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# MULTI-FREQUENCIES CHARACTERIZATION OF BUILDINGS MATERIALS: ANGULAR AND POLARIZATION ANALYSIS

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## Abstract

The engineering optimisation of wireless system, such as WIFI, WIMAX, and UWB that work at many different frequencies is based on propagation modelling. So, the purpose of this paper was to model the electromagnetic properties of various building materials over a large frequency range. A measurement campaign was done at different frequencies, incidence angles and polarization in an anechoic chamber. Results of measurements on typical construction materials are presented and discussed for horizontal and vertical polarization.

## 1 Introduction

Wireless systems, such as WIFI, WIMAX and UWB, among others, are expanding rapidly due to the increasing demand on mobile services. The deployment of these networks requires the study of the propagation environment. In indoor context, the received power is attenuated due to the interaction of electromagnetic waves with surrounding walls and furniture. It is necessary to know the reflection and transmission properties of the construction structures to simulate wave propagation in buildings. These properties are different from one material to another and depend on different parameters, such as composition, incident angle and polarisation. The polarization influence on building materials has not been investigated very often although there is much literature on building materials at different frequencies [1,2].

Some reported analysis [3,4] show different results on dielectric constants that can be explained by different experimental configurations such as antennas, radio links or materials. The characterization of building materials over a large frequency band [2-16 GHz] using the same experimental conditions will allow an objective analysis of the frequency dependence of the materials.

A measurement campaign was performed at the Orange Labs centre in Belfort, on several typical construction materials, glass, plasterboard, door and cinder-block using vertical-vertical (VV) and horizontal-horizontal (HH) polarisation. The objective of this study is to estimate the dielectric parameter value of various building materials by comparing

the measured transmission coefficients with predictions obtained from a theoretical model as a function of the polarization, frequency and incident angle.

## 2 Theoretical modelling

The literature includes various methods that can be used to determine the dielectric properties [5]. If the assumption can be made that the sample is a homogeneous dielectric, the transmission coefficient  $T$  is expressed by:

$$T = \frac{1 - R'^2 \exp[-j(\delta - k_0 d)]}{1 - R'^2 \exp(-j2\delta)} \quad (1)$$

where  $\delta = \frac{2\pi d}{\lambda} \sqrt{\epsilon_r - \sin^2 \theta}$ ,  $k_0 = \frac{2\pi}{\lambda}$ ,  $\lambda$  is the wavelength in free space,  $d$  is the thickness of the sample,  $\epsilon_r$  is the relative complex permittivity of the sample, and  $\theta$  is the incident angle.  $R'$  is substituted by the Fresnel's reflection coefficient in the cases where the field is in horizontal or vertical polarization.

If the sample has a layered structure that can be modelled by a dielectric N-layer, the transmission coefficient is given by:

$$T_{total} = T'_{0,1} \quad (2)$$

$$T'_{i,i+1} = \begin{cases} \frac{T_{i,i+1} T'_{i+1,i+2} \exp(-j\Delta_{i+1})}{1 + R_{i,i+1} R'_{i+1,i+2} \exp(-j2\delta_{i+1})} & 0 \leq i \leq N-1 \\ T_{N,N+1} & i = N \end{cases} \quad (3)$$

Where  $\delta_i = \frac{2\pi d_i}{\lambda} \sqrt{\epsilon_{r_i} - \sin^2 \theta}$ ,  $\Delta_i = \delta_i - k_0 d_i \cos \theta$ ,  $\lambda$  is the wavelength in free space,  $d_i$  is the thickness of the  $i$ -th layer sample,  $\epsilon_{r_i}$  is the relative complex permittivity of the  $i$ -th layer, and  $\theta$  is the incident angle.  $R_{i,i+1}$  and  $T_{i,i+1}$  are the Fresnel reflection and transmission coefficients for the interface between the  $i$ -th layer and the  $i+1$ -th layer, in the cases where the field is in horizontal or vertical polarization.

### 3 Measurement setup

Measurements were carried out inside an anechoic chamber where the material was fixed vertically on a rotating arm. The angle of incidence with respect to the normal to the material was varied by turning the material in  $5^\circ$  increments. Measurements were made for angles of incidence between  $-65^\circ$  to  $+65^\circ$ . The angles of incidence were limited to this range in order to comply with the width of the first Fresnel ellipsoid [6]. Table 1 lists the selected samples and their dimensions.

