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Measurement of Attenuation by Building Structures in Cellular Network Bands

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***Abstract*—The power transmitted through obstacles is lower than the incident one due to reflection and absorption by them and this attenuation of electromagnetic waves reduces the radio coverage of any wireless communication system. This letter presents a study for the loss introduced by multiple building structures - brick, cavity and solid concrete block, and plasterboard walls; tile and slate roofs; and 10 types of modern windows. The investigation is conducted in an anechoic chamber over the frequency range from 400 MHz to 2.7 GHz. Normal incidence is considered and both linear co-polarizations (vertical-vertical and horizontal-horizontal) are tested. Strong frequency and polarization dependent attenuation is observed for the cavity concrete block wall and windows. The results demonstrate that the windows have the highest losses, among the tested structures, which can reach up to 50 dB.**

***Index Terms*—Radio propagation, measurement, attenuation, building materials.**

I. Introduction

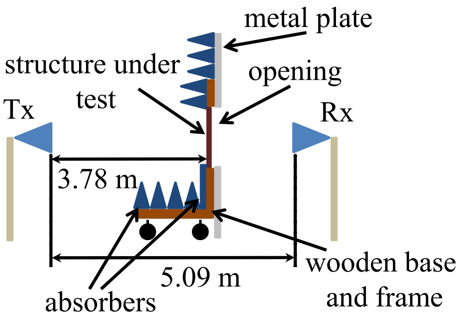
THE PERFORMANCE of any wireless communication system depends on the power level of the received signal. The attenuation of the signal due to the penetration through obstacles (e.g. walls, windows) can significantly limit the radio coverage of the system or even to make the establishment of a radio link impossible. This shows a possible problem with outdoor-to-indoor communications. The indoor coverage by outdoor signals is of great interest to mobile operators since the users are often located inside the building. The attenuation experienced by the signal penetrating into the building depends on the material. Therefore the commonly used materials for constructing buildings have to be tested and thus to develop a large dataset of values for the attenuation which is helpful for the network operators in their radio planning tasks.

The focus of this letter is to investigate the coupling through walls, roofs and windows. Results for four types of walls are presented: walls made of cavity and solid concrete blocks, bricks and plasterboard. Due to the wide spread use of these materials, data for attenuation: for brick have been presented in [1]–[3], for cavity concrete block and plasterboard in [2], [3]. However, to the authors best knowledge, solid concrete block has not been studied yet. Two types of roofs are tested: made of tiles and slates. Information about tile can be found in [3], but there is no data about the attenuation for slate even though more and more building have roofs made of it. Yet, in most of the above mentioned publications, only the scenario vertical-vertical polarization has been studied, but not horizontal-horizontal. Investigating the polarization response of a structure is important since if one of the polarization combinations provides lower attenuation then it can be employed for improving the radio coverage.

In the past years, there has been substantial evolution in designing windows. Old windows usually contain one thin glass pane mounted on a wooden frames. However, new windows have sophisticated frames with several thick glass panes. This construction together with metal coating of the glasses aims to achieve good thermal isolation (high energy-efficiency) by reflecting the infrared radiation and to prevent the ultraviolet part of the spectrum to enter the building [4], [5]. At present, information about the loss introduced by these advanced windows is even more important than before. The reason is that the façades of the modern office buildings, where multiple mobile users are located, consist mostly from windows. It has been shown that modern windows introduce higher attenuation than the old ones [4], [6]. Other works studying the loss for contemporary windows can be found in [5], [7]. However, all these publications have been focused on a small number of windows and the polarization dependence has not been studied. Due to the large diversity of windows available today, multiple samples should be tested in order to determine average penetration loss which is helpful when designing mobile communication systems in urban environment.

II. Measurement Setup

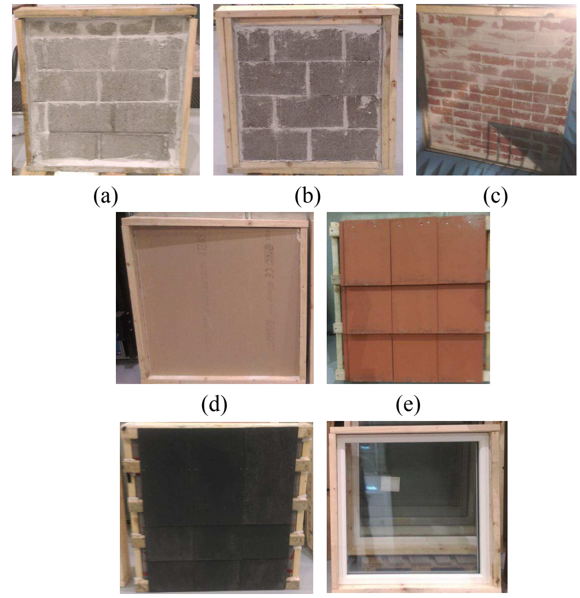
All measurements were performed in an anechoic chamber since it is controllable and well determined environment. In general, realistic outdoor-to-indoor study can have higher uncertainty. Also, it is challenging to test roofs as well as to find so many different types of windows mounted on buildings in such a way that they can be easily studied. In addition, for *in-situ* investigations, free space reference measurement needs to be conducted separately because the structure (e.g. wall) cannot be removed and therefore it is more complicated to ensure that the distance Tx-Rx as well as their alignment is the same in both free space and case of structure. The campaign was conducted by using VNA (Rohde & Schwarz ZNB 20) since it was "off-the-shelf" equipment. For such a study, time-domain channel sounder is another possibility, but one was not available for our tests. Two identical dual-ridge horn antennas (SH400 manufactured by MVG) were connected to the VNA. Horn antennas were selected due to their directional radiation properties ensuring that mainly the structure of interest is illuminated and thus no or very low undesired interference



