solid and composite wall are not as close as might be expected upon examining the results in Figure 18, especially between 2 and 20 m. The total received power is a function of both the magnitude and phase of the reflection coefficient (Γ). The results in Figure 18 only depict the magnitude of Γ, the phase of Γ for the composite and solid walls can behave quit differently from each other depending upon the geometry and material properties of the walls, and this characteristic is equally important in determining the total received power.

These examples illustrate how the predicted signal level can vary for block walls with different geometries and material properties. Depending on the block wall parameters, the predicted signal level for short path propagation can correlate to either a solid slab wall, or to a wall composed of a perfect conductor. It can also behave differently from either of these two types of walls.

5. REFLECTION FROM A TWO-DIMENSIONAL BLOCK WALL

The two-dimensional composite structure shown in Figure 2 is replaced by the four-layer medium shown in Figure 5. Layers 1 and 4 are free space, layer 3 is a solid medium with $\epsilon_r = 6.1$, $\sigma = 1.95 \cdot 10^{-3}$ and $l_3 = 4.75\ cm$, and layer 2 is a periodic medium with effective material properties given by equations (8) and (9). For this medium it is assumed that $\epsilon_r = 6.1$, $\sigma = 1.95 \cdot 10^{-3}$, $a = 2.7\ cm$, $d = 15.3\ cm$ and $l_2 = 12.8\ cm$

Figure 22 shows results for the reflectivity of this composite structure for both perpendicular and parallel polarizations. Also shown in this figure are the results of a solid wall 17.55-cm thick, where $\epsilon_r = 6.1$ and $\sigma = 1.95 \cdot 10^{-3}$. Notice that the resonance behavior of the solid wall for the perpendicular polarization is different than that for the composite structure.

