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Window and Wall Penetration Loss On-Site Measurements with Three Methods

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Abstract—Three methods suitable for on-site window and wall penetration loss measurements are presented and compared. The methods are (i) outdoor-to-indoor channel measurement, (ii) far-field penetration loss measurement, and (iii) near-field penetration loss measurement. It is shown that the different methods give similar penetration loss results. The measured window exhibits bandstop characteristics due to the internal reflections in the periodic structure of the triple-layer window. The brick wall has penetration loss that increases as a function of the frequency.

Index Terms—measurement, outdoor-to-indoor propagation, penetration loss, propagation losses, radiowave propagation.

I. INTRODUCTION

Radio wave propagation from outdoor base station to indoor mobile is strongly affected by the penetration loss through windows and walls. In recent years energy-efficient buildings and 5G have created interest in measurements of penetration loss of various materials [1]–[4].

Material penetration loss measurement methods can be divided to anechoic chamber (other laboratory facility) measurements, e.g. [2], [4]–[8], and to on-site measurement methods, e.g. [2], [3], [9], [10]. Outdoor-to-indoor (O2I) directional channel measurements, e.g. [11], [12], can also be used to determine penetration loss of the direct path between transmitter (Tx) and receiver (Rx) provided that the angular and/or delay resolution is sufficient for detecting the direct path.

In this paper, three measurement methods that can be used in on-site material penetration loss measurements are compared. Penetration loss is measured in an office building through a window and a brick wall. The first method is a spatio-temporal O2I measurement where the penetration loss is calculated for the direct path. In the second method, the measurement antennas are in far-field and the material is between the antennas. This is a commonly used penetration loss measurement method, e.g. [5]. The third method is similar to the second one with the exception that the antennas are placed close to the material. Despite the differences in the methods the penetration losses through the window and brick are very similar in the overlapping frequency range from about 1 to 6 GHz.

The rest of the paper is organized as follows. The measurement site is described in Section II and the three measurement methods are introduced in Section III. The penetration loss

Fig. 1. Measurement site. Penetration loss is measured through the window and through a brick wall into the corridor on the left side in this photograph.

results are presented and compared in Section IV. Finally, conclusions are presented in Section V.

II. DESCRIPTION OF THE MEASUREMENT ENVIRONMENT

The penetration loss measurements are conducted in a normal office building in Espoo, Finland. A photograph from the measurement site is shown in Fig. 1. The measurements focus on determining the loss from outdoors to indoors through both a window and through a brick wall. The window is a triple-layer window. The wall has a layer of concrete on the inside, wind shield and insulation in between, and brick layer. An illustration of the site layout, showing the floor map and the antenna locations, is presented in Fig. 2.

III. MEASUREMENT METHODS

The penetration loss of a window and a brick wall is measured with three methods. The following subsections introduce the measurement equipment and the measurement techniques. The results are presented and compared later in Section IV.

A. Method 1: Outdoor-to-Indoor Channel Measurement

Spatio-temporal O2I radio channel measurements can be used to measure penetration loss on-site in addition to other channel properties. The penetration loss is obtained by identifying the direct penetrated path based on the angle and delay. The O2I channel measurements at frequency range 4.4 - 4.9 GHz are conducted with a measurement setup illustrated in Fig. 3. The setup is based on a vector network analyzer (VNA) that measures the channel transfer function and inverse fast Fourier transform is used to derive the delay-domain

Fig. 2. Measurement site layout. Both the outdoor and indoor include several different antenna locations for the different measurement techniques.

complex impulse response. The effect of the measurement equipment is compensated by direct connection back-to-back calibration. Furthermore, the Tx and Rx antenna gains of 2 and 9 dBi, respectively, are subtracted from the measured channel amplitude to remove the effect of the antennas. Both antennas were at the same height. A log-periodic antenna, with about 50° half power beam width, is rotated at the outdoor Rx location and an omni-directional Tx antenna is located indoors. The Rx antenna is rotated in azimuth plane with 5° steps over a total of 180° towards the measurement target, i.e., the window or the brick wall. The measurement resolution in delay domain is 2 ns given by the measurement bandwidth of 500 MHz. The 2 ns delay resolution corresponds to 0.6 m in propagation path length at the speed of light.

The direct path from the Tx to the Rx is identified from the power angular delay profile (PADP) based on the delay and angle calculated from the x - and y -coordinates of the antennas. Penetration loss is the difference between the direct path amplitude and the free-space path loss. Penetration loss of the window and the wall is determined from several measurements with different Tx locations. Same Rx location was used in all of these measurements. Other channel properties that could be extracted from these channels are not reported in this paper.

