Factors influencing outdoor to indoor radio wave propagation

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I. INTRODUCTION

An important requirement from mobile radio systems is the provision of reliable services, to the increasing number of users across the outdoor to indoor interface. To achieve this and at the same time reduce the possibility of interference, the radio network has to be carefully planned and optimised. For this reason the radio propagation modeller has to appreciate the conditions, which can influence the accuracy of modelling predictions or even the practical measurements which are carried out for planning purposes.

This paper starts by briefly describing the different factors, which have been reported and can influence outdoor to indoor propagation, highlighting some apparently contradictory observations obtained through measurements. Some researchers have suggested that building penetration loss decreases with frequency over a certain range, while specific losses through materials increase with frequency.

The work presented here tries to explain the reasons for the results obtained above. Findings in this paper have been obtained through simulation work. These include the non-linear variation of material loss with material thickness or frequency and the average predicted penetration loss versus frequency for a windowed wall. Detailed explanations are given why these effects take place, providing a possible answer on the contradicting observations.

II. BACKGROUND

This section introduces some of the factors, which can influence the received signal power inside a building.

Material loss measurements recorded by different researchers at different frequencies suggest that the associated transmission loss for an interface increases with an increasing angle of incidence [1][2]. Similarly it has been found that the reflection and transmission coefficient of these materials, which can be defined respectively as the ratio of the reflected and transmitted electric field to the incident electric field, will change as the angle of incidence changes [3][4].

Since in a mobile environment, the user is expected to enter buildings, which are illuminated under different incident angles, the effect of the angle of incidence is something that has to be accounted for. Certain models [5] include in their formulation the effect of this angle, where an extra loss factor is added to the loss under normal incidence for non zero incidence angles. A similar approach is presented in [1] for an external windowed wall at 1.2GHz.

It has been also shown that, when the transmitting and receiving antennas are located in a relatively clear space [6], the path loss mechanism can be understood in terms of the first Fresnel zone ellipsoid.

The Fresnel zones can be considered as containing the propagated energy in the propagating wave. Contributions within the first zone are all in phase, so any obstructions, which do not enter this zone, will have little effect on the received signal [7]. Successive Fresnel zones have the effect of alternately providing constructive and destructive interference to the received signal.

If the antennas are close enough so that the first Fresnel zone ellipsoid lies completely within a clear area, the fields associated with the direct (strongest) ray will not be affected by the presence of the floor and ceiling clutter [8][9]. In this case the path loss will have the same dependence of $1/(\text{distance})^2$ as in the free space loss case. The path loss is related to $1/(\text{distance})^2$ and not to $1/(\text{distance})^4$ because of the lack of the reflection contribution due to the obstructing clutter and the close spacing between the antennas. Similar behaviour has been reported in [10].

If now the distance between the transmitter and receiver antennas starts increasing, the Fresnel zone will expand in size, as a result of which the clutter of the room will be within this zone. In this case the path loss would be greater than that of the free space loss.

Although the previous observations refer to an indoor scenario, the influence of the indoor clutter can be extended in the outdoor to indoor case.

Another factor is that depending on the layout of the outdoor to indoor setup, it is possible that different ray paths between the transmitter and receiver can contribute to the overall field [11]. In addition to a direct ray path, other possible paths include diffraction around windows and reflection from neighbouring buildings. These contributions are affected by the clutter within rooms and the reflection and transmission coefficients of neighbouring buildings.

It has been reported that nearby buildings could block or reflect the signal into different floors of the building under investigation [12] [13], [14][15].

Penetration loss studies at frequencies ranging from 400 to 2300MHz have shown that penetration loss decreases as the height of the building increases [13][14][15][16][17]. A rate of change of 1.2dB to 2.4dB has been reported [13][14][15][18] although for higher floors (usually above 5th floor) penetration loss increases again or levels off [13][15][18]. Also there were cases where the rate of change was as high as 7dB/floor [12]. Another interesting observation by [12], was that at 950MHz and 1800MHz penetration loss was lower by 2-4 dB on lower floors for 950MHz whereas it was equal or higher than the 1800 MHz penetration loss on higher floors. In contrast to this it has also been found by measurements conducted at 1700MHz [19][20] 912MHz 1920MHz and 5990MHz [21] that penetration loss neither decreases or increases as a function of increasing floor level. Unfortunately, a direct comparison of the above is not possible because the measurement environments have not been exactly the same. This environment difference can influence penetration loss since this loss can depend on the position and nature of nearby buildings and effectively the illumination of building under investigation.

