Wireless Personal Communications **9:** 95–111, 1999.

Radio Propagation Measurements and Modeling of Indoor Channels at 1800 MHz

N. PAPADAKIS, A. ECONOMOU, J. FOTINOPOULOU and P. CONSTANTINOU
National Technical University of Athens, Department of Electrical and Computer Engineering, Electroscience Division, 9 Heroon Polytechniou Zografou, 157 80 Athens, Greece
E-mail: npap@tinos.mobile.ece.ntua.gr

Abstract. Indoor radio communication systems gain increasing interest of cellular network operators. A prerequisite to the design of these systems is the knowledge of indoor radio propagation characteristics. This knowledge should include information, concerning the in-building structure which strongly affects the signal transmission. The results presented in this paper provide a prediction of the signal behavior in indoor corridor environment and dynamic effects of people. Narrowband propagation measurements were conducted within a four storey building at National Technical University of Athens (NTUA). The purpose of the measurement campaign is to derive a path loss model considering site specific information. A description of the measurement environment and experimental set-up is given. Path loss exponents and absolute path loss values are estimated for each measured case. Statistical analysis of the measured data is also presented.

Keywords: indoor propagation, personal communications, cellular systems.

1. Introduction

In recent years, the expansion of the wireless communication has attracted great attention for application within offices, residential buildings, factories, airport terminals. The challenging development of PCS (Personal Communication Services) has led to the view that the knowledge of radio propagation inside buildings, is absolutely essential. The indoor propagation environments, which have not yet been generally characterized are among the important service areas of PCS. The capacity of the current 900 MHz cellular operating systems is inadequate to cover the large growth of PCS. As a result, new bands at 2, 6 and 11 GHz are now under investigation. PCS will require low transmitting power (about 10 milliwatts), omnidirectional portable devices and omnidirectional base stations. Furthermore, microcell with radii of 1000 meters and picocells with radii of 100 meters, as opposed to today's 5 km radii for cellular mobile radio, are under careful consideration in both indoor and outdoor mobile services. The purpose of this paper is to contribute to the modeling of the propagation conditions in a multipath indoor (corridor) environment at 1.8 GHz. It is worth pointing out that, indoor radio propagation is very complex and difficult, because the shortest path between transmit and receive locations is usually blocked by walls, floors, ceilings, doors or other objects. The variability of architectural configurations, the internal layout and the building materials influence drastically the indoor radio channel.

The variation of the received signal level in indoor areas can be characterized by a slow fading and a fast fading component. The slow fading describes the fact that the average signal level decreases, normally as the distance from the transmitter increases. The fast fading component describes the fluctuation of the received signal from its mean. This rapid variation is

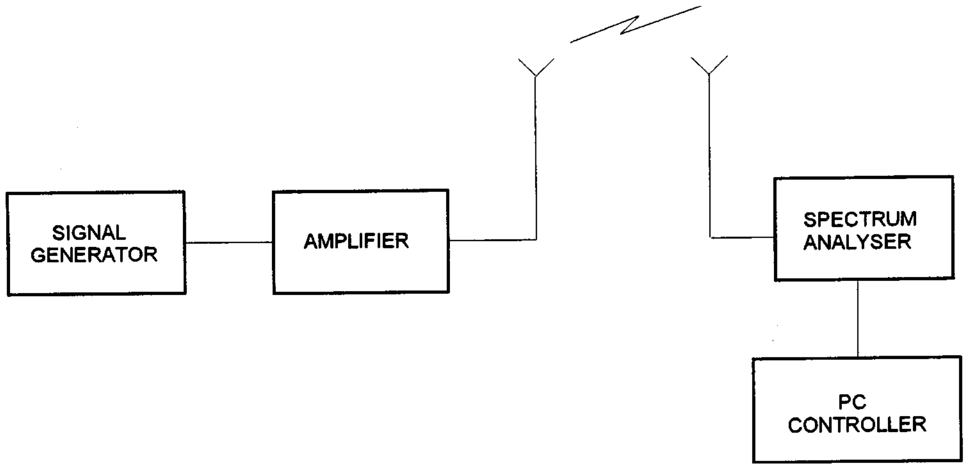


Figure 1. Block diagram of the indoor radio propagation measurement set up.

attributed to the interference of the received multipath signals and is determined taking into consideration the distribution and the statistics of the signal level from the mean.

This paper reports the results of an investigation of radio propagation campaign within a University building and characterization of indoor channel. As is the case in outdoor mobile systems, there are several important parameters that have to be examined. The path loss and the statistical characteristics of the received signal envelope are the most important for coverage planning applications. Multipath propagation measurements of the average signal strength have been performed in two floors (having quite similar structure and dimensions), of a building at NTUA, including corridor and office areas. The signal variability over small distances – fast fading – was measured in LOS (Line Of Sight) and NLOS (Non Line Of Sight) conditions. Models of propagation losses, taking into account the variable local features and the blue print of the floor under consideration, are proposed.

