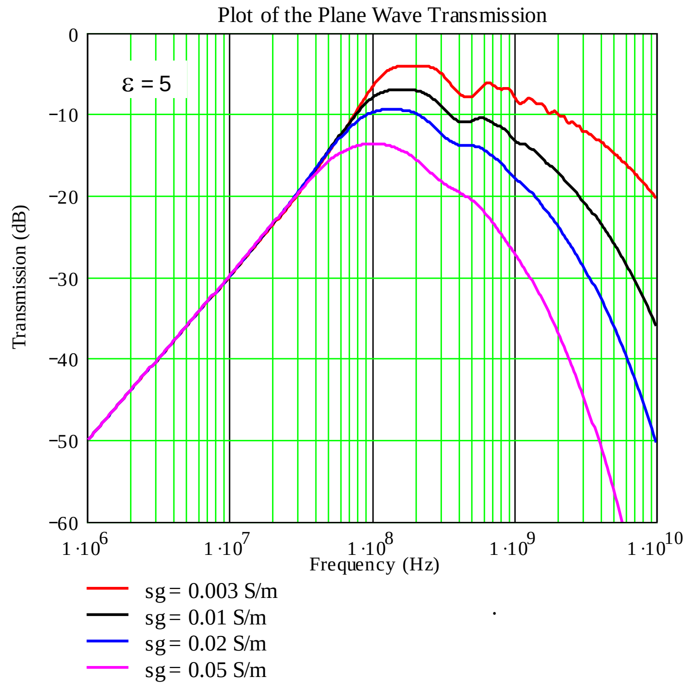

Figure 10.Plots of the concrete/rebar slab transmission function as a function of frequency for an assumed relative permittivity ε = 5 and appropriate conductivities to replicate the data of figure 8

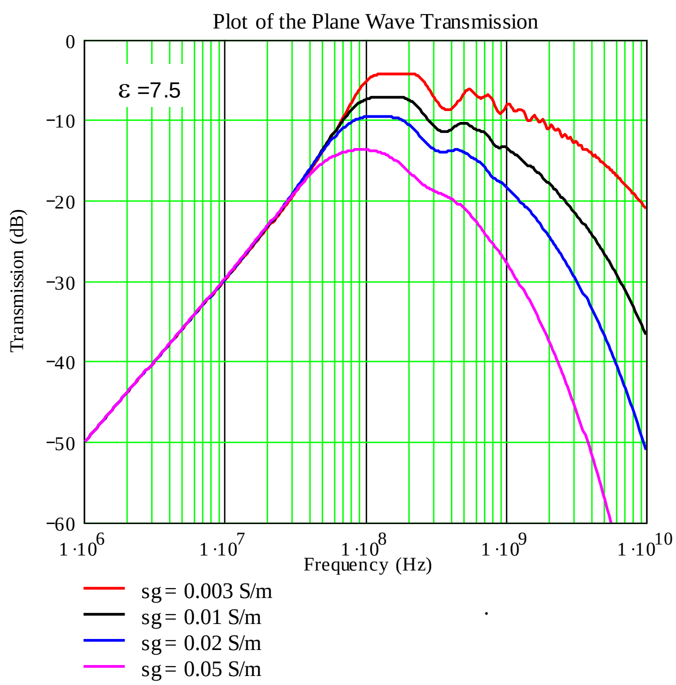

Figure 11.Plots of the concrete/rebar slab transmission function as a function of frequency for an assumed relative permittivity ε = 7.5 and appropriate conductivities to replicate the data of Figure 8

