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Characterization of Radio Wave Propagation Into Buildings at 1800 MHz

E. F. T. Martijn and M. H. A. J. Herben

***Abstract*—This paper presents results of signal strength measurements at 1800 MHz in four office buildings in The Hague, illuminated by an outdoor base station with an antenna above the rooftop. The objectives of these experiments are to study the behavior of the received signal strength at different floors of a building and to determine the main characteristics concerning cell coverage, namely, signal attenuation and variation within these buildings. It is shown that large fluctuations occur between average signal levels in line-of-sight (LOS) and non-LOS areas of multifloor buildings.**

***Index Terms*—1800 MHz, building height, building penetration loss, cellular radio, outdoor-to-indoor propagation, propagation loss measurement, UHF radio propagation.**

I. INTRODUCTION

IN personal wireless communication systems, a great deal of the radio coverage inside buildings is still being provided with the use of base stations (BS) located outside the buildings. In addition to the signal degradation on the outdoor radio channel, the mobile station (MS) of a user inside a building at ground floor will experience extra attenuation and the effects of indoor multipath propagation, which will deteriorate the signal-to-noise ratio even more. The building penetration loss (hereafter, simply called the building loss) is defined as the difference between the average signal strength in the local area around a building and the average signal strength on the ground floor of that building. The term *ground* floor used here is equivalent to the American *first* floor used by Rice in his original definition [1]. The *room loss* is defined as the difference between the average signal strength in the outdoor area adjacent to a room located on the ground floor of a building and the average signal strength in that room. The building loss is calculated by averaging all room losses on the ground floor. For radio planning purposes, the building or room loss factor can be used as an addition to the predicted signal loss for the surrounding local area. At higher floors, the received signal strength will be in general higher than at the ground floor. This is important for radio planning because it may cause higher interference levels at higher floors in global system for mobile communications (GSM) cells. In order to model this, the propagation loss at higher floors is often related to the building loss by means of a so called *floor height factor*.

To study the building loss, floor loss, and floor height factor, signal strength measurements were carried out in and around four office buildings (here denoted as B1 to B4, see Fig. 1) in The Hague. The experiment was carried out in a GSM1800 cell on the downlink channel. In this particular experiment, indoor measurements at ground level could be performed only in building B4. Therefore, the measurements inside the other three buildings were performed at the first floor and higher. The main building materials of B1, B2, and B3 are reinforced concrete and uncoated glass, while B4 is made of brick and uncoated glass.

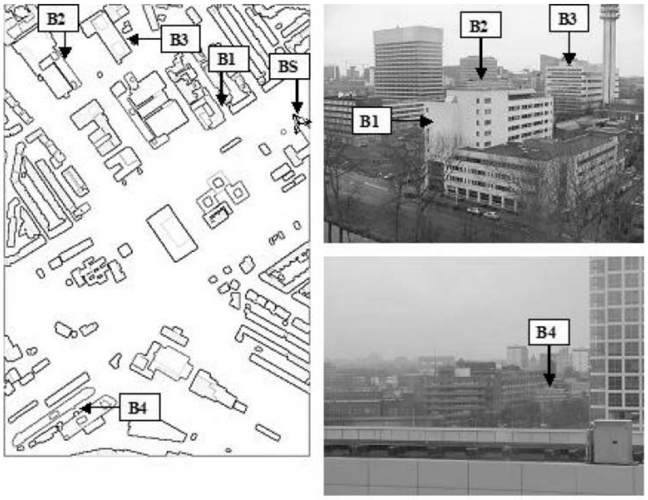

Fig. 1. Right: panoramic views of the four buildings seen from the BS. Left: a map of the site in The Hague.

In Section II, the experimental setup is presented and, in Section III, the main measured results are discussed. Section IV treats empirical modeling and the conclusions are given in Section V.

II. THE EXPERIMENT

The measurements were done in two cells of a tri-sector site with a radius of approximately 1 km (see Fig. 1). The transmit antenna (BS) was located above rooftop at 40 m height and the effective isotropic radiated power was 51 dBm. The Ericsson Test Mobile System (TEMS) Light GSM Measurement System (BS) was used to measure the normalized received signal power $RxLev$ given by

$$RxLev = \overline{P_r}(\text{dBm}) + 110 \quad [\text{dBm}]. \qquad (1)$$

The accuracy of the measured $RxLev$ is ± 1 dB. The measurement range of the received signal power P_r is from 0 dBm to -110 dBm, where -110 dBm is the noise floor. P_r is the average received signal power measured within one slow associated control channel (SACCH) multiframe of approximately 480 ms. In total approximately 100 samples are taken within one SACCH multiframe. This averaging means that the recorded signal strength cannot be used for small-scale signal characterization. The measurements were done by an individual walking in the office rooms (after working hours) and carrying the BS at a height of approximately 1.5 m. In every room, the total measurement time was

