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New upper and lower bounds line of sight path loss model for mobile propagation in buildings

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Abstract

This paper proposes a method to predict line-of-sight (LOS) path loss in buildings. We performed measurements in two different types of buildings at a frequency of 1.8 GHz and propose a new path loss model with its upper and lower bounds. The upper and lower bounds depend on max and min values of sampled path loss data. This makes our model limit path loss within the boundary lines. The model includes time-variant effects from the object movement from people in the building and cars in parking areas. These influence reasonably on wave propagation. The results have shown that the proposed model will be useful for the design of the indoor wireless communication systems.

Keywords: Indoor LOS path loss; Upper and lower bounds; Time variant effects

1. Introduction

Indoor wireless communication is widely used in different types of buildings therefore it needs appropriate network planning to provide the best services. This makes it necessary to have a way to predict the propagation in indoor environments in order to determine the best location of the base stations to provide efficient services. Furthermore, it can be employed to limit the received signal level in order to comply with public health regulations.

For indoor communication system design, the line-of-sight (LOS) path loss characteristics have to be clarified because the transmitter is generally installed in sections of a corridor. Therefore, a path loss model for LOS is still needed. Previously, there were three different approaches, both LOS and non-line-of-sight (NLOS), for the prediction of the field strength inside buildings. Firstly, there are empirical models, based on the regression of measurement data [1,2]. Secondly, deterministic models like ray tracing are employed [3–5]. Finally, there are semi-deterministic models based on the regression of measurement data and/or some of the uniform theory of diffraction (UTD) [6]. These models do not include time-variant effects from object movement such as from people in the building, cars in parking areas and doors or windows opening. Their influences on wave propagation are very high, because the dimensions of the windows, doors, people or cars are nearly equal to those of time-invariant walls and columns. Compared with the influences in outdoor environments, time-variant effects are often negligible because their dimensions are small compared with those of time-invariant buildings.

In deterministic models, it is impossible to include these time-variant effects in the data base, including with the ignorance of the wave scattering. Although the authors of [7] have shown that the human body affects the indoor propagation. They have, however, neither shown the building data base in details nor considered the nature of people in the building.

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To solve this problem, we propose a new LOS model that takes upper and lower bounds into account for consideration of the time-variant effects, including breakpoint distance the distance from the transmitter to a point where wave propagation is still LOS and propagation beyond the distance is highly attenuated. The spread of upper and lower bounds depend on the maximum and minimum values of the path loss data. Therefore, the model would provide accurate prediction within its boundaries, which still respected with the least square error. Although upper- and lower-bound estimations have been performed for outdoor communications in UHF band [8] and microwave band [9], they cannot be applied for indoor communications because of the different environment. In our model, we also consider the breakpoint distance to separate the propagation region into two zones for our calculation. We found that the breakpoint distance depends on the ceiling height only, but not on the corridor width, because there are only three dominant reflections: the first from the direct path, the second one coming from the floor, and the third one from the ceiling. However, the reflection from side walls in the studied buildings is affected insignificantly since it mostly penetrates through the glass and porous materials.

2. Measurement procedure and location

2.1. Measurement procedure

The equipment for propagation measurement consisted of a fixed transmitter and a portable spectrum. We set a resolution bandwidth of 300 kHz with a span of 10 MHz at a frequency of 1.8 GHz. This equipment with the small bandwidth could be employed to assess 200 kHz bandwidth of the typical GSM channel. The fixed transmitter consisted of a signal generator (with 18 dBm power output) and $\lambda/4$ omni-directional antenna with $10 \times 10\,\text{cm}^2$ ground plane (2.2 dBi gain). We also used the same type antenna for signal strength measurement via recorder as shown in Fig. 1.

To receive propagation data for modelling, the samples of the actual field at a frequency of 1.8 GHz were acquired by moving the mobile unit along LOS corridors in the building areas. To detect the fast fading effect, we took the sample data every distance of $\lambda/4$ since the standing waves repeat every $\lambda/2$. The velocity of the mobile unit is about 8.3 cm/s, then the effective sampling rate is approximately two samples/s at the frequency of 1.8 GHz.

To characterize the time-variant objects along the LOS way, we selected days and times with high traffic in the buildings for recording. That is at midday for a school building and a Saturday afternoon in the car park inside the shopping mall building.

