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A Quantitative Analysis of GSM Air Interface Based on Radiating Columns and Prediction Model

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***Abstract*—**This paper explains the cause of nonlinearity in floor attenuation hither to left unexplained. The performance degradation occurring in air interface for GSM signals is quantitatively analysed using the concept of Radiating Columns of buildings. The signal levels were measured using Wireless Network Optimising Drive Test Tool (E6474A of Agilent Technologies). The measurements were taken in reflected signal environment under usual fading conditions on actual GSM signals radiated from base stations. A mathematical model is derived from the measurements to predict the GSM signal levels in different floors. It was applied on three buildings and found that the predicted signal levels deviated from the measured levels with in +/- 2 dB for all floors. It is more accurate than the prediction models based on Floor Attenuation Factor. It can be used for planning proper indoor coverage in multi storey buildings.

***Keywords*—**GSM air interface, nonlinear attenuation, multistory building, radiating columns, ground conduction and floor attenuation factor.

I. Introduction

THE studies on air interface degradation in multi storey buildings reported in various papers reveal invariably nonlinearity in floor attenuation. Contradicting views were published on the cause of nonlinearity and the phenomenon is not explained fully till date. The study was mostly conducted on locally generated UHF signals simulating GSM signals and tried to attribute the nonlinearity to diffraction, cross floor isolation etc... Even though actual GSM signals were measured in [1], the propagation up to only three floors was explained. The nonlinearity was attributed to Ground waves and no quantitative analysis was provided to derive any mathematical model. In this paper actual GSM signals are measured adopting the same technique for measurements as in [1] and the nonlinearity in attenuation is explained using a new concept of 'Radiating Columns' and Ground waves. A quantitative analysis also is provided and a prediction model is derived. This prediction model is more accurate than other popular models. The contents of this paper organized as follows. Section II analyses various on nonlinearity in floor attenuation. Section III explains Theory of Radiating Columns. Section IV describes the measurement procedure. Section V presents theoretical analysis and prediction model. Section VI is the conclusion.

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II. Views on Nonlinear Attenuation

The air interface degradation was reported in [1]-[10] for UHF signals propagated through identical floors. The attenuation is expected to be proportional to the number of floors the signals penetrate. But in all the cases a non-linearity in attenuation with regard to the number of floors was observed.

In [1], the nonlinearity up to three floors was explained using ground waves. The effect of ground waves on nonlinearity in higher floors was not discussed.

In [7] and [8], it was noticed that the nonlinearity consisted of two distinct regions. The attenuation per floor was large when the transmitter and the receiver were separated by one or two floors and it was small when more floors were there in between the transmitter and the receiver.

The low rate of increase in attenuation with increase in number of floors was attributed to propagation through elevator shafts (and staircases) in [7]. This signal was considered to be dominant after a separation of one floor.

Another explanation using diffraction theory was put forth in [8]. It was considered that the signal passing through the window getting diffracted at 90° by the window frame, travelling along the wall and getting diffracted at 90° for the second time, back into the building through the window frame in another floor would be having significant strength.

The field strength in the shadowed region (diffraction zone) is a vector sum of fields due to all the secondary Huygens sources in the plane above the knife- edge. In the case under consideration, for diffraction at an angle of 90°, no such secondary Huygens sources will have line of sight with the receiver. In other words, the distance of the receiver from the knife-edge is zero and hence the Fresnel-Kirchhoff diffraction parameter becomes $-\infty$. The graphical solution of the Fresnel integral indicates that the attenuation suffered by the signal in such a diffracted path is infinite.

Giving credence to the observations in [7] and [8], it can be considered that there exists a signal behaving similar to diffracted signal but not the diffracted signal itself.

When a floor with solid metal sheet separated the transmitter and the receiver, a path loss of 26 dB was observed in [10]. It was termed as cross-floor coupling. It was not accepted and attributed to diffraction in [8]. The diffracted signal is expected to decrease only marginally when traversed additional floors in space. The mean signal level was attenuated by 60 dB to 65 dB for four-floor separation in [10]. An average attenuation of about 15 dB per floor may not justify diffraction or signals through elevator shaft.

It is explained in the following chapter that the signal behaving like a diffracted signal is a combination of two signals; the ground wave signal and column radiated signal.

III. Theory of Radiating Columns

Only the Direct signal from the transmitter was considered in early literature which was not sufficient to explain the non-linear attenuation in different floors.

The existence of second signal is attributed to the radiation from the columns.

A third signal, Ground conducted signal explained in [1] also is considered to quantitatively explain the non uniform attenuation.

