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BUILDING PENETRATION LOSS FOR SATELLITE SERVICES

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1. CURRENT STATE OF RESEARCH IN THE STUDIED PROBLEM

1.1. Introduction

As new satellite navigation and telecommunication systems are emerging, the possibility of indoor reception of such services is of a great interest nowadays, especially when e.g. Galileo and other services are considered. It is a well-known fact that for example the widely used concurrent Global Positioning System (GPS) navigation service is not available inside buildings. Although many terrestrial systems provide indoor coverage and a lot of is known about the corresponding outdoor-to-indoor propagation channel including valid propagation models [Berg99], [FeKu06], [KüMe02], [MaHe03] and [ToTu98], there are many cardinal differences between the terrestrial- and satellite-to-indoor scenarios that a focus is put on providing new studies. In contrast to terrestrial services, crucial features of satellite-to-earth links are: high elevation angles that may be varying in time (high percentage of line-of-sight propagation conditions), different frequency bands used (L-band and higher bands), limited output power at transmitters and much higher levels of free space loss (tight power budget) and longer round-trip time. So far, several different studies dealing with signal penetration into building for satellite-to-indoor channel have been provided, but addressed different frequency bands and different ranges of elevation angles [AxTh03], [GlHa00], [HoHa06], [HoPe07], [PéHo08], [PeNu10], [VeKa07], [VoKl97] and [VoTo93]. Further, a standardized definition of penetration loss is not available although it must be used when calculating building penetration loss from the experimental data obtained indoors. As a result, a generally-valid building penetration loss model is still missing. This is why an extensive measurement campaign, covering a representative set of typical buildings in an urban area and aimed at building penetration loss for high elevation angle satellite services at L-, S- and C-band, was performed in Prague during the years 2009 and 2010. Throughout the measurements, a remote-controlled airship was used as a pseudo-satellite carrying a transmitter which provided unmodulated continuous wave left-handed circularly polarized signals at 2.0 GHz, 3.5 GHz, 5.0 GHz, and 6.5 GHz. Based on a thorough analysis of the resulting experimental data, it was possible to meet the goals of the dissertation thesis and derive new elevation dependent empirical models for corresponding frequencies.

1.2. Review of Existing Outdoor-to-Indoor Satellite Services

An empirical model divided into three cascade blocks is presented in [FrMo96] covering free space loss, slow fading (shadowing effect of obstacles in the surroundings of receiver) and fast variations of the received signal (mainly multipath). To create such a model, CW measurements at 2420 MHz and 1620 MHz and at elevation angles from 30° to 80° were held at a seven-storey office building over the whole azimuth range. On the 1st and on the 4th floor, penetration loss was an increasing function of elevation on the contrary to results for the 7th floor. Reported losses were higher at 2420 MHz than at 1620 MHz but both had similar dependence on elevation.

In [GlHa00], continuous wave (CW) measurements were carried out at 5.1 GHz in a multi-storey office building for elevations almost from 0° to 90°. The measured penetration loss varied from 10 dB to 45 dB with a harmonic average of 19.1 dB and 22.3 dB for the elevation and azimuth dependence measurements, respectively. The shielding loss model is based on the COST 231 outdoor-to-indoor model for low elevation angles and an additional loss which covers the Fresnel knife-edge diffraction loss on building rooftops of surrounding buildings for lower elevation angles is added to equation (41).

CW measurements from 700 MHz to 1800 MHz were carried out in six different buildings at elevations from 12° to 48° and results in a form of signal distribution parameters were presented in

[VoTo93]. A frequency dependent model was presented to calculate the percentage of positions at which the average received signal level is less than a threshold relative to a clear line-of-sight (LOS).

Vogel and Kleiner reported results from wideband fade experiments providing time, space and frequency domain structure of the indoor channel. The measurements were taken at L- and S-band in six different buildings and covered a range from 500 MHz to 3000 MHz at elevations from 18° to 41°.

Results of wideband measurements using a channel sounder and covering the frequency range from 2470 MHz to 2670 MHz and elevations from 15° to 60° were introduced in [PéHo08] and averaged penetration loss for all the measurement sites was linearly fitted.

Measurements at 1478.224 MHz were carried out with the use of a geostationary satellite in different types of buildings at elevation angles of 46° and 32°, respectively [HoHa06]. The model presented here is based on ray-tracing where the loss due to penetration, reflection and diffraction is added to the free space loss of each ray and the mean signal level is calculated.

Holis and Pechac introduced in [HoPe07] an empirical model for penetration loss as a function of elevation angle for urban areas. The model was compared to CW measurements carried out at 2.0 GHz and 3.5 GHz in different types of buildings in Prague at different elevation angles ranging from 10° to 90°. Overall average penetration loss was modelled here by using empirical parameters provided in a table for the two measured frequencies.

[VeKa07] describes a measurement campaign at an elevation of 45° for a typical office building at 10.8 GHz and 11.1 GHz using a vertical and a horizontal polarization, respectively. The results are provided in a form of cumulative distribution functions (CDFs) for different distances from a window and penetration loss was modelled as an exponential function of an entry distance from a window.

Axiotis and Theologou studied the impact of high elevation angles on building penetration loss at 2 GHz using a 3-D ray-tracing simulation considering the diffraction from building edges and rooftops [AxTh02]. The simulation included eleven buildings of different shapes in different areas (city centre, urban and suburban) and covered elevation angles from 60° to 90°. Further, they extended in [AxTh03] the COST 231 outdoor-to-indoor model for low elevation angles and came up with an empirical model for penetration loss at 2 GHz based on simulations introduced in [AxTh02].

2. OBJECTIVES OF THE DOCTORAL THESIS

Based on the presented review of satellite-to-indoor propagation models, it is obvious that the existing models are available for different ranges of elevation angles, frequency bands, building types, and propagation conditions, not to ignore the fact that they applied different definitions of penetration loss. To propose a more generally valid penetration loss model that can be used when planning the outdoor-to-indoor services using high elevation angle links, the targets of this thesis were specified as follows:

- Preparation and planning of the measurement campaign. This includes selecting a representative set of typical buildings in an urban area, planning of flyovers of the airship above each measurement sites, selecting the penetration loss definition and proposing a suitable calibration method of the measurement system.