Another basic parameter that has been investigated, is the effect of human presence and movement on the radio path. A mathematical model based on the 1 slope model (1SM) is used for calculations of path loss in indoor environment [2]. Results for small scale path loss, signal f ading over small tracks and temporal fading variation due to personnel movement in the building are presented, based upon the empirical data.

2. Measurement Equipment

The measurement apparatus is shown schematically in Figure 1. The experimental transmit system includes a Signal Generator, operating at the frequency of interest (1800 MHz). The output signal (7 dBm) is driven to an amplifier which is connected to the transmitting antenna through a 1 dB loss cable- an omnidirectional vertically polarized monopole $\lambda/4$, having a calibrated gain of 2.1 dBi. The output power is 500 mW. The transmitting antenna is mounted vertically on a 1.85 m long mast.

The Continuous Wave emission is detected by the receiving antenna (similar to the transmitting one) fixed at a 1.65 m long mast. This antenna is connected through a coaxial cable to an HP8593A Spectrum Analyzer. The received signal envelope was sampled by the spectrum analyzer, using defined selective frequency settings and six 10 second sweep times. Each sweep produced 400 digitized samples with 2 digits accuracy in a 80 dB range. Resolution

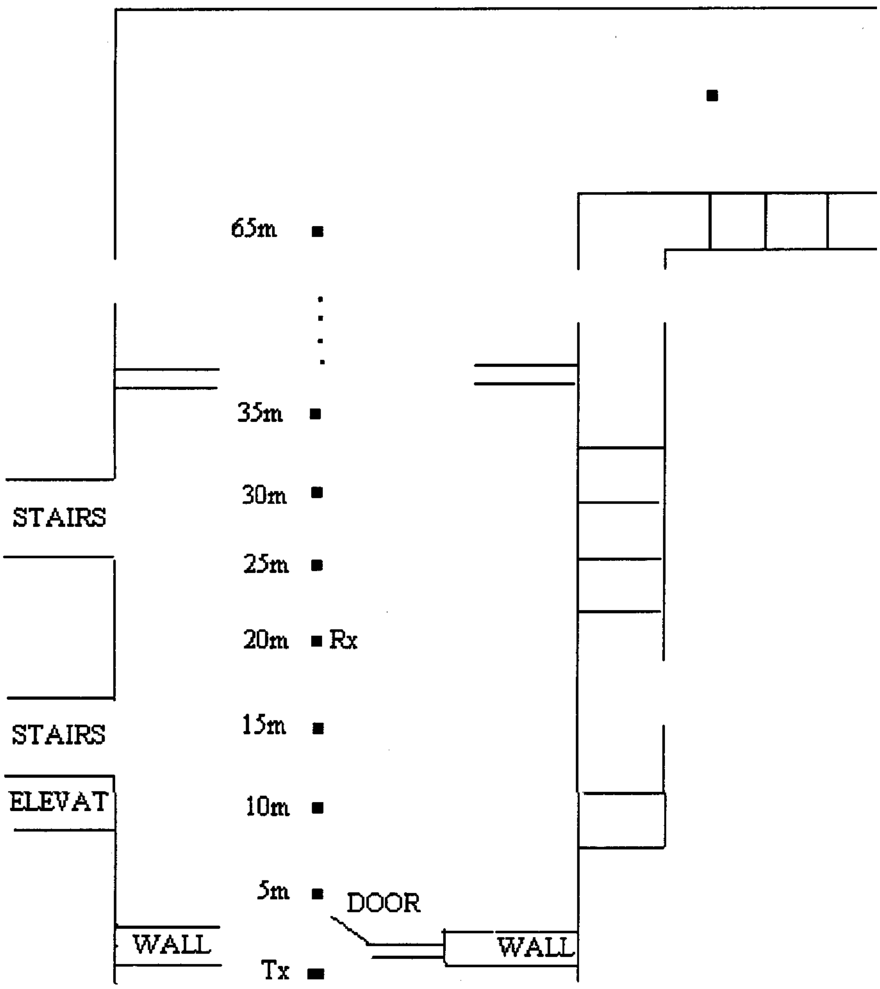


Figure 2. Layout of corridor environment. (NTUA – second floor).

bandwidth was set to 10 KHz. The output data of the Spectrum Analyzer was recorded on to the hard disk of a P.C. via an HPIB Interface Bus, in a fully automated process. During the measruements, the transmit system was stationary and the receiving equipment was housed on a trolley, specially designed for indoor movement.