2.2. Measurement location

The stationary transmitter was placed at the end of a corridor of the building to determine the effects of wave propagation. For measurement, the mobile receiver was moved thoroughly away from the transmitter along the LOS corridors in the building. Two different buildings were considered for modelling as follows:

1. *The concrete school building*: The concrete building of the Faculty of Engineering, Mahidol University was built in 1993. It consists of five floors with dimensions of $100 \times 270\,\text{m}^2$ as shown in Fig. 2. The construction of the building is concrete block, plaster board, and mirror walls. The floor to ceiling height is 3.5 m, and the light plasterboard suspended ceiling, covering all air conditioning and service ducts, is 2.6 m above the floor. The material of walls in corridor are 60 of concrete block. The building capacity is an average 490 people per floor.
2. *The car park inside the shopping mall building*: The parking lot in the shopping mall building of Future Park Center was completed in 1990. It consists of eight floors with dimensions of $130 \times 260\,\text{m}^2$ as shown in Fig. 3. The construction of the car park building is of concrete column and flat ceiling. The floor to ceiling height is 2.25 m. The ceilings are mostly hard concrete. The building capacity is about 300 cars per floor.

3. Single regression line models

The mean LOS path loss is a function of distance to the power n as below:

$$L_{\text{LOS}} = L(d_0) + 10\log_{10}\left(\frac{d}{d_0}\right)^n, \tag{1}$$

where L_{LOS} is the path loss at distance d from the transmitter, and $L(d_0)$ is the path loss at the reference distance, d_0 from the transmitter. Because of the first Fresnel zone region, propagation loss as a function of distance has two distinct regions as follows:

$$PL_{\text{bp}}(d) = \begin{cases} L_{\text{bp},1} + 10\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right)^{n_1} & \text{for } d \leqslant d_{\text{bp}}, \\ L_{\text{bp},2} + 10\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right)^{n_2} & \text{for } d > d_{\text{bp}}, \end{cases} \tag{2}$$

where d_{bp} is the distance at the end of the first region from the transmitter, defined as breakpoint distance. The $L_{\text{bp},1}$ and $L_{\text{bp},2}$ are path loss at breakpoint distance on either side of the breakpoint, and n_1 and n_2 are the path-loss exponents on the first region and the second region, respectively.

The breakpoint distance d_{bp}, for the wavelength λ, can be calculated by $Z_{\text{f}} \approx \sqrt{\lambda d_{\text{bp}}}$ [6] where Z_{f} is the diameter of the first Fresnel zone. However, for the wide corridor, which has a width much more than ceiling height, we found that the first Fresnel zone is affected by only the reflection from the ceiling, and the reflections from side walls can be ignored.

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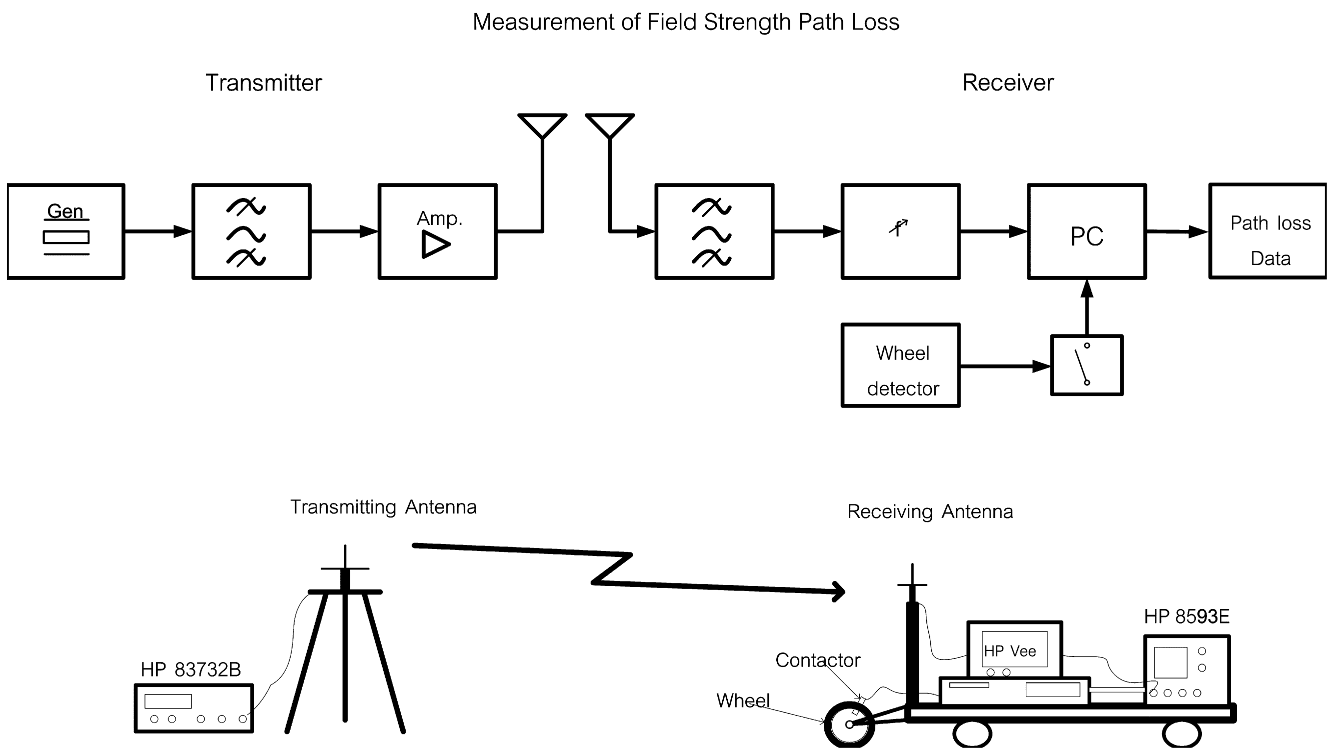

Fig. 1. Measurement system.

