Influence of Antenna Characteristics on Elevation Dependence of Building Penetration Loss for High Elevation Links

Milan KVICERA, Pavel PECHAC

Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, 166 27 Prague, Czech Republic

kvicemil@fel.cvut.cz, pechac@fel.cvut.cz

Abstract. *Building penetration loss models presented in our previous paper [1] were valid for various scenarios, propagation conditions, frequency bands, and hemispherical receiving antenna pointing towards zenith. These models had a significantly rising trend of penetration loss with increasing elevation angle of the link in common. In this paper we show that when working with such non-isotropic terminal antennas, this trend relates primarily to the elevation trend of the reference level [2] dependent on the receiving antenna radiation pattern. This is demonstrated by the results of single-input multiple-output (SIMO) measurement trials performed at L-band in an office building and a brick building in the city of Prague. Further, based on the detailed analysis, a method to modify the elevation trend of a particular penetration loss model for different receiving antenna radiation patterns is derived and experimentally validated.*

Keywords

Propagation measurements, satellite mobile communication, building penetration loss, modeling.

1. Introduction

Our previous paper presented building penetration loss models for satellite services at L-, S- and C-band, which are valid for a wide range of high elevation angles and common scenarios achieved in an urban area [1]. These models are based on a statistically significant amount of experimental data for a set of five different representative types of buildings that are commonly found in built-up areas. To calculate penetration loss using signal levels received inside a building, a reference level is needed [2] according to the ITU-R definition which states that penetration loss is an excess loss caused by the presence of a building wall and other building features [3]. In [1] and other studies focused on satellite-to-indoor channel, e.g. [4] and [5], the reference level was taken on a flat open field where the ground terminal, let us further assume a receiver (Rx), was in a line-of-sight towards the transmitter (Tx) located on a pseudo-satellite. This clearly defined and generally valid reference level enables relevant and repeatable results to be produced [2]. The focus of this paper is a situation where a non-isotropic, let us further consider a directional, radiation pattern of an indoor, hand-held terminal is taken into account. It must be noted that in this case, ground reflections at the reference site, as well as multipath received indoors, play an important role and the received signal level is influenced by the Rx antenna radiation pattern.

The signal received indoors comprises not only the direct signal between Tx and Rx antennas attenuated by the building, but also a significant contribution from multipath components, as reported in [4]-[7]. From a physical point of view, the amount of multipath present inside any building is a feature of the building and the corresponding measurement scenario. The presence of windows causes significant influence as they generally introduce lower attenuation than walls [1], [7], thus allowing multiple-reflected or diffracted outdoor signals to penetrate buildings more easily. Further, a significant diffraction on window frames results in a higher level of multipath [7].

It can be assumed that the level of the rich multipath present inside a building is constant for a wide range of elevation angles and can be even higher than the level of the direct signal between Tx and Rx antennas attenuated by the building. This would result in obtaining similar elevation trends of received signal level for different Rx antenna radiation patterns. However, this is not the case of the reference level where only the ground reflection exists. As a result, the elevation trend of building penetration loss would be mainly determined by the elevation trend of the reference level. Consequently, the difference between elevation trends of penetration loss for different Rx antenna radiation patterns would be predominantly given by the difference between elevation trends of the corresponding reference levels for these cases.

To address this phenomenon, we performed a SIMO measurement campaign at the frequency of 2.0 GHz during the summer of 2011 in a corridor on the sixth floor of an office building and a hall on the first floor of a brick building, *Building A* and *Building B* respectively in [1].

The same unmanned airship [8] was utilized as a pseudo-satellite, but two different types of transmitting antennas and four different receiving antennas were selected. Based on the results obtained, this paper presents a correction method which adjusts elevation trends of penetration loss models from [1] for directional terminal antennas and enables to obtain tentative results as far as the absolute values of penetration loss are concerned.

Sections 2 and 3 present our measurement setup and data processing. Analysis of the experimental results is provided in Section 4. Section 5 introduces the correction method. The paper is concluded by a short summary in Section 6.

2. Measurement Setup

Transmitter Station

The transmitter station consisted of a continuous wave generator providing 27 dBm output power at a stable frequency of 2.0 GHz and was placed under the unmanned battery-powered airship.

Receiver Station

A sensitive portable receiver with four fully-synchronized parallel channels and a 100 Hz sampling rate was used, which enabled us to record multipath of the received signal. The noise floor of this receiver was less than -126 dBm within a 12.5 kHz bandwidth during the measurements. In this way, up to 60 dB of penetration loss could be detected. The measured signal levels were recorded by a laptop connected to the receiver via USB.