3. Measurement Environment and Experimental Procedure

Propagation measurements were performed in two, same structured floors of the Electroscience building at NTUA. The building is partitioned into many small offices and laboratories.

A long corridor at the second floor was selected for the first set of measurements. The dimensions of the corridor at 65 m in length, 4 m in width and 6 m in height. The construction type of the corridor and the experimental procedure are shown in Figure 2.

This figure illustrates a plan of the measurement environment showing the Transmit (*Tx*) and the Receive (*Rx*) positions in which the signal strength was sampled. The transmit system was placed at the one end of the corridor, 2 m before the intervening door. The dividing walls and the ceilings are constructed mainly by brick, concrete and wood and the floors were constructed by marble. Along the corridor there are doors made from wood, glass and metal. There are also a 10 m width staircase and an elevator, situated 15 m and 10 m from the *Tx*, respectively.

The distance of 1 m along the corridor was chosen as the reference distance [1], since the signal is expected to have a strong LOS component, which predominates any signal components scattered by the local environment. The one meter reference is later used to model the indoor path loss. Starting 5 m from the transmit antenna, measurements are taken at equal intervals of 5 m. *To obtain average signal strength in every measurement position the receive unit was moved 1 m front and back from the fixed measured position.* A total distance of 65 m was covered in the corridor. During all measurements the transmitter remained stationary and the receiver was moved as previously quoted, at constant velocity, providing equally spaced digitized samples for each measurement position. At each measured site 180 samples of the received signal strength are stored. The measurements were conducted in direct LOS conditions in the main corridor. However, as shown in Figure 2, there are strong reflection conditions because of the geometry of the location.

The same measurement procedure was followed for a second set of measurements in the corridor with the transversal door (constructed by wood with glass windows) closed (partial LOS). From Figure 2 the exact location of the door (between *Tx* and the 1st measured position) can easily be seen.

The variation of received power when turning the corner between two corridors (NLOS conditions), was also studied. Measurements have been done 2 m before and 2 m after the turning point. The diffraction area of the corner is highly absorptive, containing walls of brick and concrete.

Another set of measurements has been carried out with *Tx-Rx* located in different floors, following exactly the previously mentioned procedure. Locating the receiver at specific measurement sites, one floor up from the floor where the transmitter was located, attenuation loss has been studied.

Measurements were performed during times of typical activity. The temporal variation of the indoor channel has been experienced for motion around both transmitting and receiving antennas.

4. Data Analysis and Results

4.1. Signal Fading

The variation of signal strength over small distances – called fast fading – is the main reason that degrades the performance of an indoor system because of the rapid changes in signal level. Figure 3 shows these typical signal fluctuations, known as envelope fading, over 2 m back and front antenna displacement, for *Tx-Rx* separation distance 30 m and 50 m. In most cases, data analysis indicated that the dynamic range seen by a mobile over a small distance is typically 5–20 dB.

Fast fading is usually reported in terms of the signal level from the local average, and the associated statistics, which are very important for calculating the reliability of a radio access design. Although the spacing of the samples in time may vary, depending on the speed of

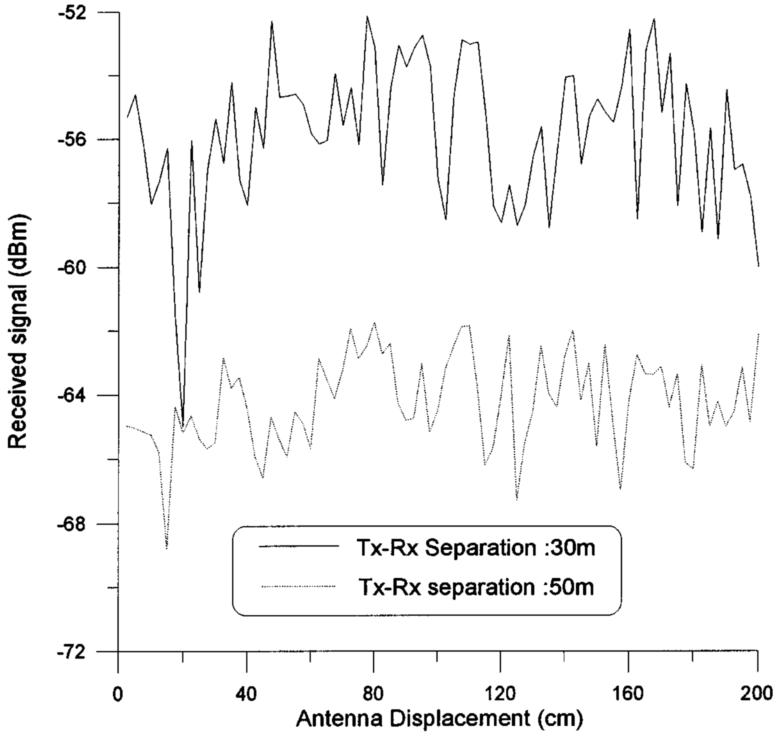


Figure 3. Received signal envelope in 2 m track antenna displacement for *Tx-Rx* separation 30 m and 50 m.

the mobile cart, the fast fading statistics do not change, providing that the sampling rate is uniform.