- Carrying out the measurement trials. It is also necessary to provide a detailed documentation of the measurements and assign the recorded experimental raw data to each measurement site.

- Processing and analyses of the experimental data. This means synchronizing the signal levels received indoors and the flight data provided by the airship's sensors and calculating penetration loss for each measurement site. Further, a method for advanced processing of the experimental data must be suggested. As a next step, a detailed analysis of the resulting data must be carried out. This requires addressing the dependence of penetration loss on propagation conditions, elevation, azimuth, frequency, distance of the receiver from a window or a wall, type of a building, and type and size of windows presents in the building or in front of the receiver.

- Proposing generally valid empirical models for building penetration loss at L-, S- and C-band based on the detailed analyses and results for each of the case-study buildings. This requires deriving proper formulas that correspond to both the elevation trend and absolute values of penetration loss obtained for the representative set of buildings in an urban area. Further, the validity of the experimental data as well as the derived models must be verified by a comparison with other results and models that are available in the literature. As a last step, the influence of the measurement setup, namely the types and radiation patterns of Rx and Tx antennas, needs to be addressed.

3. THE MEASUREMENT CAMPAIGN

3.1. Measurement Setup

A basic experimental setup is shown in Fig. 3.1. A nine-meter-long remote-controlled airship carrying a transmitter station attached to its bottom was used as a pseudo-satellite. Four unmodulated CW signals at 2.0 GHz, 3.5 GHz, 5.0 GHz, and 6.5 GHz were transmitted by left-handed circularly polarized (LHCP) planar wideband spiral antennas land received by a receiver station (Fig. 3.2) placed at a fixed position inside each of the case-study buildings. A single LHCP circularly polarized planar wideband spiral antenna was used to receive the four frequencies. By using a sensitive radio receiver controlled by a laptop, it was possible to detect up to 60 dB of penetration loss considering the link budget of the experimental link. Measurement time stamps were used to synchronize the recorded signal levels and flight data provided by the airship's sensors (GPS position, pitch, roll, and compass). For a precise determination of the airship position, a separate Differential GPS receiver was used. Details of the measurement system can be found in [PECS09].

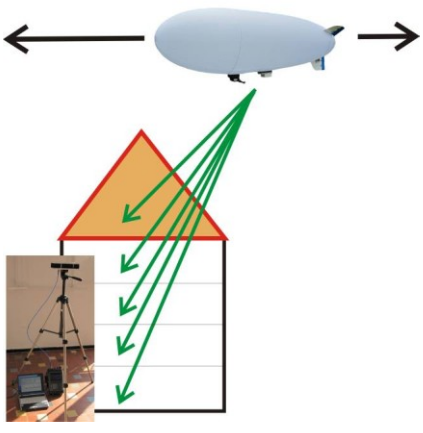

Fig. 3.1 Basic experimental setup

Fig. 3.2 Measurement performed at two different positions in parallel

3.2. Measurement Method

At least four flyovers of the airship were planned above each measurement site to obtain statically relevant data for a wide range of elevation angles from 20° up to 90° at different azimuths as seen from the position of the receiver station (Fig. 3.3). One flyover was usually approximately 1.5 km long and the airship average altitude of approximately 200 m was kept constant during the measurements. The speed of the airship was kept between 2 and 6 meters per second based on the speed and direction of the wind. The receiving antenna was always fixed during the measurements and placed on a plastic tripod at a constant height of 1.5 m above floor level.

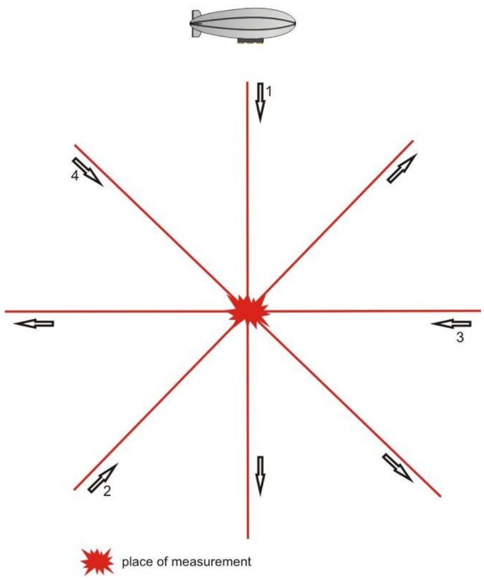

Fig. 3.3 Four flyovers planned above each measurement position

3.3. Measurement Scenarios

The measurements were performed at five different types of buildings located in Prague. The buildings were selected to represent a set of typical buildings in an urban area. Two additional measurement sites were utilized for calibration purposes. The measurement campaign was carried out during May - July 2009 and April 2010. An overview of the measurement locations is shown in Tab 3.1.

Table 3.1 Overview of the measurement locations

Location/Building	Date	Type	No. of Rx positions	Meas. on roof
A-FEE	May 2009 June 2009	Panel building	21	✔
B-Rector's office	May 2009	Brick-built house	8	✔
C-Residential house	May 2009	Brick-built house	10	✘
D-Office building	May 2009	Inner city office	8	✔
E-Shopping Centre	July 2009 April 2010	Shopping mall at city outskirt	5	✔
F-Calibration place-field	June 2009	Open space	1	-
G-Calibration place-FEE	May 2009	Open space	1	-

3.4. Calibration Method

The calibration method using a reference level obtained on a flat open field was found to be suitable for this measurement campaign. This means that the reference level is measured with the receiver (Rx) placed on a flat open field in a LOS towards the transmitter (Tx) for all the elevation angles used during the following in-building. These measurements were carried out on a field selected almost 30 km far from Prague where a very dense combination of elevation and azimuth angles was achieved. In addition, less extensive measurements were taken in another open field scenario for validation purposes only.

4. MEASUREMENT DATA PROCESSING

4.1. Basic Data Processing

All measured datasets were cleared of any noise data respecting the noise floor of the receiver station and only data relevant to a steady flight kept within a +/- 5 degree tolerance of pitch and roll of the airship were used for further processing.