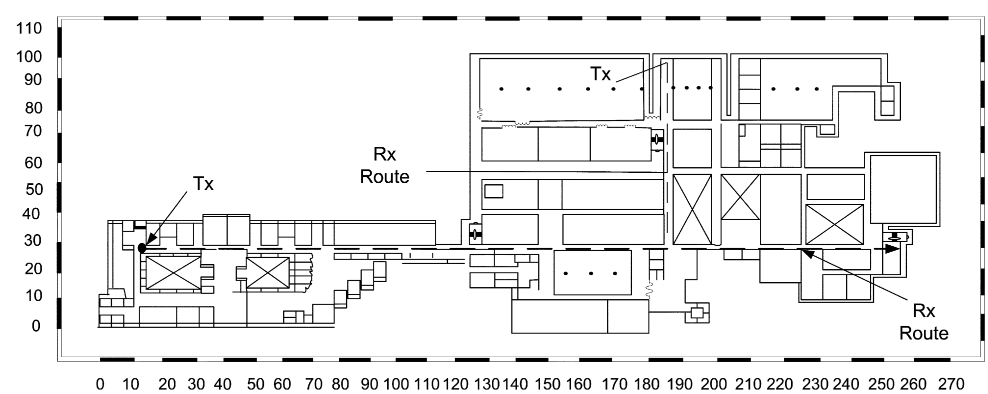

Fig. 2. Measurement location of the concrete school building.

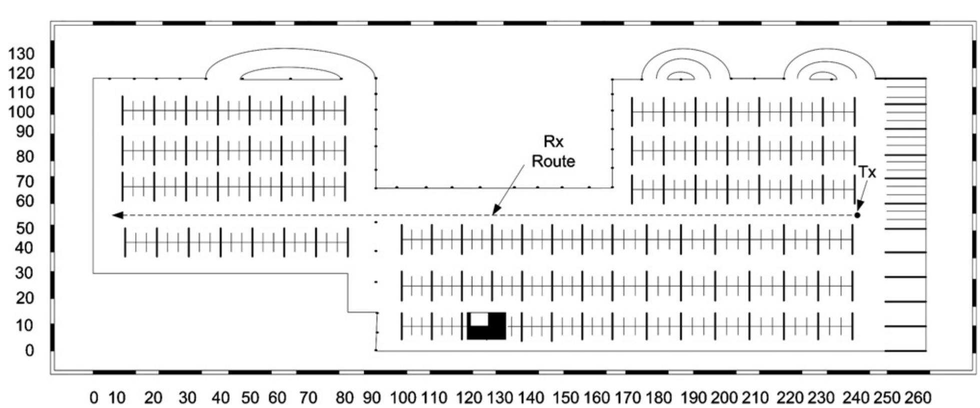

Fig. 3. Measurement location of the car park inside the shopping mall building.

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Therefore, the breakpoint distance can be calculated using the three-ray model [10] as illustrated in Fig. 4 by

$$d_{bp} = 4(H - h_2)h_2/\lambda, \quad (3)$$

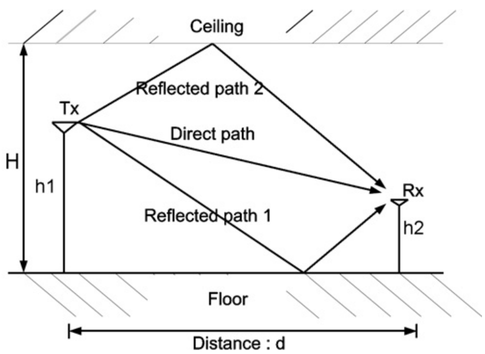

Fig. 4. The three-ray model.

where H and h_2 are the ceiling height and receiving antenna height, respectively. For a ceiling height of 3 m and a receiving antenna height of 1.5 m, the d_{bp} is at distance of 54 m from the transmitter for the concrete school building as shown in Fig. 5. The path loss-distance characteristics of the second floor (no people moving) and first floor (with people moving) of concrete school building are shown in Fig. 5(a) and (b), respectively. We found that the breakpoint distance in Fig. 5(a) was the same as in Fig. 5(b), although the number of walls on both floors is different. This confirms that there are only three dominant ray paths travelling from the transmitter to the receiver. Fig. 5(b) shows that a lot of fast fading and path loss exponents changed when people moved between the transmitter and the receiver. It is observed that there is disconnection in the scattering plots. This would be caused by the building gap situated only on the first floor. Fig. 6 shows the scatter plot and regression line of the path