Amplitude fading in a multipath environment may follow different distributions on the area covered by measurements. Cumulative Distribution Functions (CDF's) normalized about the mean of the received signal strength were computed from the collected data, for each recorded measurement data set and were plotted against the theoretical Rayleigh and Rician distribution, for comparison.

Rayleigh distribution describes small scale rapid fadings in absence of a strong received signal component. The Rician distribution describes the case in which the signal is the sum of two vectors: a scattered Rayleigh vector and a vector representing the fixed path. The latter, is a strong dominant signal that exists either in strong LOS conditions or when a path goes through much less attenuation compared to other arriving components [3]. In indoor environments the addition of the random multipath signals can only be approximated by a Gaussian distributed signal, and therefore the envelope of the addition of the LOS ray and random rays is mainly approximated Rayleigh or Rician distributed. Data analysis proved that the standard deviation of the measured signal level often exceeds 5.6 dB which is the theoretical upper bound of Rayleigh and Rician distribution.

We firstly analyze the corridor data measurement at different distances from the transmitting site. The standard deviation of the measured signal level at different distances from the transmitter is illustrated in Figure 4.

It can be observed that the standard deviation of the signal level is relatively small, when the receiver is close to the transmitter, (the direct power component is dominant), and increases

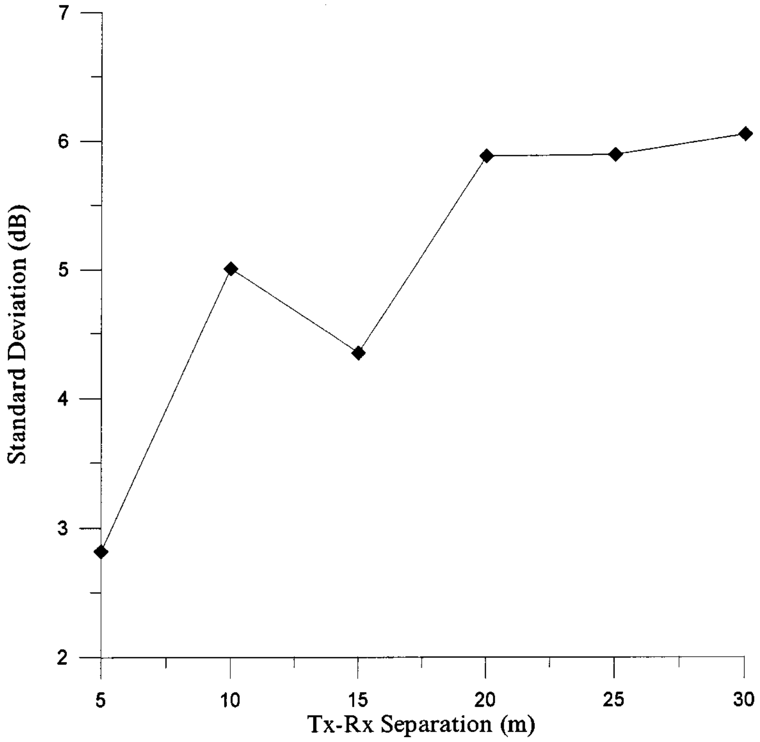


Figure 4. Standard deviation of signal level in corridor at different distances.

(close to 6 dB) as the power contribution of the random rays is enhanced, when the receivers moves further away from the transmitter.

In order to determine which distribution provides the best fit, the Mean Square Error (MSE) test was employed. The MSE between the experimental and the theoretical distribution was calculated. The theoretical distribution with the smallest MSE provides the best fit. Parameters of the theoretical distributions were estimated from the data using the moment method, in which the two first moments are equated with the corresponding empirical moments estimated from the data [4].

Analysis of the small scale fading indicates, that the experimental results compares well with Rayleigh distribution, in most cases. A limited number of LOS conditions exists (no strong LOS conditions) due to the particular interior configuration. A significant amount of received power arrives from additional paths that are believed to be from multiple reflections and diffraction on the surrounding obstacles.