B. Method 2: Far-Field Penetration Loss Measurement

This measuring method is designed for measuring attenuation of various building materials at the building site. Firstly, setup contains two horn antennas (A-INFO JXTXLB-880-NF), one as the Tx and the other as the Rx antennas. The measurement setup is shown in Fig. 4. Transmitting antenna was connected to a signal generator (Rohde&Schwarz SMJ100A) and receiving antenna to a spectrum analyzer (Rohde&Schwarz FSG) via coaxial cables. Transmitting antenna was placed inside the building during the measurements. Both antennas were at same height, which was about 1.5 m. Used frequency range in measurements was from 740 MHz up to 6 GHz. To ensure that the measurements take place in the far field zone, the distance of the transmitting and receiving antennas was

Fig. 3. Setup for the 4.4 - 4.9 GHz outdoor-to-indoor channel measurement (Method 1). Spatio-temporal radio channel is measured with a VNA using 500 MHz bandwidth and by rotating a log-periodic antenna with a 50° half power beam width.

Fig. 4. Setup for the far-field penetration loss measurement (Method 2).

Fig. 5. Setup for the near-field penetration loss measurement (Method 3).

set to 3 m. The distance of the measured material from Tx and Rx antennas was 1.5 m, and both antennas were aligned in straight line against each other. calibration measurement is performed with free line-of-sight between the antennas with the same distance between the antennas. The result of the calibration measurement is subtracted from the result of actual material measurement removing the effects of, e.g., attenuation of the cables and devices, antenna gain, and free-space path

loss. This is a commonly used penetrations loss method in anechoic chamber or laboratory, e.g. [5].

C. Method 3: Near-Field Penetration Loss Measurement

The near-field measurement setup for wall penetration loss is shown in Fig. 5. The measurements were done using VNA and two ridged horn antennas (ETS-Lindgren EMCO 3115) placed on the both sides of the measured wall. The antennas were placed directly on the inner/outer side of wall or window so that there was no gap between antenna and wall or the gap was small. The VNA (Agilent model 8722ES) was controlled by of a laptop. The measurements frequency range was 1 - 18 GHz limited to by the antennas. The measured complex S-parameters were stored into laptop memory for future processing. Only penetration phenomena were studied and therefore the S21/S12 were taken for more precise study. To get the penetration loss of the material under study one must remove the free space loss between the measuring antennas. This was done by measuring the free space connection loss where the distance between the antennas was the same as measuring the window or wall. After the measurements, time domain gating was used for removing unwanted scattering from environment and multiple reflections between the antennas. The time gating is carried out through convolution process between measured transmission and Gaussian window function. The Gaussian window was chosen so that it's length (-10 dB) in time domain is 3 ns.

This measurement method has been chosen from two reasons. Firstly, compared to the far-field horn penetration loss measurement a smaller area on the sample under measurement is illuminated. This is important in particular if the sample structure is not homogeneous. Secondly, if the sample is of a limited size one can avoid by this mean the wave diffraction from sample edges.

IV. COMPARISON OF RESULTS

The measurement locations are illustrated in Fig. 6. The 13 indoor antenna locations and the outdoor antenna locations of the outdoor-to-indoor channel measurement (method 1) are shown in Fig. 6. The indoor antenna locations with the far-field (method 2) and near-field (method 3) penetration loss measurement methods approximately followed the same locations as with the method 1. Not all locations were measured with methods 2 and 3, see Table I. The outdoor antenna was 3 m from the indoor antenna with the method 2. With method 3, both antennas were touching the window or the wall.

The penetration loss results are presented in Table I and illustrated in Secs. IV-A - IV-C. The method 1, measured at 4.4 to 4.9 GHz, gives only a single penetration loss value that illustrated with a single marker at the center frequency. The method 2 was used at select frequencies¹ between 740 MHz and 6 GHz. A frequency range from 1 to 18 GHz was scanned with the method 3. In general, the three methods give similar results for the window and the wall.

¹Locations 1-4, 8, and 11 at 16 frequency points and locations 9 and 10 from 740 MHz to 6 GHz with 20 MHz steps.