All the three signals are considered simultaneously to explain the air interface characteristics of GSM signals.

A. Direct Signal

The signal emanating from the transmitter, travelling along the straight line connecting the transmitter and the receiver and being received by the receiver is considered as Direct signal. If the transmitter and the receiver are separated by a few floors the direct signal gets attenuated by every floor.

The signal power in n^{th} floor due to direct signal is given by

$$P_{dn} = P_{dn+1} - A_f \quad (1)$$

where A_f is the attenuation per floor in dB. It is constant for all the floors in the absence of other signals.

B. Column Radiated Signal

Generally the columns in any building have four ribbed-torsteel rods of large diameter in four corners and a few ribbed-torsteel rods of small diameter on the sides, which are held in position by binding wires of very small diameter as shown in fig 1. It can be visualized as a large wave guide, if the outer portion is covered with a metal sheet. The combined rod structure picks up the E M signals from top and transmits down to the ground all the way radiating.

C. Ground Wave Signals

Considering the case of the UHF signal radiated from a GSM tower located on top of the building, the ground outside the building receives the signal from the direct beam where line of sight is possible. The ground nearer to the building receives less intense diffracted signal than the line of sight signal. The ground under the roof receives only a very small signal conducted by the ground from outside. This signal also tries to penetrate the higher floors in the same manner like direct signal, but in the opposite direction. The signal power in n^{th} floor due to ground wave is given by:

$$P_{gn} = P_{gn-1} - A_f \quad (2)$$

where A_f is the attenuation per floor in dB which is considered for direct signal also.

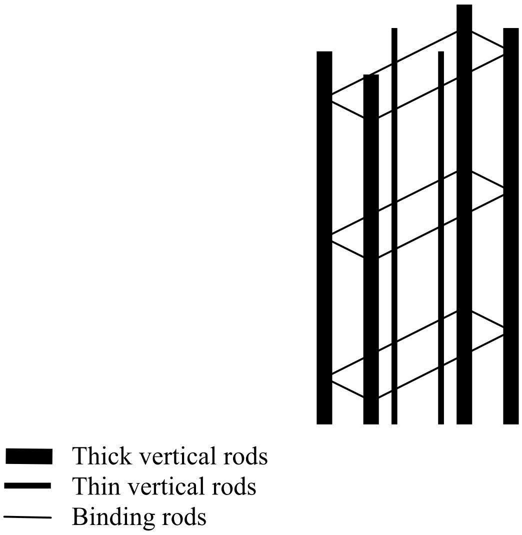

Fig. 1 Typical rod structure in columns

D. Combined Effect

While the top portions of the rod structure gets coupled to the direct signal, the bottom portions of the columns pick up the ground wave signal.

The power difference between the signals picked up from the top and the bottom is mostly attenuated and a small portion of it is dissipated as radiation by the columns. The attenuation in the column is assumed to be log linear.

Attenuation per floor in a column is given by:

$$A_c = (P_t - P_b) / N \quad (3)$$

where P_t and P_b are the signal powers in dB at the top and the bottom of the column and N is the number of floors in between.

The signal power in n^{th} floor due to radiation,

$$P_{rn} = P_t - (N - n) A_c - \Gamma \quad (4)$$

where Γ is the radiation coupling factor in dB.

IV. Measurement Procedure

The measurement set up is a laptop computer loaded with Agilent E6474A Wireless Network Optimisation Platform software connected to a Sagem OT-55 phone. The software is compatible with Windows operating system. It was configured for measuring the GSM signal level in 900 MHz band. The received signal level of the Broadcast channel (BCCH) is measured in every frame for 100 frames and the average level is displayed every 480 ms in Excel format. The readings were taken for two minutes at a stretch and the average of all the readings is considered as the received signal level at the location of measurement. They were measured by holding the phone in the palm at about one meter height from the floor. The signal levels at any location were fluctuating due to fading. To minimise the effect of fading the measurements were taken in two adjacent floors simultaneously using two calibrated and synchronised Drive Test Tools. The locations of measurements were vertically one over the other with out any lateral displacement. Even though variations in signal level was noticed in each of the locations with in the two minutes time slot for measurement, the difference between the signal levels in two floors were almost constant since the fading affected the signals in both the floors almost to the same extent. The difference between the average signal levels in two floors is considered as the attenuation offered by the lower floor. The average signal levels measured on the terrace and top floor are considered as the signal levels of terrace and top floor. The floor attenuation measured for next to top floor is deducted from the signal level of top floor to determine the signal level in next to top floor. This method is adopted to overcome the average signal level variations between measurements. Similarly the signal levels for all the floors are calculated.The measurements were taken in three different buildings in Hyderabad, India; Soundarya Residency a six storey residential complex, Sharada Gopalan apartments a five storey residential building, and Venkata Ashray apartments a four storey residential building.