The process of obtaining penetration loss levels was as follows. At first, signal levels of both the calibration and the data measured inside a building were recalculated to a uniform distance of 20 km. Because the calibration data suffered from multipath resulting in fadings, these data needed to be averaged out by applying the moving average technique. Then, for the combination of elevation, azimuth and Rx and Tx antenna orientations reported for the signal level taken inside a building, the matching combination of these parameters was found in the calibration dataset. By subtracting these two values, building penetration loss could be calculated in a simple way. This basic processing was accomplished for all measurement datasets from all locations.

5. BUILDING PENETRATION LOSS MODELLING

5.1. Measurement Data Processing

5.1.1. Comparison of Penetration Loss Definitions

The following study on the building penetration loss definition was introduced in [KvHo10]. As the ITU-R definition (an excess loss due to the presence of building wall and other building features, [ITURP1411]) is too general, different definitions of penetration loss can be found in the literature. To compare between the most common definitions and support our choice of the "*Flat open field*" definition, additional measurements were performed on the roof and at street level at building B-Rector's Office and in the anechoic chamber. Four different definitions of penetration loss were compared at 2.0 GHz and 5.0 GHz within the range of elevation angles from 80° to 90° and from 50° to 60° at two different azimuths.

These definitions of interest were:

- "*Above FSL*", which calculates penetration loss by subtracting the signal level measured indoors from the signal level calculated with respect to free space conditions
- "*Roof*", which relies on reference signal levels measured on the roof of the studied building
- "*Flat open field*", described in Section 3.4
- "*Street level*", which uses a reference level measured at street level immediately outside the case-study building.

It was found that the results obtained using references "*Flat open field*" and "*Roof*" differed by a negligible difference when the rooftop was the highest in the vicinity and the receiver was in a clear LOS towards the transmitter.

When comparing the "*Flat open field*" and the "*Above FSL*" references, the absence of ground reflections when considering the "*Above FSL*" reference results in lower reference levels that are produced. Further significant discrepancies are caused by the fact that it is almost impossible to accurately calculate the power balance of the link for each elevation and azimuth combination accomplished during the measurement campaign.

As the "*Street level*" reference is influenced by a strong multipath caused by the presence of nearby buildings and basically involves NLOS conditions for lower elevations and LOS conditions for higher elevations, it cannot be recommended for since both LOS and non-line-of-sight (NLOS) propagating conditions normally exist at the street level based on the elevation angle and specific geometry.

As a result, the "*Flat open field*" reference meets all the criteria for a generally valid and clearly defined reference level which can produce repeatable results and which addresses only LOS propagating conditions, as required for satellite services.

5.1.2. Data Advanced Processing

After the data basic processing, it was necessary to perform advanced processing consisting of the following steps:

- Insufficient amount of data within a selected time interval was left out. The criterion was set so that at least 2 and 19 values were within 5 and 50 second intervals, respectively.
- Moving average with ten-degree size of the averaging window was applied to the data measured indoors to average out the multipath.
- For each measurement site, the shape of the investigated building was outlined and plotted together with the flyovers of the airship. The data were divided into LOS, NLOS and parallel to the building facade. According to the planned flight paths (Fig. 3.3), each LOS or NLOS dataset contained data samples within up to approximately ±45° azimuth range. Within these LOS or NLOS cases, data were processed regardless of azimuth for each measurement site. In order to thoroughly average out multipath and to obtain proper average values of penetration loss for each measurement site, separately within the LOS and NLOS cases, we decided to calculate penetration loss as a mean from all data within five-degree intervals in elevation ranging from 22.5° to 87.5°, which preserved enough information about the elevation dependence.

- The final output file was a text file containing a table with penetration loss within the elevation intervals for LOS, NLOS and parallel cases for each of the measurement sites.
- Based on the final output files, data enabling comparison of the different types of buildings were obtained as follows: only measurement sites where the receiver was placed 1 meter in front of a closed window were considered. From such data, for each of the case-study buildings, a mean value of penetration loss was calculated for each of the five-degree intervals in elevation respecting the frequency and LOS/NLOS propagation conditions. The parallel cases were excluded from this analysis as explained in Section 6.3.1. Afterwards, output files containing tables with elevation intervals and corresponding mean of penetration loss in dB for each building were generated.

5.2. Data Analysis

5.2.1. LOS and NLOS Propagation Conditions

According to the data analysis, it was distinguished between LOS and NLOS propagation conditions with respect to the illuminated wall (Fig. 5.1). This division follows the terms directly and indirectly illuminated wall used for example in [HoPe07] and [GlHa01].

These two propagation conditions are completely different: under LOS, the signal propagates mainly through the wall or window in front of the receiver, whereas under NLOS the signal propagates mainly through upper floors and throughout the building as well, which introduces much stronger multipath.

Usually, several flyovers of the airship were also parallel to the facade of the investigated building, which resulted in problematically defined propagation conditions and thus these datasets were not further analyzed.

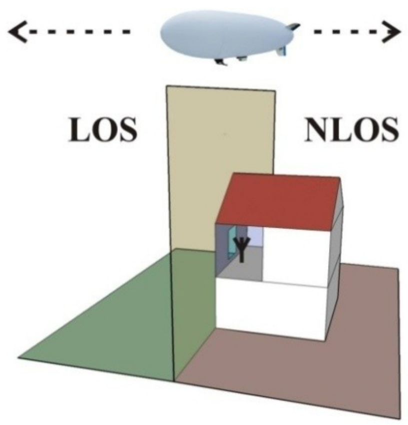

Fig. 5.1 Propagation conditions with respect to the illuminated wall

5.2.2. Azimuth Angle

The dependence of penetration loss on azimuth was not analyzed in detail as it turned out not to be clear. One reason was the lack of statistically relevant amount of experimental data and the fact that the flyovers were distributed very sparsely in the azimuth. Although penetration loss at 0° of azimuth should be the lowest and the loss at azimuth angles of -45° and +45° should be almost identical [PeHo09], this was not always true and was rather random, regardless of the frequency.

