Research Article

Penetration Loss Measurement and Modeling for HAP Mobile Systems in Urban Environment

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The aim of this paper is to present the results of a measurement campaign focused on the evaluation of penetration loss into buildings in an urban area as a function of the elevation angle. An empirical model to predict penetration loss into buildings is developed based on measured data obtained using a remote-controlled airship. The impact on penetration loss of different buildings and user positions within the buildings is presented. The measured data are evaluated as a function of the elevation angle. The measurement campaign was carried out at 2.0 GHz and 3.5 GHz carrier frequencies, representing the frequency band for high altitude platform third-generation mobile systems and, potentially, next generation mobile systems, mobile WiMAX, for example, the new penetration loss model can be used for system performance simulations and coverage planning.

1. INTRODUCTION

Urban areas are covered by a variety of mobile wireless systems. One disadvantage of these systems is that they are vulnerable to disasters—either natural or manmade disasters such as terrorist attacks. To avoid this, terrestrial networks could potentially be complemented with high altitude platforms (HAPs) situated in the stratosphere at an altitude of about 20 km [1]. HAPs can be promptly deployed and easily change their locations. In addition, HAPs can be located in multiple deployments [2]. A great benefit of HAPs against terrestrial mobile networks is the absence of shadowing for high elevation angles. HAP stations located in the stratosphere offer noticeably lower free space loss than satellites. Another benefit when compared to satellites is the HAP position maintenance, with deviation of only 0.5 km [3]. Based on these facts, it is obvious that HAPs can be successfully used for urban outdoor coverage, but there is a question of whether HAP can also provide mobile or wireless services in general inside the buildings. Prospective mobile systems for HAPs seem to be the third-generation universal mobile telecommunication system (UMTS) operating in a frequency band of about 2.0 GHz, which is also allocated to HAPs [4], and the emerging mobile WiMAX systems [5] operating in the frequency band between 2–6 GHz.

The problems of penetration loss inside the buildings is a challenging area for HAP systems. Currently, an HAP elevation-based empirical model has been published to predict penetration loss into buildings at a frequency of 2.0 GHz for high elevation angles only [6, 7]. This model applies to scenarios where the coverage of urban/suburban areas is achieved at elevation angles ranging between 55–90 degrees and the HAP is positioned above the city center. In [8], the authors studied the impact of high elevation angles in the propagation mechanisms; it was shown that in urban coverage scenarios by HAPs most of the buildings have at least one of the walls and the rooftop directly illuminated.

The propagation prediction model for terrestrial systems is not defined as a function of the elevation angle [9, 10], which is the crucial parameter in the case of the HAP systems. The aim of this paper is to introduce a novel empirical model of penetration loss inside buildings in urban areas as a function of the elevation angle developed based on empirical data obtained from trials using a remote-controlled airship. The remote-controlled airship was used to measure penetration loss inside the buildings because of its perfect flight control possibilities (so that a whole range of elevation angles can be observed). The measurements were carried out in different types of buildings, at different positions, at different heights, and at frequencies of 2.0 GHz

FIGURE 1: Remote-controlled airship.

and 3.5 GHz. The ray tracing approach was not used here since the scenarios are very complicated to describe, and the aim of this paper is to develop a universal model applicable to urban areas rather than a detailed description of a single concrete situation.

The second section of this paper describes the measurement campaign, introduces details about the airship used, the developed payload, the antennas, and the considered scenarios. The third section deals with the processing of the measured data. A novel, universal empirical model is introduced as a function of the elevation angle. During the measurements, the airship was flying over a building in various directions in order to obtain results statistically independent on the azimuth angle and so the final model is not a function of the azimuth angle. The final section discusses the applicability of a universal model at frequencies of 2.0 and 3.5 GHz. In addition, this model can be successfully used for planning of prospective HAP mobile systems in S band.

2. MEASUREMENT CAMPAIGN

The measurement campaign was planned in different types of buildings and using selected scenarios in the center of the city of Prague. A statistical analysis of the collected data was then performed as a function of the elevation angle.