It has also been noted that another important factor is the internal construction and size of the penetration side (room) under investigation. Other important factors influencing penetration and effectively overall path loss is the number and size of windows that exist at the illuminated building. These windows can provide a relatively low loss propagation path. Also, insulation used in walls can play an important part in radio wave attenuation since transmission of electromagnetic waves through walls is an important mode of propagation [14][15][16][17] [22][23].

Another issue is that building materials might absorb moisture (water). The general trend that has been reported under water absorption is that tangent loss and relative permittivity increases [26][27][28], resulting in increased losses compared with the dry case.

Some residential radio penetration studies at 912MHz, 1920MHz and 5990MHz have shown that penetration loss increases as the frequency increases [21]. In contrast to this it has been also reported that penetration loss decreases with increasing frequency. These measurements were contacted at 35MHz and 150MHz [24], 441MHz, 900MHz and 1400MHz [14][25] 880MHz and 1922MHz [13], 900MHz, 1800MHz and 2300MHz [18]. It is obvious that there are certain factors influencing the frequency-penetration loss trend. Although one of these reasons could be the variation of the constitutive parameters at different frequencies, some other possible reasons are highlighted in the following section.

III. SIMULATIONS

An interesting situation arises when examining what happens to the transmission loss of a material, when varying its thickness or the frequency of operation.

Plots shown in Fig. 1, are obtained through the use of a transmission model which utilises the wave-chain-matrix theory for a single and multiple dielectric layer [29]. The first plot refers to a single pane window having a thickness of 8mm. The second plot refers to a double glazed window where the glass pane is 8mm and the air separation 4mm. Both types are defined as having a relative permittivity of 4 and a loss tangent of 0.0012 [30].

From the plotted data it is obvious that transmission loss does not increase necessarily in a linear way with increasing frequency.

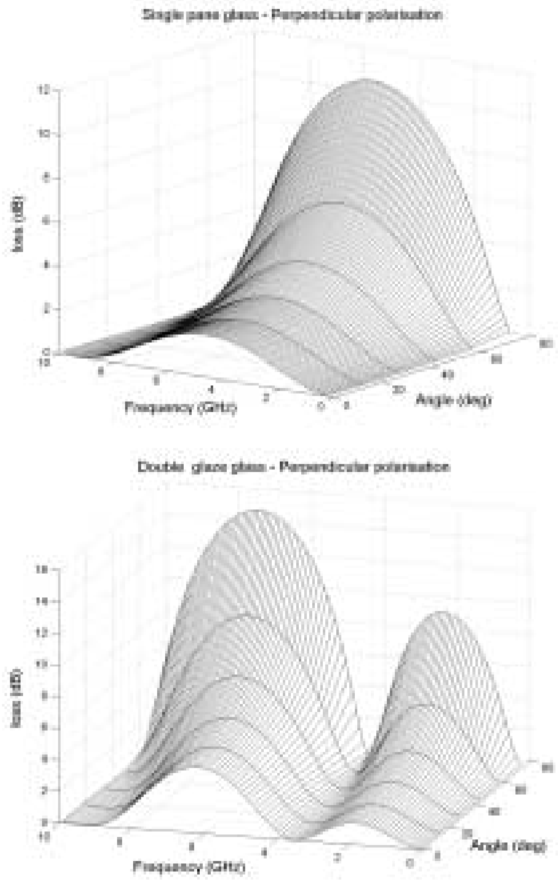

Figure 1: Theoretical transmission loss for perpendicular polarisation

The above phenomenon can be explained by examining the input impedance at the normalised air dielectric interface with reference to Figure 2 where the layer material and air interface are represented by a transmission line analogy.