5.2.3. Elevation Angle

Elevation dependence of penetration loss was observed at all of the measurement sites. We can notice approximately a linear rise with elevation under LOS and a tendency to be close to constant for high elevations under NLOS. Detailed analysis is provided in this Section 5, where the elevation dependent model of penetration loss is introduced as well.

5.2.4. Azimuth Receiver Position

Several measurements were performed at different distances from a window inside each of the investigated buildings. The purpose of these measurements was to find out, how much the attenuation increases when the receiver is placed deeper in the building.

It can be supposed that the deeper the receiver is placed inside a building, the less difference between LOS and NLOS propagation conditions should be observed; the LOS case should be closer to penetration loss under NLOS conditions at the one-meter-distance due to richer multipath and less contribution from the direct signal, whereas penetration loss should be nearly indifferent of distance for the NLOS case. Although this is generally dependent on the specific building structure, this proved to be true throughout our measurement scenarios.

To sum up, generally, it can be stated that providing results for the one-meter-distance from a window for both LOS and NLOS can be used to estimate common limits of penetration loss for other distances from a window.

5.2.5. Different Types of Buildings

Only the datasets taken at the uniform one-meter distance from a window were used to characterize average penetration loss for each building.

As far as the absolute values are concerned, one notices that penetration loss was observed to be highest inside both office buildings A and D and lowest inside building B, for both LOS and NLOS cases, which can be explained by the respective structures of these buildings

Another difference between the case-study buildings is the slope of the dependence of penetration loss on elevation. Concerning LOS, a sharp rise of loss inside building B is present at low elevations due to the fact that the signal propagates through the large non-tinted windows and starts to propagate more through the brick wall or upper floors with increasing elevation. Regarding NLOS, the trend is almost the same for all the buildings: penetration loss rises significantly with elevation up to approximately 60° and then tends to remain nearly constant. Under LOS, penetration loss rises almost linearly within the whole range of elevations.

5.2.6. Influence of Windows

Measurements with open and closed window in front of the receiver were carried out in the corridor on the sixth floor of the building A, where the windows are made of tinted glass. As expected, by opening the window in front of the receiver, penetration loss noticeably decreased in the same way by up to 20 dB at each frequency for the LOS case. Under NLOS, although nearly no influence caused by opening the window was expected, a noticeable decrease of penetration loss was observed when the receiver was placed one or two meters from the window. This can be explained by multipath caused by other blocks of building A and subsequent diffraction at the window frame, which led to stronger received signal levels when the window was open.

To sum up, it can be stated that by opening a window in front of a receiver, penetration loss can significantly decrease and that this change is less significant when the receiver is placed deeper inside a building and when NLOS conditions are considered.

5.2.7. Frequency

Based on all the obtained results, it was not possible to clearly address the frequency dependence of penetration loss within L-, S- and C-band. Although, overall lowest penetration loss was observed at 2.0 GHz and highest loss basically occurred at 6.5 GHz with absolute values of 5 dB or 10 dB higher than at 2.0 GHz, it cannot be stated that penetration loss is rising with frequency. In some cases, even lower penetration loss was observed at 6.5 GHz than e.g. at 5.0 GHz, and almost no difference was observed between penetration loss at 3.5 GHz and 5.0 GHz. As it turned out that the presence of a tinted window in front of the receiver can introduce specific frequency dependence of attenuation, the frequency dependence should be possible to address using the NLOS results; however, this also did not prove to produce convincing results.

5.3. Building Penetration Loss Modelling

The dependence of penetration loss on the elevation angle, for each of the selected frequencies separately for the LOS and NLOS cases, was modelled based on the overall results for the case-study buildings. This means that only measurement sites where the receiver was placed 1 meter in front of a window were included and that the azimuth dependence of penetration loss was not covered. An important presumption is that the selected buildings form a representative set of buildings and outline an interval within which levels of penetration loss inside any other common urban buildings should fall. As it was shown, the loss reported for the office buildings can be more than 20 dB higher than the values for the brick building. We decided to provide models for overall minimum and maximum penetration loss together with a model for its mean value. The reason for this approach is as follows: as we covered minimum and maximum penetration loss frequently observed in an urban area, penetration loss can now be estimated to be closer to these minimum or maximum borderlines based on the structure of a particular building. Further, the model for mean penetration loss predicts an average estimation if no detailed information about the building is available.

This section is separated into two parts, depending on whether LOS or NLOS occurs. In addition, a comparison with selected penetration loss models for satellite services is provided. The new propagation models were published in [KvPe11].

5.3.1. LOS

With respect to the almost linear rise of penetration loss in dB with elevation for the LOS case, we implemented a linear model based on the following equation:

$$L_{\mathrm{PL,LOS}}(\alpha) = A + B\alpha \quad (1)$$

where A in dB and B in dB/° are held constant for a given frequency and α is the elevation angle in degrees. Theoretically, A could stand for penetration loss at an elevation of 0°, however, the model is valid only from an elevation of 25°; parameter B characterizes the slope of the fitted curve.

The empirical model was obtained as follows. First, at each frequency, minimum, maximum and mean values of penetration loss within each elevation interval were determined based on the overall mean penetration loss for each of the case-study buildings. Then, the least-square method was used to fit (1) to these values. It was found that parameter B did not significantly vary with frequency for each of the minimum, maximum or mean fits, which enabled us to reduce the number of values representing B for the fitted curves in the following way: from the four values of B for the minimum fit at the four corresponding frequencies, an average represented further by parameter B_{min} was calculated. The same process was applied to the maximum and mean fits so that parameters B_{max} and B_{mean} were obtained. To obtain the correct values of parameter A, (1) had to be fitted again to the minimum, maximum and mean penetration loss at each frequency, but the corresponding parameters B_{min}, B_{max} and B_{mean}, respectively, had to be used. Finally, three values of parameter A were obtained at each frequency: A_{min}, A_{max} and A_{mean}. As a result, for example, the model for the minimum penetration loss at 2.0 GHz is represented by the value of $A_{min} = -6.3$ dB and by the value of $B_{min} = 0.44$ dB/°, which is independent of the frequency. All the necessary values of the parameters mentioned are clearly summarized in Tab. 5.1. The fitted curves, together with corresponding experimental data, are shown in Fig. 5.2.