2.1. The remote-controlled airship

A remote-controlled airship [11] was utilized to carry the transmitters. This airship (see Figure 1) is designed to be low altitude, but for the trial we have presented here it is not necessary to reach the stratosphere. The key point is to obtain a sufficient range of elevation angles during the trial. This requirement excellently suits the remote-controlled airship, which offers the great benefit of flexible manoeuvrability. The main parameters of the airship used for the experiment are as follows:

  (i) length 9 m,
 (ii) maximum diameter 2.3 m,
(iii) payload 7 kg,
 (iv) hull filling helium.

The altitude is limited by visual contact with the operator at this stage of airship development. The altitude fluctuated by hundreds of metres during the experiments. Another significant benefit of the airship for the trial is the possibility it offers of fast and simple transportation.

During the measurements, the airship was flying over a building in various directions in order to obtain results statistically independent on the azimuth angle. Small movements of airship were compensated using a special stabilization platform to equalize inclinations caused by wind gusts.

2.2. Penetration loss measurement

The measurement campaign was planned and executed in the following way. The signal was transmitted from the airship and received inside a building. The special payload designed for this trial was mounted in the airship gondola. Continuous wave (CW) generators with an output power of 26 dBm and rectangular patch antennas were used to transmit the signal. The carrier frequencies were equal to 2.0 GHz and 3.5 GHz. These frequencies represent the central value of the carrier frequency for the third-generation mobile services UMTS and mobile WiMAX systems.

The receiver station was composed of a spectrum analyzer and a spiral broadband antenna (circular polarization) receiving the signal. The receiving antenna was situated 1.5 m above the floor and 2 m in front of a wall. The wide beamwidth antennas were utilized for this trial in order to minimize the effect of antenna radiation patterns on the interpretation of propagation effects. The possible error caused by antennas was lower than 3 dB. The position of the airship was recorded using the global positioning system (GPS), and the altitude of the airship was measured based on a barometer, which provides more accurate information concerning the altitude. The airship position determines the distance between the receiver station and the transmitter antennas. The penetration loss can then be calculated from the measured received signal level separating the impact of free space loss (FSL) and the measurement system (antenna gain, transmitted signal level, cable losses, etc.). The penetration loss is usually defined as the difference between the mean received signal strength in the surroundings of a building and the mean signal strength inside the building. In this paper, the penetration loss is defined as the additional path loss with respect to the FSL from the transmitter up to the building. Figure 2 presents an example of received signal level during the measurement at a frequency of 2.0 GHz in the ground floor of an office building during two flyovers of the airship above the building. Figure 3 illustrates the path loss in addition to FSL from the measured signal level. It is obvious from Figure 3 that the additional path loss lies in the range 10–60 dB depending on the airship's position (lower additional path loss was obtained for higher elevation angles and in a situation where the HAP directly illuminated the wall neighboring the receiver station). The very high additional path loss was measured for very low elevation angles, where there is a high probability that the signal is incoming across more walls inside the building, and other propagation effects such as shadowing and diffraction on surrounding buildings affect the final signal level.

2.3. Selected scenarios

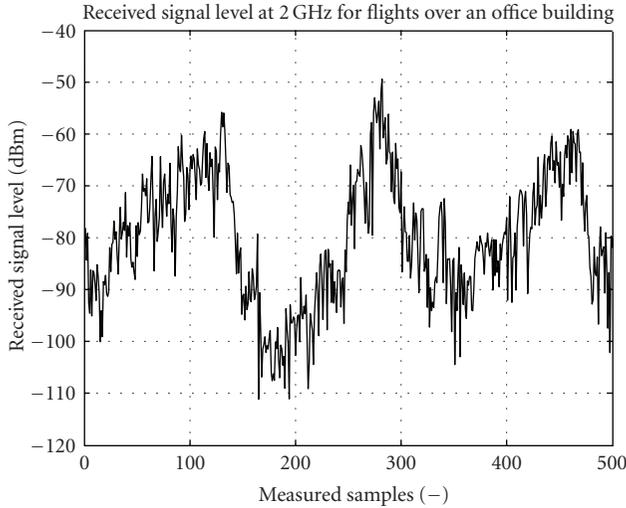Measurements were carried out in four different types of buildings:

Received signal level at 2 GHz for flights over an office building

FIGURE 2: An example of measured received signal level at 2.0 GHz.