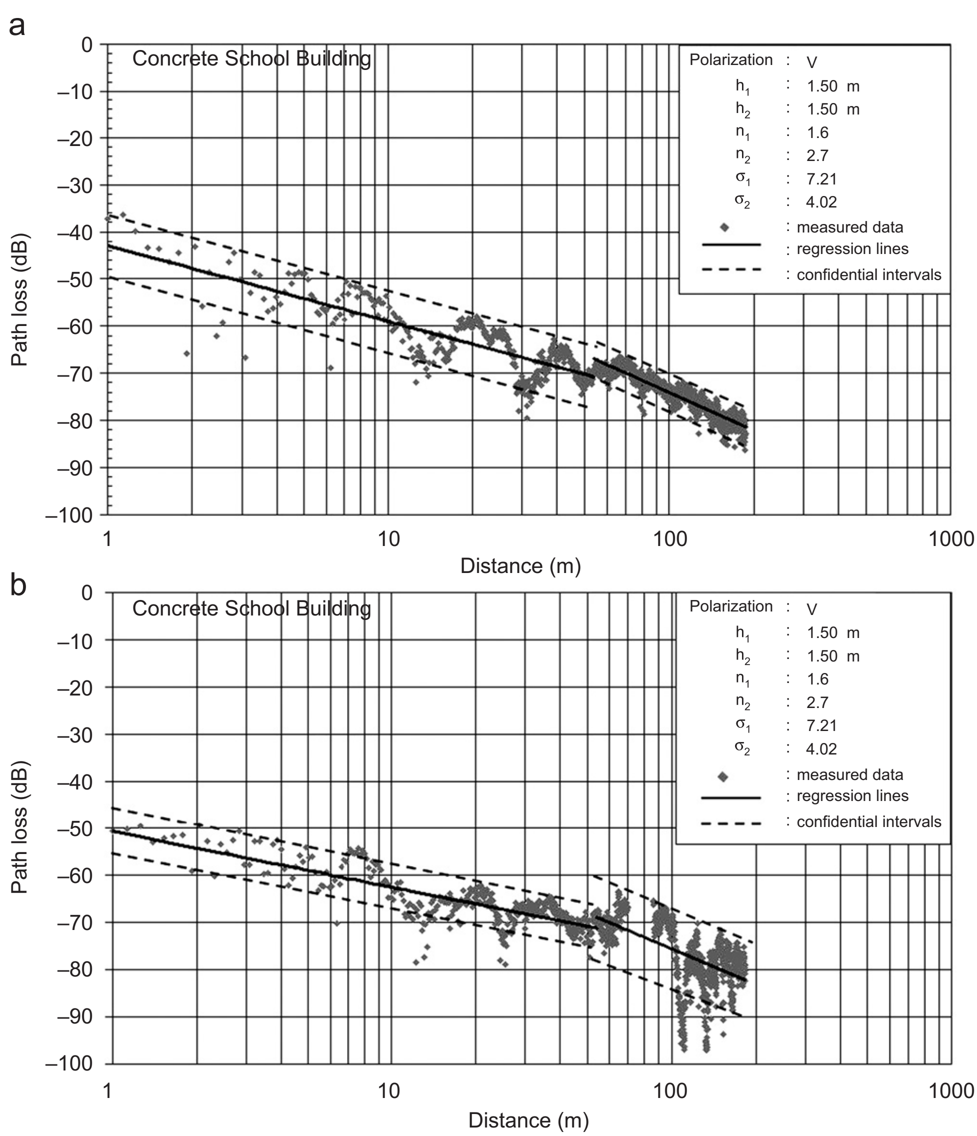

Fig. 5. The path loss measurement and the regression lines in the concrete school building. (a) Second floor (no people moving) (b) First floor (with people moving).