A. *Measurements in Soundarya Residency*

Soundarya Residency is of 18m height with a GSM mast of 12m on top. The RF channel 80 with a carrier frequency of 950.8 MHz is radiated from the antenna mounted on the top position of the mast. The ground floor is used as car parking area with out any partitions. The measurements were taken vertically below the antenna on the terrace and in all other floors. In all the floors excepting ground floor the location of measurement was on the corridor of 1m wide and 9m long linking two residential apartments facing each other. One side of the corridor is completely blocked by a wall excepting the access for lift and stair case. The other side is having a protective parapet wall of 1m height.

TABLE I
SIGNAL LEVELS IN SOUNARYA RESIDENCY

	Signal level (dBm)	Attenuation (dB)
Terrace	-18	
5th floor	-33	15
4th floor	-45	12
3rd floor	-50	5
2nd floor	-55	5
1st floor	-60	5
Ground floor	-55	-5

The signal levels were measured simultaneously on the terrace and the fifth floor at a stretch for 2 minutes and recorded as the signal levels of the respective floors. The average signal level difference between fifth and fourth floor is considered as the attenuation of fourth floor. Similarly the attenuations for all other floors were measured and the signal levels were recorded. The results are given in Table I. From Table 1, it can be seen that the signal got attenuated by 15dB in the top floor. The average floor attenuation is 13.5dB for two floors, 10.67dB for three floors, 9.25dB for four floors, 8.4dB for five floors and 6.17dB for six floors. The observations recorded in [7]-[9] also showed a similar trend.

The measurements were taken in [2] with the transmitter on the first floor while the mobile receiver traversed the second through fifth floors. Still the observations revealed the same trend.

Fig 2 shows the signal level at different floors in Soundarya Residency. While the measurements were taken for each floor only in one location, these points have been connected with continuous lines for clarity. It can be observed that there are three different regions of floor attenuation. The signal level drops steeply in 5th and 4th floors and moderately in 3rd, 2nd and first floor. The signal level in the ground floor is more than the first floor as observed in [1]. Hence it can be easily predicted that there ought to be three different mechanisms each dominating the others in one of the three regions.

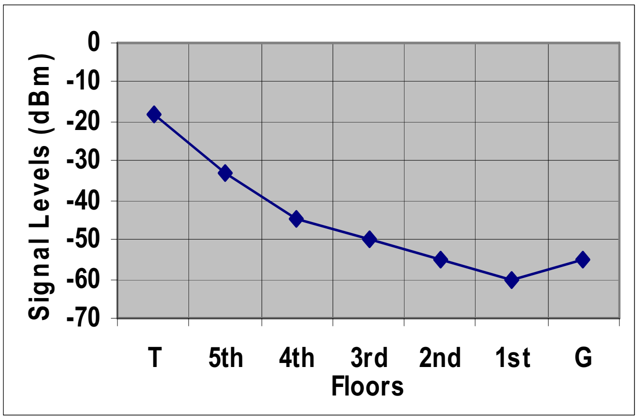

Fig. 2 Signal levels in Soundarya Residency

B. *Measurements in Sharada Gopalan Apartment*

Sharada Gopalan apartments building is a five storey building located at a distance of 180m from the antenna radiating 950.8 MHz. The entire building of 15m height is illuminated by the main beam.

From ground floor to fourth floor, in every floor two apartments are separated by a corridor of 3m x 5m. The stair-case and a lift are located at one end of the corridor; where as the other end is closed with a parapet a wall of 1m height. The lift is surrounded by the stair case in all the three sides. The signal levels were measured in front of the lift in all the floors and the results are given in Table II.

The average floor attenuation and the signal levels for each of the floors in Sharada Gopalan apartments are shown in fig 3. Three different slopes can be observed in the chart which is strikingly similar to those in fig 2. In this case also the first region covers only top two floors and the third region covers ground floor only. But the middle region covers only two floors instead of three floors.