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TABLE I
OVERALL RESULTS PER FLOOR OF THE FOUR BUILDINGS

Building	Tx-Rx [m]	Height [m]	Outdoor *RxLev* [dBm]		Indoor *RxLev* [dBm]		Building loss [dB]	
			Mean	SD	Mean	SD	Mean	SD
B1 f1	130		53	2	40	2	13	2
B1 f3		14			41	3		
B1 f5					48	4		
B1 f7		26			49	6		
B2 f1	465		43	1	38	4	5	4
B2 f4					48	8		
B2 f7		27			51	6		
B3 f1	365		57	5	53	7	4	7
B3 f2					54	5		
B3 f5					58	9		
B3 f6					60	5		
B3 f7					59	5		
B3 f8					58	6		
B3 f9					58	9		
B3 f10					57	4		
B3 f12		41			53	6		
B4 f0	745	-	42	9	30	7	12	4

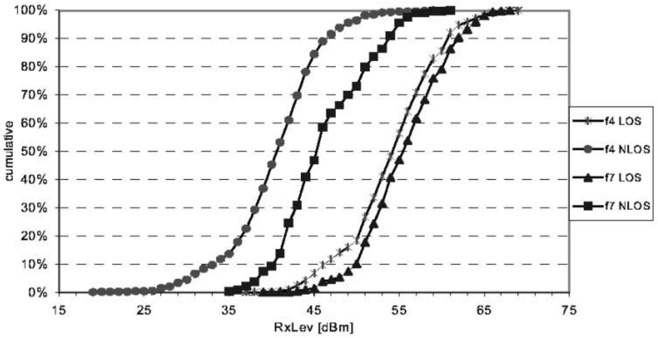

Fig. 2. Cumulative probability distribution for LOS and NLOS areas on floor 4 and floor 7 of building 2.

about one minute, giving approximately 120 $RxLev$ samples per room distributed over the accessible area within the room.

III. EXPERIMENTAL RESULTS

In Table I, the average $RxLev$ measured both inside the room and outside the building and the corresponding standard deviation (SD) are presented per floor. The average building loss and its SD given are calculated over the average values of all the room losses on the lowest floor of the buildings. The low losses for the buildings B2 and B3 are a result of a difference in outdoor path loss (e.g., due to diffraction at buiding B1) between the first floor and street level. An indoor measurement at the ground floor would have given a more accurate building loss. For building B1, which is located just in front of the transmit antenna, the difference between measurements at street level and the first floor due to the antenna radiation pattern is less than 1 dB. Also the large scale effect of other structures or vegetation is expected to be the same for the first and third floor of B1. Therefore, we can assume that the building loss measured here is close to the loss that would have been measured indoor on the ground floor. The results presented in Table I are in accordance with the those from other studies done at 1800 MHz [2], [4].

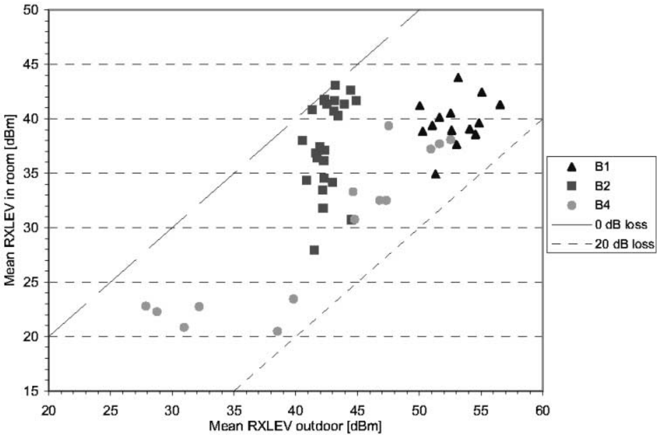

Fig. 3. Mean $RxLev$ values measured in rooms on the first floor (ground floor for building B4) and values measured outdoor in the street adjacent to the room.