Table 5.1 Parameters of the empirical model for LOS

Parameter	**Frequency (GHz)**			
	2.0	**3.5**	**5.0**	**6.5**
A_{min} (dB)	-6.3	-2.3	0.5	0.3
A_{max} (dB)	23.0	24.6	28.4	26.0
A_{mean} (dB)	11.6	14.4	17.7	16.3
B_{min} (dB/°)	0.44			
B_{max} (dB/°)	0.28			
B_{mean} (dB/°)	0.31			

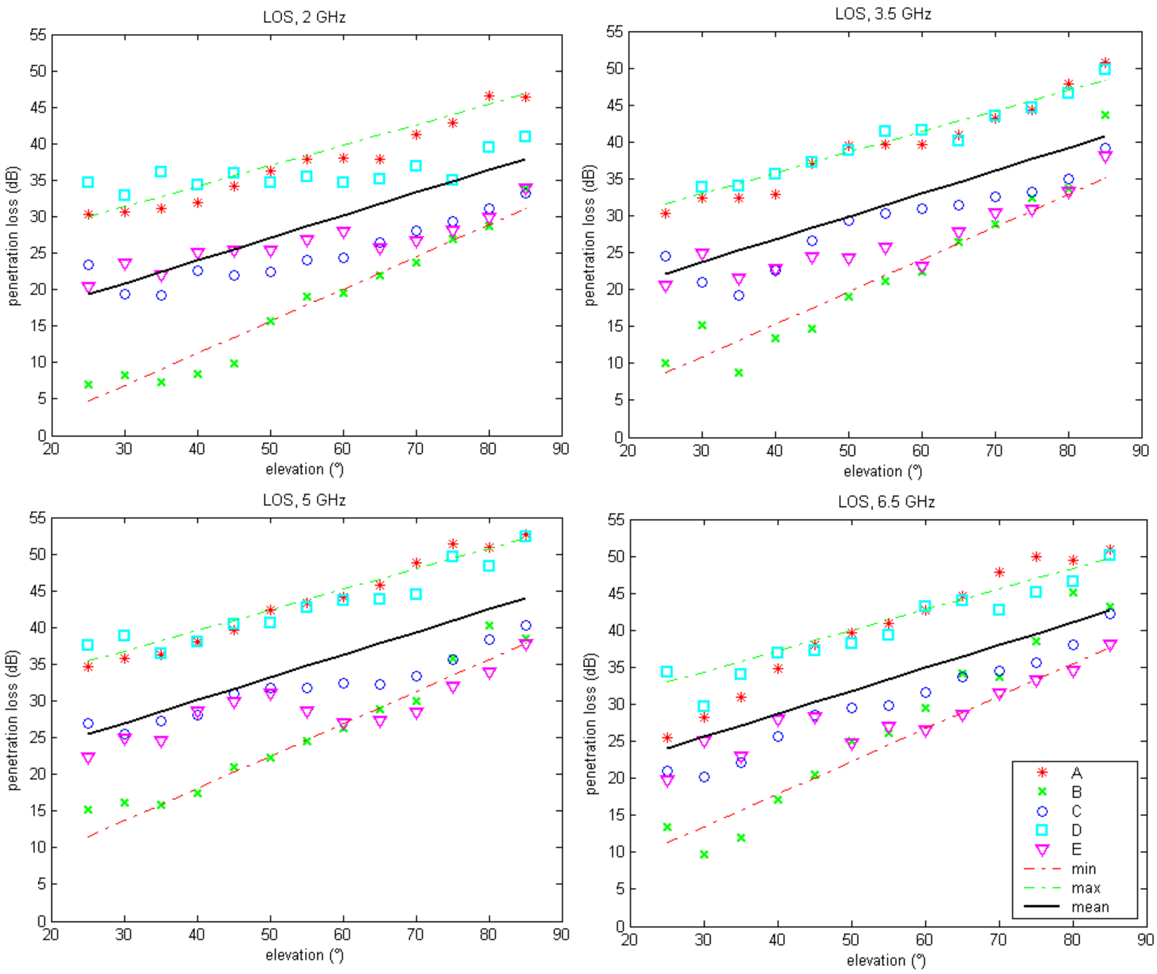

Fig. 5.2 Mean fit (solid) of the experimental data together with the minimum (red) and maximum (green) border lines, LOS

5.3.2. NLOS

For the NLOS case, penetration loss first rises with elevation and then tends to be nearly constant at high elevation angles. To embed this effect in the empirical model of the loss in dB at each frequency, the following equation was used to fit minimum, maximum and mean of the overall penetration loss for all case-study buildings:

$$L_{\mathrm{PL,NLOS}}(\alpha) = C - D(90-\alpha)^E \tag{2}$$

where parameter C in dB represents maximum penetration loss at an elevation of 90°, parameter D in dB/° represents the difference between minimum and maximum penetration loss at elevation angles 25° and 90°, respectively, and parameter E determines the course of the fitted curve.

In contrast to the LOS case, it was noticed that at each frequency the dependence of minimum, maximum and mean penetration loss on elevation was very similar simplifying the modelling in the following way: using the least-square method, (2) was fitted at each frequency to the mean values of penetration loss calculated in the same way as for the LOS case. It was found that the four obtained values of parameter E varied only from 2 to 3.1 and the course of the curve was not significantly sensitive to this parameter. This is why the mean value of E was calculated and its value of 2.5 was later used. Next, (2) was fitted again to mean values of penetration loss at each frequency, but this time with $E = 2.5$. As a result, a total of four values of C_{mean} and four values of D_{mean} were obtained, one at each frequency as before. Based on the previously mentioned similar dependence of minimum, maximum and mean penetration loss on elevation, it was necessary to change only the value of C_{mean} to model minimum and maximum penetration loss, while the value of D remained unchanged. At each frequency, we manually increased the value of C_{mean} by the interval Δ in dB so that only one value from the found maximum penetration loss was allowed to exceed penetration loss outlined by the corresponding maximum fit of more than 1 dB. An analogous approach was applied to the minimum fit. We also found only a single value of Δ at each frequency, which could be subtracted from or added to a value of C_{mean}. For example, at 2.0 GHz, the minimum penetration loss can be modelled by (2), where C_{min} is obtained by subtracting the value of Δ = 9.5 dB from the value of $C_{mean} = 38.9$ dB, $D_{min} = D_{mean} = 2.4 \cdot 10^{-4}$ dB/° and $E = 2.5$. All the necessary parameters clearly summarized in Tab. 5.2 and the fitted curves, together with corresponding experimental data, are shown in Fig.5.3.