Transmitting Antennas

Two types of Tx antennas with different radiation patterns were selected. The first was a left-handed circularly polarized spiral antenna (*Tx_L*), the same as in [1], with the maximum of its hemispherical radiation pattern pointing downwards from the airship. The second was a quarter-wavelength monopole (*Tx_lin*) placed so that the maximum of its omnidirectional pattern was alongside the airship's main axis.

Receiving antennas

Four Rx antennas with maxima of their hemispherical radiation patterns in the same direction were placed on a tripod and connected by coaxial cables with SMA connectors to corresponding channels of the receiver. To simulate an Rx antenna directional pattern of a handheld terminal and its common antenna orientations in a satellite-to-indoor scenario, the antenna holder was positioned so that the maximum of the radiation pattern was either in a vertical (i.e. towards the zenith, see *Vert* in Fig. 1) or horizontal (i.e. parallel to street level, see *Hor* for the LOS case in Fig. 1) direction. The first two antennas were rectangular patches with horizontal (*Rx_H*) and vertical polarization (*Rx_V*). The other two were left- (*Rx_L*) and right-handed (*Rx_R*) circularly polarized spiral planar antennas.

3. Data Processing

The basic experimental data processing was similar to [1]. Indoor measurements at both measurement sites were taken at a uniform one-meter distance from a closed window in front of the receiver. Elevation angles from 20° to 90° were covered and the LOS and NLOS cases were distinguished using GPS coordinates provided by the airship. For the NLOS case, the *Hor* orientation was toward the opposite wall, i.e. in the direction opposite of that shown in Fig. 1. The airship flyovers followed a star-shape pattern so that one flyover was perpendicular to the building facade and two were separated by +/- 45° in azimuth.

The experimental data were recalculated to a uniform distance of 20 km and processed using a moving average with a window length of 10 wavelengths to average out fast fading. A mean value of penetration loss was then calculated within five-degree intervals in elevation by using the reference data taken on a flat open field. This required standalone measurement trials performed on the flat open field prior to the indoor measurements.

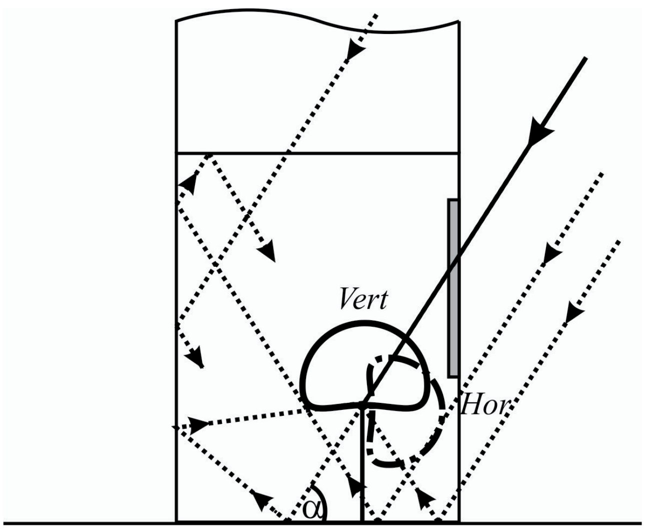

Fig. 1. Selected *Vert* (solid line) and *Hor* (dash-dotted line) orientations of the Rx antenna hemispherical radiation pattern under LOS propagation conditions. The elevation of the link is denoted by α, the direct signal between Tx and Rx antennas propagating through a window is shown by the solid line and multipath components of the transmitted signal are illustrated by the dotted lines.

4. Results and Analysis

To avoid any ambiguities, only the following combinations resulting in clearly defined polarization states of the propagation channel were considered for this study: *Tx_L* and *Rx_L*, *Tx_L* and *Rx_H*, *Tx_lin* and *Rx_L* (or

Tx_R), *Tx_lin* and *Rx_V*. In these cases, at least one component of the transmitted signal was co-polarized with the Rx antenna for both its *Vert* and *Hor* orientations for the whole range of elevation angles.

As the results obtained in *Building A* and *Building B* were the same in terms of the elevation trends of penetration loss, only the results for *Building A* are shown here.

In Fig. 2 we see penetration loss for the LOS case when the orientation of the Rx antenna was *Vert,* and for the four selected combinations of Tx and Rx antennas, we notice the rising elevation trend of penetration loss. Under NLOS, penetration loss also rose with elevation for the four considered cases.