Fig. 6. Measurement locations. Method 1: outdoor Rx antenna location (marked with a star) and 13 indoor Tx locations. Method 2: Indoor antenna locations same as with method 1 and the outdoor antenna located at 3 m distance. Method 3: Indoor antenna locations close to locations with method 1 and 2 so that the antenna is touching the window/wall and the outdoor antenna on the other side of the window/wall. Only some of the 13 indoor location were measured with methods 2 and 3, see Table I.

TABLE I
LOCATION NUMBER, DESCRIPTION, AND RESULT (FIGURE NUMBER, MEASURED PENETRATION LOSS, OR *not available* (N/A))

Location	Description	Method 1	Method 2	Method 3
1	Window	9 dB	Fig. 7	N/A
2	Window	13 dB	Fig. 7	N/A
3	Window	16 dB	Fig. 7	N/A
4	Window	11 dB	Fig. 8	Fig. 8
5	Door	7 dB	N/A	N/A
6	Door	1 dB	N/A	N/A
7	Wall	21 dB	N/A	N/A
8	Wall	13 dB	Fig. 10	N/A
9	Wall	25 dB	Fig. 10	Fig. 10
10	Wall	15 dB	Fig. 11	N/A
11	Wall	20 dB	Fig. 11	Fig. 11
12	Wall	21 dB	N/A	N/A
13	Wall	19 dB	N/A	N/A

A. Window

The penetration loss was measured on locations 1-4 and results are presented in Figs. 7 - 8. The loss is low up to 4 GHz after which it increases to about 20 dB. Interestingly, the penetration loss decreases again to below 10 dB at 9 GHz. The window seems to work as a bandstop filter. For the overlapping frequency ranges the three methods agree very well. Some negative loss values, e.g., in Fig. 7, are probably due to measurement uncertainties in calibration or multipaths that have not been removed by time gating.

Assuming that the window consists three 4 mm thick glass layers ($\epsilon_r = 6 - 0.01j$, $\mu_r = 1$) separated by two 10 mm air gaps², the transmission and reflection coefficients can be calculated theoretically. The transmission coefficient, shown in Fig. 9, has a minimum that corresponds quite well with the measured behavior of the penetration loss in Fig. 8. This shows that the observed relatively high loss at about 5 to 9 GHz can

²The exact ϵ_r of the glass and the thickness are not known.

Fig. 7. Measured penetration loss through window in indoor locations 1-3 (see measurement location in Fig. 6) with methods 1 and 2.

Fig. 8. Measured penetration loss through window in indoor location 4 (see measurement location in Fig. 6) with methods 1, 2 and 3. The window works as a bandstop filter.

be explained by the internal reflections in the periodic window structure. Also in [4], penetration loss is found to fluctuate as a function of the frequency which is explained by theoretical analysis including multiple internal reflections.

B. Glass Door

Measurements at locations 5 and 6 through a glass door (see Figs. 1, 2, and 6) were conducted only with method 1. The penetration loss of the detected direct path is very low; only 7 dB and 1 dB at locations 5 and 6, respectively. The reason for the low loss, as compared to the window penetration loss at locations 1-4 in Figs. 7 - 8 with the method 1, is that the optical cable connecting the transmitter to the VNA went through the

Fig. 9. Simulated transmission (solid black line) and reflection coefficient (dash red line) of the window.

Fig. 10. Measured penetration loss through the wall in indoor locations 8-9 (see measurement location in Fig. 6) with methods 1, 2 and 3.

door, leaving the door slightly open, leading to the relatively low losses.³

C. Wall

The measured penetration loss through the brick wall is presented in Figs. 10 - 11. Up to 6 GHz the loss is still relatively low, at about 10 to 30 dB, and increases to about 30 to 50 dB at higher frequencies. In general, a clear increasing trend as a function of the frequency can be observed. Again, the results with the three methods agree quite well.

V. CONCLUSION

Three on-site penetration loss measurement method are compared and it is found that the results agree well. The measurement are conducted in an office building and the loss through a window and a brick wall is measured. The measured window exhibits bandstop characteristics due to the internal reflections in the periodic structure of the triple-layer window. The penetration loss is low below 5 GHz and above 9 GHz.

³Oops!

Fig. 11. Measured penetration loss through the wall in indoor locations 10 and 11 (see measurement location in Fig. 6) with methods 1, 2, and 3.

Between 5 and 9 GHz, it is about 10 to 20 dB. This bandstop behavior is confirmed with a simulation. The brick wall has penetration loss that increases as a function of the frequency. At about 1 GHz, the penetration loss through the wall is about 10 to 20 dB and increases to about 30 to 50 dB for frequencies above 7 GHz.

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