(a)

(b)

Fig. 1: (a) Sketch of the measurement setup geometry, and (b) photo of actual measurement for red brick wall.



(a) (b) (c) (d) (e) (f) (g)

Fig. 2: Tested structures: (a) solid concrete block wall, (b) cavity concrete block wall, (c) red brick wall, (d) plasterboard wall (e) tile roof, (f) slate roof, and (g) window. Only one window is shown since there is no visual difference with the rest of the windows.

Material	Thickness (cm)
Solid concrete block	9.9
Cavity concrete block	21.2
Solid red textured brick	6.5
Plasterboard	1.25
Concrete flat red roof tile	3.05
Thrutone plus relief black roof slate	0.45

TABLE I: Materials used for making the walls/roofs and their thickness. Each structure contains a single layer of the material.

signals are present. The 3-dB beamwidth of the antenna varies between 30° and 100° in E-plane and between 30° and 75° in H-plane with frequency. The realized gain changes between 6.5 dBi and 12.5 dBi, while the side lobe level is below -10 dB over the studied band.

The sample under test was placed in a wooden frame which on the other hand was mounted on a wheeled wooden base. The size of the samples was approximately 1m x 1m. In the chamber, the test fixture was backed by a thick metal plate with a square opening in its center. This opening was located right behind the sample and also had a size of 1 m x 1 m. Both base and frame were covered with absorbers. The samples were also partly covered with absorbers so that its tested (opened) size was approximately 0.98 m x 0.98 m. The purpose of covering with absorbers was to make the transmission happen mainly through the center square window of the sample and thus to additionally decrease the corruption (if some) of the results due to interference signals. All above mentioned is illustrated in Fig. 1(a) and the implementation in Fig. 1(b).

The distance between the apertures of the antennas was 5.1 m and the distance between the Tx antenna and the front interface of most samples was approximately 3.78 m (the largest deviation was for tile roof - 3.71 m due to the introduction of supporting wooden bars as shown in Fig. 2(e)). The distance back boundary of the material - Rx antenna depended on the thickness of the sample. The studies were performed for normal incidence and for the two linear co-polarizations [vertical-vertical (V-V) and horizontal-horizontal (H-H)]. Spatial variation test was conducted for each sample by moving both antennas at three different positions lying on a line perpendicular to the signal propagation path: -3 cm (left from the middle of the chamber width), 0 cm (at the middle), and +3 cm (right from the middle). The averaged frequency response is presented, even though the difference in results at the three positions is not very high. In total 16 structures were tested as shown in Fig. 2 (only one window is presented since visually there is no difference with the rest). The measurements were conducted over the band 0.4 - 2.7 GHz which fulfils the far-field criterion.

III. Results and Discussion

The results presented in this section are normalized to the free space path loss in order to see the effect only of the structure. The measurement data was not fitted due to the fact that most of structures do not show smooth change of the attenuation with frequency and therefore use of very high order polynomials for the fitting is needed which makes it inconvenient. The materials used for constructing the walls and roofs along with their thickness are given in Table I.

Fig. 3(a) shows the attenuation for solid and cavity concrete block walls. The cavity block introduces stronger attenuation than the solid one. The heterogeneity of the interior of the cavity block (contains two large holes) causes different frequency response for the two polarizations. Two peaks are observed for the case H-H polarization and significant increase in the loss for V-V case is seen at the end of the tested spectrum.