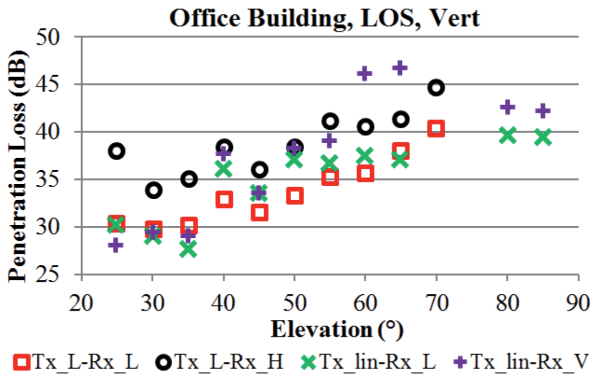

Fig. 2. Penetration loss for the office building under LOS for *Vert* orientation of the Rx antenna.

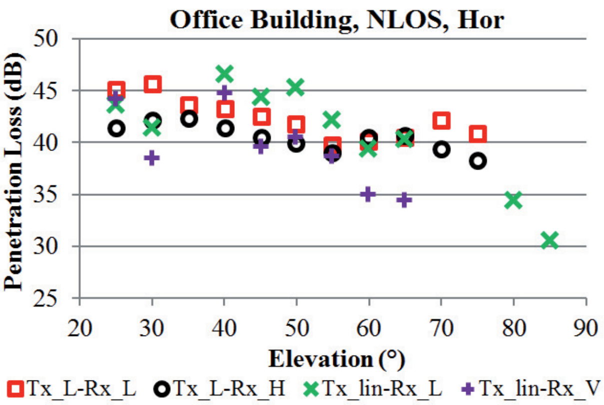

Fig. 3. Penetration loss for the office building under NLOS for Hor orientation of the Rx antenna.

Opposite to the previous case, penetration loss decreased with rising elevation for the Hor orientation of the Rx antenna. Fig. 3 shows penetration loss obtained under NLOS propagation conditions. Under LOS, the decreasing elevation trend of penetration loss was observed as well.

The only reason for the opposite elevation trends of penetration loss in Figs. 2 and 3 was the change in orientation of the Rx antenna from *Vert* to *Hor* which can be assumed to equal the change of the Rx antenna radiation pattern.

Because of the similarity between results obtained for each of the selected combination of Tx and Rx antennas only the *Tx_L-Rx_L* case is further analyzed in detail here. Moreover, this configuration is similar to the measurement setup in [1].

The results under LOS for the *Tx_L-Rx_L* case are shown in Fig. 4. The situation for the *Vert* orientation of the Rx antenna is represented by the squares and shows the linear rising elevation trend of penetration loss from Fig. 2. We can further see that these results are, in terms of the elevation trend, as well as absolute values, in good agreement with the model for maximum penetration loss under LOS from [1] shown by the solid line in Fig. 4, as expected. On the other hand, the almost linear decreasing elevation trend of penetration loss observed for the *Hor* orientation of the Rx antenna is represented by the circles in Fig. 4.

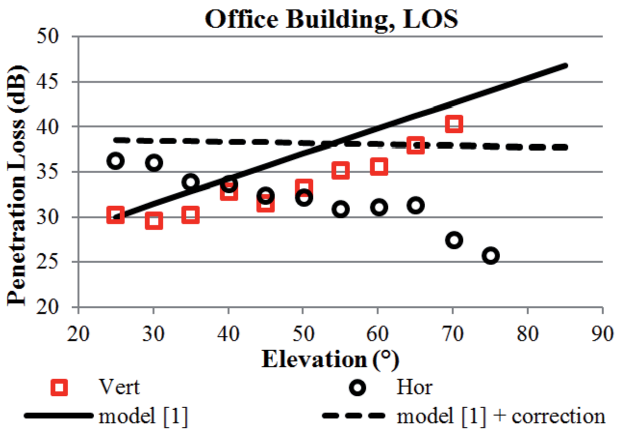

Fig. 4. Penetration loss for the office building under LOS for *Vert* and *Hor* orientations of the Rx antenna together with the model for maximum penetration loss from [1] (solid line) and the linear fit after its correction (dashed line).