Materials	Thickness (cm)	Dimension (cm×cm)
Glass	0.5	127.5×84.5
Plasterboard	1.3	100×120
Door	4.5	200×83
Cinder Block	10	100×100

Table 1: Material dimension

Two identical standard horn antennas (ETS Lindgren 3117) that covered the frequency range from 1 to 18 GHz were used as transmitting and receiving antennas. The measured material was placed at the midpoint between both antennas (Figure 1). The distance between antennas was 4.60m such that the material sample object was in the far field of each antenna. With this configuration, the incident electromagnetic field that arrives on the material is essentially a plane wave. A schematic sketch of the free space measurement system is presented in Figure 1.

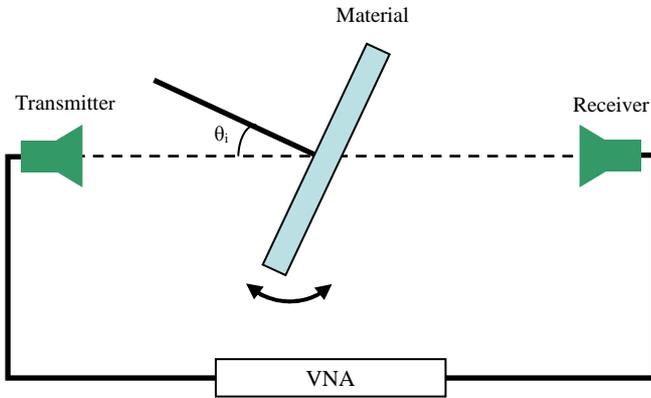


Figure 1: Illustration of the measurement setup

The measurement procedure consists in a frequency-swept method, performed with a Vector Network Analyzer (ZVB 20). By connecting antennas to the two ports of the analyzer and by measuring the  $S_{21}$  parameter, the frequency response of the channel was obtained.  $S_{21}$  was measured at 6000 stepped frequency points in the range of 2 GHz to 16 GHz. A time domain gating function was used to filter out edge diffraction effects and reflections from other parts of the system such as cables, connectors and analyzer, to mention but a few, and guaranteed that only the direct signal was measured. The following steps were applied for the measurement. Firstly, measuring the channel without material between the antennas performed the free space calibration with the effect of antennas. Secondly, the measurement was

realized with the material between the antennas. Measurements were repeated for the two combinations of polarizations (HH, VV). The measured  $S_{21}$  with and without material gives the transmission coefficient from which the relative complex permittivity ( $\epsilon_r = \epsilon_r' - j\epsilon_r''$ ) is extracted.

### 4 Data analysis method

The data analysis method consisted in comparing the experimental transmission coefficient to an internal multilayer model for transmission and reflection coefficients. The comparison result made the reconstruction of the dielectric properties of the sample studied easier. A least-squares criterion is used and the optimal couple ( $\epsilon_r', \epsilon_r''$ ), which minimize the function error  $S$ , is researched:

$$S = \sqrt{\frac{1}{NM} \sum_{j=1}^N \sum_{i=1}^M \|T_{theo}(f_j, \theta_i, \epsilon_r', \epsilon_r'') - T_{exp}(f_j, \theta_i)\|^2} \quad (4)$$

where  $N$  is the number of measurement points in frequency domain,  $M$  is the number of measurement points in angular domain,  $T_{theo}$  is the theoretical transmission coefficient (single layer or multilayer), and  $T_{exp}$  is the measured transmission coefficient. The value of this function gives the corresponding RMS modelling error and indicates the accuracy between the measured data and the analytical data

### 5 Experimental and theoretical results

The transmission coefficient of a number of materials was measured using HH and VV polarisation of the two antennas.