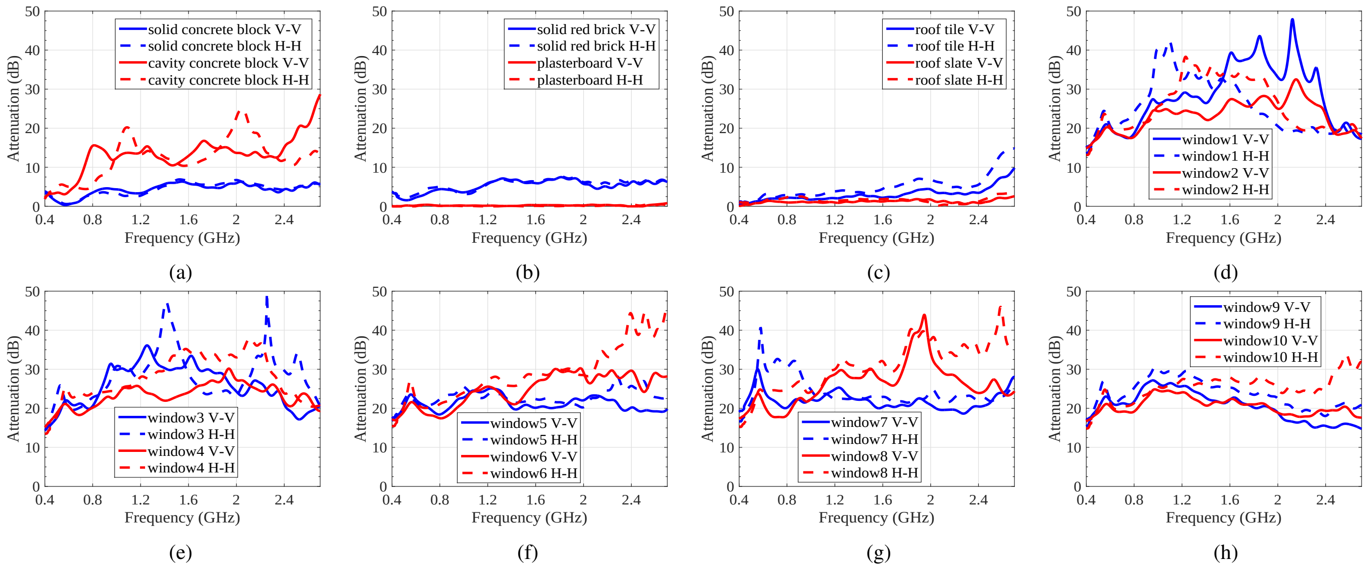


Fig. 3: Measured attenuation for both co-polarizations (V-V and H-H) for: (a) solid concrete block and cavity concrete block walls, (b) red brick and plasterboard walls, (c) tile and slate roofs, (d) window1 and window2, (e) window3 and window4, (f) window5 and window6, (g) window7 and window8, (h) window9 and window10.

Window	Number of panes	Thickness (cm)
PVC standard window (1)	2	2.4
PVC standard window (2)	3	3.6
PVC passive-future proof window (3)	2	2.4
PVC passive-future proof window (4)	3	5.2
Aluclad window (5)	2	2.4
Aluclad window (6)	2	5.2
Alu passive-echotherm window (7)	2	2.4
Alu passive-echotherm window (8)	3	5.2
Hardwood window (9)	2	2.4
Hardwood window (10)	3	3.6

TABLE II: Studied windows, number of glass panes for each of them and thickness (from the front interface of the first glass pane to the back interface of the last one). The numbers in the parenthesis are used for designating the window, e.g. PVC standard window (1) is labelled as window1 throughout this letter. The column “Thickness” presents the total thickness of all glass panes, i.e. from the front interface of the first glass to the back interface of last one.

In [2], for 20.3 cm thick cavity block variation of the loss between 8.3 dB and 11.5 dB over the band 0.5 - 2 GHz has been observed, while in [3] it has been found for 3.5 cm thick wall attenuation of 6.71 dB at 2.3 GHz. A higher loss can be seen from our test and the reason for mismatch in the results is that different types of cavity blocks have been studied.

Due to the monolithic structure of bricks and plasterboard walls (similarly to the solid block one), a weak polarization dependence is observed for both materials (Fig. 3(b)). The loss introduced by plasterboard is negligible (similar results have been presented in [2], [3]). The brick lowers the signal less than cavity block and slightly more than solid block. In the literature: 11 cm thick hollow brick with attenuation between 1 dB and 22 dB over the band 680 MHz - 2.7 GHz has been observed in [1]; loss varying between 0.5 dB and 5.4 dB over the band 0.5 - 2 GHz for 8.9 cm thick brick with three circular holes has been shown in [2]; attenuation of 4.4 dB for 10.2 cm thick brick at 2.3 GHz has been presented in [3]. The difference between the results is due to the different composition and structure of the tested bricks.