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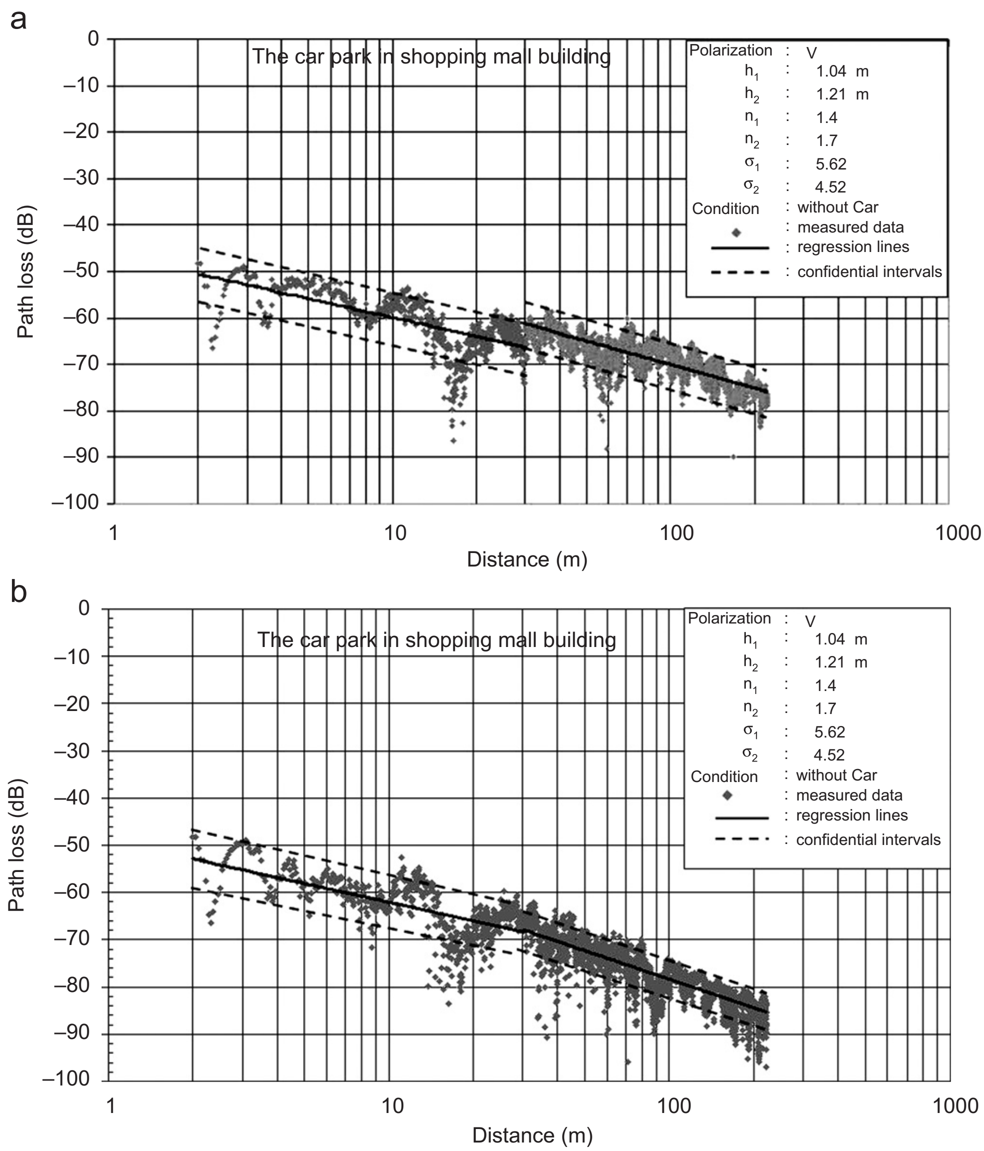

Fig. 6. The path loss measurement and the regression lines in the car park inside the shopping mall building. (a) no cars moving (b) with cars moving.

loss-distance characteristics in the car park inside the shopping mall building. We also found that a lot of fast fading and path loss exponents changed when cars moved between the transmitter and the receiver. The dotted lines in the figures show the regression lines before and after breakpoint distance. Fig. 7 shows the time variant the path loss fading at distance of 30 and 102 m from the transmitter. We found small differences in fading between people and cars moving at the breakpoint distance, and larger fading at distance far from the breakpoint distance.

The estimation for the path loss exponent n and the correlation coefficients R^2 are summarized in Table 1 , where subscripts 1 and 2 denote the case for before and after the breakpoint distance, respectively.

Typically, the outdoor path loss exponent n_1 is 2.0 and n_2 is 4.0 [9]. However, we found that our indoor path loss exponents n_1 and n_2 are less than the typical values. This is because of the influence of the effect of the wave-guiding in the first Fresnel zone region. We employed the correlation coefficient, R^2, as the index to show how good the regression is. The value of R^2 for regression with people or cars was always less than those without either people or cars. There must be fast fading from people or cars to shadow the wave travelling to the receiver, consequently, making the path loss data scattering from the regression line. The confident intervals, as illustrated in Figs. 5 and 6, provide prediction accuracy within a certain range of standard deviation. However, the fast fading data were still out of the line intervals.