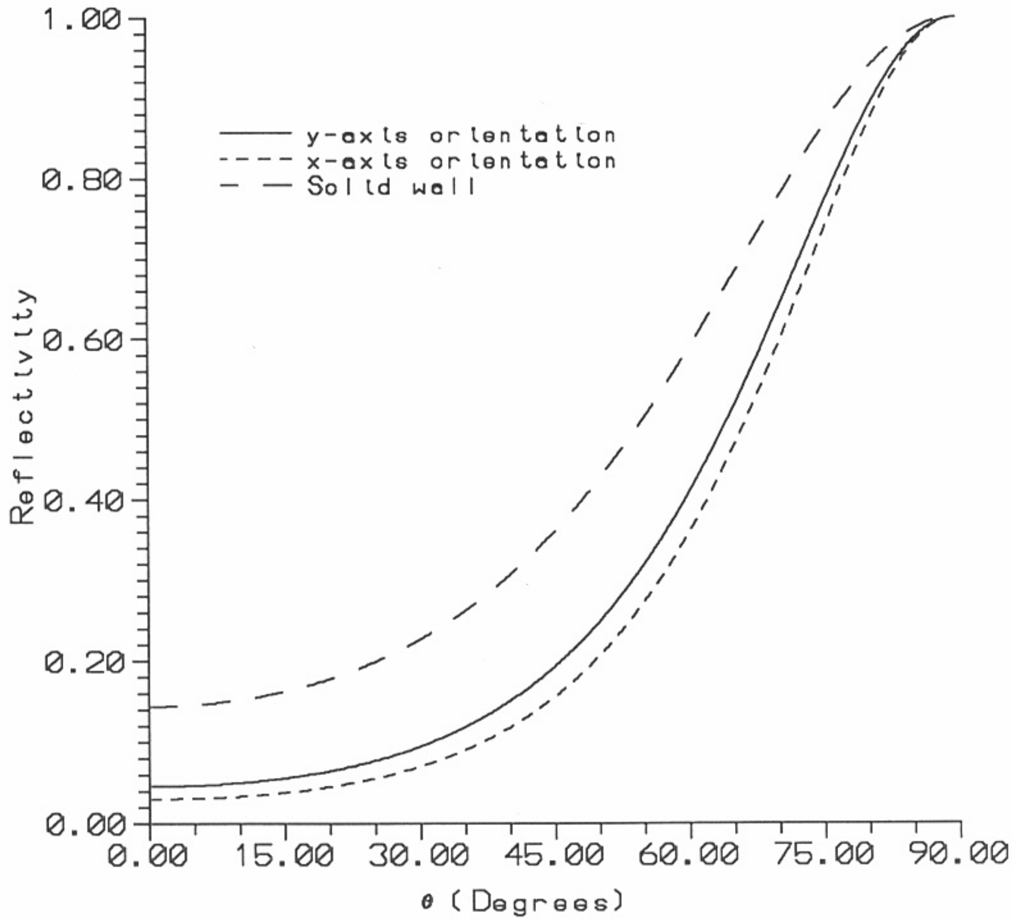

Figure 18. Reflectivity versus angle of incidence for a perpendicular polarized wave. These results are for a 7.2-cm concrete block wall (block # 3 in Table 1) with slabs oriented along both the $y - axis$ and $x - axis$ and with $f = 900$ MHz. The large dashed curve represents the results for a single layer slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y - axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x - axis$.

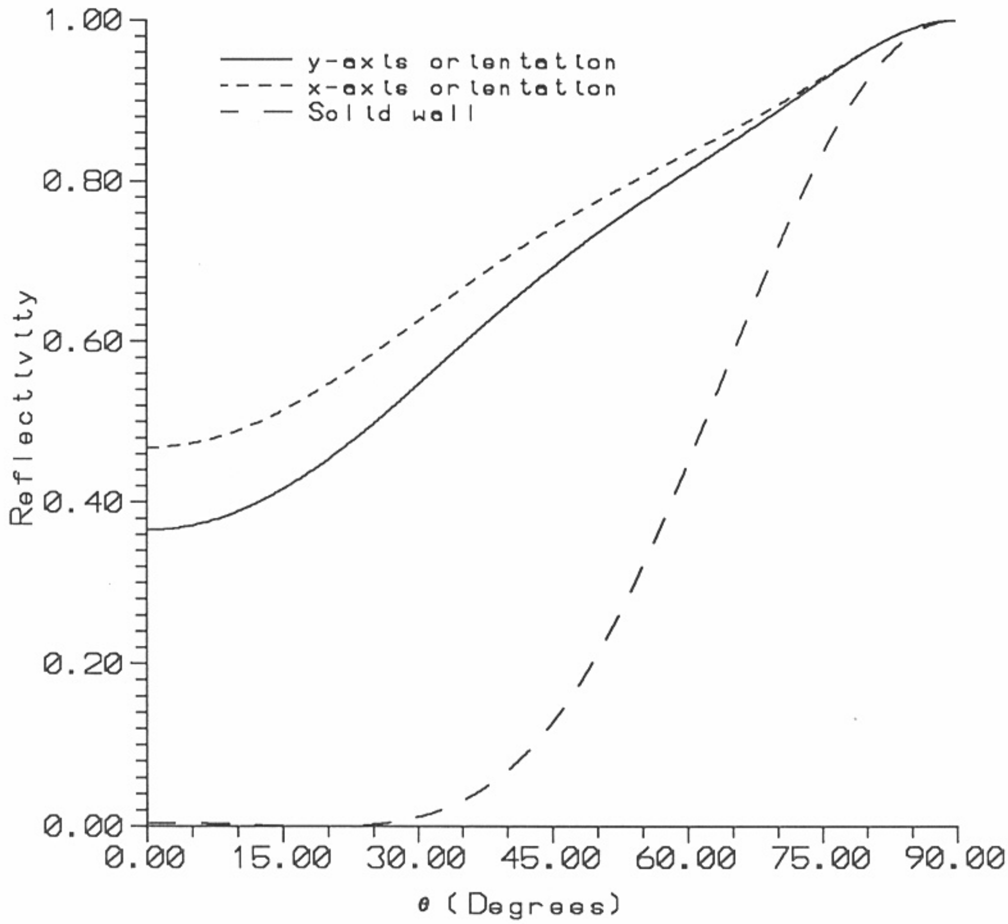

Figure 19. Reflectivity versus angle of incidence for a perpendicular polarized wave. These results are for an 19.6-cm concrete block wall (block # 4 in Table 1) with slabs oriented along both the $y-axis$ and $x-axis$ and with $f = 900$ MHz. The large dashed curve represents the results for a single layer slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y - axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x - axis$.