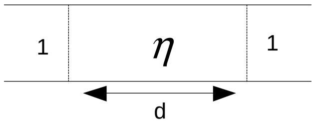

Figure 2: Transmission line analogy for the air-layer-air interface

The input impedance at the air-dielectric interface is given by [29],

$$\eta_{in} = \frac{\eta(1 + j\eta t)}{\eta + jt}, t = \tan\left[\frac{2\pi}{\lambda_0} d\sqrt{\left(\varepsilon_r - \sin^2(\vartheta_i)\right)}\right]$$

where d is the thickness (m), ε_r the permittivity, λ_0 the wavelength (m) and ϑ_i the angle of incidence.

For a reflectionless layer, the normalised impedance η_{in} should be equal to 1; meaning t should be equal to 0. Under this condition, the thickness d for a reflectionless layer can be defined as,

$$d = \frac{m\lambda_0}{2\sqrt{\left(\varepsilon_r - \sin^2(\vartheta_i)\right)}} \text{ with } m = 0,1,....$$

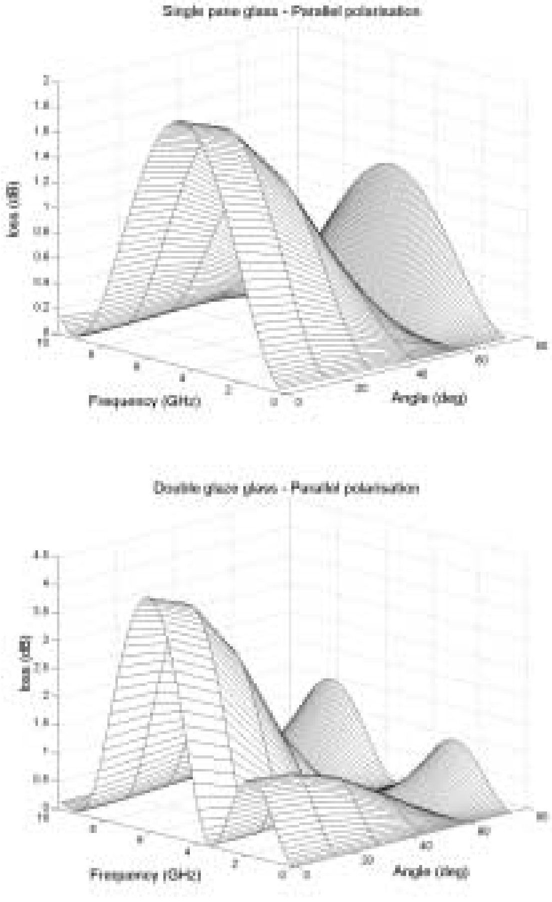

Figure 3: Material loss for parallel polarisation

This reveals that the loss will not necessarily increase linearly with increasing material thickness, or frequency, but there would be cases when it will follow a max-min pattern defined by thickness d of the material, or frequency λo, and will depend on the electrical parameters and angle of incidence. Similar results are observed for other materials.

Figure 3 shows another interesting result obtained after analysing what happens when the propagating wave is parallel polarised. In this case, the loss pattern obtained is different than the one obtained for the perpendicular case. This is due to the existence of the Brewster angle. As the angle of incidence reaches this angle, transmission loss reaches a minimum and then increases again.

The above theoretical analysis suggests another possible answer to the contradicting results found by different researchers when measuring penetration loss at different frequencies and different buildings. Same building materials can give rise to different transmission losses, with varying material thickness or frequency of operation, due to matching.

Another possible explanation for the different observations can be given by utilising a formulation, which combines all the different contributions through an external wall [31]. A simple example is shown in Figure 4 where a receiver is placed behind a brick windowed wall. The transmitter is operating at 3GHz, moving along the wall at both directions. The electrical permittivity and loss tangent of the wall section were set to 4 and 0.045, while for the glass area these parameters were set to 4 and 0.0012 (corning glass 7070) [30]. The brick wall thickness was set to 30cm and the glass thickness to 8mm.