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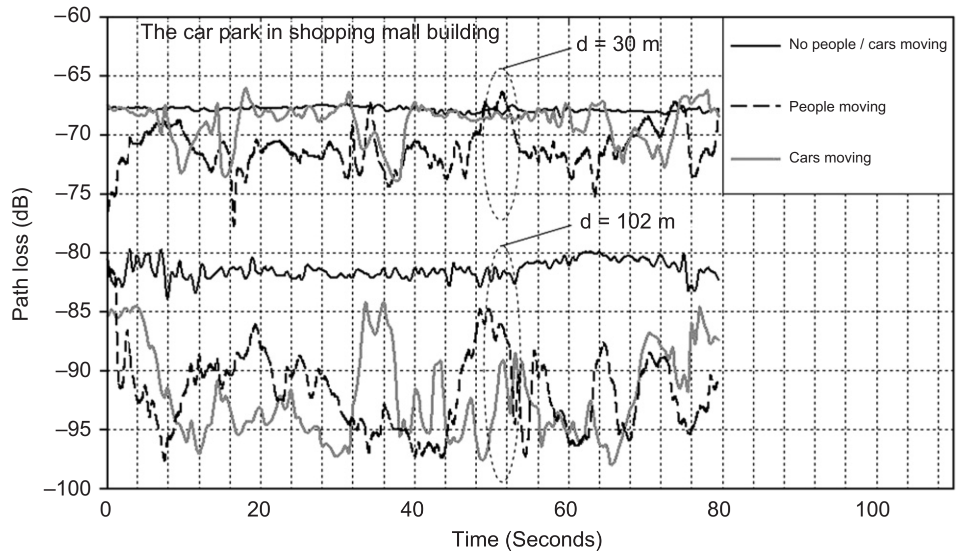

Fig. 7. The fading path loss measurement.

Table 1. Estimation of path loss exponents and correlation coefficients

Building type	No time-variant effect				With time-variant effect			
	n_1	n_2	R_1^2	R_2^2	n_1	n_2	R_1^2	R_2^2
Concrete school								
First floor	1.3	2.1	0.71	0.78	1.2	2.5	0.66	0.28
Second floor	1.6	2.7	0.68	0.86	–	–	–	–
Car park	1.4	1.7	0.43	0.68	1.3	2.0	0.4	0.65

4. The new upper and lower bound models

The upper and lower bound evaluations for linear regression analysis have been done using fuzzy liner regression model (FLR model) [11]. We applied those evaluations to the mobile propagation path-loss characteristics as follows:

The general regression model $\tilde{Y}$ is written in the form

$$\tilde{Y} = Z\tilde{A}, \tag{4}$$

where Z obtains the independent variables and $\tilde{A}$ is the matrix of the coefficient of variables. It may be expanded as the equation

$$\tilde{y}_i(z_i) = \tilde{a}_0 + \tilde{a}_1 z_{i1} + \tilde{a}_2 z_{i2} + \cdots + \tilde{a}_k z_{ik}, \quad i = 1, 2, \ldots, n, \tag{5}$$

where k is the total number of the independent variables, and n is the number of the data. The FLR model is represented using symmetric triangular fuzzy parameters $\tilde{a} = [a_c, a_r]$ as shown in Fig. 8 by

$$\tilde{y}_i(z_i) = [a_{0c}, a_{0r}] + [a_{1c}, a_{1r}]z_{i1} + \cdots + [a_{kc}, a_{kr}]z_{ik}, \tag{6}$$

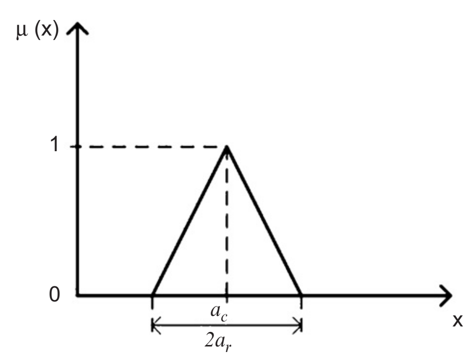

Fig. 8. Triangular form of fuzzy number.

$$y_{ic}(z_i) = a_{0c} + a_{1c}z_{i1} + \cdots + a_{kc}z_{ik}, \tag{7}$$

$$y_{ir}(z_i) = a_{0r} + a_{1r}z_{i1} + \cdots + a_{kr}z_{ik}, \tag{8}$$

where y_c and a_c are center parameters of fuzzy numbers at membership function μ=1, y_r and a_r are the spreads of fuzzy numbers, geometrically, equal to a half of the triangular base.

The parameters $\tilde{a}_i$'s of the vector $\tilde{A}$ for the FLR model are determined by a solution of linear programming, LP, problem which is to minimize the sum of spreads $y_{ir}(z_i)$

of elements of the vector $\tilde{Y}$. Therefore, the following LP problem is formulated:

$$c = y_{1r}(z_1) + y_{2r}(z_2) + \cdots + y_{nr}(z_n) \to \text{Minimum}, \quad (9)$$