Table 5.2 Parameters of the empirical model for NLOS

Parameter	**Frequency (GHz)**			
	2.0	**3.5**	**5.0**	**6.5**
$C_{mean}(dB)$	38.9	44.5	45.5	46.7
Δ (dB)	9.5	8.0	8.0	6.5
D_{mean} (10^{-4} dB/°)	2.4	3.0	4.6	4.4
E (-)	2.5			
$C_{min} = C_{mean} - \Delta$				
$C_{max} = C_{mean} + \Delta$				
$D_{min} = D_{max} = D_{mean}$				

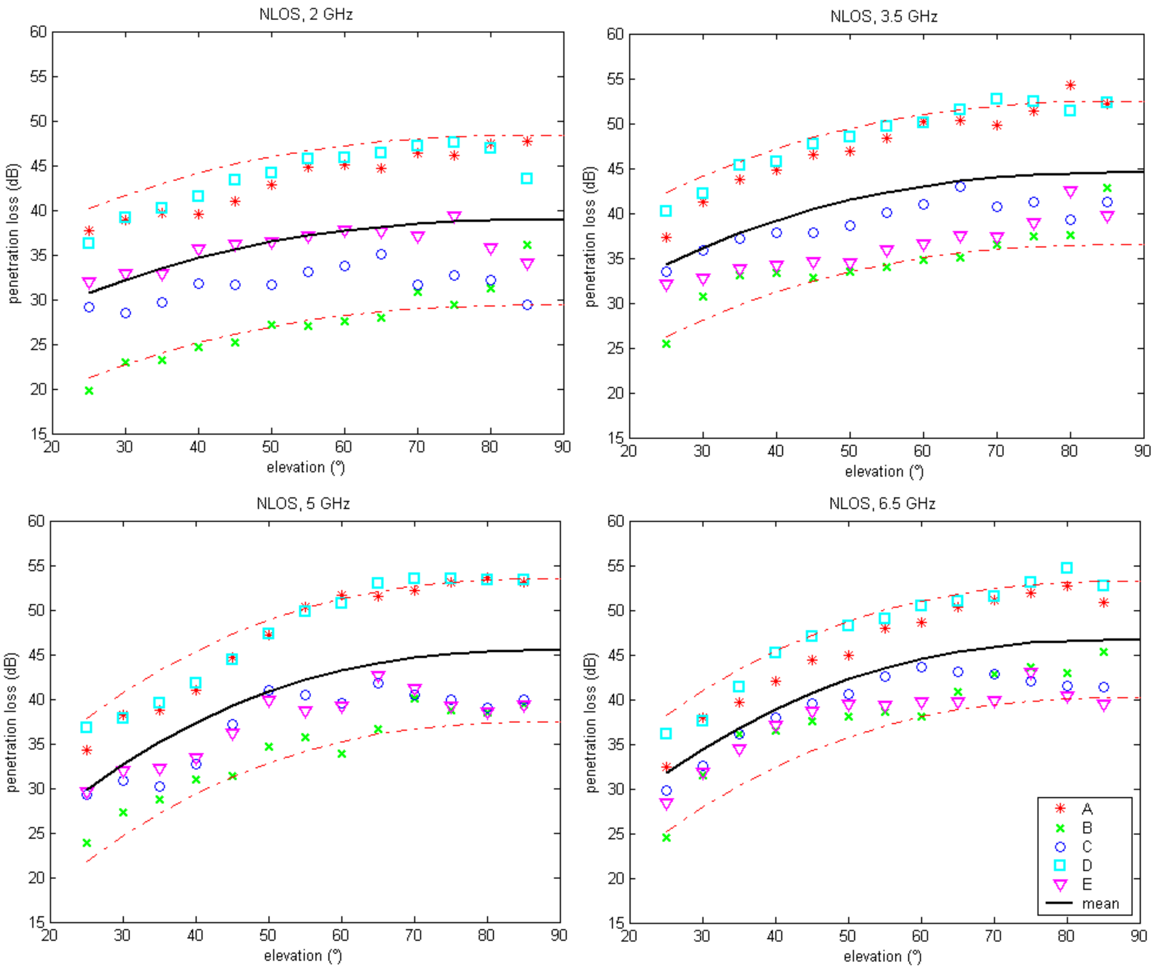

Fig. 5.3 Mean fit (solid) of the experimental data together with the minimum and maximum (dash-and-dot) border lines, NLOS

5.3.3. Comparison to Other Models

Based on the presented results, it is obvious that penetration loss strongly depends on the type and structure of a particular building and that a strong dependence on elevation angle is evident.

As with our study, the models provided in [PeHo09], [PeNu10], [GlHa00], and [AxTh03] employ a linear or nearly linear rise of penetration loss with elevation for the LOS case. In [HoPe07], the LOS case can be considered only for high elevation angles where the linear rise is also noticeable. In addition, the experimental data presented in [FrMo96] for lower floor levels show the same linear trend as do the results for higher elevations in [HoPe09].

The model in [PeHo09], designed to be used with the building entry angle, addresses primarily LOS conditions at 2.5 GHz and predicts a linear rise of penetration loss from 20.7 dB to 28.5 dB for elevation angles from 25° to 90°. This fits well between the minimum and maximum borderlines given by our model at 2.0 GHz.

