Characterisation of Radio Transmissions Into and Within Buildings

A.M.D. Turkmani and A.F. de Toledo

The University of Liverpool, UK

Abstract Previously reported measurements of radio propagation into and within buildings at 900, 1800 and 2300 MHz, have established that the Rayleigh plus Lognormal model can describe successfully the statistical distribution of the received signal within buildings. In this paper, a multiple regression analysis method is used to predict the signal path loss encountered by radio transmissions into and within buildings at these frequencies. Statistical methods have been also used in order to determine the reliability of the prediction.

1. Introduction

The move towards personal communications has led to the realisation that not enough is known about radio propagation either into or within buildings. In this context, **into** is used to identify the propagation scenario where a base station, often located on a hilltop site or rooftop of a high building, communicates with a radio receiver that is inside another building, and **within** is used to identify the case when both transmitter and receiver are inside the same building. Several researchers have studied the problem of receiving radio signals into buildings and model it as the distance-dependency of the path loss when the mobile is outside a building, plus a building loss factor, which is included in the model to account for the increase in attenuation of the received signal observed when the mobile is moved from outside a building to inside. This model was first proposed by Rice [1] and has been used in most subsequent investigations. For personal communications with cell diameter even less than 500m, it was concluded in reference 2 that prediction of the path loss for radio transmissions into buildings should be undertaken directly and not merely as an extension of outdoor propagation models. A similar approach was adopted by Barry and Williamson [3] in order to analyse measurements undertaken in New Zealand at 851 MHz.

One of the earliest approaches to statistical modelling of propagation totally within buildings was reported by Alexander [4], who stated that the path loss within buildings at 900 MHz can be predicted using the simple distance/power law. Motley and Keenan [5] have also undertaken a series of indoor measurements at 900 and 1700 MHz, and they have shown that a better fit to the experimental data can be achieved by introducing, to the Alexander model, a correction factor (F_{floor}) representing the signal attenuation per floor.

The primary emphasis of this study is to examine the above (into and within buildings) models and to determine their relative accuracy in modelling the indoor environments. The experimental data of a previously reported series of field trials [6] will be used in this paper. The validity of the models will be assessed by evaluating the root mean square error (RMSE) between the predicted and measured path loss values. In addition to the evaluation of the previous models, the emphasis of this study is also to investigate and develop ways of improving these models, such as their RMSE values are reduced to acceptable levels. This will be undertaken by introducing as many additional factors as necessary.

Measurements of the received signal strength were undertaken within buildings in the University of Liverpool precinct. The Buildings were Blocks A and B of the department of Electrical Engineering & Electronics and the Departments of Computer Science and Life Sciences. A general description of the buildings was given previously in reference 6. Perhaps it is important to point out that experiments were conducted in every single room and corridor of the four buildings. Enough data samples were collected in each experiment in order to determine accurately the mean signal level in every room/corridor. The path loss for a given floor of a certain building is the mean of the path loss values of all rooms and corridors in that floor. In this study only the mean floor path loss values will be used in developing the into building model.

The within buildings measurements were undertaken within the same four buildings. Twenty two survey measurements at 1800 and 2300 MHz, and six survey measurements at 900 MHz were conducted within the four buildings. In every survey, experiments were conducted, once again, in every room and corridor of the building for a certain base station location.

2. Modelling

It has been previously found [6] that propagation into buildings is highly affected by the condition of transmission, i.e. the presence or absence of a line-of-sight path. Therefore, it was decided to include this as a variable. The line-of-sight variable was subjected to two different treatments. The first approach was to consider it as a qualitative factor, S_1, of value 0 or 1, depending upon whether or not a line-of-sight exists between the transmitter and the receiver. The second approach was to consider the number of building sides seen by the transmitter on each floor of the building housing the receiver. If the transmitter could see only one side, then the line-of-sight quantity, S_Q, was valued at 0.25 (i.e. 1 divided by 4). Obviously, when no line-of-sight existed or two sides of the building were seen by the transmitter, S_Q was given the value 0.0 or 0.5.

