Determination of the permittivity of building materials through WLAN measurements at 2.4 GHz

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Abstract—In this paper a new approach for the calibration of electromagnetic material parameters (permittivity) of 3D ray tracing prediction model at 2.4 GHz is presented. The calibration procedure is based on measurements of the channel impulse response using cross-correlation techniques and the 802.11b preamble. Further developments of a method, which was presented to COST 273 in an earlier contribution, are presented. The analysis of the permittivity of different walls determined from a short measurement campaign is shown.

Keywords-component: ray tracing, calibration, indoor channel, impulse response, permittivity

I. INTRODUCTION

Many researchers have been investigating the indoor channel modeling either by modeling the indoor channel statistically through direct measurements of the Channel Impulse Response (CIR) [1], or by using a deterministic modeling with geometric optics-based predictions [2]. This also includes a verification of the prediction models by comparison with measurements, as e.g. in [3]. In order to apply ray tracing methods for indoor predictions information about the building properties is required. Whereas the data about the geometry of the buildings can be easily obtained even with high accuracy, it is difficult to get data about the material properties of the building walls. One possibility to derive such parameters is to use measurements for calibration. The work presented in this paper is devoted to the development of a low cost, simple, and compact indoor channel modeling system, e.g. for WLAN, by combining measurements and prediction for the determination of the material parameters. The main characteristics of this method of calibration were introduced in an earlier contribution to COST 273 [4]. This contribution focuses on the effect of simple walls and empty rooms without furniture and persons. The goal is first to validate the approach.

In order to calibrate the prediction model parameters relating to reflection and transmission factors, properties about the indoor directional channel are required. Thus, three principle components, as shown in Figure 1, should be considered to set up the calibration system:

1. a prediction model to be calibrated,
2. directional measurements considering the Angle of Departure (AoD) and Angle of Arrival (AoA) of multipath components, which are used to identify the reflecting walls in space domain,
3. Cross-correlation techniques based on a known bit sequence spread by the IEEE 802.11b PN-code in conjunction with a pulse extraction algorithm in order to identify the reflecting walls in time domain.

This paper focuses on the calibration of the materials dielectric constant (permittivity). First results from calibration measurements of different building walls are presented. The paper is organized as follows: The calibration procedure is explained in section II followed by a description of the calibration results of two stone walls, a concrete wall and a glass wall. Concluding remarks are given in section IV.

Figure 1. Prediction model calibration system setup

II. CALIBRATION PROCEDURE

The measurement system consists of one laptop transmitting standard IEEE 802.11b signals and of a 2.4 GHz satellite receiver modified to provide the directional cross-correlation. The 3D ray tracing prediction model runs on another laptop together with a pulse extraction software and the calibration algorithm, both implemented using MATLAB. The transmitting laptop is connected to a directional patch antenna via a WLAN PCMCIA card. On the receiver side, the data acquisition module is connected to an identical patch antenna. In a more advanced version the system has been integrated into one laptop, see e.g. Figures 5 and 6. For the measurements presented in this paper, the patch antennas are kept at an azimuth angle of 40 degrees from the normal to the wall surface under test. Thus both antennas have been directed towards the reflection point on the wall whose permittivity is going to be calibrated. During the measurements a line-of-sight (LOS) always exists...
between the transmitting and receiving antenna. The LOS contribution is decreased by the combined effect of the antennas patterns and directions. The LOS contribution is desired to scale the comparison between the measured and simulated CIR.

In order to calibrate the permittivity of a structure within a given environment, the simulated and the measured reflected path within the channel impulse response should be compared, see Figure 2.

First, both simulated and measured impulse responses (CIR) will be normalized considering the respective direct LOS path which has the shortest time delay of arrival. Then, using the ray tracing results, we identify the time delay of the once-reflected path for the wall under consideration. Thus, the amplitudes $\alpha_n$ and $\alpha_s$ of the measured and the simulated contribution from the single reflection are obtained. Since the amplitudes are proportional to the reflection coefficient, we can then calculate the measured reflection coefficient $R_m$ from the following formula using the reflection coefficient $R_s$ applied in the prediction:

$$R_m = R_s \frac{\alpha_n}{\alpha_s}$$

(1)

The Snell’s law provides the reflection coefficient $R$. For a vertical polarization:

$$R = \frac{\sqrt{\varepsilon_r} \cos(\theta_i) - \cos(\theta_r)}{\sqrt{\varepsilon_r} \cos(\theta_i) + \cos(\theta_r)}$$