In Table I, a larger SD of the received power can be noticed for most floors when compared to the outdoor SD. This is because in reality there is a difference in wave propagation for different parts of a building, for instance one or two sides could be in line-of-sight (LOS) with the transmitter while the other sides are in non-LOS (NLOS). In four cases, namely on the fifth and seventh floors in building B1 and on the fourth and seventh floors in building B2, a significant difference was measured between the average signal strength in LOS and NLOS areas. This is illustrated in Fig. 2 with the cumulative distribution functions of samples taken in LOS and NLOS areas of the fourth and seventh floors of building B2.

This effect is less noticeable on lower floors. On the other hand, a certain dependence can be found between the mean $RxLev$ measured in a room at the lowest floor and the mean $RxLev$ measured in the streets adjacent to the corresponding room. The calculated correlation coefficient from the results shown in Fig. 3 equals 0.7. This may indicate that at lower floors the signal is mainly determined by outdoor propagation effects combined with the penetration losses through the local external wall, while at higher floors, the received signal strength is mainly influenced by the illumination angle and internal structure of the floor.

In practice, it is not possible to calculate or predict a penetration loss at higher floor levels using an outdoor reference. The floor-height factor can be used to give an estimate of the received signal level at higher floors. The floor-height factor (or floor-height gain) is defined as the difference between the average $RxLev$s of two consecutive floors. Since all the buildings considered have approximately the same floor height, the factor is given in decibels per floor. In Fig. 4, the difference between the mean $RxLev$ measured indoor and the mean $RxLev$ measured outdoor is plotted. For the buildings B1, B2, and B3 there is a positive trend for increasing floor level, for building B3 the trend becomes negative above the seventh floor. Linear regression using the least square method gives the slope coefficients shown in Table II. These figures are in accordance with results found in other studies [3]–[5]. The coefficient of determination R^2 as defined in [6], indicates a good fit to the data.

There are, however, some aspects to be considered. First, the difference in mean $RxLev$ between floors 3, 5, and 7 in B1 can be explained as an effect caused by the radiation pattern of the transmitting antenna. Second, the antenna radiation pattern, which has an electrical downtilt of 6°, causes a decrease in signal strength

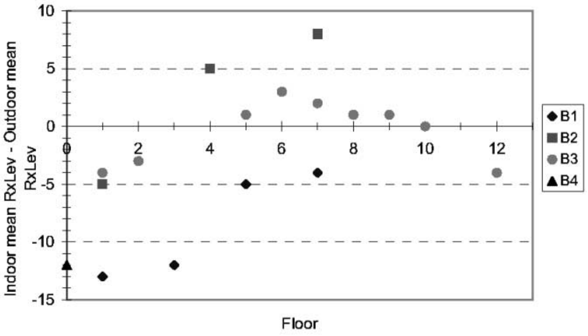

Fig. 4. Difference between the indoor mean $RxLev$ and outdoor mean $RxLev$ for all floors of the four buildings.

TABLE II
ESTIMATED FLOOR HEIGHT FACTORS FOR BUILDING B1–3 UP TO FLOOR 6 AND FOR B3 FOR FLOOR 7 THROUGH 12

Building	Floor height factor (dB/floor)	R^2
B1	1.7	0.9
B2	2.2	0.9
B3<7	1.4	1.0
B3>6	-1.1	0.9

when moving upwards in the buildings B2 and B3. Nevertheless, an increase in signal strength is noticed. This can be regarded as an effect resulting from propagation in the surrounding environment, the urban clutter. In an urban area, the lower floors are affected by the “depth” of their position in the area. The waves arriving at lower floors encounter more diffraction, reflection, and scattering than waves arriving at the higher floors. After the seventh floor, we notice a negative decibel/floor value. This is probably the point where the negative coefficient caused by the antenna radiation pattern takes over from the positive coefficient caused by departure from the clutter. Also, as shown earlier, there are substantial differences in the average received signal strength when comparing rooms at LOS and NLOS on higher floors. Therefore, even though it can be said that, in general, there is an increase in the average signal strength when the receiver is moved upwards in a building (up to floor seven) in reality this increase is not linear and can be attributed to different causes.