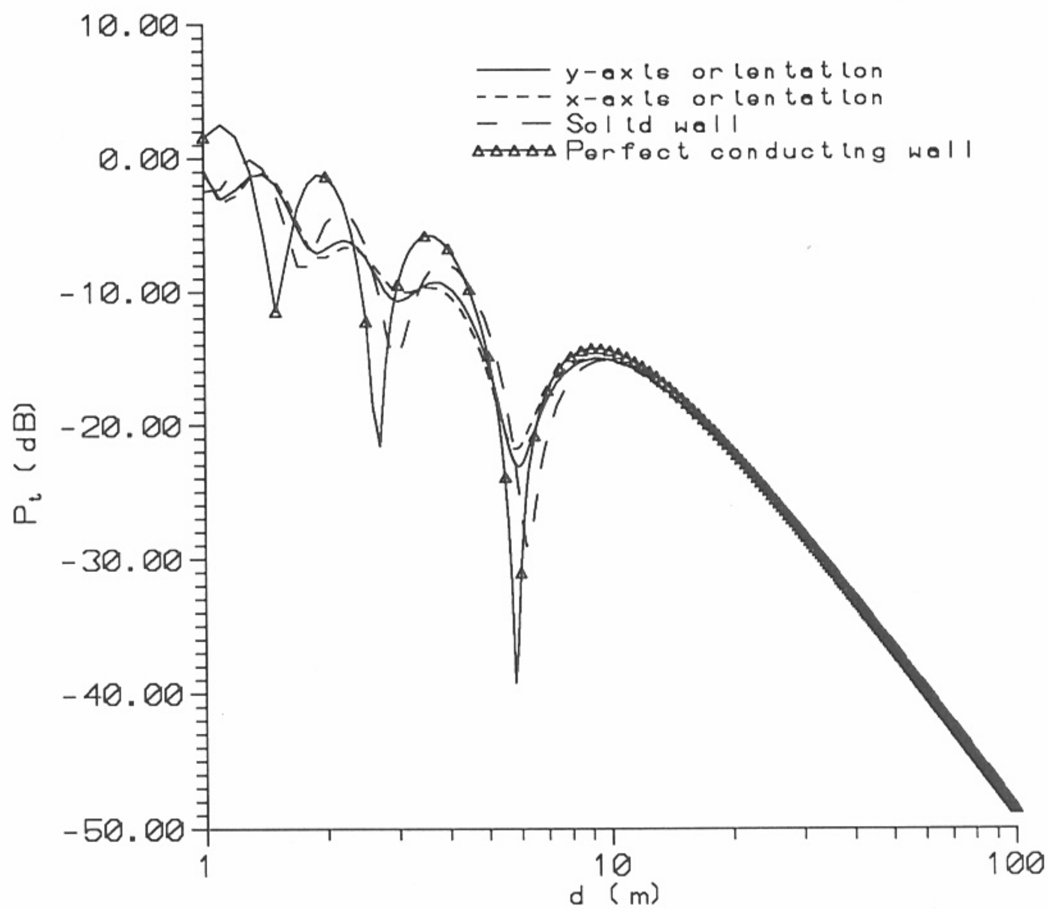

Figure 20. Received power versus antenna separation for the four-ray model. These results are for a 7.2-cm concrete block wall (block # 3) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 1 m from each of the two walls.

