Evaluation Of Building Penetration Loss For 100 Buildings in Belgium

DAVID PLETS, WOUT JOSEPH, LEEN VERLOOCK, EMMERIC TANGHE, LUC MARTENS
Ghent University, Dept. of Information Technology / Interdisciplinary institute for BroadBand Technology (IBBT); B-9050 Ghent, Belgium [david.plets@intec.ugent.be]

ETIENNE DEVENTER, HUGO GAUDERIS
Flemish Radio and Television Network (VRT); B-1043 Brussels, Belgium

ABSTRACT

Building penetration loss measurements of a DVB-H signal at 602 MHz have been performed in 100 buildings in Ghent, Belgium. Buildings are categorized in different types (office buildings, apartments, villas, mansions, terraced houses, stations) and the rooms are classified according to the number of outside radiated walls. The cumulative distribution function of the penetration loss is determined and lognormality is investigated. Models are developed to calculate the penetration loss as a function of the number of radiated walls. This research enables the calculation of indoor coverage probability for wireless networks.

INTRODUCTION

The digital broadcasting standard DVB-H (Digital Video Broadcasting - Handheld) enables a high data rate broadcast access for hand-held terminals (e.g., portable, pocket-size battery-operated phones). It is based on the specifications and guidelines of ETSI [1–4]. The broadband downstream channel features a useful data rate of up to several Mbps and may be used for audio and video streaming applications, file downloads, and many other kinds of services.

There is only limited literature available about penetration loss at UHF frequencies [4, 7, 8]. Mostly, only a limited number of buildings is investigated (e.g., 4 in [7]).

In this paper, the penetration loss of 100 buildings in Ghent will be investigated at 602 MHz (248 measured rooms in total). Buildings will be categorized in different types (office buildings, apartments, villas, mansions, terraced houses, stations) and models will be provided dependent on the number of radiated walls. This research will enable the broadcasters to calculate the indoor coverage probability for wireless networks, especially DVB-H networks.

METHOD

Transmitting Network

The transmitting network is located in a suburban environment in Ghent, Belgium. The SFN (Single-Frequency Network) contains three base station antennas (BS). All transmitting antennas Tx are omnidirectional. The heights of these Tx are $h_{T_x} = 57$ m, $h_{T_x} = 64$ m, and $h_{T_x} = 63$ m, respectively. The EIRP (Equivalent Radiated Power) used for these Tx is 36.62 dBW, 39.93 dBW, and 40.90 dBW, respectively. The constellation used for the tests is 16-QAM 1/2 with an MPE-FEC rate of 7/8, corresponding with a useful bit rate of 9.68 Mbps [5,6].

Measurement Method

The penetration loss of a building is determined as the ratio of the average electric-field strength outside a building $E_{out}$ on the ground floor and the average electric-field strength inside that building $E_{in}$ (possibly on different floors):

$$\text{PenL [dB]} = E_{out} [\text{dB} \mu \text{V/m}] - E_{in} [\text{dB} \mu \text{V/m}],$$

For detached houses, the average field strength outside the building is determined by measuring the field strength along a route around the building and the average electric-field strength inside that building $E_{in}$ (possibly on different floors):

For buildings attached to other buildings on one or more sides next to it (e.g., terraced houses), the field strength is measured by collecting samples on as many sides of the building as possible (in front of the building, garden or courtyard, etc.). To process the field strengths inside the buildings, each room is classified on the number of radiated sides (RS). A side of a room is radiated if it is part of an outer wall of the building.

For this measurement campaign, 100 buildings in Ghent have been investigated. These buildings are divided into 6 categories:

- **office buildings** (large building with multiple stories, rather large rooms, many large windows): 9 investigated buildings
  - coated (office building with coated windows): 2 investigated buildings
  - non-coated (office building without coated windows): 7 investigated buildings

- **apartments**, **villas**, **mansions**, **terraced houses**, **stations**

The outline of this paper is as follows. First, the transmitting network and the measurement method will be described, followed by a discussion of the results and the proposed models. Finally, the conclusions are presented.
• apartments (high building with lots of different (rather small) rooms): 7 investigated buildings
• mansions (large house, multiple stories, high ceilings, wooden floors, houses on both sides): 15 investigated buildings
• detached houses or villas (house with no building on any side of the house): 17 investigated buildings
• terraced houses (smaller house with buildings on both sides): 51 investigated buildings  
  ○ shops (terraced house with a large front window): 5 investigated buildings  
  ○ bank office (terraced house with a thick front window): 2 investigated buildings  
  ○ private house (regular terraced house): 44 investigated buildings
• station (train station): 1 investigated building

This selection of the categories is representative for cities in Belgium. The measurements are performed with a DVB-H tool implemented on a PCMCIA (Personal Computer Memory Card International Association) card with a small receiver antenna Rx (gain -5 dB). The electric-field values are measured with this tool. The PCMCIA card is plugged into a laptop, which is used to collect and process the measurement data [5,6].