Subject to

$$y_i \in \tilde{Y}(z_i), \quad i = 1, 2, \ldots, n, \quad (10)$$

$$a_{ir} \geqslant 0, \quad 1, 2, \ldots, k, \quad (11)$$

from the FLR model (6)–(8), the LP problem (9)–(11) can be written as follows:

$$\sum_{i=1}^{n}(a_{0r} + a_{1r}|z_{i1}| + \cdots + a_{kr}|z_{ik}|) \to \text{Minimum}, \quad (12)$$

$$a_{0c} + \sum_{j=1}^{k}(a_{jc}z_{ij}) - a_{0r} - \sum_{j=1}^{k}(a_{jr}|z_{ij}|) \leqslant y_i, \quad i = 1, 2, \ldots, n, \quad (13)$$

$$a_{0c} + \sum_{j=1}^{k}(a_{jc}z_{ij}) + a_{0r} + \sum_{j=1}^{k}(a_{jr}|z_{ij}|) > y_i, \quad i = 1, 2, \ldots, n. \quad (14)$$

The parameters $\tilde{a}_i = [a_{ic}, a_{ir}]$ of vector $\tilde{A}$ are determined as the optimal solution of the LP problem. Then, the FLR models for propagation path loss are presented in the form

$$L_{\text{LOS}} = [a_{0c}, a_{0r}] + [a_{1c}, a_{1r}]\log(d), \quad (15)$$

where the upper bound can be written as

$$L_{\text{LOS},u} = [a_{0c} + a_{0r}] + [a_{1c} + a_{1r}]\log(d), \quad (16)$$

and the lower bound can be written as

$$L_{\text{LOS},1} = [a_{0c} - a_{0r}] + [a_{1c} - a_{1r}]\log(d), \quad (17)$$

where d is the distance between transmitter and receiver. The LP problem corresponding to the given data was formulated. By solving this LP problem, the upper and lower bound path loss models for the two inspected buildings are obtained as follows:

4.1. Concrete school building

The measured path loss data with people moving, i.e. the data from the first floor, were employed for modelling. The results can be written in the form of (15) as

$$L_{\text{LOS1}} = [49.6, 11.5] + [15.4, 0]\log(d) \quad \text{for } d \leqslant d_{\text{bp}} \quad (18)$$

and

$$L_{\text{LOS2}} = [10.8, 0] + [35.5, 7.1]\log(d) \quad \text{for } d > d_{\text{bp}}, \quad (19)$$

where L_{LOS1} and L_{LOS2} are path losses before and after the breakpoint distance, respectively.

4.2. Car park inside the shopping mall building

The measurement of the path loss data with car moving was utilized for modelling. The results can be written in the form of (15) as

$$L_{\text{LOS1}} = [44.5, 10.8] + [12.3, 0]\log(d) \quad \text{for } d \leqslant d_{\text{bp}}, \quad (20)$$

and

$$L_{\text{LOS2}} = [27.5, 2.5] + [28.5, 6.5]\log(d) \quad \text{for } d > d_{\text{bp}}, \quad (21)$$

where L_{LOS1} and L_{LOS2} are path losses before and after the breakpoint distance, respectively.

From the results above, the average path loss exponents n_1 is $(15.4 + 12.3)/2 = 13.9$ and n_2 is $[(35.5 - 7.1) + (28.5 - 6.5)]/2 = 25.2$. From the data in Fig. 5(b) and 6(b), the maximum fading depth of the indoor propagation was about 30 dB. Thus, we have modified the boundary indoor path loss models as

$$L_{\text{LOS},u} = L_{\text{bp}} + \begin{cases} 14\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right) & \text{for } d \leqslant d_{\text{bp}}, \\ 25\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right) & \text{for } d > d_{\text{bp}} \end{cases} \quad (22)$$

and

$$L_{\text{LOS},l} = L_{\text{bp}} + 30 + \begin{cases} 14\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right) & \text{for } d \leqslant d_{\text{bp}}, \\ 25\log_{10}\left(\dfrac{d}{d_{\text{bp}}}\right) & \text{for } d > d_{\text{bp}}, \end{cases} \quad (23)$$

where L_{bp} is propagation loss at d_{bp}. According to the three-ray model in Fig. 4, the received power P_{r} is

$$P_{\text{r}} = P_{\text{t}}\left(\frac{\lambda}{2\pi d}\right)^n \sin^2\frac{\Delta}{2}, \quad (24)$$

where P_{t} is the transmitted power, and Δ the phase difference between the direct and reflected waves. A lower bound occurs when $\Delta/2 = \pi/2$. From above equation with setting $d = d_{\text{bp}}$, and $\sin^2(\Delta/2) = 1$, in conjunction with $d_{\text{bp}} = 4(H - h_2)h_2/\lambda$, then L_{bp} can be defined as

$$L_{\text{bp}} = \left|20\log_{10}\left\{\frac{\lambda^2}{8\pi(H - h_2)h_2}\right\}\right|. \quad (25)$$