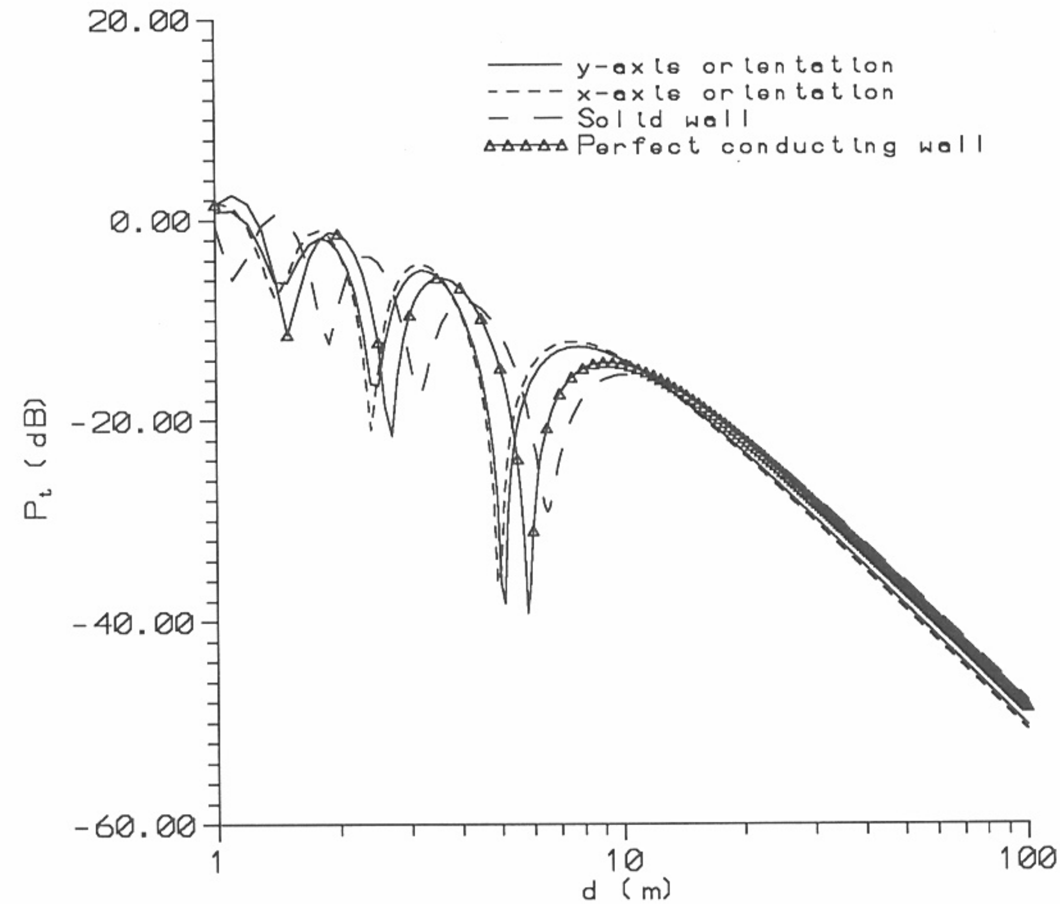

Figure 21. Received power versus antenna separation for the four-ray model. These results are for an 19.6-cm concrete block wall (block # 4) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 1 m from each of the two walls.

Figure 23 illustrates the results of the received power for the four-ray model with a frequency of 900 MHz and the antenna placed 1 m from the wall. The results shown in this figure assume a solid wall, a composite two-dimensional structure, and a perfectly conducting wall. Here again, as for the concrete block wall, the results from the three different walls approach one another for long propagation paths. However, for short propagation paths (< 1 km) a difference of about 5 dB can be predicted. This again illustrates the importance of properly representing the wall reflections for short propagation paths.

6. VALIDITY OF THE EFFECTIVE MEDIUM MODEL

The underlining assumption in the effective material properties model used in this paper, is that the period of the structure is small compared to a wavelength. For how large of a period compared to a wavelength can we expect valid results? This question can be answered by referring to homogenization results for a similar problem.