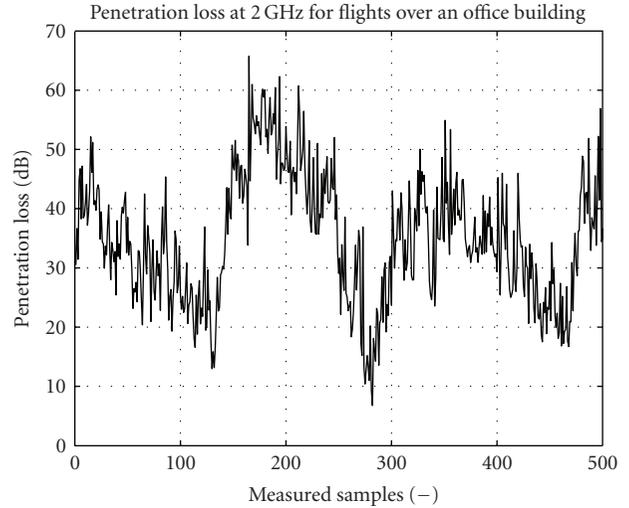Penetration loss at 2 GHz for flights over an office building

FIGURE 3: An example of extracted penetration loss into the ground floor of an office building.

(i) an office building,
(ii) an office building with storeys higher than surrounding buildings,
(iii) a brick building,
(iv) a prefab residential building.

In addition, the receiver station was situated in different typical positions inside the buildings. It will be shown that the resulting penetration loss is crucially dependent on the receiver position within the building. One of the selected positions of the receiver station was, for example, 2 m in front of the external wall, and another in the middle of the building and distant from directly illuminated external walls, and so forth. The storey number influences the penetration loss as well, but the impact of the floor level was not as crucial as the position of the receiving station within the floor. More than 50 000 measured samples were used for further processing. About 5 samples per second were collected during measurements.

3. PENETRATION LOSS

This section described the processing of the measurement results. Figure 4 shows an example of the processed data measured on the second floor of an office building at 2.0 GHz. The measured samples were averaged in 1 degree step of the elevation angle. A histogram of measured data for the elevation angle of 33 degrees is shown inside Figure 4. The receiver station was situated 2 metres in front of an external wall. The dependence of the penetration loss in decibels (dB) on the elevation angle (θ) can be found by the following function:

$$L_{PL}(\theta) = \sqrt{a - b(\theta - c)^2}, \tag{1}$$

where a, b, and c are empirical parameters.

The measurement was carried out in the same position three floors above the ground floor. All of these floors are below the rooftop level of surrounding buildings in the area.

Measured penetration loss inside an office building-2nd floor, $f = 2$ GHz
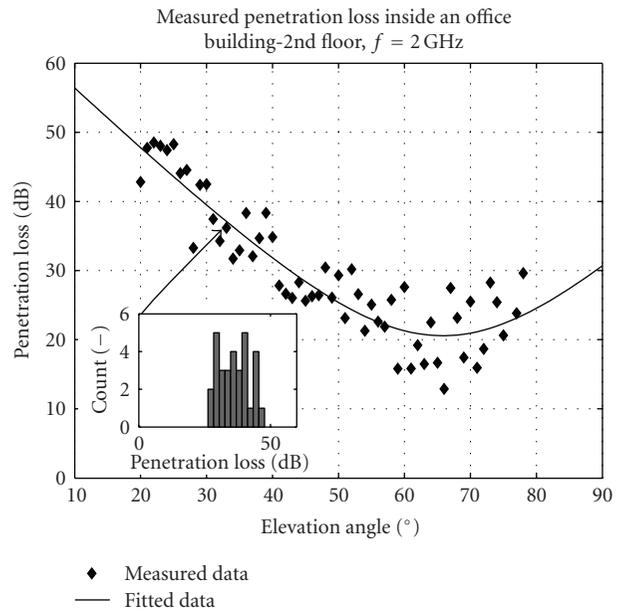

Measured data
Fitted data

FIGURE 4: Penetration loss as a function of the elevation angle on the second floor of an office building at 2.0 GHz.

The fitted measured data are presented in Figure 5. The very similar dependence of the penetration loss on the elevation angle is distinguishable from Figure 5.