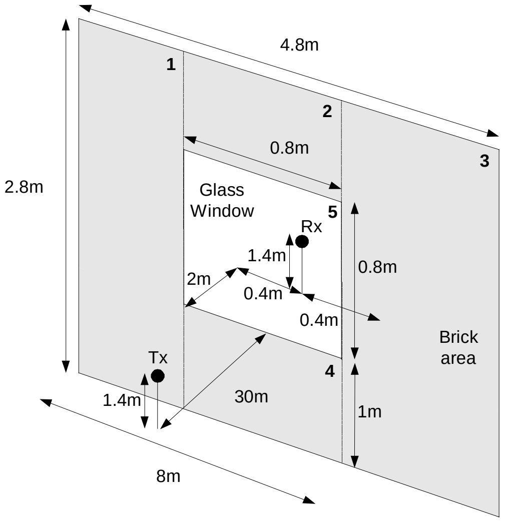

Figure 4: Windowed wall

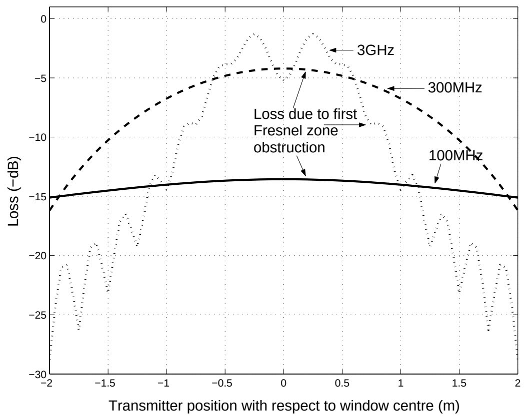

Figure 5: Effect of obstructing the first Fresnel zone and loss due ti simplified single ray models

Results presented in Figure 5 show the predicted loss when only the single window glass aperture of Figure 4 is considered with the brick area treated as a blocking screen. In this case the transmitter was placed 2m away from the aperture. The glass type was set again to corning 7070 because it has almost constant constitutive parameters at most frequencies (4 and 0.0012). This was necessary in order to isolate the effect of the constitutive parameters and investigate what will happen after changing the frequency of operation or effectively the aperture size. The results shown in Figure 5, reveal the variation of the suffered loss with respect to the transmitter position and the Fresnel zone obstruction. For lower frequencies the first Fresnel zone is larger than that of higher frequencies and significant contributions to the received field are blocked thus the loss suffered is greater. As the frequency increases (300MHz), the loss through the window glass is decreased since the first Fresnel zone is less obstructed. For the setup described above the radius for the first Fresnel zone for 100MHz, 300MHz and 3GHz is calculated to be 1.7m, 1m and 0.31m.

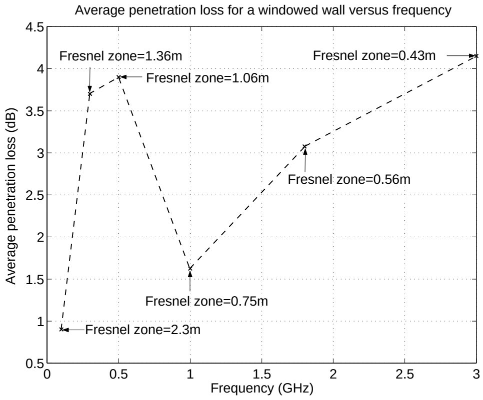

Figure 6:Average predicted penetration loss versus frequency

An interesting situation arises if one now considers the overall contributing field effect of the surrounding brick area of Figure 4. Figure 6 shows the average penetration loss behaviour for the whole wall area versus frequency by utilising the formulation in [31]. Results shown suggest that although at low frequencies (100MHz) the significant contributions through the low loss glass window are obstructed (Fresnel zone 2.3m, glass window 0.8m), nevertheless the average loss is kept low because significant contributions can pass through the brick area. As the frequency increases the loss increases because less significant contributions pass through the brick area and the first Fresnel zone through glass is still obstructed. At 1 GHz the loss decreases suddenly because at this point the First Fresnel zone is smaller than the glass window aperture (Fresnel zone 0.75m, glass window 0.8m). After this point the loss increases due to the loss suffered by the actual material at higher frequencies.

IV. CONCLUSIONS

This paper has tried to provide an answer to the reported contradiction concerning the relation of frequency variation and penetration loss. This possible answer was based on the effect of Fresnel zone and the matching effects of a material.

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