In earlier work, one-dimensional wedges and two-dimensional pyramidal absorber structures were analyzed [33]-[35] using the same techniques presented here. Reference [34] and [35] illustrate that with the effective properties of the periodic absorbing structures, the reflection coefficients can be obtained by solving a classic inhomogeneous layered media problem. The theoretical reflection coefficient obtained with these effective material properties have been compared to both experimental results, [36] and [37], and to results obtained from a full numerical simulation of the absorbing materials, [34] and [38]. Experimental results from Ellam [36] and Pues [37] have indicated that the effective material properties model used to analyze the absorbing material were valid for a period as large as 1-3 free space wavelengths.

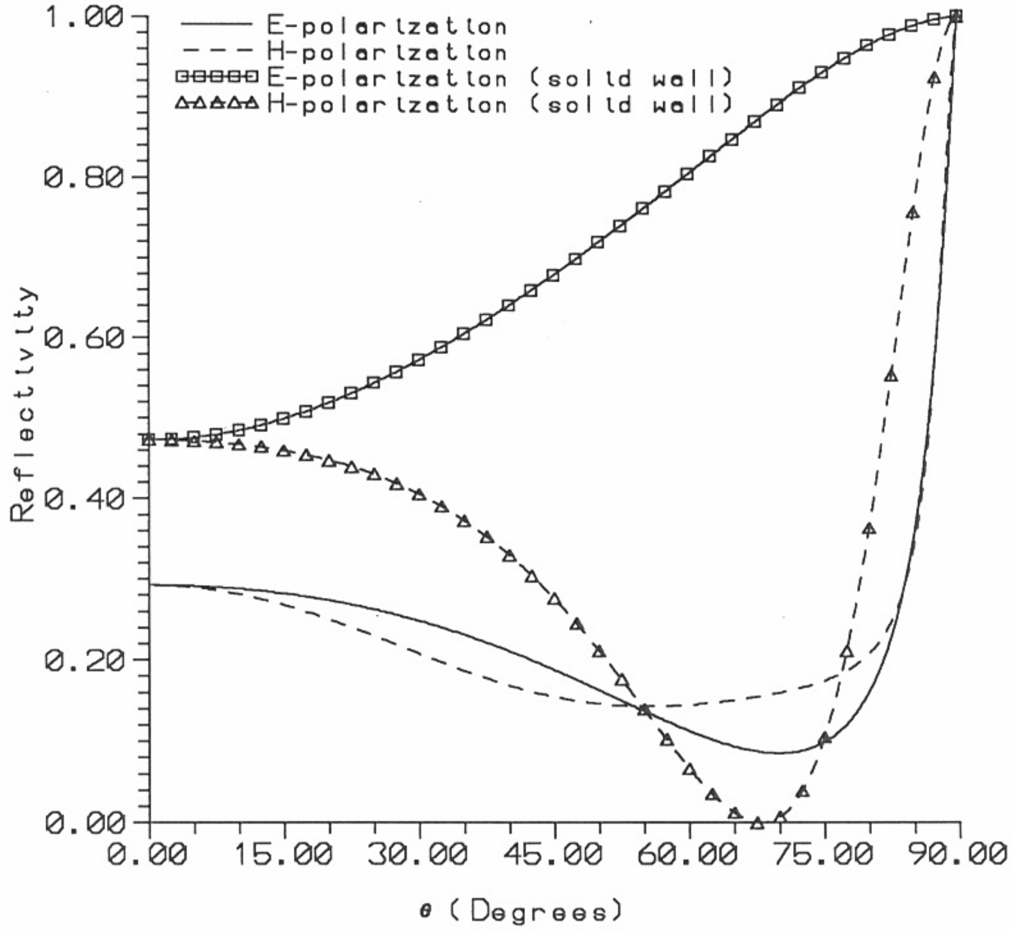