To validate the proposed model, we performed path loss measurements for different locations at high traffic hours in other locations, i.e. another floor of the car parking building and a building in the university. The former and the latter locations have ceiling heights of 2.25 and 2.77 m, respectively. Their measured data are shown in Fig. 9(a) and (b), respectively. Note that the values of distance breakpoints are adjusted to be in the measurable range by the varying of the transmitting and receiving antenna height. The path loss bounds are estimated and shown as the solid lines in Fig. 9. The L_{bp} are −61.1 and −63.97 dB, and the d_{bp} are

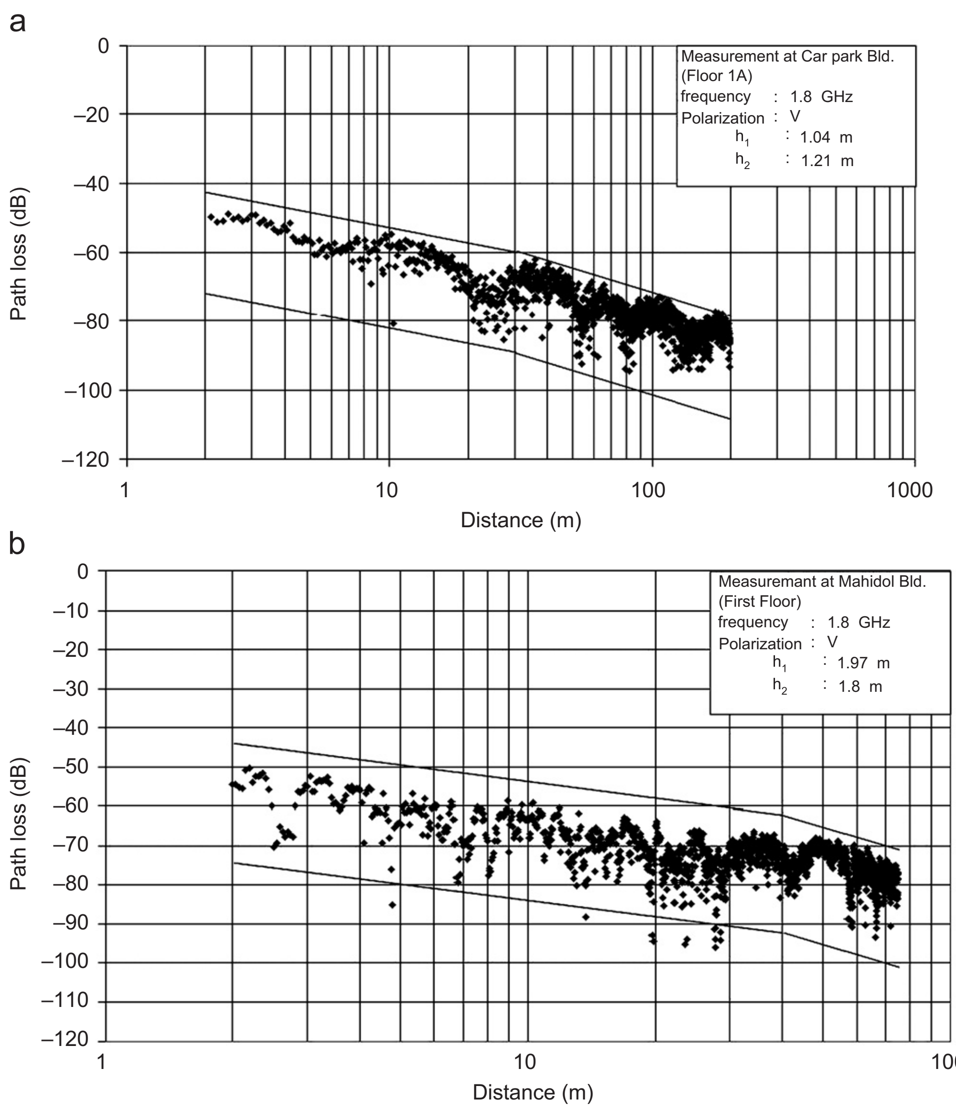

Fig. 9. The path loss measurement and the proposed models in different building. (a) Car park inside the shopping mall building (b) Concrete school building.

30.2 and 46 m for path loss models in Fig. 9(a) and (b), respectively. Therefore, the proposed upper and lower bound model agrees with the measured path loss data for both locations.

5. Conclusion

The new upper and lower bound models were proposed for mobile communications in the business buildings. These models were based on FLR of the measured data, and also taking the time-varying object movement into account. The path loss measurements were performed at a frequency of 1.8 GHz in the LOS corridor in several buildings. We found that the breakpoint-distance characteristics depend on the ceiling height and the height of the antennas. These models agree with the measured data at a frequency in the mobile communication band.

The proposed model can predict the path loss with accuracy within the boundaries. This could be useful for the cell and system design of the indoor wireless communications in realistic propagation environments. This includes prediction of the limitations of the signal levels received for compliance with public health regulations and immunity of medical equipment, etc.

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