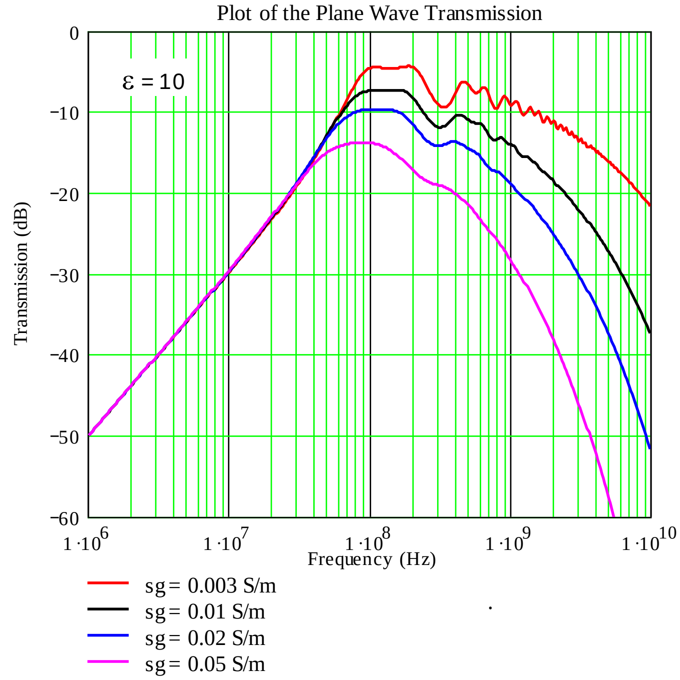

Figure 12. Plots of the concrete/rebar slab transmission function as a function of frequency for an assumed relative permittivity ε = 10 and appropriate conductivities to replicate the data of figure 8

Based on these calculations and comparisons with other data, it appears that the 3-slab BCS model for the (concrete + rebar) duplicates the responses reported in [13]. This model which incorporates the frequency dependence of the slab parameters is an useful improvement over the previous version. It is suggested that assuming the water content is an input parameter, we use the measured data of Flanagan [13] , to select the electrical conductivity of the concrete, together with a value of the concrete permittivity of ε = 5.

4. Cinder Block Structures

A study of RF propagation in [14] was performed on a cinder block building on the Kirtland Air Force Base, NM. This building was used for a command post training facility. Consequently the building has no windows, which makes is ideal for studying the RF penetration through its walls. The construction is primarily concrete post and beam with all exterior walls formed by hollow 8 in. x 8 in. x 16 in. cinder blocks with cement mortar joints. In order to test and record the incident and transmitted field over the 200 MHz to 3 GHz frequency range, three different power amplifiers were used. A single wide-band log periodic antenna oriented to produce vertical polarization was used to illuminate the building. The test point where the receiving antenna gathered the transmitted field was placed 15 m from the source antenna. The cinder block wall was 2 m from the receiving antenna and roughly 13m from the transmitting antenna. Shown in figure 13 are the measured internal magnetic field (lower curve) and the incident magnetic field (upper curve). From 200 MHz up to 1 GHz, the attenuation varies from 13 to 22 dB except for the deep nulls. Above 1 GHz, a greater attenuation behavior is observed. Note that the straight line near 1 GHz is due to a band that was skipped to avoid interfering with GPS frequency bands.

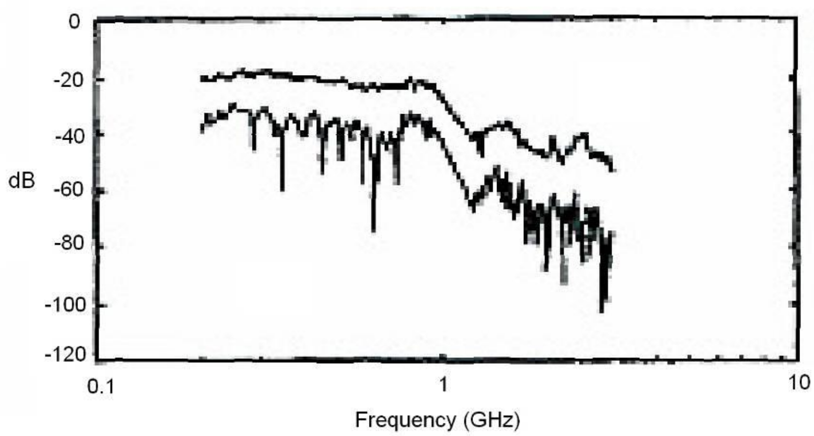

Figure 13. The measured magnetic field compared with the incident magnetic field (upper curve)

5. Brick Structures

The brick wall test procedures and in-depth explanations of the results are covered in [6]. The wall tested was made of bricks and mortar covered by a layer of stucco. The overall wall thickness was 23 cm. The frequency used was 890MHz and the electrical parameters were found through backwards calculations using a single ray model similar to that of figure 1. The dotted lines below in figure 14 are curves of the measured data and the values of the permittivity and conductivity that best fit those curves are $\varepsilon_r = 4$ and $\sigma = 0.022 S/m$ for perpendicular polarization and $\varepsilon_r = 4$ and $\sigma = 0.024 S/m$ for parallel polarization. The attenuation at normal incidence is 5.2 and 5.6 dB for perpendicular and parallel polarization, respectively. It was found that the wall transmission coefficient depends much more on conductivity than on permittivity [6].