The path length, d (i.e. the distance between the antennas), area of the floor, A_f, average room area on each floor, a_R, receiver height, h_{RX}, number of rooms, N_R, on each floor, the relation between the number of rooms which contain external windows and the number of rooms with no windows, R_{win}, the relation between the length and the width of the floor, R_l, and the angle of illumination, Θ, were some of the other independent variables considered. Some of these variables, however, were considered in both linear and logarithm terms. Overall, 15 variables were considered for the multiple regression analysis.

As in the case for propagation into buildings, the path length, d, area of the floor, A_f, room area, a_R, number of rooms, N_R, on each floor, and the receiver height, h_{RX}, were also considered as independent variables for the modelling of the within buildings measurements. It has been shown previously [6] that part of the transmitted signal propagates from inside the building to the outside and then returns back to the other floors of the same building. The first approach to account for this propagation situation was to introduce a new qualitative variable, S_{sig_1}, which is called sight. S_{sig_1} can take the value 1 or 0, depending upon whether or not the surveyed rooms were located at the same side of the building where the transmitter was located. The second approach was to consider the variable sight (represented by S_{sig_2}) as a quantitative factor: for rooms located at the same side of the building where the transmitter was located S_{sig_2} was given the value 1. For rooms located in the lateral sides (i.e. the sides which are perpendicular to the side where the transmitter was located) S_{sig_2} was given the value 0.5. The S_{sig_2} factor was made equal to 0.25 for the rooms located on the opposite side of the building to where the transmitter was located. Finally, for internal rooms where no windows existed towards the outside, S_{sig_2} was considered equal to 0. In fact, the above treatment is similar to the line-of-sight factor discussed above.

Because of the signal levels were consistently higher on the floors where the transmitter was located, a third approach was investigated for the variable sight. In addition to the specification used for S_{sig_2}, in areas, rooms and corridors which are close to the room housing the transmitter, and where the barriers between the transmitter and the receiver include only wooden doors, the variable sight (identified now simply by S_{sig}) was made equal to 1, 0.5 or 0.25 depending upon the proximity and the number of corners which have to be turned in the free path joining the transmitter and the receiver: for rooms located in front of the room housing the transmitter, S_{sig} was considered equal 1. If there was one corner (or two corners) in the corridor joining the transmitting and receiving rooms, S_{sig} was made equal to 0.5 (or 0.25). S_{sig} was considered equal to 0 for any other condition. Life Sciences was described in reference 6 as an eleven-floor reinforced concrete building with an annex structure (in its south direction) from the ground floor up to the second floor. Therefore, a new variable, B_{annex}, was created mainly for this building, in order to deal with this specific situation, and it was treated as a qualitative factor. B_{annex_1} was made equal to 1 for all rooms located below the third floor. Obviously for rooms located above the second floor B_{annex_1} was equal 0. In the second approach, only the rooms located in the half partition of the building, in the south direction, where the annex structure is present, had the factor $B_{annex\_2} = 1$.

Some buildings include main corridors which provide access to most of the rooms on both sides of the building. A new qualitative indicator variable identified by C_{main} can be used in this building and made equal to 1 for the main corridors or 0 for every other area, room or secondary corridor.

The analyses of past measurements such as those reported in reference 6 have shown that the signal levels in the first two floors of a building tend to be relatively higher than expected. That was due to signals propagating from the inside of the building at higher floors and then returning back to the building at the lower floors. A new qualitative variable, identified here as ground factor, G_G, and which defines whether the rooms are located on the first two floors ($G_G = 1$), or are positioned on any other floor ($G_G = 0$),was introduced to account for this situation.

3. Modelling of the into buildings measurements

Both the overall and partial quality tests [2] have been applied to the regression analysis of the experimental measurements at 900, 1800 and 2300 MHz. The level of significance, α, for the F and t tests was set to 1%.