Figure 5a depicts the Cumulative Distribution Function computed from the recorded data in NLOS conditions, compared with Rayleigh.

It has been found that Rayleigh distribution is consistently better than lognormal distribution when used to fit the received signal level collected in hallway. Thus, we can conclude that the fast signal level from mean in hallways, can be well approximated as a Rayleigh distributed random variable with a standard deviation of 5.3 dB.

A Rician CDF corresponding to K ratio of 2 dB is shown in Figure 5b, providing good fit to the experimental data, when LOS conditions were established and the receiver was at the other end of the corridor (relative to the transmit system), where there is a dominating reflection in the back wall.

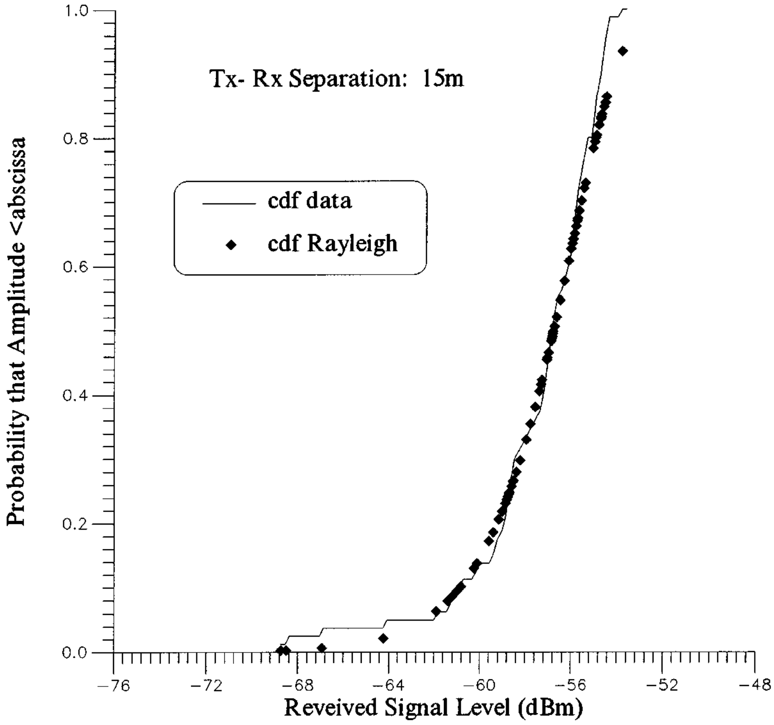


Figure 5a. Cumulative Distribution Function for Envelope Fading compared with Rayleigh distribution.

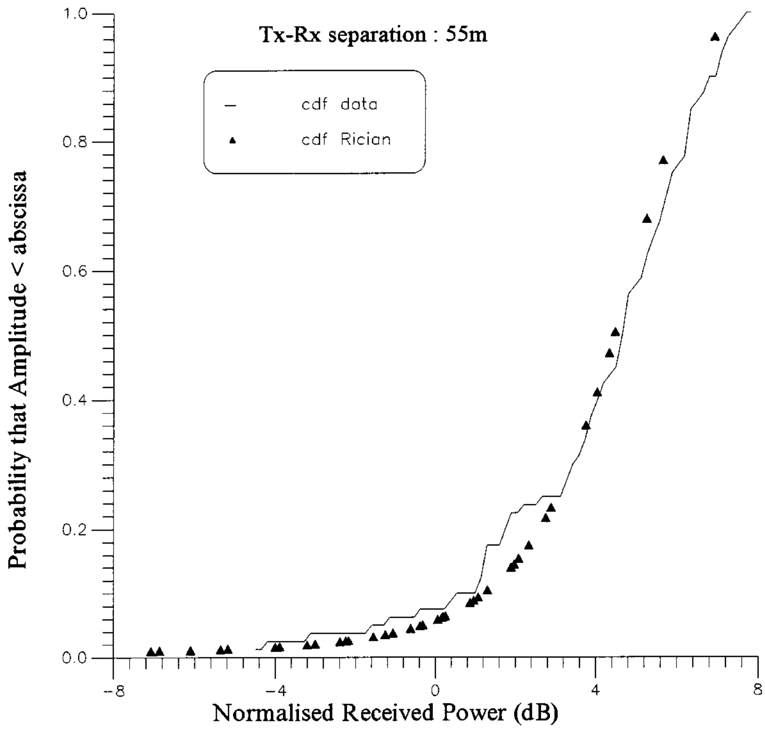


Figure 5b. Cumulative Distribution Function for Envelope Fading compared with Rician distribution.

Table 1. Statistics of recorded data during personnel activity.