(2),

where $\varepsilon_r$ is the relative permittivity of the wall, $\theta_i$ and $\theta_r$ are the incident and the transmitted angles, respectively. Additionally, the transmission angle $\theta_t$ also depends on the relative permittivity $\varepsilon_r$ such as

$$\theta_t = a \sin\left(\frac{\sin(\theta_i)}{\sqrt{\varepsilon_r}}\right)$$

(3),

Knowing $R_s$, the corresponding relative permittivity $\varepsilon_r$ has been computed through interpolation of the non-linear function (2). Even though a single measurement is theoretically sufficient, several measurements for different transmitter-receiver positions can be conducted as shown in Figure 3 in order to better estimate the permittivity of a wall. The final estimation of the permittivity $\varepsilon_m$ is then simply done by averaging all the computed permittivity $\varepsilon_m = E[\varepsilon_m]$.

Using 1.5 GHz PC laptops, the overall calibration takes about 10 minutes for one permittivity value. The ray tracing process takes about 30 sec, the measurement itself is about 3 min but the autocorrelation process takes more than 5 minutes to obtain a CIR using MATLAB; the final computation of the permittivity value takes only 1 min and has also been implemented using MATLAB.

III. CALIBRATION RESULTS

In order to illustrate the measurement procedure a measurement campaign has been conducted within a lecture room at the building of the Institut für Nachrichtentechnik.

In this measurement campaign, the azimuth angle is kept at 40 degrees from the normal to the wall surface. The distance between transmitter and receiver is 1.30 m and the distance from the wall to be calibrated is 3 m.

A. Measurement sensitivity

The stability of the measurement system has been investigated. Also, the sensitivity of the measurement results to the accuracy of the antennas positions has been checked out in the configuration shown e.g. in Figure 4. First, two measurements within an interval of 5 minutes have been conducted without moving the antennas to verify the stability of the measured values. Then, the receiver position has been moved by 1 centimeter on the x axis and on the y axis, respectively. The goal of these measurements is to check the effect of slight inaccuracies in the position on the results.

The different estimated values of the relative permittivity are shown in Table 1. As it can be noticed, three measurements out of four are consistent. It seems therefore reasonable to carry out at least three times the same measurement in order to avoid errors due to unknown fluctuations in the measurement equipments.
Furthermore, slight (1 cm) changes in the RX location do not affect the results. Further measurements should be carried out to reinforce this conclusion.

**Table I. Measurements Sensitivity**

<table>
<thead>
<tr>
<th>Receiver Positions</th>
<th>Relative Permittivity $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX 1</td>
<td>5.2</td>
</tr>
<tr>
<td>RX 2</td>
<td>3.8</td>
</tr>
<tr>
<td>RX 3</td>
<td>3.4</td>
</tr>
<tr>
<td>RX 4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

**B. Measurement results**

During the measurements, the transmitter has been kept in the same position, whereas the receiver has been moved along a straight line several times with a step distance of 50 centimeters.

The different estimated values corresponding to the relative permittivity of the stone wall are presented in the following Table II.

**Table II. Measured Permittivity of the Stone Wall**

<table>
<thead>
<tr>
<th>Receiver Positions</th>
<th>Relative Permittivity $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX 1</td>
<td>5.9</td>
</tr>
<tr>
<td>RX 2</td>
<td>4.3</td>
</tr>
<tr>
<td>RX 3</td>
<td>2.8</td>
</tr>
<tr>
<td>Average</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Although the fluctuations observed in Table II could be surprising, the variation of the permittivity values might be explained through the mixed composition of the stone wall. Indeed, the wall is a mixture of different materials as shown in Figure 7, which shows a variety of stones connected together with concrete. Additionally, this wall is reinforced with an inner metal grid with elements of 10 cm.

Some further measurements have been carried out for an outer wall of the same type of material at an outdoor terrace of the Institute as shown in the layout of Figure 8. Therefore, it was expected to get similar values of relative permittivity.
The different estimated values of the permittivity determined from the measurement of the outdoor terrace wall are presented in Table III.