#### 5.1 Glass

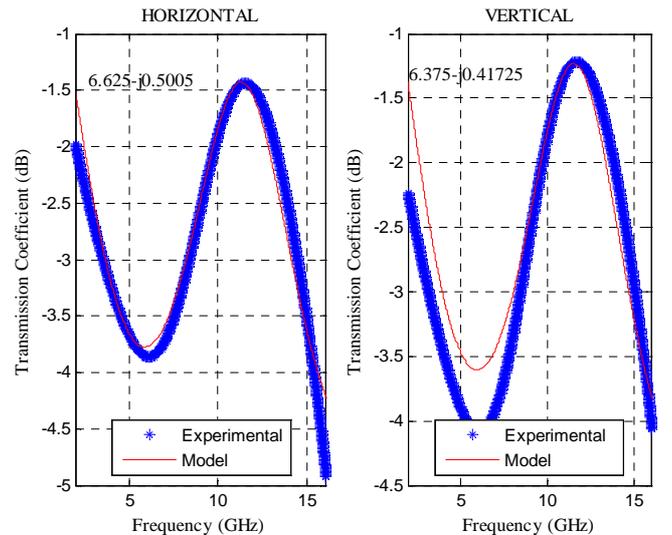


Figure 2: Transmission coefficient of glass from measurement and the theoretical model

The dielectric constant was firstly estimated for glass. The values obtained from measured transmissivity were found to

be  $\epsilon_r = 6.625 - j*0.5005$  with an RMS error between measured and theoretical values (the single layer model was used) of 0.0614 for HH polarization and  $\epsilon_r = 6.375 - j*0.41725$  with an RMS of 0.078 for VV polarization.

Figure 2 represents the measured and computed values obtained at normal incidence. The results obtained show small variations between the model and the experimental value. The 0.5 dB difference in the 2-8 GHz band for the vertical polarization may be explained by negligible variations in  $\epsilon_r$  estimations for this band. Yet, the dielectric parameters are close for the two polarizations. The approach used is validated by plotting the transmission coefficient for the angle range analyzed (Figure 3 and Figure 4).

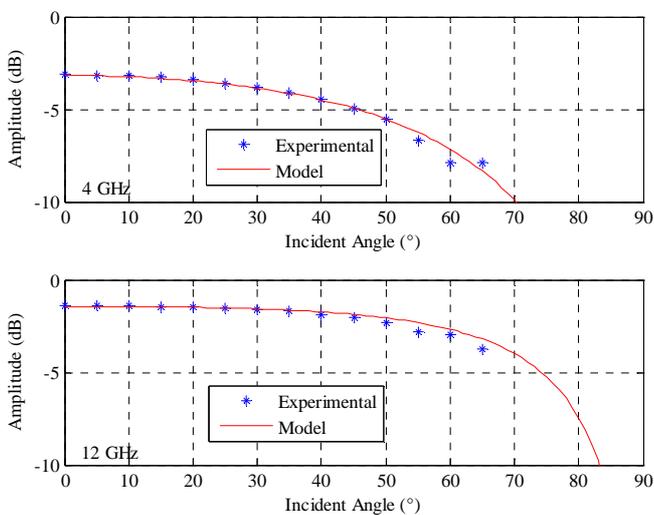


Figure 3: Transmission coefficient of glass from measurement and theoretical model using HH polarisation.

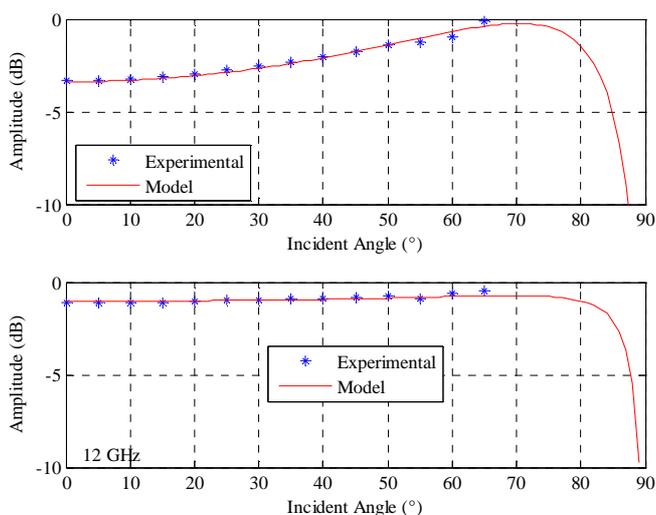


Figure 4: Transmission coefficient of glass from measurement and theoretical model using VV polarisation.