Data set	1	2	3	4	5
Personnel movement	2	2	2	3	3
Maximum (dBm)	–49.8	–55.3	–56.2	–50.5	–51.5
Minimum (dBm)	–61.4	–75.5	–74.9	–74.2	–59.6
Mean (dBm)	–55.6	–64.5	–65.6	–62.1	–55
Std. dev. (dB)	1.4	1.51	1.48	2.2	2.39
Fading depth (dB)	2.5	3.7	4.6	6.2	5.5

The cumulative distribution of a fast fading signal level, in corridor environment is also used to estimate the radio link availability. It was found that the probability of fades deeper than 6 dB is 15% for signal at all distances, except at 10 m transmitter receiver antenna separation.

4.2. Dynamic Effects of Moving People

Several data sets were collected in the hallway with different Transmitter–Receiver antennas separation, during personnel activity in the vicinity of the two antennas. During each measurement recording the carts were at fixed locations and readings, up to 5 minutes intervals, were recorded in data files. Personnel activity during working hours affects the multipath signals so that the received signal envelope varies with respect to the reference value established under quiescent conditions [2]. Figure 6a presents a typical plot in a 30 seconds time period where deep fades of a 10 dB range occurred, lasting only a few seconds.

The transmitting and receiving antennas were fixed at same heights above the ground, as previously quoted and up to 5 people were moved in the vicinity of the two antennas (2–3 m far away from them) during the entire time period. Table 1 presents the basic statistics of 5 data sets collected, during personnel activity. The low standard deviation seems to correlate with the amount of people activity in the region of propagation during the measurement time.

The cumulative distribution function of data in NLOS condition superimposed with the cdf of Rayleigh distribution are shown in Figure 6b, and as it can be seen, the data can be approximated by Rayleigh distribution. The percentage of deep fades is generally low and it depends on the amount of people activity during the measurement span period. The standard deviation seems to correlate with the amount of activity by people.

In environment with LOS conditions, the temporal short term fading has been observed to follow Rice distribution with a K factor within the range 2–10 dB. Furthermore, statistical tests were additionally performed to the data measurements using Laplacian distribution function. It was found that fading rate caused by personnel movement, in some cases can be approximated by the above distribution with a standard deviation of 7 dB/sec. Weibull and Nakagami distributions were also found suitable in predicting the temporal fading variability as also quoted in [11].

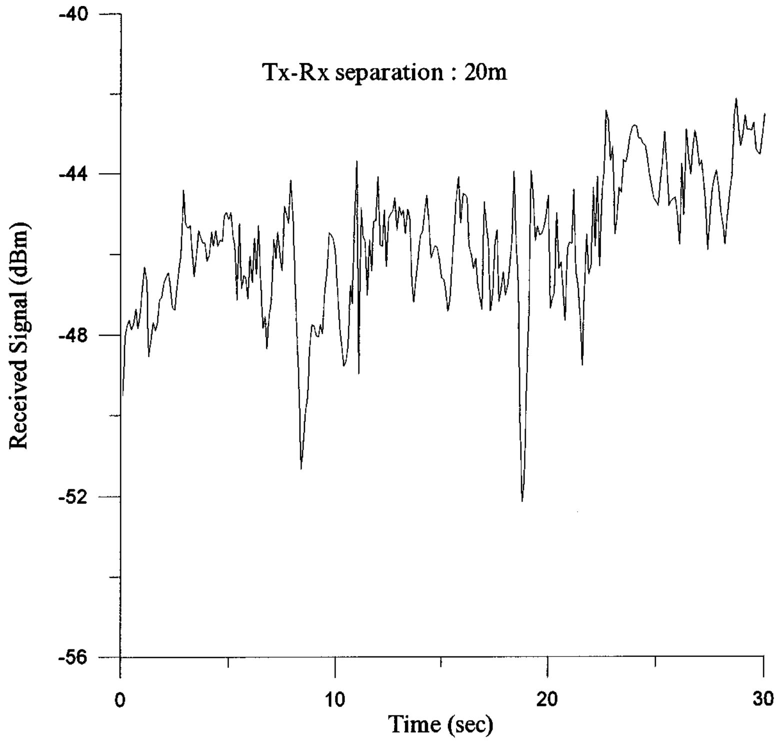


Figure 6a. Received Signal Level due to personnel movement in 30 seconds time period).