TABLE II
SIGNAL LEVELS IN SHARADA GOPALAN APARTMENTS

	Signal level (dBm)	Attenuation (dB)
Terrace	-23	
4^{th} floor	-38	15
3^{rd} floor	-51	13
2^{nd} floor	-57	6
1^{st} floor	-65	8
Ground floor	-60	-5

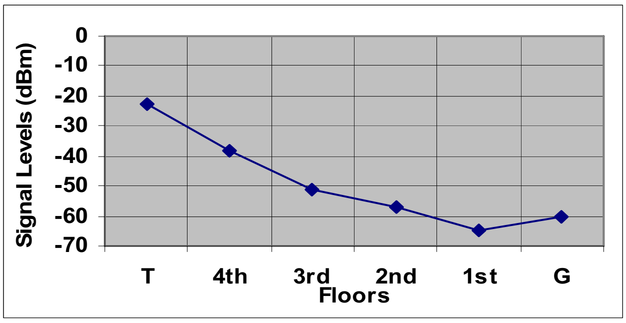

Fig. 3 The signal levels in Sharada Gopalan Apartments

C. Measurements in Venkata Ashray Apartments

Venkata Ashray Apartments is a four storey residential building of 12m height. The measurements were taken in front of the lift, in the narrow passage of about 1m wide and 8m long separating two apartments and recorded in Table III. Neighbouring buildings are located within 3m on either side of the passage. The measured frequency is 949.4 MHz corresponding to GSM channel 73.

TABLE III
SIGNAL LEVELS IN VENKATA ASHRAY APARTMENTS

	Signal level (dBm)	Attenuation (dB)
Terrace	-44	
3^{rd} floor	-51	7
2^{nd} floor	-56	5
1^{st} floor	-65	9
Ground floor	-75	10

Since it is only a four storey building three attenuation zones are overlapping and the signal level in the ground floor is less than first floor.

V. THEORETICAL ANALYSIS AND PREDICTION MODEL

The measurements taken in Soundarya Residency are considered for theoretical analysis and the results are applied on the measurements taken in other buildings for verification. As explained in section III, in any floor the signal level is the vector sum of direct signal, column radiated signal and ground wave signal. In the fifth floor, the direct signal present is attenuated by only one floor where as the ground wave signal is attenuated by five floors before reaching the fifth floor. Moreover the ground wave signal in ground floor itself is 37 dB below the direct signal on the terrace. Hence the contribution of ground wave signal in the fifth floor can be neglected as insignificant. The column radiated signal also may not be significant in the fifth floor, since the column picks up the signal only in the area of its cross section where as the direct signal penetrates the entire area of the terrace. So, the 15 dB signal attenuation can be attributed mainly to the floor attenuation which is referred as A_f in equation (1). The attenuation per floor A_f referred in equation (2) also is the same and is 15 dB.

Thus the equation (1) for signal power in n^{th} floor due to direct signal gets modified as:

$$P_{dn} = P_{dn+1} - 15 \quad (5)$$

The equation (2) for signal power in n^{th} floor due to ground wave gets modified as:

$$P_{gn} = P_{gn-1} - 15 \quad (6)$$

Direct as well as ground reflected signals encounter three floors before reaching the third floor and the attenuation per floor A_f is 15 dB. Consequently, both the signals suffer a loss of 45 dB from the terrace and ground. Hence the effect of the direct and ground wave signals will be the minimum in the third floor. So, the third floor is considered for evaluating the radiation coupling factor Γ.

The signal power at the top P_t = - 18 dBm
The signal power at the bottom P_b = -55 dBm
Number of floors N = 6

By applying these values in equation (3) the attenuation per floor in the column is calculated and A_c = 6 dB. From equation (4) the radiation coupling factor is calculated and Γ= 14 dBm. Radiation is found to be dependent on attenuation and Γ is considered as 1 dB less than the attenuation of the top floor.

The equation (4) for signal power in n^{th} floor due to radiation gets modified as:

$$P_{rn} = 6n - 68 \quad (7)$$

For all the floors of Soundarya Residency the direct signal power $P_{d,}$ ground wave signal power P_g and column radiated signal power P_r are calculated using equations (5), (6) and (7) respectively and given in dBm in Table IV. The maximum of all the three signal levels Pmax for each floor and also the measured signal levels P_m are given.

TABLE IV
CALCULATED AND MEASURED SIGNAL LEVELS

	P_d	P_g	P_r	P_{max}	P_m
Terrace	-18			-18	-18
5th floor	-33	-130	-38	-33	-33
4th floor	-48	-115	-44	-44	-45
3rd floor	-63	-100	-50	-50	-50
2nd floor	-78	-85	-56	-56	-55
1st floor	-93	-70	-62	-62	-60
Ground floor		-55		-55	-55

The power of the strongest among signals P_d, P_g and P_r can be predicted as the signal level in any floor, since they are at least 4 dB above other signals. The maximum difference between the predicted and the measured values in any floor is only 2 dB. The dominant signal in the 5th floor is direct signal; in the ground floor it is ground conducted signal and in all other floors it is column radiated signal.