## 5.2 Plasterboard

Measurements were repeated for the plasterboard sample. The results obtained were  $\epsilon_r = 2.25 - j*0.0175$  with an RMS error (the single layer model was used) of 0.0741 for HH polarization and  $\epsilon_r = 2.41 - j*0.0258$  with an RMS of 0.085 for VV polarization. The curve fitting obtained for measurements is shown in Figure 5. Following the glass, a small dissimilarity exists between experimental and model value but it is negligible (0.1 dB).

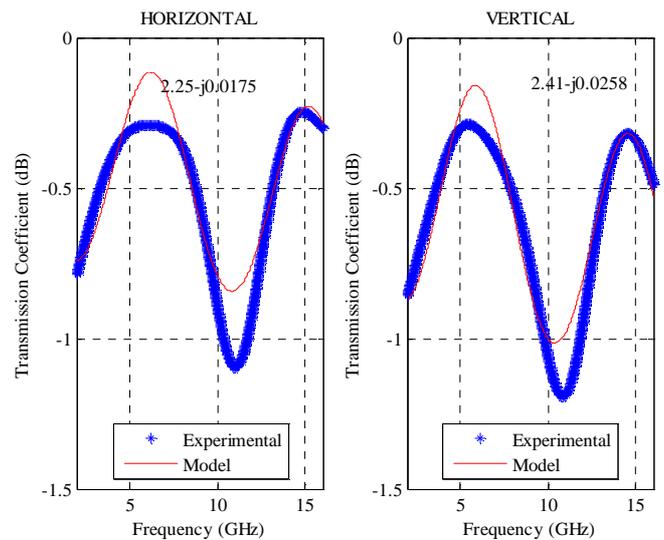


Figure 5: Transmission coefficient of plasterboard from measurement and the theoretical model

Figures 6 and 7 show the comparison results in terms of incident angle for horizontal and vertical polarizations, respectively. The values  $\epsilon_r$  obtained for glass and plasterboard are comparable with those reported in [7].

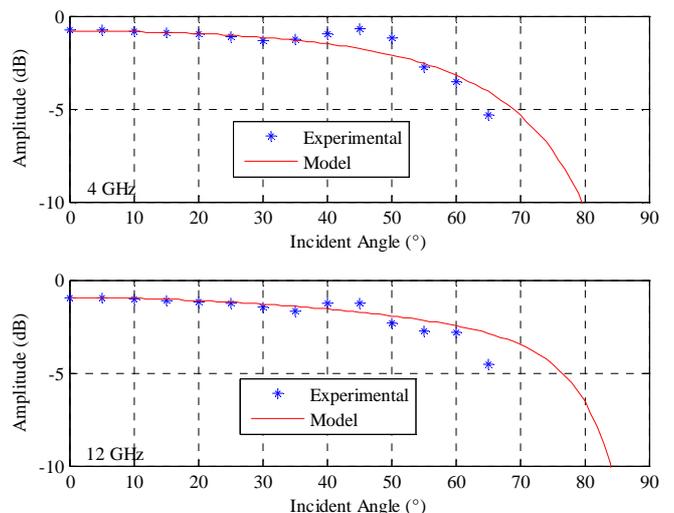


Figure 6: Transmission coefficient of plasterboard from measurement and theoretical model using HH polarisation.

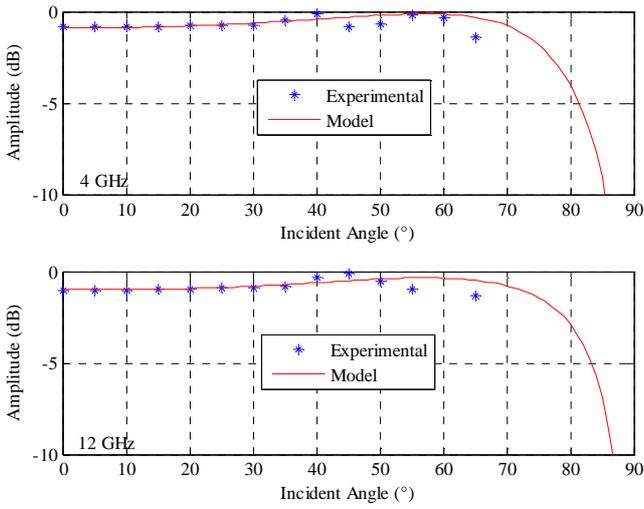


Figure 7: Transmission coefficient of plasterboard from measurement and theoretical model using VV polarisation.