Using [ITU10], where the results at 2.57 GHz from [PeHo09] and at 5.2 GHz from [PeNu10] were clearly summarized for elevation angles of 15°, 30°, 45°, and 60° at different azimuth angles, we compared our LOS model for minimum, maximum and mean penetration loss for 2.0 GHz and 5.0 GHz with penetration loss inside the following buildings: Millennium Tower 44th and 22nd floor, an office building and gate and a conference room at an airport. These building are in Fig. 5.4 marked as Mil_44, Mil_22, Office, Air_G, Air_C, respectively. The model in [PeHo09] is marked as PeHo09, and the predictions provided by our models are marked as min, max and mean. Although the considered measurements were wideband, carried out at slightly different frequencies and included different types of buildings than our measurement campaign, a good match was mostly, as can be clearly seen from Fig. 5.4. However, the [PeHo09] elevation dependent linear model evidently shows a very different slope when compared to our models, which is caused by slightly different measurement techniques and definition of penetration loss applied in [PeHo09] and [PeNu10].

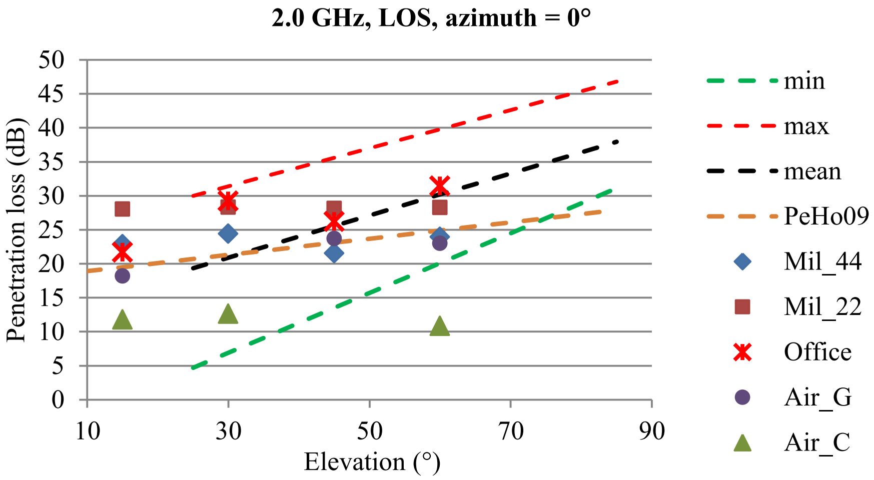

Fig. 5.4 Comparison of our model for 2.0 GHz with the model from [PeHo09] and data from [ITU10]

5.3.4. Correction for Directional Antenna Characteristics

The derived building penetration loss models were based on measurement trials where both the Tx and Rx antennas had hemispherical radiation patterns. Following the "*Flat open field*" definition of penetration loss and the fact that the attenuation of the direct signal between the Tx and Rx antennas is determined by the case-study building only, we can state that the observed elevation trend of penetration loss may significantly depend on the large amount of multipath received indoors, which is determined not only by the building itself, but by the radiation pattern of the Tx and Rx antennas and their orientations as well. To address this phenomenon, as presented in [KvPe12], we performed a single-output multiple-input (SIMO) measurement campaign at the frequency of 2.0 GHz during the summer of 2011, in Prague, in a corridor on the sixth floor of building A and a hall on the first floor of a building B.

Based on the results obtained, it was possible to propose a correction method that enables to subtly modify the derived penetration loss models for different Rx and Tx antenna configurations [KvPe12]

$$PL_2(\alpha) = PL_1(\alpha) + \left(P_2(\alpha, F_{Tx2}, F_{Rx2}) - P_1(\alpha, F_{Tx1}, F_{Rx1})\right) \tag{3}$$

where α is the elevation angle, and $PL_1(\alpha)$ and $PL_2(\alpha)$ are the penetration loss models before and after the correction, respectively. The received signal strength on the flat open field that was measured or simulated by a two-ray model for the original and the required antenna configuration is represented by P_1 and P_2, respectively, which are functions of elevation angle and Tx and Rx antenna normalized radiation patterns denoted here as F_{Tx} and F_{Rx}.

6. CONCLUSION

A thorough review of propagation models addressing building penetration loss has been provided in the first section of this thesis. On its basis, the measurement campaign was prepared carefully respecting several crucial aspects. This includes selecting the reference level and the different representative types of buildings, specifying corresponding elevation and azimuth angle ranges that will be covered by the campaign and finally setting up the link budget for the measurements.

The third section introduced the measurement system, the five selected buildings with the two calibration sites and the calibration method. Section 4 described basic processing procedure of the experimental raw data.

Section 5 dealt with advanced data processing, analysis and modelling. Final results for all the case-study buildings were introduced It should be noted that within LOS or NLOS case, no apparent dependence of penetration loss on azimuth was found, which may have been caused by the measured range of azimuths of only up to ±45°. Further, no clear frequency dependence of penetration loss was observed, although overall lowest penetration loss was reported for the frequency of 2.0 GHz. On the other hand, penetration loss was significantly dependent on the elevation angle and was determined mainly by the type of a building, type of windows in front of the receiver, distance of the receiver from the window and LOS/NLOS propagation conditions. The lowest penetration loss was reported for the brick building with non-tinted windows, whereas the highest was observed inside the two office buildings with tinted windows. To summarize the results at all four frequencies:

- Building penetration loss is significantly influenced by the geometry of the scenario, that is, the position of the receiver inside a building with respect to the building orientation and satellite position. This is why the LOS/NLOS criterion was utilized rather than precisely considering the azimuth angle and the facade orientation.

- There is a strong dependence of penetration loss on the elevation angle. We notice an almost linear rise of penetration loss with elevation for the LOS case and a tendency to stay close to constant for the NLOS case with maximum loss reached at approximately 60° of elevation.

- Significant differences between the absolute values of penetration loss were found amongst the selected types of buildings with the maximum loss seen inside the modern, office buildings and the minimum loss observed inside the brick building. The presence and type of windows clearly influence penetration loss.

- The measurement results for the receiver placed 1 m from a window can be used to estimate building penetration loss for other indoor receiver positions. The minimum and maximum expected values are represented by the LOS and NLOS results, respectively.