Lower penetration loss was measured at the higher floors for some elevation angles. The multipath propagation plays an important role here, so that the lowest penetration loss for higher elevation angles was measured on the first floor. Nevertheless, differences in penetration loss were not as crucial in this measurement scenario. In order to obtain a universal model, all the data from this measurement scenario were processed together. The final dependence of the penetration loss on the elevation angle in the office building for storeys situated below the rooftop level of surrounding
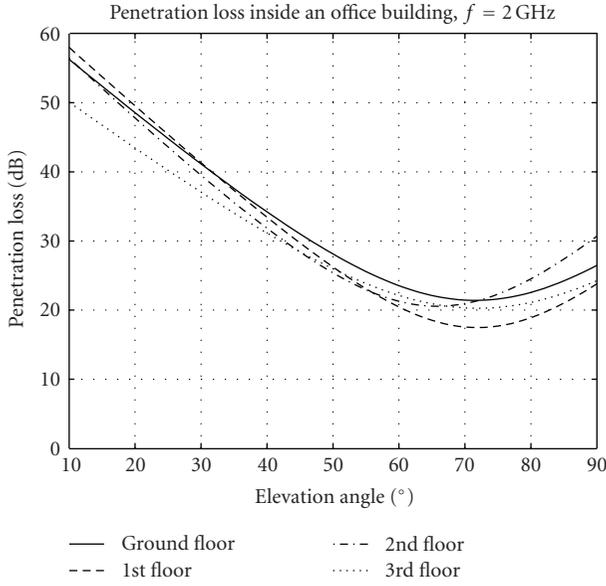
Penetration loss inside an office building, $f = 2$ GHz

——— Ground floor   ·—·— 2nd floor
– – – 1st floor   ·········· 3rd floor
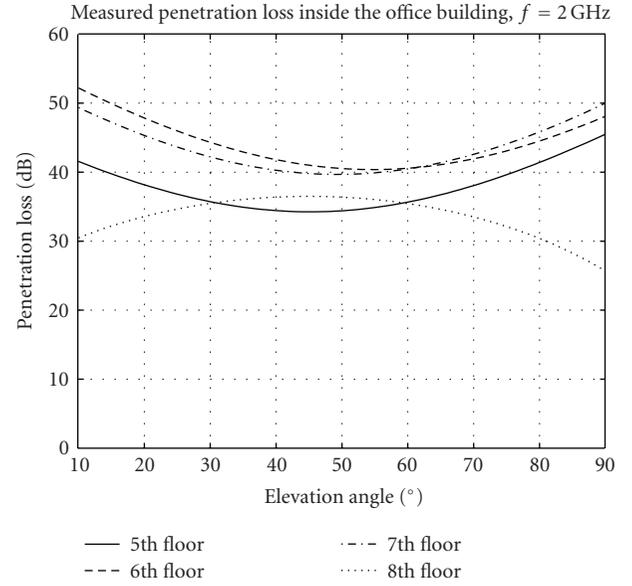
FIGURE 5: Penetration loss as a function of the elevation angle for range of floors in office building, $f = 2.0$ GHz.

Measured penetration loss inside an office building, $f = 2$ GHz

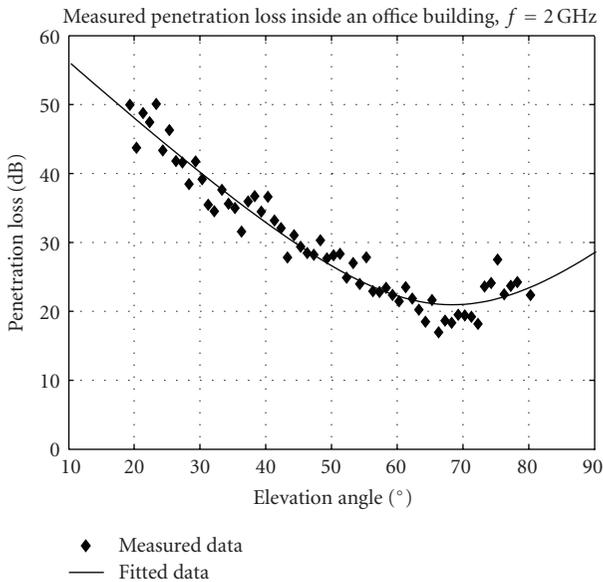♦   Measured data
——— Fitted data

FIGURE 6: Mean penetration loss as a function of the elevation angle in office building at 2.0 GHz.

buildings is depicted in Figure 6. The corresponding empirical parameters for model (1) are summarized in Table 1. This dependence can easily be used in system level simulation for the planning of a wireless system provided using HAP stations.