RESULTS

General Results

Table 1 shows the average penetration losses $\mu$ and standard deviations $\sigma$ for the different building types and for a different number of radiated sides. The number of investigated rooms is shown between brackets for each combination of building type and number of radiated sides. Table 1 shows that the penetration loss decreases for rooms with more radiated sides: on average 9.24 dB for 0 RS, 8.53 dB for 1 RS, 7.57 dB for 2 RS, and 3.58 for 3 RS. The average penetration loss is smaller for villas (4.67 dB) than for mansions (8.19 dB), because villas mostly have more radiated sides than mansions. Private houses have an even larger penetration loss (9.76 dB), due to even less radiated sides, but a lower one than coated office buildings (21.94 dB). Coated office buildings have of course a larger loss than non-coated office buildings (5.30 dB), due to the metallized coating on the windows. The standard deviation varies from 2.37 dB (villas) to 9.37 dB (shops). In [4], a median value of 11 dB is assumed, with a standard deviation of 6 dB. Here, an average value for the penetration loss of 8.10 dB and a median value of 7.28 dB was obtained. The standard deviation is 6.23 dB. In the Flemish DVB-H trial, the network is designed for indoor coverage of terraced houses with 1 RS, i.e. $\mu = 11.19$ dB and $\sigma = 5.73$ dB. These values agree reasonably well with those of [4], but the average value of 8.10 dB of course depends on the weight given to each building category. Although the houses are classified on the number of radiated sides, there is still a difference in penetration loss between the types of houses, even for rooms with the same number of radiated sides. The difference is caused by the non-radiated sides. The more rooms between a non-radiated wall and outside, the higher the expected penetration loss will be. For detached houses, the number of rooms with non-radiated walls is likely to be low as all four sides of the building are radiated. Terraced houses are likely to have (at least) two non-radiated walls with a larger number of rooms next to it, because other houses are present on either side of the house. The loss for terraced houses in Table 1 is indeed higher than for detached houses with the same number of radiated sides (1 RS: 11.19 dB vs. 6.22 dB, 2 RS: 8.78 dB vs. 4.74 dB).

Only mansions in between other buildings have been selected. The investigated mansions are thus terraced houses, but with different characteristics: older buildings, larger rooms, higher ceilings, wooden ceilings,... Their behavior is in between that of terraced houses and detached houses. Penetration losses equal 7.77 dB for 1 RS and 6.40 dB for 2 RS.

Cumulative Distribution Function

Fig. 1 shows the cumulative distribution function of the penetration losses of the 100 investigated buildings and lognormal fit.

Fig. 1 shows the cumulative distribution function of the penetration losses of the 100 investigated buildings. This cdf is then being fit using a cdf of a normal distribution (in dB). The average value of the experimental penetration losses is 8.10 dB, the standard deviation 6.23 dB. The lognormal fit has an average value of 7.57 dB, and a standard deviation of 5.68 dB. The respective average values and standard deviations agree fairly well with the experimental values (Table 1, row ‘Total’). Moreover, the data (in dB) also passed a Kolmogorov-Smirnov (K-S) test for normality at significance level $\alpha = 5\%$, indicating that the
penetration losses (in dB) are normally distributed. In Fig. 2 the cumulative distribution functions are compared for 17 villas, 44 private houses, 15 mansions, and all 100 buildings together. It shows that villas have the lowest average penetration loss (4.67 dB), and the lowest standard deviation (2.37 dB, steepest slope of the cdf). Mansions have higher average penetration losses (8.19 dB), and the standard deviation is higher (3.70 dB). Private houses have an average penetration loss of 9.76 dB, with a standard deviation of 6.04 dB. The cdf of all 100 buildings lies in between these three curves (average value 8.10 dB, standard deviation 6.23 dB).

Figure 2: Experimental cumulative distribution function of the penetration losses of villas, private houses, mansions, and all 100 investigated buildings

Modeling Of Penetration Loss As A Function Of The Number Of Radiated Sides

In this section the penetration loss is modeled as a function of the number of radiated sides for the different categories of buildings. Fig. 3 shows the average penetration loss for different numbers of radiated sides and for three different building types (villas, mansions, private houses). The penetration loss is lower for villas than for mansions and private houses. The penetration loss also decreases for rooms with more radiated sides. The experimental values for the different number of radiated sides #RS have been fit for the different building categories (private house, mansion, villa) to the following model:

$$\text{PenL} [\text{dB}] = \text{PenL}_1 [\text{dB}] - (#RS - 1) \cdot p [\text{dB}] + \chi,$$

where \(\text{PenL}_1 [\text{dB}]\) is the penetration loss for one radiated side and \(p [\text{dB}]\) is a decrease factor (called the penetration loss decrease here), \(\chi\) is the statistical variation on the model and has a standard deviation \(\sigma\).

Two types of fits will be investigated, one with two parameters (\(\text{PenL}_1 [\text{dB}]\) and \(p\), noted as model 1), and one with one parameter (\(p\), noted as model 2).