### 5.3 Door

A door was measured. Figure 8 shows the measured transmission coefficient and that predicted from the 3-layer and the 1-layer model. The single layer model does not give a satisfactory result for the door sample.

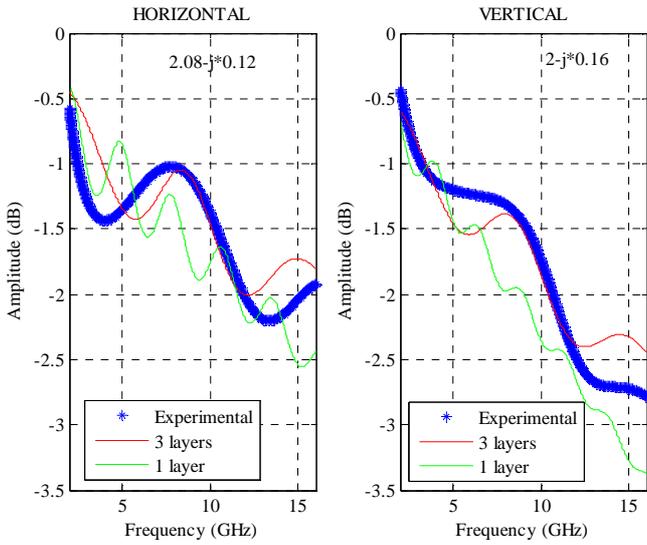


Figure 8: Transmission coefficient of door from measurement and the theoretical model

Figure 9 presents the horizontal section of the door. Considering the internal geometry, the multilayer transmission coefficient was used in (4) to fit the experimental data. The door was represented by a 3-layered model, 2 layers of chipboard and one of air. Determination of the thickness of each layer was included in the optimisation.



Figure 9: Interior structure of door

The results obtained for the door sample were  $\epsilon_r = 2.08 - j*0.12$  with an RMS error of 0.056 for HH polarization and  $\epsilon_r = 2 - j*0.16$  with an RMS of 0.061 for VV polarization. The thickness estimation obtained from the optimization was 1.24 cm for the chipboard layer and 1.93 cm for the air gap in the HH polarization. Values for VV polarization was 1.42 cm for chipboard layer and 1.87 cm for the air gap. The RMS for the 1 layer model was 0.139 for the HH polarization and 0.154 for the VV polarization.

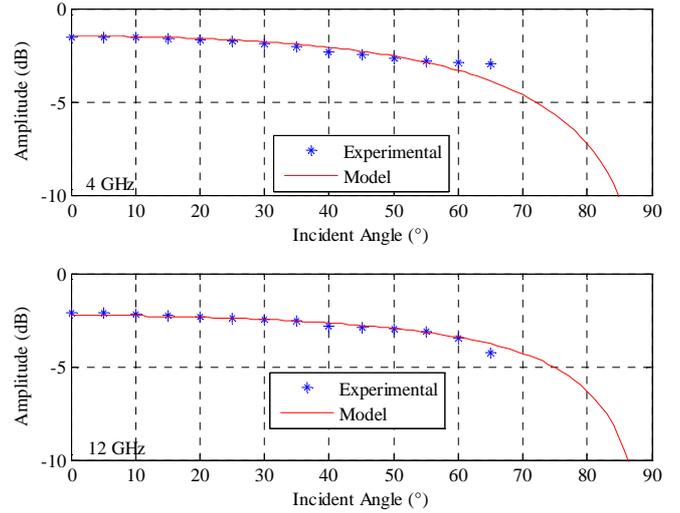


Figure 10: Transmission coefficient of door from measurement and theoretical model using HH polarisation