At the beginning of this section some cumulative distributions of measured samples were presented. Normally, these samples would contain both small scale fading effects as well as large-scale fading effects, however, as shown earlier the small scale characteristics are averaged out for a great deal by the measurement equipment. Therefore, it can be expected that the large-scale signal fluctuations will dominate the statistical nature of these distributions. It has been well established in literature that the logarithm of local mean is normally distributed in outdoor, indoor, and outdoor to indoor propagation as well [1], [4]. For the verification of this distribution the groups of data were too small to do a chi-square analysis. Therefore, a graphical test making use of rank-ordered statistics was chosen to check whether the data is normally distributed or not [7], [9]. In this test, the percentage of exceedance is converted to a parameter $\mathrm{Q_i}$ in such a way that if the random variable is normally distributed the new cumulative distribution function is a straight line with the mean value of the random variable at $\mathrm{Q_i} = 0$. The slope of the line is related to the variance of the random variable. Fig. 5 shows the measured distribution functions for four floors in building B1 together with reference curves corresponding to a normal distribution with the same mean value and variance as the measurements. For the first and third floor, a relatively good fit can be noticed indicating a normal distribution. However, in the case of floors 5 and 7, the measured samples lie scattered around the straight lines. Fig. 6 shows that for building B2 there is no close fit to the normal distribution. It seems that the data points are divided in two subgroups for each of the three floors. The division of the higher floors into LOS and NLOS areas was already noticed in the previous sections. However, the differences in mean $RxLev$ between LOS and NLOS areas are less pronounced at lower floors.

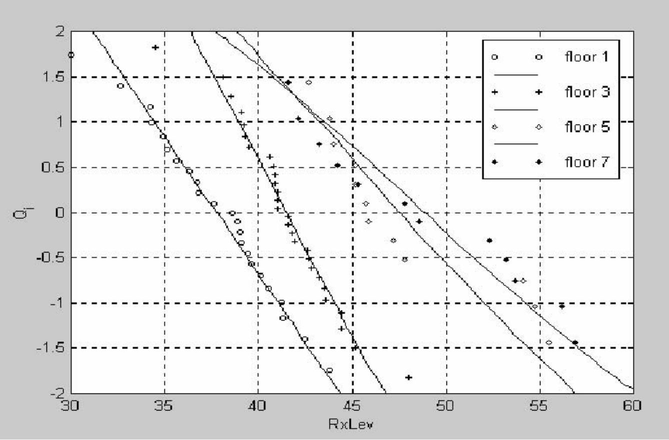

Fig. 5. Cumulative probability distribution of Mean $RxLev$ for four floors in building B1.

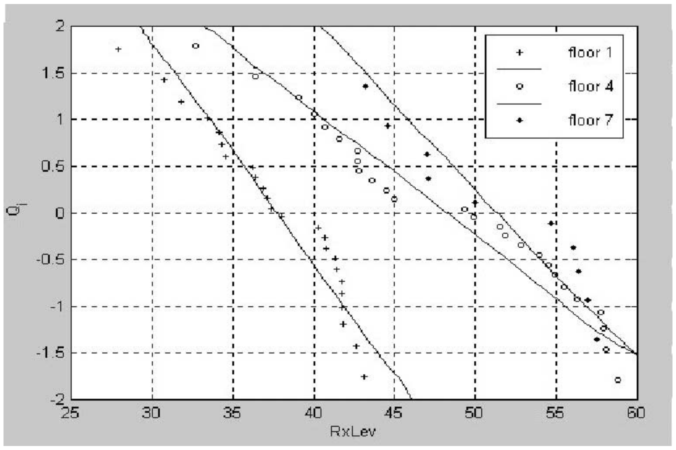

Fig. 6. Cumulative probability distribution of Mean $RxLev$ for three floors in building B2.

IV. MODELING

Most of the models developed for the prediction of path loss in the case of radiowave propagation into buildings have used the technique proposed by Rice [1]. First, the median signal level in the neighboring streets is predicted and then the building loss is added as a factor. Our objective was to test the well known model of Hata [8] and the above mentioned technique. Despite the restrictions given for this model, it has been extensively used with success. The calculated path loss is defined as

$$L_b = P_t + G_t - L_t - RxLev + 110 \quad \text{[dBm]} \qquad (2)$$

with the receiver antenna gain G_r and receiver cable losses L_r set to 0 dB. To indicate the accuracy of the model the predic-

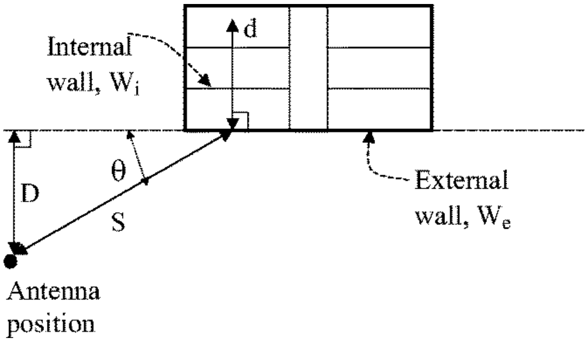

Fig. 7. Top view of the illumination of a building according to (5)–(7).