In the second scenario, the receiver station was situated in the same office building, but in the floors above the rooftop level of surrounding buildings. In this case, the effect of multipath propagation is not so dominant as the signal cannot reflect from neighboring buildings and so forth. The measured data were again successfully approximated by (1). The results for the four floors are shown in Figure 7.

Measured penetration loss inside the office building, $f = 2$ GHz

——— 5th floor   ·—·— 7th floor
– – – 6th floor   ·········· 8th floor

FIGURE 7: Penetration loss as a function of the elevation angle for a range of floors in an office building, $f = 2.0$ GHz.

In the 6th and 7th floors, a higher penetration loss was measured than in the 5th floor because the reflections from surrounding buildings can be still dominant for the 5th floor. The atypical behavior in the 8th floor is given by the position of the receiver station (directly under the flat roof of the building being studied), and by the fact that the 8th floor is a superstructure with smaller floor projection than the 7th floor so that the signal can reflect from the 7th floor roof rim.

In another scenario, the receiver station was situated in 7 floors of a prefab residential building. It was placed in the corridor in the middle of the building so that the rooms were symmetrically located around the receiver station, meaning that the receiver station was as far as possible from the external walls. For this measurement scenario, the penetration loss at 2.0 GHz was about 50 dB almost independently of the elevation angle. The mean measured value for the receiver station situated in the middle of the residential building is depicted in Figure 8. Figure 8 shows the impact of the type of building and the receiver position inside the building on the penetration loss.

The penetration loss into an older building built of bricks was also measured. The receiver station was situated 2 m from an external wall. The data measurement was divided to cover two situations. In the first, the external wall, in front of which the receiver station was located, was directly illuminated by the transmitter. In the second, the external wall was not directly illuminated, that is, the airship was situated on the opposite side of the building. The results of this study are presented in Figure 9. For the situation where the external wall was directly illuminated, the penetration loss decreased for higher elevation angles. On the other hand, the penetration loss increases for a decreasing angle of elevation in the case of external wall that was not directly illuminated. The empirical model for high elevation angles [6] assumes that the external wall is directly illuminated.
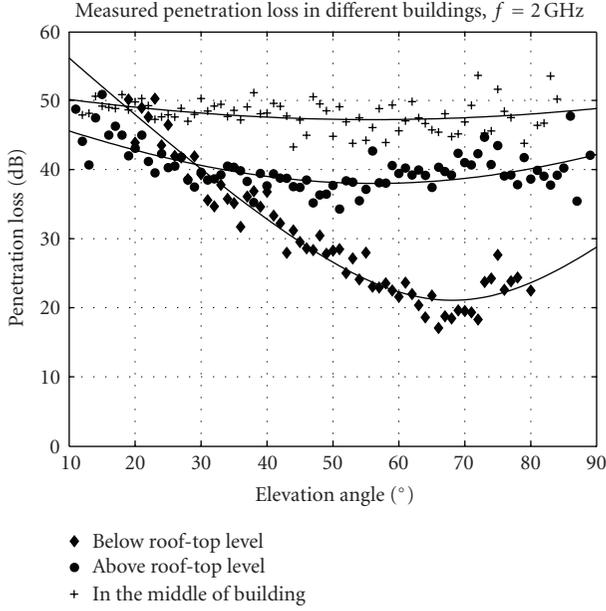
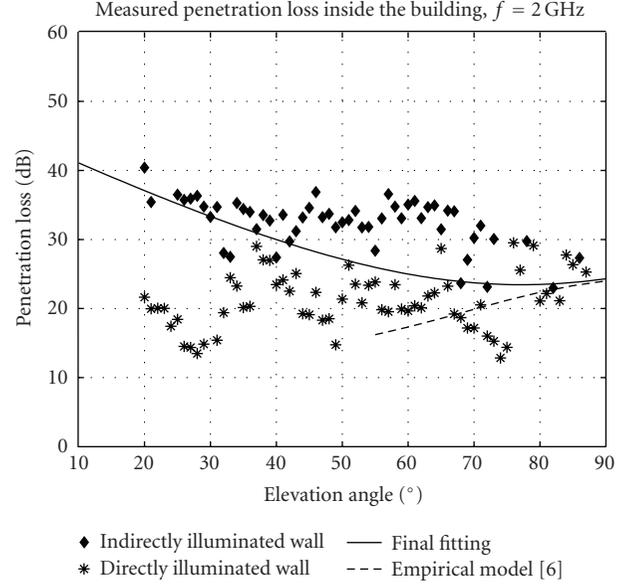FIGURE 8: Penetration loss as a function of the elevation angle for different scenarios, f = 2.0 GHz.