In order to mimic a real roof, roofing underlayment was stretched and nailed on the wooden frame. For holding the tiles and slates, they were nailed to additional wooden bars (as in a real roof) which on the other hand were nailed to the frame. Vertical overlapping between the tiles was 8 cm (horizontally were also overlapping as this is from the structure of the tiles), while for slates 35.5 cm (horizontally they were placed next to each other, i.e. no overlapping). All this is shown in Fig. 2(e) and (f). As one can see in Fig. 3(c), the slate roof introduces lower attenuation than the tile one. Stronger polarization dependence can be observed for tiles, compared to slates, which is due to their structure on the back side. Attenuation for 0.73 cm thick tile of 2.22 dB has been observed in [3], which is approximately 1 dB lower than the one presented in this letter.

When studying windows, intentionally only the external edges of the frame were covered with absorbers in order to make the study realistic, i.e. some effects due to the frame can be present in the results. The studied windows are given in Table II and all of them were equipped with low-emissivity glasses. The trade names of the windows come from the types of the frames. For convenience, the numbers given in parenthesis (Table II) are used in the rest of the letter for referring to the corresponding windows (e.g. window1). For each window, one glass pane had a thickness of 4 mm.

The attenuation of all tested windows is shown in Fig. 3(d)-(h). Each graph presents comparison between the same type of window but having different number (2 or 3) glass panes. Large difference in the attenuation between the windows can be seen and the employment of more panes (i.e. more energy-efficient windows) does not necessarily introduce higher loss.

Structure	Delay (ns)	
	V-V	H-H
Solid concrete block	0.43	0.43
Cavity concrete block	1.3	1.3
Solid red brick	0.43	0.43
Plasterboard	0	0
Roof tile	0.43	0.43
Roof slate	0	0
Window1	0.87	0.87
Window2	0.43	0.87
Window3	0.43	0.87
Window4	0.43	0.43
Window5	0.87	0.87
Window6	0.87	0.87
Window7	0.43	0.43
Window8	0.87	0.87
Window9	0.43	0.87
Window10	0.43	0.43

TABLE III: Time delay associated with the passing of signal (for both polarizations) through each of the structures.

Also, difference in the polarization responses for the windows can be observed. Reasons for the diversity in the results are (comparing all windows together and comparing the ones with the same name, but different number of panes): different composition and structure of the glasses, different metal coating material (conductivity and thickness), and difference in the number of coated glasses. A maximum attenuation of around 50 dB is observed for window1 (V-V polarization) and window3 (H-H polarization). At frequencies falling within the studied band in this latter, maximum attenuation has been found for modern windows of: 60 dB in [4]; 38 dB in [5]; 22 dB in [6]; and 36 dB in [7]. These results also indicate the high losses which the contemporary windows introduce.

The propagation time delay associated with an EM pulse penetrating through a material (in the media the wave has lower speed than in free space) affects the accuracy of distance measurement. That is, in presence of material error appears in the estimated range and therefore information about this delay is needed for compensating the inaccuracy [2]. Table III shows the time delay for both polarizations for each structure, calculated by peak-to-peak impulse comparison (in case of material and in free space) in time domain [8]. The similarity in some of the obtained results is due to the finite resolution, i.e. if the studied bandwidth was larger then the delay will be more precise. Due to the largest total thickness, the highest delay is found for cavity concrete block while the small thickness of slates and plasterboard results in low delay. Differences in the time-of-flight between the two polarizations for some of the structures can be observed.

IV. Summary and Conclusion

In this letter, results from measurement campaign for the power attenuation introduced by 4 types of walls, 2 types of roofs and 10 types windows have been presented. The values for loss presented below are obtained by averaging over all studied frequencies for each polarization (the mean attenuation is useful for mobile operators for estimating the radio coverage). It has been found that the attenuation introduced by brick (5.24 dB for V-V and 5.54 dB for H-H) and solid block wall (4.32 dB for V-V and 4.36 dB for H-H) is not very significant and there is no advantageous polarization for any of these materials. The plasterboard introduces negligible attenuation with no polarization dependence. The use of cavity block for better energy efficiency has been found to lower the signal most compared to the rest of the walls. Even though the mean values are similar (13.16 dB for V-V; 12.37 dB for H-H), strong polarization dependence of the attenuation with significant transmission losses at frequency bands of interest has been observed, which might lead to restrictions for wireless systems. A stronger loss has been observed for tile roof (3.03 dB for V-V and 4.94 dB for H-H) than for slate one (1.22 dB for V-V and 1.6 dB for H-H). It has been found that contemporary multi-pane windows with metallized glasses introduce significant signal degradation. All windows show frequency and polarization dependent attenuation with high losses at currently used parts of the spectrum. If average over all tested windows is taken then the mean loss for V-V polarization is 23.6 dB while for H-H is 26.3 dB. That is, generally speaking on average the use of V-V polarization ensures stronger signal penetrating the building. The high attenuation introduced by modern windows could be a problem for cellular indoor coverage, especially for buildings having façades mainly of windows. Possible solutions of this are: densification of the networks, use of repeaters, and employment of frequency selective surfaces. The data presented in this letter is helpful for network planning of mobile communication systems in urban area.

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