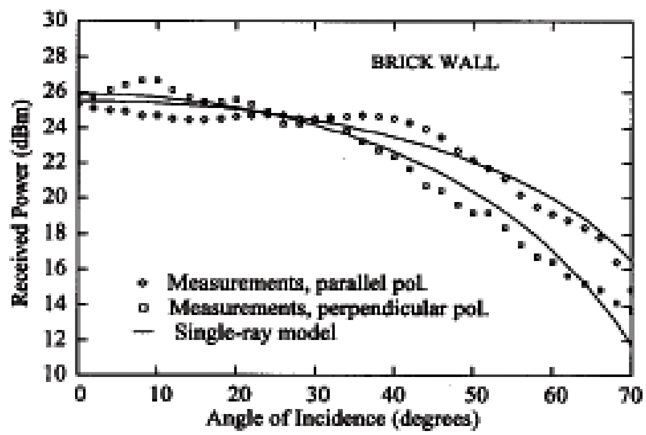

Figure 14. Received power for brick wall

6. Residential Structures

Residential buildings in the United States are made up of wood frame structures and/or concrete structures. However, the most common type of residential housing structure is the wood frame structure [15]. The external wooden frame is made up of Douglas Fir 2x4 inch studs, 16 inches apart on center with a sheathing layer of 0.75 inch plywood on the external side [16]. An example of this is shown in figure 15. On the internal side of the 2x4 inch studs a layer of drywall is nailed up. Between that layer of plywood and drywall is the insulation. Insulation with a rating of R-11 or R-19 is required in newly constructed homes. In short, the higher the R value of an insulator, the greater the material resists the movement of heat [15]. On the outside of the plywood black weather paper is applied which prevents moisture from reaching the wood. The weather paper has little nails protruding allowing chicken wire to be fastened for stucco work. Stucco is a type of concrete. On houses only an inch thick layer is applied [16].

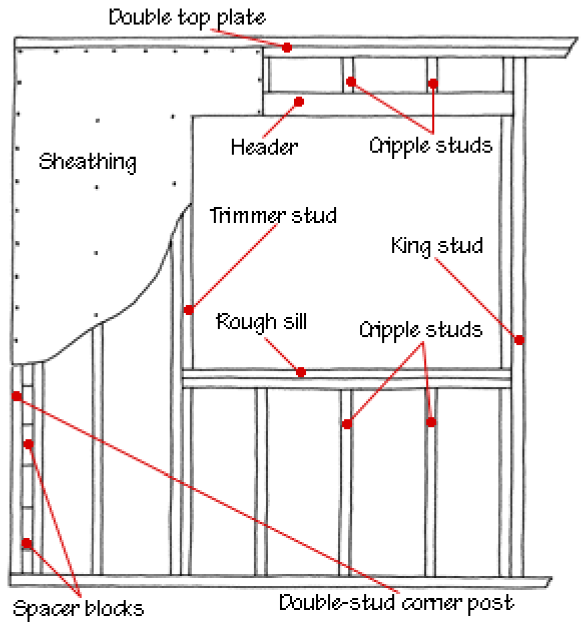

Figure 15. External wood frame wall with 2x4 in studs on center and 0.5 inch plywood sheathing.

Determining the attenuation of EM fields through wood-framed residential walls is a difficult task. There are limited resources regarding the shielding of residential walls due to their complex structure and unknown electrical properties of the materials used. Studies have been done to determine the attenuation of a wood frame structure by itself (figure 16, lower darkened curve [17]) and a wooden frame with drywall mounted (figure 16, upper darkened curve). However, these results are only for one type of drywall (density 235 kg/m^3) and cannot be accepted as a general case.

The information reported in Section 3 regarding concrete only structures can give us an idea of how the stucco on the external wall of a house will attenuate EM fields. Using the data plotted for the C85 (101.5mm thick) concrete wall of figures 5 and 6, one can only infer how a stucco layer an inch thick, a quarter of the thickness of the C85 slab (101.5 mm = 4 inches), will cause shielding of EM fields.