In total, over 60 models have been considered: some of them failed completely, while others have shown a reasonable degree of acceptance. Table 1 shows only 13 examples of the analysis conducted with the data at 2300 MHz. The first two models of Table 1 compare a number of possible combinations using six independent variables. These included two of the four variables generally found to be influential in modelling path loss (mobile antenna height, h_{RX}, and path length, d), three variables which were used in the Barry and Williamson model [3] (floor area, A_f, angle of arrival of the signal, Θ, and number of rooms in the tested floor, N_R) and finally, a sixth independent variable relating the number of rooms without and with windows, R_{win}. It can be observed that there is a general improvement in the overall quality of the multiple regression equation, i.e. with a few exceptions, the coefficient of determination, r^2, and the F-value have increased. The interesting fact about the 11th model was the coefficient 37.8, calculated for the independent variable $\log_{10}d$, significantly close to 40 dB per decade, which is the predicted coefficient in the theoretical model for path loss, when two waves are combined: a direct wave and a reflected wave. Coefficients close to 40 were always observed after replacing d by $\log_{10}d$ (e.g. see models 8 to 11). For the following models, the coefficient of the independent variable $\log_{10}d$ was assumed equal to 40 and the measured path loss was adjusted accordingly. The best of all results (13th model) was obtained when only two variables were present in the regression equation and, the resulting model for the path loss, at 2300 MHz, was found to be

$$Y_{2300}=-7.9+40.0\log_{10}d+16.1\log_{10}A_f-27.3S_Q \quad (1)$$

where the RMSE determined was 1.7 dB. It must be noted that although the coefficient of determination, r^2, was found to be slightly better for the 12th model when comparing it to the 13th model (e.g. 96.4 versus 96.1% respectively), the independent variable h_{RX}, of the 12th model yielded an unacceptable t-coefficient (e.g. t equal to 1.5), and it was therefore dropped in the 13th model. In contrast to the coefficient of determination, the F-value improved substantially when h_{RX}, was dropped (e.g. the F-value increased from 231.0 to 331.1).

A similar analysis carried out for the measurements at 1800 and 900 MHz yielded respectively the following equations:

$$Y_{1800}=-27.9+40.0\log_{10}d+23.3\log_{10}A_f-20.9S_Q \quad (2)$$

and

$$Y_{900}=-37.7+40.0\log_{10}d+17.6\log_{10}A_f-27.5S_Q \quad (3)$$

with RMSEs equal to 2.2 dB and 2.4 dB respectively. The appropriateness of the models was verified graphically. Fig. 1 compares the proposed and Barry and Williamson models, with the measured values. The path loss between antennas for Electrical Engineering Block A are shown as cases 1 to 7, Electrical Engineering Block B as cases 8 to 11, Computer Science as cases 12 to 20 and Life Sciences as cases 21 to 30. Examination of this graph reveals a very good agreement between the proposed model (i.e. eqn. 1) and the measured values.

4. Modelling of the within building measurements

Table 2 shows some of the successful models for the within buildings measurements conducted in the Life Sciences building at 2300 MHz. The first model corresponds to the well-known distance/power law that was proposed by Alexander [4]. It can be observed that the linear regression is defined by regression coefficient (gradient) 51.7dB/decade. The RMSE was found to be 12.4 dB, and the coefficient of determination r^2 was 0.44; i.e. 44% of the path loss is explained by the line defined by the gradient 51.7 dB/decade. The Motley and Keenan model, i.e. the second model of Table 2, displays improved RMSE and r^2: the RMSE decreased by 0.3 dB and the coefficient of determination increased by 3%. Additional improvements were obtained in the values of RMSE and r^2 in models 8 and 9, where the other two variables C_{main} and G_G are used. In these two models $B_{annex} = B_{annex\_2}$. Compared with the Alexander model, the last model decreased the RMSE by 45% (from 12.4 dB to 6.8 dB), and improved r^2 by 91% (from 0.44 to 0.84). It is also interesting to observe that the improvement of the Motley and Keenan model in relation to the Alexander model was only 2% for the RMSE and 7% for r^2. The resulting model for the path loss for the Life Sciences building with the transmitter in room R411 (located in the middle of the building), is given by the equation.