FIGURE 9: Penetration loss as a function of the elevation angle for different scenarios at 2.0 GHz.

This assumption significantly simplifies the calculation. In any event, there is a high level of agreement between the data measured in the case of a directly illuminated wall and the empirical model [6] for the high elevation angle, but this model does not consider the scenario of a wall that is not directly illuminated, which has a crucial impact on the final signal level. The final dependence for all data measured in the brick building has similar shape of curve to Figure 6, for example.

Finally, the impact of the carrier frequency was also studied. The trial was accomplished at frequencies of 2.0 GHz and 3.5 GHz. It is obvious that the penetration loss is higher for the higher frequencies. The behavior of the penetration loss dependence on an elevation angle was found to be almost the same at 2.0 and 3.5 GHz. The increase of penetration loss at 3.5 GHz compared to 2.0 GHz depends on the type of building. For an office building where metal frames are used, the penetration loss at 3.5 GHz is about 5.0 dB higher than for a frequency of 2.0 GHz. In the residential building, a difference in penetration loss of 2.3 dB was found. This trend concords with the measurements carried out for terrestrial systems [9].

Figure 10 illustrates the comparison of penetration losses as a function of the elevation angle for both frequencies and two types of buildings. For more clarity, only a fitted curve is shown for 2.0 GHz.

The aim of this work was to explore the behavior of penetration loss into the building as a function of the elevation angle in urban areas for HAP systems. The different behavior of penetration loss dependence on the elevation angle was observed in different scenarios. This means that for precise modeling model (1) should be calibrated according to the specific scenarios. Anyway, the final universal model as a function of the elevation angle was determined based on the
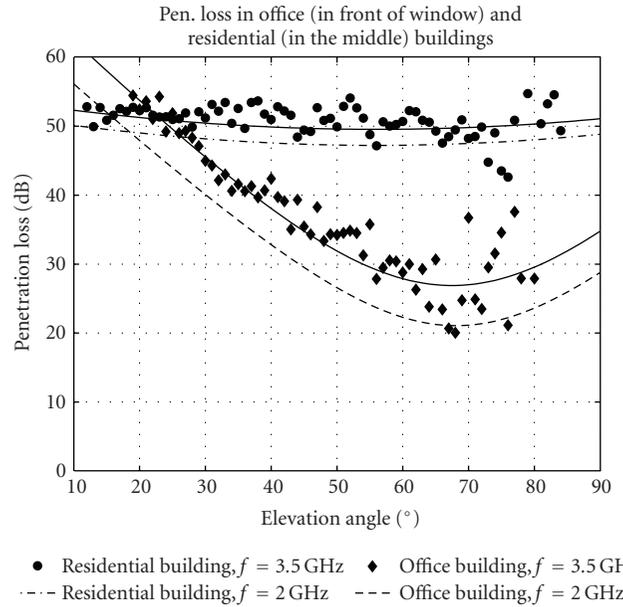

FIGURE 10: Comparison of penetration loss as a function of the elevation angle for different environments and carrier frequencies of 2.0 GHz and 3.5 GHz.

all measured data from the most common scenarios:

$$L_{PL}(\theta) = \begin{cases} \sqrt{506 + 0.512(\theta - 70.4)^2}, & f = 2.0 \text{ GHz}, \\ \sqrt{692 + 0.571(\theta - 70.2)^2}, & f = 3.5 \text{ GHz}. \end{cases} \quad (2)$$

The empirical parameters for (1) are summarized for different environments in Table 1 including the final model.

TABLE 1: Parameters of the penetration loss model for different environments and frequencies in an urban area.