- Although the overall lowest penetration loss was observed at 2.0 GHz, no clear frequency dependence of the penetration loss could be reported.

Based on the results for the case-study buildings, new elevation dependent empirical models were introduced at each frequency separately for the LOS and NLOS propagation conditions. The LOS model applies a linear fit to the experimental data and the NLOS model follows the trend of the experimental data to stay close to constant at higher elevation angles.

Futher, in Section 5, the influence of Tx and Rx antennas on building penetration loss was presented based on results obtained during experimental SIMO measurement trials performed at a frequency of 2.0 GHz in two buildings. It was shown that the elevation trend of building penetration loss depends on the orientation and type of Tx and Rx antenna radiation patterns. A correction method that enabled us to modify building penetration loss models when considering different Tx and Rx antenna configurations was proposed.

To conclude, all objectives were successfully accomplished and the new narrowband models that were published in [KvPe11] together with the corresponding correction method in [KvPe12] can be used as a universal tool enabling prediction of building penetration loss for a wide range of satellite-to-indoor scenarios at a broad frequency range.

As far as future work is concerned, the satellite-to-indoor propagation channel should be addressed in a more extensive way, i.e. considering its wideband characteristics, addressing higher frequency bands, providing channel statistics, or considering more complicated satellite-to-indoor channel configuration than SISO (namely SIMO/MISO or even MIMO) to include the benefits of diversity techniques.

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List of Candidate's Works Relating to the Doctoral Thesis

Articles in Impacted Journals

[KvHo10] M. Kvicera, P. Horak, P. Pechac, F. Perez-Fontan, "On a definition of building penetration loss for high elevation angles," *IEEE Transactions on Antennas and Propagation*, 2010, Vol. 58, No. 12, p. 4115-4118. (25%)

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[KvPe12] M. Kvicera, P. Pechac, "Influence of antenna characteristics on building penetration loss for high elevation links," submitted to *IEEE Transactions on Antennas and Propagation*, October 2011. (50%)

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[Kv_Eu10] M. Kvicera, P. Horak, T. Korinek, J. Zela, M. Simunek, P. Pechac, "Building penetration loss measurements for satellite-to-indoor systems: preliminary results," In *Proceedings of the 4th European Conference on Antennas and Propagation EuCAP 2010*, Barcelona, Spain, April 2010, p. 1-4, ISBN 978-84-7653-468-7. (17%)

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SUMMARY

This doctoral thesis deals with building penetration loss for satellite services. Although several penetration loss models as well as experimental data are available for satellite-to-indoor propagation channel, a generally-valid building penetration loss model is still missing. The reason is that the available studies addressed different frequency bands, different ranges of elevation angles or applied different definition of penetration loss. This is why an extensive measurement campaign, covering a representative set of typical buildings in an urban area and aimed at building penetration loss for high elevation angle satellite services at L-, S- and C-band, was performed in Prague during the years 2009 and 2010.

Throughout the measurements, a remote-controlled airship was used as a pseudo-satellite carrying a transmitter which provided unmodulated continuous wave left-handed circularly polarized signals at 2.0 GHz, 3.5 GHz, 5.0 GHz, and 6.5 GHz. Based on a thorough analysis of the resulting experimental data obtained at a number of measurement positions inside each of the selected case-study buildings, it was possible to thoroughly address building penetration loss for satellite services at the given frequency bands.

First, penetration loss was analyzed with respect to its dependence on elevation, frequency, propagation conditions, type of a building, and distance of a receiver from a window. Based on these analyses, it was possible to proceed with deriving corresponding elevation-dependant penetration loss models for LOS and NLOS propagation conditions. To verify the proposed models, a comparison with the selected existing penetration loss models was carried out. As a result, further analysis was made addressing the influence of receiving and transmitting antenna characteristics on these models and a correction method was proposed.

As all the objectives of the doctoral thesis were successfully met, the possibilities for future work have been suggested as well.

RESUMÉ

Disertační práce je věnována problematice šíření družicového signálu do budov. Ačkoliv několik modelů pro průnik signálu do budov lze společně se souvisejícími experimentálními daty nalézt v odborné literatuře, žádný z těchto modelů není všeobecně platný z následujících důvodů. Každý je navržen pro odlišné frekvence, různé rozsahy elevací, případně při jeho návrhu byla uplatněna rozdílná definice útlumu signálu způsobeného průnikem do vnitřku budovy. Proto byla v Praze během let 2009 a 2010 provedena rozsáhlá měřicí kampaň v pásmech L, S a C, jejímž cílem bylo důkladně prozkoumat útlum signálu způsobený jeho průnikem do vnitřku několika budov, která byly vybrány tak, aby tvořily reprezentativní vzorek budov typické městské zástavby.

V průběhu dané měřicí kampaně byla využita dálkově řízená vzducholoď, na jejíž spodní části byl umístěn vysílač vysílající nemodulovanou kruhově polarizovanou vlnu na frekvencích 2.0 GHz, 3.5 GHz, 5.0 GHz, and 6.5 GHz. Na základě analýzy experimentálních dat získaných na mnoha místech uvnitř každé z vybraných budov bylo možné detailně zkoumat průnik signálu do budov v daných frekvenčních pásmech.

Nejdříve byl útlum signálu analyzován z hlediska jeho závislosti na elevaci, frekvenci, podmínkách šíření signálu, typu budovy a vzdálenosti přijímače od okna. Následně bylo možné přistoupit k návrhu odpovídajících elevačně-závislých modelů tohoto útlumu pro podmínky přímé a nepřímé viditelnosti. Aby byla ověřena správnost takto navržených modelů, bylo provedeno srovnání s vybranými relevantními modely, které jsou k dispozici v odborné literatuře. Zde se ukázalo, že je dále možné kompenzovat vliv anténních charakteristik vysílací a přijímací antény na daný model a následně byla navržena odpovídající korekční metoda.

Lze konstatovat, že všechny definované cíle disertační práce byly beze zbytku úspěšně splněny. Zároveň byly nastíněny možnosti týkající se budoucí výzkumné činnosti v rámci dané problematiky.