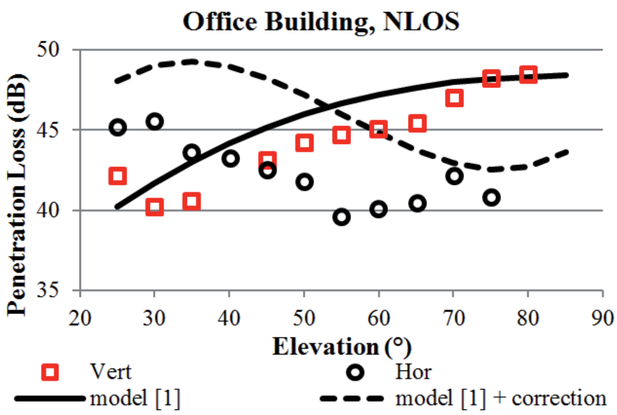

Fig. 5. Penetration loss for the office building under NLOS for *Vert* and *Hor* orientations of the Rx antenna together with the model for maximum penetration loss from [1] (solid line) and the polynomial fit after its correction (dashed line).

Fig. 5 shows results for the NLOS case and we again see the rising elevation trend of penetration loss for the *Vert* orientation as plotted by the squares. Moreover, in terms of the rising elevation trend and absolute values, these results are again in good agreement with the model for maximum penetration loss under NLOS from [1] plotted by the solid line in Fig. 5. On the other hand and similar to the LOS case, penetration loss decreases with increasing elevation for the *Hor* orientation of the Rx antenna as plotted by the circles.

As stated in the Introduction, there is a significant level of multipath present inside a building. As a result, we can assume that the elevation trend of signal level received indoors will not depend on the Rx antenna radiation pattern or its orientation as significantly as the reference level where the direct signal dominates. Consequently, the change of the elevation trend of penetration loss would be given mainly by the change of elevation trend of the corresponding reference level. This assumption is proved by Fig. 6 which presents the elevation dependence of mean reference signal strength as obtained for the *Tx_L-Rx_L* antenna combination on the flat open field after the recalculation to the 20 km distance. It can be seen that the received signal strength rose significantly or stayed almost constant with increasing elevation when the receiving antenna orientation was *Vert* or *Hor*, as represented by the squares and circles in Fig. 6, respectively. The differences between the elevation trends of these two reference levels considerably correspond to the differences between the elevation trends of penetration loss obtained for corresponding cases when the Rx antenna was oriented in the *Vert* or *Hor* direction, as shown by Fig. 2 and 3 (or 4 and 5), respectively.

At this point, we can briefly summarize that in the case of the directional Rx antenna, the elevation trend of penetration loss is significantly influenced by the elevation trend of the corresponding reference level given by the Tx and Rx antenna radiation characteristics and their respective orientations.

5. Correction Method

Following the analyses above, it should be possible to obtain elevation trends of penetration loss for various Rx antenna radiation patterns simply by accounting for differences in elevation trends of corresponding reference levels. Based on this assumption, we have proposed a corresponding correction method.

We will demonstrate the suggested method using the data shown in Figs. 4-6 and the penetration loss models from [1] which match the results for the *Vert* orientation of the hemispherical Rx antenna. Firstly, the differences between the reference levels for the *Vert* and *Hor* orientations of the Rx antenna, which were represented by circles and squares in Fig. 6, must be calculated. For the five-degree intervals in elevation, considering that we want to modify penetration loss from the *Vert* to *Hor* case, we get a positive difference for elevation angles below an elevation of approximately 45 degrees, and negative differences for higher elevations as the reference for the desired *Hor* case is subtracted from the reference for the *Vert* case. It is then possible to add this difference to the models for maximum penetration loss from [1] that were plotted by the solid lines in Figs. 4 and 5. After applying a linear fit and a polynomial fit to the LOS and NLOS cases, respectively, the results obtained in this way are shown by the dashed lines in Figs. 4 and 5. These fits now represent the models for maximum penetration loss in a typical urban area adjusted for the case when the Rx antenna orientation is *Hor*. We can see that the decreasing trends of these fits are in good agreement with the experimental results for a single measurement site at *Building A*, represented by circles in Figs. 4 and 5. The differences between the corrected models and the experimental results can be explained by the fact that these models now represent maximum penetration loss for an urban area for the *Hor* orientation of the Rx antenna, whereas the particular penetration loss on the sixth floor of the office building may be slightly different in terms of absolute values of penetration loss, as well as its corresponding elevation trend.