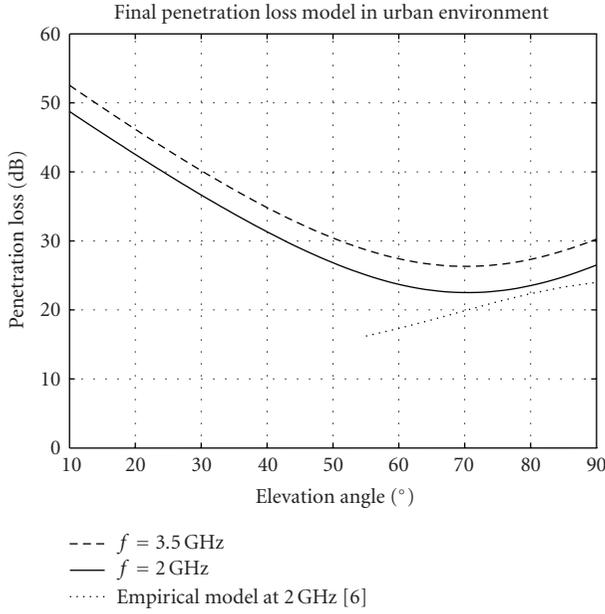|		Office building		Brick building	Final
		Below rooftop level	Above rooftop level		
	a	444	1443	550	506
2.0 GHz	b	−0.802	−0.296	−0.252	−0.512
	c	68.1	56.3	77.2	70.4
	a	723	1858	664	692
3.5 GHz	b	−0.960	−0.324	−0.251	−0.571
	c	67.5	54.8	79.0	70.2

FIGURE 11: Comparison of the new penetration loss model with an empirical model developed for high elevation angles in [6].

4. DISCUSSION

The penetration loss as a function of the elevation angle was measured using a remote-controlled airship. The campaign was motivated by a lack of penetration models for HAP systems with the exception of an empirical model for building penetration loss at 2.0 GHz for high elevation angles [6]. This model was developed for a scenario, where the 2 walls of a room with the receiver are directly illuminated. This condition is very hard to achieve, especially for lower elevation angles below 60 degrees. As shown above, the penetration loss closely depends on the position of the HAP and the receiver position within a building. Based on the measurement data, a model was developed for typical scenarios in urban areas. The penetration loss calculated using (2) is shown in Figure 11 and compared with the empirical model for high elevation angles [6]. Difference in penetration loss at 2.0 GHz and 3.5 GHz is about 3.6 dB, but it depends on building material. Generally, it could be from 1 to 6 dB [12].

The total propagation loss for HAP mobile systems when the mobile terminal is situated inside a building can be determined based on the free space loss and the empirical penetration loss model (2):

$$L = L_{FSL} + L_{PL}, \tag{3}$$

where L_{FSL} is the free space loss in dB, and L_{PL} is the penetration loss in dB defined in (2). The free space loss is equal to

$$L_{FSL} = 20 \log (d_{km}) + 20 \log (f_{GHz}) + 92.4, \tag{4}$$

where f_{GHz} is the carrier frequency in GHz, and d_{km} is the distance between a platform and a user in km.

For more realistic approach, an additional random log-normal fade margin should be added as a location variability. The standard deviation of the log-normal distribution for indoor environment is about 10 dB.

The multipath fading was eliminated thanks to the averaging of the narrowband measurement data. It is obvious that due to the measurement in real urban scenarios the multipath propagation effects and, especially in case of low elevation angles, the shadowing of surrounding buildings play an important role. We have not tried to distinguish the different components of the propagation phenomena since the goal was to model the average signal level for an indoor mobile station served from HAPs regardless the azimuth angle. This way the introduced penetration loss model can be, together with information such as the type of building and construction material used that collectively define a street model [13], successfully utilized for simple propagation predictions in urban areas for HAP scenarios. This model could be used for system level simulations of mobile services provided via HAPs.

5. CONCLUSION

An empirical propagation prediction model for calculation of penetration loss into the building as a function of the elevation angle is presented in this paper. The model was developed based on measured data obtained using a remote-controlled airship. It is shown that the penetration loss closely relates to the position of the user within the building as well as to the type of building. The measured data were approximated by a simple function given by three empirical parameters depending on the type of building and the frequency. The universal model was derived from the statistical processing of data obtained in different scenarios

based on measurements for four building types in the Czech Republic. Further calibration may be needed for the model to be applied in other specific scenarios. This model can be used for the radio network planning of mobile systems provided via high altitude platforms in the whole range of elevation angles.

ACKNOWLEDGMENT

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