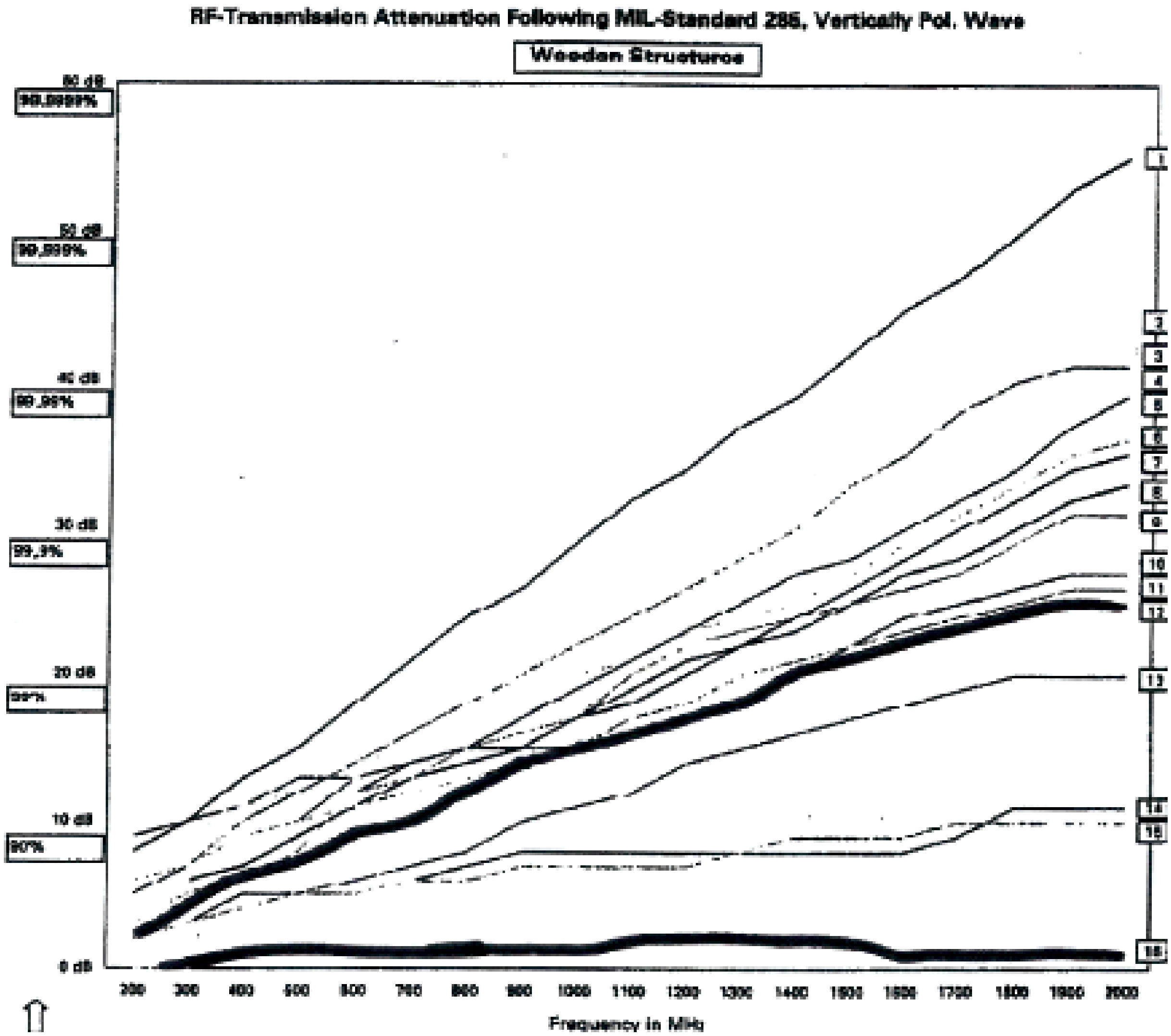

Figure 16. Typical wooden frame construction attenuation in dB (lower darkened curve) and an outside wall with protecting drywall of density 235 Kg/m^3 attenuation in dB (upper darkened curve).

Residential buildings are also known to be made of entirely concrete walls as shown in figure 17. Residential buildings are also built with stucco walls as shown in Figure 18. Figure 18 is a cutaway picture of layers needed for a stucco residential wall to be correctly built. Again the use of drywall on the interior, stucco on the exterior, and insulation to bring the wall to approximately R-20 is needed and data does not yet exist regarding how these materials attenuate waves [18]. The existing model that can be applied to get an idea of how the concrete in these walls attenuates waves is in Section 3.

Figure 17. A residential home with concrete walls.