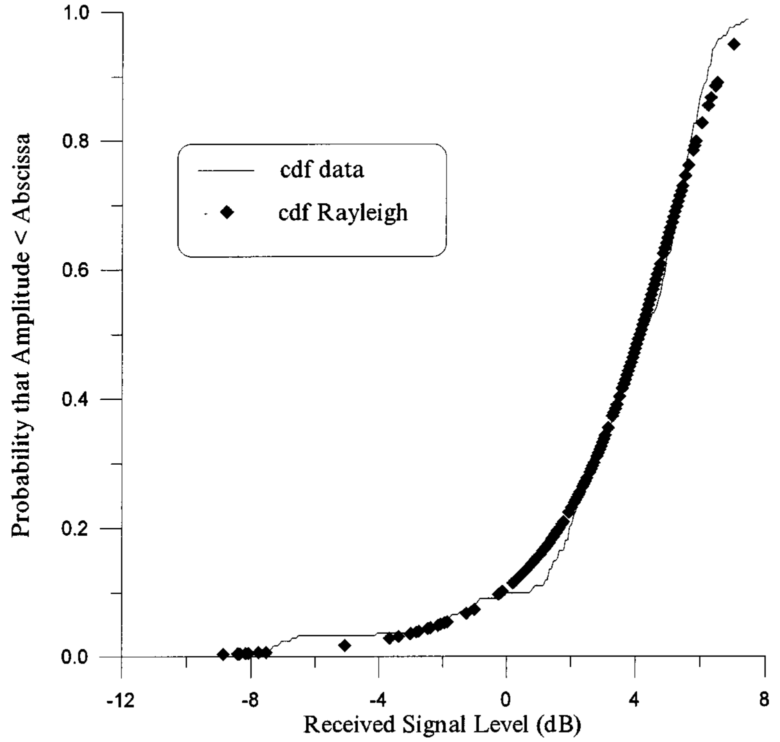


Figure 6b. Cumulative Distribution Function for Temporal Fading compared with Rayleigh distribution.

4.3. Path Loss Models

In order to classify the typical propagation conditions we estimted the average path loss for all measured runs in all the different scenarios that we have described. For every measurement location the mean path loss of the measured signal was estimated and plotted versus distance. Path loss generally increases logarithmically with distance. The simplified proposed Single Slope Model (1SM) can be described by the following equation:

$$L(\mathrm{dB}) = L_0 + 10n \log d \,, \tag{1}$$

where S: represents path loss at 1 m intercept point (clutter loss), n: the propagation loss exponent, d: distance between *Tx-Rx* in meters.

In practice, values of n, that have already been derived by other researchers [1, 6], were found around 2 (open hallways within buildings). The measured data were linearly fitted in order to derive the mathematical expression of the model mentioned previously (Equation (1)).

However, a multi-wall model has been proposed [5, 12] that gives the path loss as the free space loss, added with losses dictated by walls and floors, which obstruct the direct ray between transmitter and receiver. The above model is given by the following analytical formula:

$$L = L_{FS} + L_C + \sum_{i=1}^{I} K_{wi} L_{wi} + K_f^{\left[\frac{k_f+2}{k_f+1} - b\right]} L_f \,, \tag{2}$$

where:

L_{FS}:	free space loss between Transmitter and Receiver
L_C:	constant loss
K_{wi}:	number of penetrated walls of type I
k_f:	number of penetrated floors
L_{wi}:	loss of wall type I
L_f:	loss between adjacent floors
b:	empirical factor
I:	number of different wall types

The sum in the above equation represents the total wall loss as a sum of the walls between transmitter and receiver. Loss factors are computed as model coefficients derived by the optimization with the measured data. Normally walls have been categorized in two types: Light Walls made by brick, plasterboard, wood, simple glass or light concrete, and heavy walls made by brickstone or reinforced concrete. Corridor measurements have been used to evaluate the path loss model, previously described. The results are shown in Table 2.

The following cases are also considered:

(i) *Tx-Rx* in the same floor with LOS condition.

(ii) *Tx-Rx in the same floor without LOS conditions between them (intervening closed door).* In this case propagation is influenced by shadowing obstacles (door closed). A typical result, obtained fitting the data is shown in Figure 7a.

Table 2. Path loss parameters and standard deviation in NLOS condition.

Multi wall model				
$L_{w1(\text{dB})}$	$L_{w2(\text{dB})}$	$L_{fl(\text{dB})}$	b	Standard deviation σ (dB)
2.5	5	26.5	0.4	5.5