<table>
<thead>
<tr>
<th>Receiver Positions</th>
<th>Estimated Relative Permittivity $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX4</td>
<td>9.1</td>
</tr>
<tr>
<td>RX5</td>
<td>7.5</td>
</tr>
<tr>
<td>RX6</td>
<td>7</td>
</tr>
<tr>
<td>Average</td>
<td>7.9</td>
</tr>
</tbody>
</table>

**TABLE III. Measurement results for the permittivity of the outdoor terrace stone wall.**

Most probably the higher values of the permittivity compared to the first case of the inner wall are due to the higher percentage of moisture in the outer wall since it is exposed to the rain and to the intensive air humidity.

The figure below, reproduced from [5], shows the variation of the permittivity coefficients versus the degree of moisture at a frequency of 1.5GHz.

![Concrete dielectric constant vs. concrete moisture at 1.5GHz](image)

Figure 9. Concrete dielectric constant vs. concrete moisture at 1.5GHz [5]

It can be noticed from the graphic in Figure 9 that the concrete dielectric constant rises from about 5.8 at 50% of moisture to 7.5 at 80% of moisture, which could very well explain the measurement results for the inner and outer stone wall presented in TABLE II and III.

2) **Calibration of a Concrete wall**

More measurements have been conducted to estimate the permittivity of a concrete wall within a lecture room at the Institut für Nachrichtentechnik.

![Concrete wall calibration](image)

Figure 10. Concrete wall calibration

The measurement layout is presented in Figure 11.

![Layout of measurements of the concrete wall](image)

Figure 11. Layout of measurements of the concrete wall

The measurement results are presented in Table IV.

<table>
<thead>
<tr>
<th>Receiver Positions</th>
<th>Estimated Relative Permittivity $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX1</td>
<td>4.5</td>
</tr>
<tr>
<td>RX2</td>
<td>5.9</td>
</tr>
<tr>
<td>RX3</td>
<td>5.3</td>
</tr>
<tr>
<td>RX4</td>
<td>5.9</td>
</tr>
<tr>
<td>Average</td>
<td>5.4</td>
</tr>
</tbody>
</table>

**TABLE IV. Measured permittivity of the concrete wall.**

The value of the wall permittivity $\varepsilon_w$ entered in the ray tracing prediction was 4.95. This value corresponds to a measured dielectric constant of an air-dried concrete [6]. The average permittivity $\varepsilon_m$ found: 5.4 is within 10% of values measured by other authors [6].

The results found for this calibration are relatively constant. Although only 4 RX-TX positions have been
measured, a standard deviation has been computed and is about 0.6 which is also within ~10% of the mean value.

3) Calibration of a glass wall
A glass wall was also calibrated.

The corresponding measurement layout is shown in Figure 13.

The result of the permittivity estimation corresponding to the glass wall is shown in Table V.

<table>
<thead>
<tr>
<th>Receiver Positions</th>
<th>Estimated $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx 1</td>
<td>1.7</td>
</tr>
<tr>
<td>Rx 2</td>
<td>2.6</td>
</tr>
<tr>
<td>Rx 3</td>
<td>1.4</td>
</tr>
<tr>
<td>Rx 4</td>
<td>2.8</td>
</tr>
<tr>
<td>Rx 5</td>
<td>3.2</td>
</tr>
<tr>
<td>Average</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table V. Measured Permittivity of the Glass Wall

The resulting permittivity is about 2.3. However in the literature [7], values for permittivity of glass at 2.4 GHz are found to be 6.39. One explanation for the difference may be the composition of the glass wall. Indeed the specific glass wall investigated here is composed of two glazed layers and a gas/air insulation layer.

This last result shows that care must be taken when estimating the electrical characteristic of building material.

IV. Conclusion

This paper presents our first results from the determination of material parameters applicable to indoor channel modeling. Using a slightly modified version of the calibration method described in [4], permittivity values for three different types of walls have been determined: stone, concrete (indoor & outdoor) and glass. For the case of concrete, the permittivity values that have been determined: ~5, are in agreement with values usually given in the literature. For glass walls, values (~2) different from the literature (~6) have been obtained, which might not be so surprising since a great variety of different glass materials exists. From the measurements of similar stone walls in indoor/outdoor environments, observations (~5 / ~8, respectively) might be explained by the dependency on moisture of the walls.

In further research it will be investigated how this additional information about the building materials can be used to improve the accuracy of the coverage prediction of an indoor WLAN network. Further work should also be dedicated to determine if and how furniture, wall inhomogeneities and perhaps even people should be taken into account. Initial long term signal strength measurements in the working WLAN environment of the EIA-FR[8] have shown up to 10 dB fluctuations.

V. References