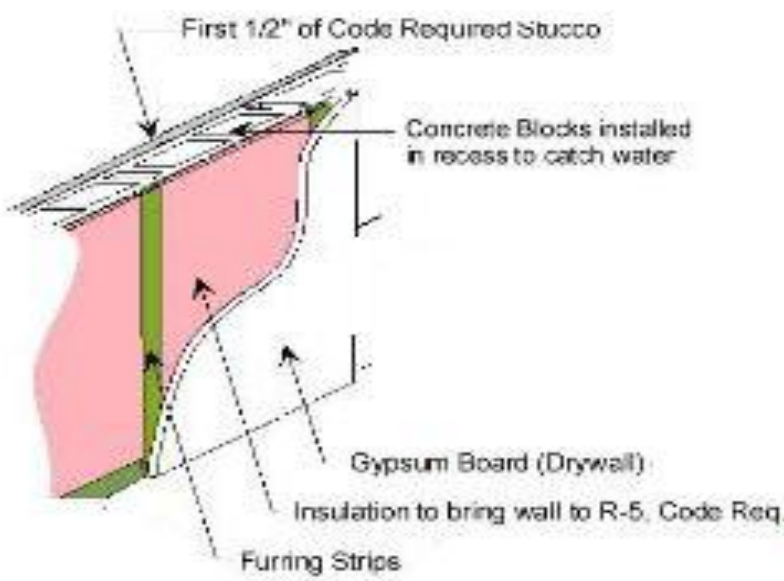

Figure 18. Cutaway diagram of the materials needed for a residential stucco wall.

The insulation used with stucco typically has a moisture barrier made of Aluminum foil on one side. The strips are not joined at the seams, but they do provide some attenuation. A stucco building has a layer of chicken wire in it which provides some attenuation.

7. Commercial Structures

Concrete is the most common building material for commercial structures. However, commercial buildings are still constructed with cinder blocks or the wood frame residential structure model [19]. Cinder block walls can be hollow with or without any rebar. Depending on the desired thickness of a concrete wall for commercial use, either a single or double rebar mesh design is used inside the concrete wall. Walls thicker than 6 inches use the double mesh design where each rebar mesh is 1 inch inside the concrete from the exterior surface of the wall. In the single mesh case, the rebar is sandwiched in the middle as shown in figure 7. In both cases the rebar used is either #7 (diameter = 7/8 inch) or #8 (diameter = 1 inch) steel rebar with 20 mm spacing. These specifications are similar to the concrete/rebar model in Section 3 therefore it is possible to accurately predict the shielding common concrete commercial structures exhibit for outdoor to indoor wave propagation. If dealing with a double rebar mesh concrete wall structure, incorporate the rebar mesh only data of Section 2 into the concrete/rebar design of Section 3.

Recall that the combined effect of a concrete/rebar structure reduces the fields penetrating through the wall. At low frequencies the rebar mesh appears to the incident EM wave as a thin plate of lossy material that attenuates the wave as it passes through. At higher frequencies the attenuation is dominated by the concrete because the wave sees large gaps in the rebar mesh making it easy to penetrate through [7 and 8].

The second type of commercial structure to be discussed is a cinder block structure. Many buildings are still being constructed using a combination of cinderblocks, cement, and rebar. The cinder blocks used are hollow 8 in. x 8 in. x 16 in. with cement mortar joints. Rebar running vertically through the center of the hollow cinder blocks was used for strength which were then filled with concrete to hold the rebar in place. No additional insulation, drywall, or weather sealant is needed using this design. A close-up of the

Rodeway Inn in downtown Chicago in figure 19 demonstrates the cinderblock arrangement of the external wall with a coat of paint [20].

Figure 19. Close-up of Rodeway Inn cinder block external wall.

The modeling in Section 4 of the cinder block building at Kirtland Air Force base in section four did not have rebar to reinforce the wall. To get an accurate idea of how today's common cinder block buildings shield EM waves, one must include the vertical rebar shielding in addition to the cinder block shielding of Section 4. Only at high frequencies can one use the cinder block only model of Section 4 without the rebar to predict attenuation and be accurate.

8. Conclusion

There exists a limited amount of published material on outdoor-to-indoor propagation. Propagation predictions depend primarily on often unavailable building construction parameters and indoor building structures. The problem with the ray-based model used today is it often encounters a large number of reflections from indoor materials and hence is computationally inefficient.

Present-day software used to predict propagation models need user defined electrical parameters of the construction material. Usually these parameters are unknown and determined through calculations to fit the measured data. The problem is that the reported results from the software are only applicable to a specific type of wall. In order for a building transmission model to be of practical value, it should be a simple model to use and only need minimal information regarding the building under study. A great deal of time is needed to determine the electrical parameters of wall structures and only after they are determined can the results be put into software that doesn't account for any indoor material reflections in the results. Lack of knowledge of diffraction coefficients for the indoor structures is an area of study for the future if a truly accurate result for attenuation through exterior walls is desired.

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