$$Y_{room,2300,LSc(R411)}=35.9+36.4\log_{10}d+2.9k_{floor}-23.7S_{sig}-16.3C_{main}-7.3B_{annex}-4.2G_G \quad (4)$$

It is evident therefore that good predictions can be made for radio transmissions within buildings where the features and transmission conditions are well known because, in that case, particular models such as those analysed previously can be applied yielding smaller errors. In the absence of these specific information, there will be a need for global models, which are more dependent on global/universal variables. Three such models were obtained by collating all the data of all the survey measurements at the three different frequencies. The models were found to be

$$Y_{room,2300}=21.6+39.1\log_{10}d+3.8k_{floor}-17.8S_{sig}-0.01A_f-8.8G_G \quad (5)$$

$$Y_{room,1800}=24.5+33.8\log_{10}d+4.0k_{floor}-16.6S_{sig}-0.017A_f-9.8G_G \quad (6)$$

$$Y_{room,900}=18.8+39.0\log_{10}d+5.6k_{floor}-13.0S_{sig}-0.024A_f-11.0G_G \quad (7)$$

where the RMSE determined were 12.4, 10.9 and 11.6 dB for 2300, 1800 and 900 MHz.

5. Conclusion

Modelling propagation into and within buildings at 900, 1800 and 2300 MHz, has been described in this paper. It has been shown that the path loss of radio transmissions into buildings was found to be linearly dependent on the logarithm of the floor area, on a relation representing the number of building sides seen by the transmitter and on the free space path loss equation. The path loss for radio transmissions within buildings has been found to be linearly dependent on the logarithm of the distance , on the floor area, on the number of floors between transmitter and receiver, and on two factors identified in this study as sight and ground. Better predictions are possible in buildings where features and transmission conditions are well known because, in that case, particular models can be applied.

6. References

1. Rice, L.P., 'Radio transmission into buildings at 35 and 135 MHz', Bell System Tech. J., 38, (1), pp. 197-210, 1959.

2. Toledo, A.F.,'Narrowband characterisation of radio transmissions into nad within buildings at 900, 1800 and 2300 MHz', Ph.D. Thesis, Department of Electrical Engineering and Electronics, University of Liverpool, 1992.

3. Barry, P.J. and Williamson, A.G., 'Statistical model for UHF radio-wave signals within externally illuminated multistorey buildings', IEE Proc. Part I, 138, (4), pp. 307-318, 1991.

4. Alexander, S.E., 'Radio propagation within buildings at 900 MHz', Electronic Letters, 18, (21), pp. 913-914, 1982.

5. Motley, A.F. and Keenan, J.M.P., 'Personal communication radio coverage in buildings at 900 MHz and 1700 MHz', Electronics Letters, 24, (12), pp. 763-764, 1988.

6. Turkmani, A.M.D. and Toledo, A.F., 'Radio transmission at 1800 MHz into and within buildings', IEE Proc., Part I, 138, (6), pp. 577-584, 1991.

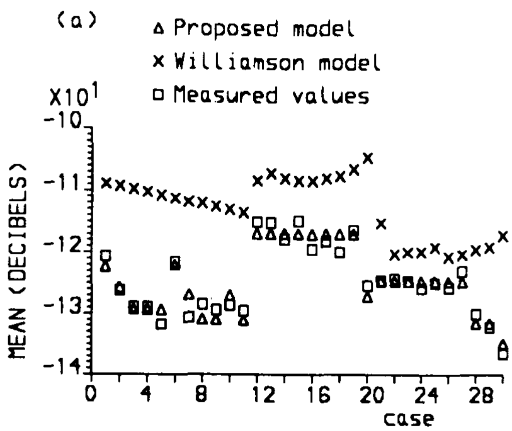

Fig. 1 Measured and predicted signal strength for into buildings measurements at 2300 MHz