tion error is calculated. The prediction error is the difference between the calculated path loss and the measured path loss. The root mean square of this error is

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\hat{L}_{\text{predicted}} - L_{\text{measured}}\right)^2} \quad [\text{dB}] \tag{3}$$

where n is the total number of rooms considered. The data consisted of the average $RxLev$ calculated outside and inside a total of 53 rooms at the first floor level (ground floor for building B4) and the average $RxLev$ calculated inside 90 rooms for the higher floor levels. In the case of building B1, corrections were made to the data to account for the effect of the radiation pattern of the transmit antenna. We calculated the root mean square error (RMSE) for the modified Hata model given by

$$L_{\text{hata\_penetration}} = 29.39 + 34.41\log(d) + w_1 + w_2 + w_3[\text{dB}] \tag{4}$$

at a frequency of 1800 MHz and receiver height equal to 1.5 m. The parameter w_1 is a correction factor used to fit the equation to the outdoor measurements, w_2 accounts for the penetration loss at ground floor and w_3 represents a constant floor height factor for the first floor. First, the minimum RMSE found for the outdoor path loss was 5 dB with $w_1 = -6$ dB $(w_2 = w_3 = 0\ \text{dB})$. Then, by varying only w_2 and keeping $w_1 = -6$ dB and $w_3 = 2$ dB a minimum RMSE of 5 dB was found with a penetration loss $w_2 = 12$ dB. Finally, the path loss was estimated for all rooms at all measured floors with the same w_1, w_2 and $w_3 = 2$ dB/floor. The lowest error in this case was 8 dB, indicating a further increase in prediction inaccuracy when considering only d and constant correction factors.

Another approach is to include parameters such as the angle of illumination and building properties that may influence the building loss. Properties such as the floor area, number of rooms and number of penetrated internal walls [3], [4], [10]. From this category the COST231 model for building penetration was tested against our measurements. With the exception of only two cases, all floors of the buildings have at least one side that has LOS, therefore, only the COST231 LOS version is considered here. At 1800 MHz the model is

$$\begin{aligned} L_{\text{COST\_LOS}} = {} & 37.5 + 20\log(S+d) + W_e + WG_e \\ & \cdot \left(1 - \frac{D}{S}\right)^2 + \max(\Gamma_1, \Gamma_2) \quad [\text{dBm}] \end{aligned} \tag{5}$$

where

$$\Gamma_1 = W_i \cdot p \tag{6}$$

$$\Gamma_2 = \alpha \cdot (d-2) \cdot \left(1 - \frac{D}{S}\right)^2. \tag{7}$$

The angle of incidence θ and the distances D, S and d are illustrated in Fig. 7.

W_e is the loss in the externally illuminated wall at an angle $\theta = 90°$, WG_e is the additional loss in the external wall when $\theta = 0°$. W_i is the loss in the internal walls and p is the number of penetrated walls. The factor α is the transmission loss inside the building given in decibels per meter . First, the best fit of the model to the data is calculated keeping the wall losses within the boundaries as recommended by COST. These are: W_e: 4–10 dB, W_i: 4–10 dB and WG_e: 20 dB. A minimum RMSE of 8 dB is reached with $W_e = 10\ \text{dB}$; $W_i = 6\ \text{dB}$; $WG_e = 20\ \text{dB}$ and $\alpha = 3\ \text{dB/m}$. Next, also the wall loss parameters were varied beyond the recommended boundaries. The calculated minimum RMSE was 6 dB with $W_e = 20\ \text{dB}$; $W_i = 2\ \text{dB}$; $WG_e = 10\ \text{dB}$ and $\alpha = 1.1\ \text{dB/m}$. The error calculated here for higher floors is smaller than the RMSE calculated for all floors with the Hata model.

V. CONCLUSION

In this paper, measurement results taken in office buildings situated in The Hague have been presented. These measurements show that large fluctuations can be observed between signal levels received in different parts of a building. While on the lower floors the large-scale fluctuations (in dBm) follow a normal distribution, significant differences have been observed at higher floors between LOS and NLOS areas. Therefore, the relationship between the floor height and extra gain with respect to the ground floor level is not linear and depends on factors such as the radiation pattern of the BS antenna and the local urban clutter. A comparison of the Hata model and COST231 model shows that slight improvements can be achieved when considering the illumination and layout of multifloor buildings.

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