<table>
<thead>
<tr>
<th># Radiated sides</th>
<th>0 RS</th>
<th>1 RS</th>
<th>2 RS</th>
<th>3 RS</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>(\mu)</td>
<td>(\sigma)</td>
<td>(\mu)</td>
<td>(\sigma)</td>
<td>(\mu)</td>
</tr>
<tr>
<td>Office building</td>
<td>Non-coated</td>
<td>8.06 (5)</td>
<td>7.90</td>
<td>8.64 (3)</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>Coated</td>
<td>25.05 (2)</td>
<td>1e-3</td>
<td>18.23 (2)</td>
<td>6.30</td>
</tr>
<tr>
<td>Apartment</td>
<td>2.49 (7)</td>
<td>5.56</td>
<td>-1.05 (5)</td>
<td>4.06</td>
<td>9.73 (3)</td>
</tr>
<tr>
<td>Villa</td>
<td>-</td>
<td>-</td>
<td>6.22 (4)</td>
<td>3.08</td>
<td>4.74 (13)</td>
</tr>
<tr>
<td>Mansion</td>
<td>-</td>
<td>-</td>
<td>7.77 (10)</td>
<td>3.36</td>
<td>6.40 (7)</td>
</tr>
<tr>
<td>Terraced house</td>
<td>Bank office</td>
<td>-</td>
<td>-</td>
<td>12.11 (1)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Shop</td>
<td>30.66 (1)</td>
<td>0</td>
<td>7.57 (3)</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>Private house</td>
<td>-</td>
<td>-</td>
<td>11.19 (17)</td>
<td>5.73</td>
</tr>
<tr>
<td>Total (average)</td>
<td>9.24 (15)</td>
<td>11.08</td>
<td>8.53 (46)</td>
<td>6.04</td>
<td>7.57 (61)</td>
</tr>
</tbody>
</table>

Table 1: Average penetration loss \(\mu\) and standard deviations \(\sigma\) for different building types and different number of radiated sides with the number of investigated rooms between brackets.
The root-mean-square (RMS) deviation of the measurement points was minimized with a linear regression fit, where PenL1 [dB] and p were adjusted. First, a fit with two parameters (PenL1 [dB] and p, model 1) was performed. Table 2 shows the resulting values for PenL1 [dB] and p. The parameters PenL1 [dB] equal 11.19 dB, 7.77 dB, and 6.24 dB and the penetration loss decreases p = 2.41 dB, 1.37 dB, 1.52 dB for private houses, mansions, and villas, respectively. The standard deviations \( \sigma \) are 5.72 dB, 4.12 dB, and 2.39 dB for private houses, mansions, and villas, respectively. Secondly, we perform a fit where only the parameter p of equation (2) is adjusted (model 2) and PenL1 [dB] is defined as the average value of the penetration loss values for one radiated side (Table 1). The standard deviations \( \sigma \) are 5.72 dB, 4.12 dB, and 2.39 dB for private houses, mansions, and villas, respectively.

Table 2 shows that the values for PenL1 [dB] and the penetration loss decrease p agree excellently for both types of fit, showing that the model with 1 parameter is sufficient.

To investigate the lognormality, the cdf of the difference between the experimental data and the model is analyzed. This cdf is then being fit using a cdf of a normal distribution (in dB). The RMS deviation is minimized with a linear regression fit, where the mean value and the standard deviation are adjusted. The resulting mean value is noted as \( \mu_{\text{fit}} \) and the standard deviation as \( \sigma_{\text{fit}} \) and is compared with \( \mu_{\text{dev}} \) and \( \sigma \) obtained from the difference of the experimental data and the model. Table 2 shows the values for \( \mu_{\text{fit}}, \sigma_{\text{fit}}, \mu_{\text{dev}}, \) and \( \sigma \). Excellent agreement is obtained between \( \mu_{\text{fit}} \) and \( \mu_{\text{dev}} \) and \( \sigma_{\text{fit}} \) and \( \sigma \), respectively, indicating that the measured values are lognormally distributed around the model. The data also passed a Kolmogorov-Smirnov (K-S) test for normality at significance level \( \alpha = 5\% \) for all four investigated models (private houses, mansions, villas, and all three categories together). Fig. 3 shows the average penetration loss for different numbers of radiated sides and for three different building types (villas, mansions, private houses) and also the model (fit with one parameter, p) for each of the building types and for all three types together. This figure shows that the respective models correspond excellently with the average penetration loss values for the different number of radiated sides for a certain building type.

**CONCLUSIONS**

In this paper penetration loss measurements for 100 buildings at 602 MHz in a DVB-H system are analyzed and discussed. A classification has been made on building type and on number of outer walls of the rooms (or number of radiated sides). The average penetration loss of 100 buildings equals 8.10 dB, the standard deviation is 6.23 dB. These values agree well with the ETSI values. Penetration losses have been modeled as a function of the number of radiated sides for terraced houses, mansions, and villas. Lognormal fits and K-S tests have demonstrated that the values are lognormally distributed around the different models. Rooms with less radiated sides have higher penetration losses (from 9.24 dB for 0 radiated sides to 3.58 dB for 3 radiated sides). Terraced houses have higher penetration losses than mansions and villas.

**ACKNOWLEDGMENT**

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REFERENCES

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