In Fig. 6 we see a very good match between mean signal strength received on the flat open field and a classical two-ray simulation considering only the sum of powers of the direct signal and one ground reflection [9] as shown by the solid and dashed lines for *Vert* and *Hor* Rx antenna orientations, respectively. For these purposes, corresponding Rx and Tx antenna radiation patterns were measured in an anechoic chamber. To simplify the calculations, the absolute value of the reflection coefficient was kept constant at 0.4 for the whole range of elevation angles which is possibly the main source of errors that caused slight discrepancies between the simulated and experimental results. However, as the reference level may not be available for a particular Rx antenna, it can be successfully obtained simply by using the two-ray model.

Following the approach described above, a formula for the correction method can be derived. The corresponding differences between the reference levels for the required and the original Rx antenna radiation pattern can be written as:

$$\left(P_2\left(\alpha, F_{Rx2}\right) - P_1\left(\alpha, F_{Rx1}\right)\right) \quad (1)$$

where P_2 and P_1 are the reference levels for the required and the original Rx antenna radiation pattern which can be obtained, for example, on a flat open field or simulated by a two-ray model. In this case, the reference levels are functions of the elevation angle α and the radiation pattern of the Rx antenna, denoted here as F_{Rx}. As this difference of the reference levels needs to be added to penetration loss for the original Rx antennas radiation pattern, $PL_1(\alpha)$, the complete formula for the correction method is:

$$PL_2\left(\alpha\right) = PL_1\left(\alpha\right) + \left(P_2\left(\alpha, F_{Rx2}\right) - P_1\left(\alpha, F_{Rx1}\right)\right) \quad (2)$$

where $PL_2(\alpha)$ is the penetration loss model after the correction.

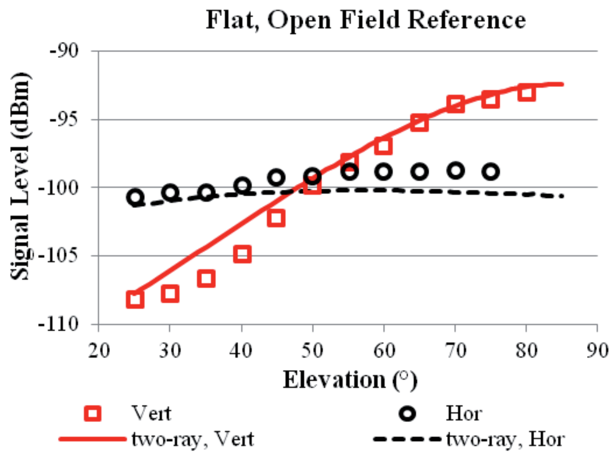

Fig. 6. Signal strength received during the reference measurements after the recalculation to the 20 km distance and corresponding two-ray models for both the *Vert* (solid line) and *Hor* (dashed line) orientations of the Rx antenna.

6. Conclusion

Based on experimental analysis, a correction method has been proposed to obtain elevation trends of penetration loss when different directional patterns of terminal antennas are considered in satellite-to-indoor scenarios.

It should be noted that (2) is only supposed to account for different radiation patterns of Rx antennas in terms of elevation trend of penetration loss as this trend depends significantly on the elevation trend of the corresponding reference level. As far as the absolute values of penetration loss are concerned, only tentative results are provided, as it is obvious that when the orientation of the Rx antenna is e.g. *Hor*, a stronger signal is received than for the *Vert* orientation due to the significant influence of windows resulting in lower penetration loss. This is clear in Figs. 4 and 5 where an approximately 5dB difference between the results given by the modified model and the experimental data can be found. To obtain precise results in terms of the absolute values of penetration loss, it can be recommended to perform penetration loss measurements with such terminal antennas as implemented by the satellite service of interest.

Although the method cannot provide absolutely precise universal results, it was shown that with a help of appropriate reference measurements or two-ray simulations, it is possible to subtly modify universal penetration loss models, e.g. [1], for different terminal antenna radiation patterns according to (2).

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About Authors ...

Milan KVICERA was born in 1983. He received the M.Sc. degree and the Ph.D. degree in Radio Electronics from the Czech Technical University in Prague, Czech Republic, in 2008 and 20012, respectively. He is currently a research worker in the Department of Electromagnetic Field at the Czech Technical University in Prague. His research interests are focused on radiowave propagation and satellite communication.

Pavel PECHAC received the M.Sc. degree and the Ph.D. degree in Radio Electronics from the Czech Technical University in Prague, Czech Republic, in 1993 and 1999, respectively. He is currently a Professor in the Department of Electromagnetic Field at the Czech Technical University in Prague. His research interests are in the field of radiowave propagation and wireless systems.