Model	Chosen set of independent variables											Analysis	
	log A_f	a_R	log a_R	θ	d	log d	h_{ax}	N_R	R_{win}	R_i	S_q	r^2	F
1	26.2(5.6)			0.04(1.9)		9.0(1.8)	-0.24(-5.8)	-0.23(-2.4)	4.1(0.9)			0.890	30.9
2	26.6(5.7)			0.05(2.0)	16.9(1.8)		-0.24(-5.1)	-0.23(-2.5)	4.2(1.0)			0.891	31.3
3	34.3(6.9)			0.1(-2.0)	29.5(2.4)		-0.24(-5.4)	0.25(-2.8)	-	-1.84(-1.3)	-	0.894	32.5
4	39.0(6.9)	0.03(3.0)	-	0.21(-3.8)	57.8(3.7)	-	-0.24(-5.5)	-		-4.4(-3.1)	-	0.896	33.9
5	22.7(8.5)	0.01(1.2)	-	-0.04(-2.0)	16.9(1.7)		-0.28(-5.6)	-	-	-	-	0.855	28.2
6	33.0(7.1)		5.8(3.1)	0.16(-3.3)	45.2(3.4)	-	-0.23(-5.4)			3.1(-2.6)	-	0.900	34.4
7	18.7(7.1)		0.2(0.1)	-	74.3(5.5)	-	-0.07(-1.4)			0.45(-1.0)	24.3(-5.3)	0.934	54.2
8	20.9(7.5)		0.8(0.6)		-	42.4(5.5)	-0.07(-1.5)	-	-	-0.64(-1.4)	-23.3(-5.2)	0.934	54.0
9	20.4(7.8)				-	42.7(5.7)	0.07(-1.4)			-0.6(-1.4)	24.3(-6.1)	0.933	66.8
10	17.9(9.2)		-	-	-	34.0(6.9)	-0.09(-.9)		-	-	21.6(-4.0)	0.926	78.1
11	16.1(9.7)	-		-	-	37.8(7.9)	-	-	-		-26.4(-11.0)	0.919	97.7
12	17.6(9.2)	-		-	-	-	-0.07(-1.5)	-	-	-	-24.5(-10.2)	0.904	231.0
13	16.1(9.8)	-	-	-	-	-	-	-	-	-	-27.3(-18.0)	0.961	331.1

Table 1 Multiple regression models for the into buildings measurements at 2300 MHz, the $t_{j's}$ are between brackets

Model	Chosen set of independent variables									Analysis	
	$\log_{10}d$	h_{floor}	S_{elg_1}	S_{elg_2}	S_{elg}	B_{annex}	C_{main}	G_C	cnst	RMSE	r^2
1	51.7(12.5)								8.8	12.4	0.44
2	43.5(9.6)	2.7(3.8)							13.0	12.1	0.47
3	48.0(10.4)	2.3(3.4)	-7.0(-4.0)						15.4	11.6	0.51
4	44.1(12.4)	2.4(4.5)		-17.9(-11.5)					21.2	9.4	0.68
5	41.5(13.4)	1.8(3.7)			21.2(-15.3)				28.2	8.2	0.76
6	42.0(13.8)	2.1(4.4)			-22.3(-15.9)	-4.1(-3.0)			28.5	8.1	0.77
7	41.3(14.4)	2.2(4.9)			-21.4(-16.7)	-9.5(-6.1)			28.9	7.6	0.79
8	36.1(13.1)	2.5(6.0)			-23.1(-19.2)	-9.0(-6.3)	-16.1(-6.3)		36.3	6.9	0.83
9	36.4(13.5)	2.9(6.7)			-23.7(-19.7)	-7.3(-4.7)	-16.3(-6.5)	-4.2(-2.8)	35.9	6.8	0.84

Table 2 Multiple regression analysis for the within building measurements in Life Sciences department (Exp. 11, Tx: room 411, 2300 MHz), the $t_{j's}$ are between brackets