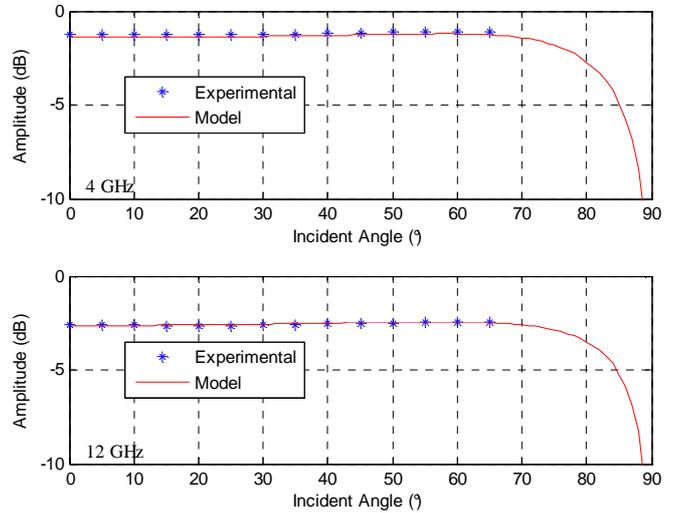


Figure 11: Transmission coefficient of door from measurement and theoretical model using VV polarisation

Figures 10 and 11 show the comparison results in terms of incident angle for horizontal and vertical polarizations, respectively. The  $\epsilon_r$  values obtained are acceptable compared with those reported in [8].

### 3.4 Cinder Block

A panel of cinder block wall was measured. The cinder block wall was more complex than the others sample (Figure 13). As does the door, Cinder block was represented by a 3-layered model, 2 layers for the block structure and one for air. Determination of the thickness of each layer was also included in the optimisation. Figure 8 shows the measured transmission coefficient and the predicted one from the 3-layer and the 1-layer model.

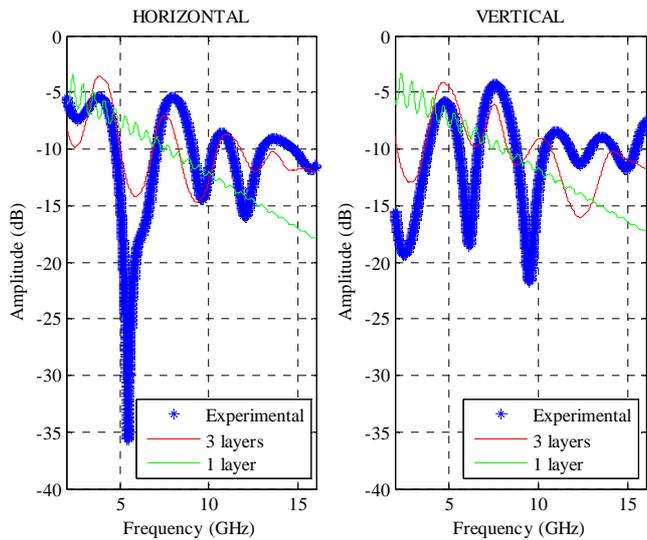


Figure 12: Transmission coefficient of cinder block from measurement and the theoretical model

The results obtained were  $\epsilon_r = 9.7792 - j*0.708$  with an RMS error (the single layer model was used) of 0.19641 for HH polarization and  $\epsilon_r = 9.72 - j*0.8424$  with an RMS of 0.211 for VV polarization. The thickness obtained from the optimization was 1.33 cm for block structure and 1.07 cm for the air gap in the HH polarization. Values for VV polarization was 1.27 cm for block structure and 1.08 cm for the air gap.

It follows from the figure 12 and from results obtained that the 1 layer model and the 3 layer model were not appropriate for the estimation of the dielectric parameters. More advanced studies on periodic structure may be undertaken to validate a theoretical model [9].



Figure 13: Structure of cinder block

## 4 Conclusion

The theoretical model, based on homogeneous material or multilayered material was used to estimate the dielectric parameters by comparing measured and predicted results. Experimental results of transmission measurements for three types of building materials using VV and HH polarisation

were presented. The results showed agreement between the predicted and the measured values for a wide frequency band and wide range of incident angle. The dielectric parameters showed no significant variation with the polarization. Furthermore, the dielectric parameters presented no variation with the frequencies for low loss materials. A single value could be used to represent the dielectric parameters for 2 to 16 GHz. As a result, the values obtained may be used to improve the prediction quality of ray-tracing models in indoor environments. Further work is needed to investigate the propagation in multilayer structure.

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