Figure 22. Reflectivity versus angle of incidence for a two-dimensional concrete block wall with $l_2 = 4.75$ cm, $l_3 = 12.8$ cm, $d = 15.3$ cm, $a = 2.7$ cm, $\epsilon_r = 6.05$, $\sigma = 1.95 \cdot 10^{-3}$, and with $f = 900$ GHz. The solid curve represents the results for the actual concrete block wall for the perpendicular polarization, the dashed curve represents the actual concrete block wall for the parallel polarization, the squares represent the the results for a single layer slab of thickness equal to $2l_2 + l_3$ for the perpendicular polarization, and the triangles represent the the results for a single layer slab of thickness equal to $2l_2 + l_3$ for the parallel polarization.

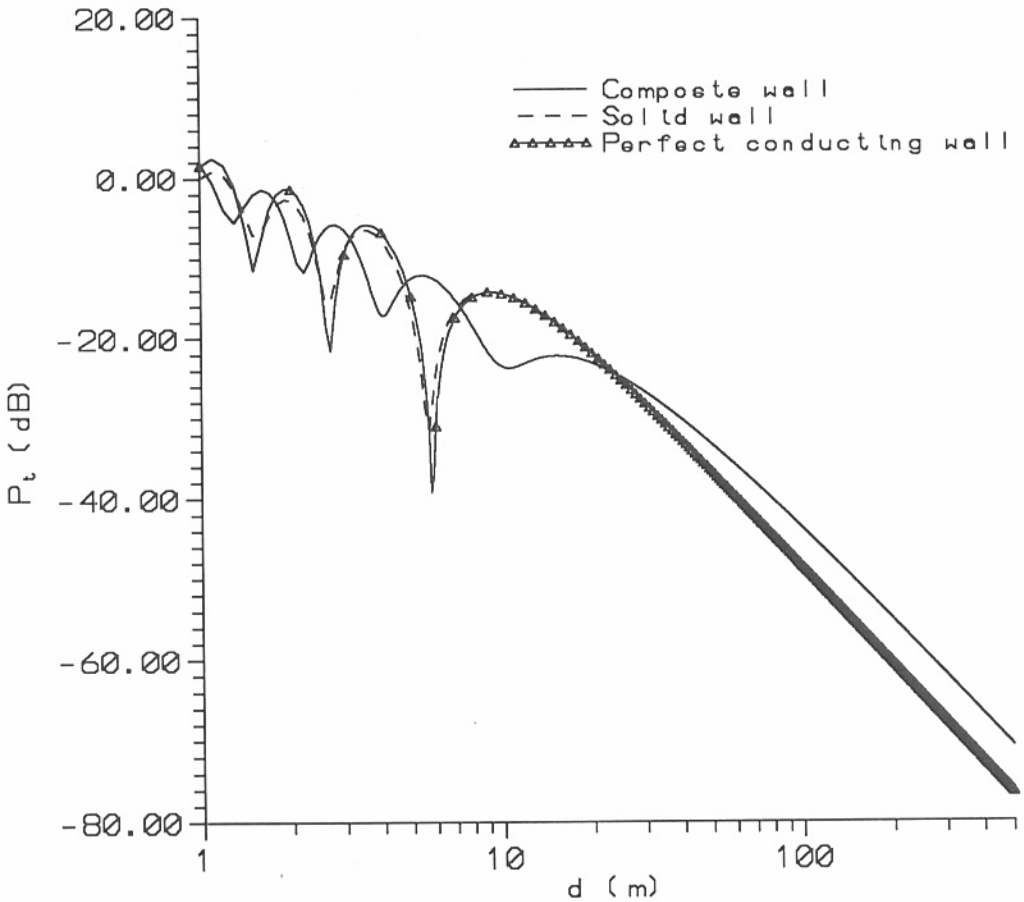

Figure 23. Received power for the four-ray model versus antenna separation. These results are for a two-dimensional block wall with $l_2 = 4.75$ cm, $l_3 = 12.8$ cm, $d = 15.3$ cm, $a = 2.7$ cm, $\epsilon_r = 6.05$, $\sigma = 1.95 \cdot 10^{-3}$, and with $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 1 m from each of the two walls.