The values of signal levels due to direct signal, ground reflected signal, column radiated signal and predicted signal levels for all the floors in Soundarya Residency are shown in fig 4. Even though the predicted signal level curve is nonlinear, its constituent signal graphs are linear.

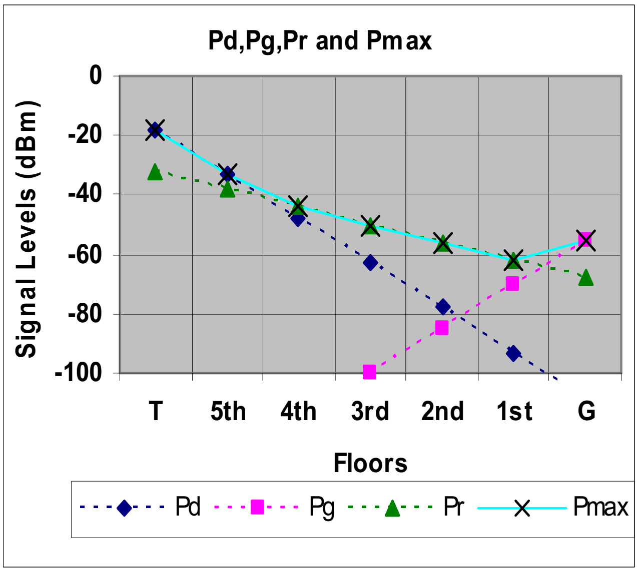

Fig. 4 Predicted and Constituent Signal Graphs for Soundarya Residency

The predicted signal level curve and the measured signal curve are shown in fig 5.

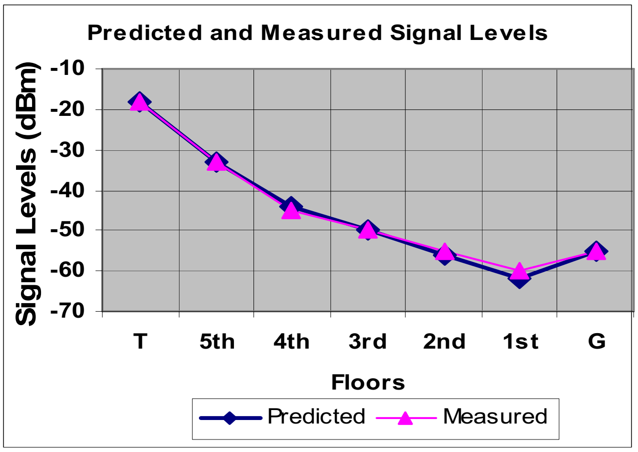

Fig. 5 Predicted and Measured Signal Levels of Soundarya Residency

Similar exercise was carried out for the other two buildings also and the results are given in Tables V and VI. It is observed that the measured and predicted signal levels differed only in the second floor by 1 dB for Sharada Gopalan Apartments and by 2 dB in the case of Venkata Ashray Apartments.

TABLE V
MEASURED AND PREDICTED SIGNAL LEVELS OF SHARADA GOPALAN APARTMENTS. (Γ=14 AND A_C=7)

	P_d	P_g	Pr	P_{max}	Pm	Difference
Terrace	-23			-23	-23	
4th floor	-38	-120	-44	-38	-38	0
3rd floor	-53	-105	-51	-51	-51	0
2nd floor	-68	-90	-58	-58	-57	-1
1st floor	-83	-75	-65	-65	-65	0
Ground		-60		-60	-60	

Venkata Ashray Apartments is constructed on a raised base of one metre from the ground and also surrounded by constructions, attenuating heavily the ground waves before reaching the location of measurements. Hence the direct signal only is having maximum influence on the receive levels in all the floors and still fits in well in our prediction model.

TABLE VI
MEASURED AND PREDICTED SIGNAL LEVELS ALONG WITH CONSTITUENTS FOR VENKATA ASHRAY APARTMENTS.
(Γ=6 AND A_c=8)

	P_d	P_g	Pr	P_{max}	Pm	Difference
Terrace	-44			-44	-44	
3^{rd} floor	-51	-96	-58	-51	-51	0
2^{nd} floor	-58	-89	-66	-58	-56	-2
1^{st} floor	-65	-82	-74	-65	-65	0
Ground		-75		-75	-75	

VI. CONCLUSION

A generalized prediction model for buildings with five or less floors has been presented with data measured around 950 MHz in three different buildings. In this prediction model, no measurements need to be taken in other floors than the terrace, top and ground floors. This requires less measurement and is more accurate than other models.

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