In [34] reflection coefficients calculated by using the effective material properties model were compared to results obtained from a moment-method calculation and excellent agreement was demonstrated. The results in this comparison were for a period of the structure equal to half a free space wavelength, and excellent agreement was demonstrated for incident angles as large as 90^{o}. Using a finite difference time domain technique, Holloway, Mckenna, and DeLyser [38] have indicated that excellent agreement is achieved for a period as large as a free space wavelength for normal incidence. Agreement was also achieved for a period of 1/2 of a wavelength for incident angles as large as 90^{o}.

These numerical and experimental results indicate that the effective material properties model presented here for the composite structure are accurate for periods at least as large as 1/2 to 1 free space wavelength and possibly even higher. The upper frequency limit for which the effective material properties of periodic structures can be used is currently being investigated [38].

The only results in the literature analyzing electromagnetic wave interaction with concrete block walls are those of Honcharenko and Bertoni [19]. We have made some comparison to their results, and for 900 MHz we get quantitatively similar, but not identical, results. Because of the error in Figure 4 of [19] we have to question if their other results are correct. Honcharenko and Bertoni [19] make no comparisons in their paper that suggest that their results are correct. We have compared our model to results from Bertoni's earlier paper [18] (the basis of [19]) and for a incident angle of 45^{o}, agreement is achieved for a period of 1/2 wave length (λ).

Bertoni, Cheo, and Tamir [18] and Pinello, Lee, and Cangellaris [26] show that for a period greater than $\lambda/2$ for incident angles of 45^{o}, higher order Floquet modes begin propagating. The homogenization model presented here cannot represent these higher order Floquet modes for large periods and the reflection coefficient based on homogenization would no longer be valid.

Watters [54] has investigated the problem of acoustical wave interactions with masonry block walls, but his results are not applicable here. Watters does however, suggest that some type of area weighted average model can be used to calculate transmission loss through these types of walls (see Figure 10 of [54]).

7. DISCUSSION AND CONCLUSION

We have presented a model for analyzing the reflections and transmissions of electromagnetic waves from periodic composite structures. With this model we have investigated the importance of correctly predicting electromagnetic field interaction with walls for short path propagation channels. For short path propagation (< 1 km), differences of 5-10 dB in received power can be predicted by modelling composite walls as either a single layer structure or as a perfectly conducting wall. This illustrates the importance of properly representing the wall reflections for short propagation paths.

For large propagation paths (> 1 km) the results for either the solid or the composite structures approach one another. This is expected because for large propagation paths, the angle of incidence of the wave on a wall approaches grazing (90^o), thus regardless of the type of wall, the magnitude of the reflection coefficient approaches one. For long propagation paths, the magnitude of the reflected energy from the walls in the vicinity of the propagation path can be treated as if the walls behave as perfect conductors with little loss of generality. The one exception to this assumption, is for a periodic structure in which the period is large enough to guide energy in the structure. For this situation the periodic structure acts like a waveguiding structure, and energy can be carried away as waveguide modes, and so is not reflected off the surface in a spectral direction.

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For short propagation paths, correctly representing reflectionsof electromagnetic energy from surfaces is critical for accurate signal level predictions. In this paper, the method of homogenization is used to determine the effective material properties of composite material commonly used in construction. The reflection and transmission coefficients for block walls and other types of materials calculated with these homogenized effective material properties are presented. The importance of accurately representing the reflections for signal level prediction models is also investigated. It is shown that a 5- to 10-dB error in received signal strength can occur if the composite walls are not handled appropriately. Such accurate predictions of signal propagation over short distance is applicable to microcellular personal communications services deployments in urban canyons as well as indoor wireless private branch exchanges and localarea networks.

16. Key Words *(Alphabetical order, separated by semicolons)*

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