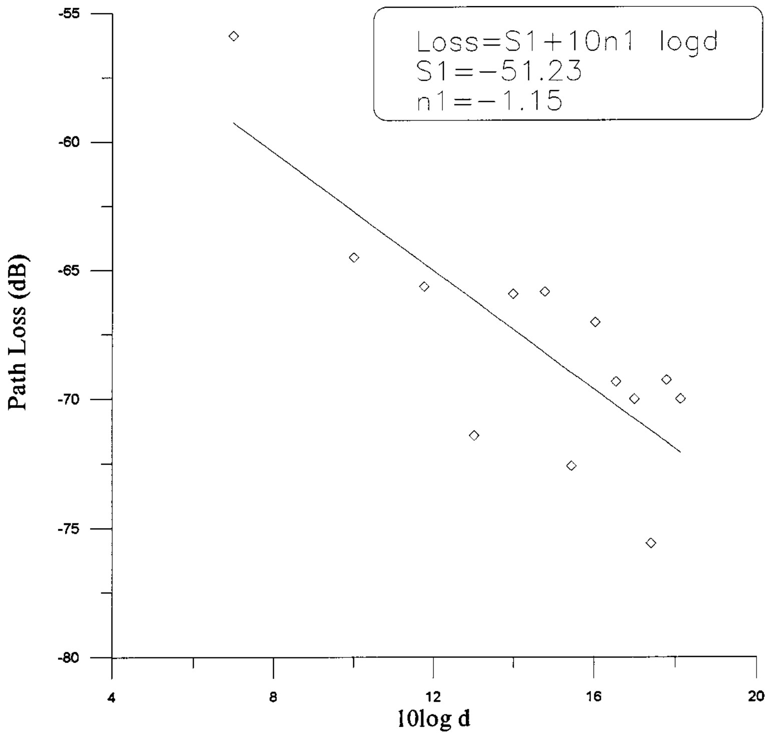


Figure 7a. Tx-Rx in the same floor without LOS conditions between them (intervening closed door).

(iii) *Tx-Rx in the same floor – path loss model due to temporal fading.* A typical result, obtained fitting the data is shown in Figure 7b.

Table 3 summarizes the above path loss parameter values derived for the previous different categories at 1800 MHz.

4.4. RESULTS

The measurements that have been taken in the main corridor show signal re adings higher than in free space. This is due to reflections that occur when the geometry of the location, associated to a line of sight, favors a *wave guided* effect. It is reported [7] that when a wave encounters an obstacle, there will be reflections which can be canalized by certain wall configurations and which bring about significantly higher signal levels that would be in the case with free space propagation. This effect has been observed in long and narrow corridors [8].

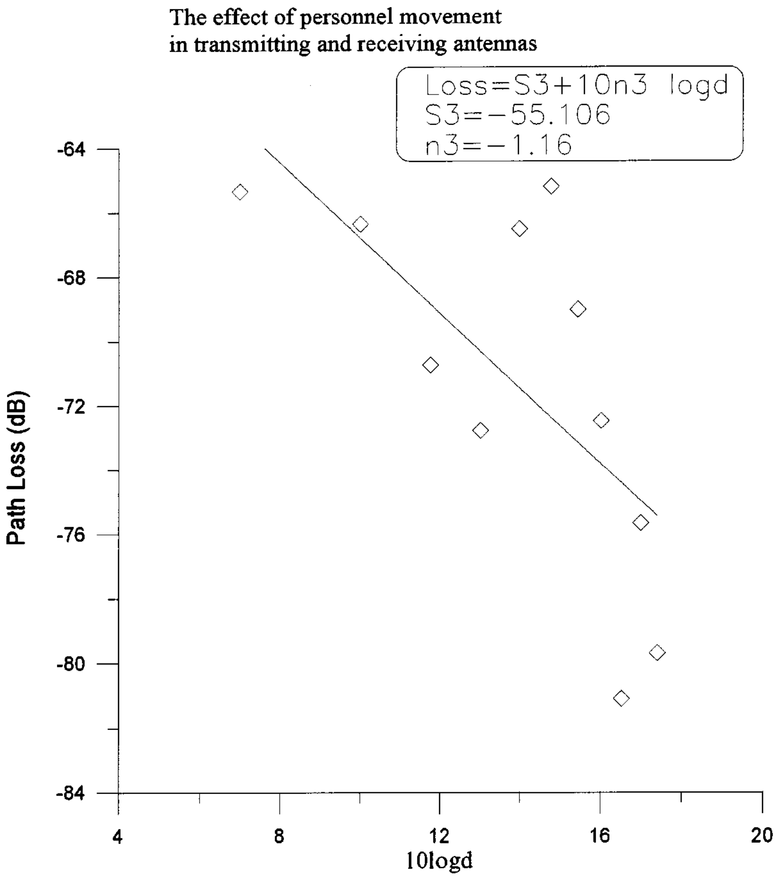


Figure 7b. *Tx-Rx* in the same floor – path loss model due to temporal fading.

Figure 7. Results for loss model – door open, personnel movement.

Table 3. Path loss parameter values and standard deviation.

Path loss model parameters			
	Clutter loss *S*	Propagation exponent *n*	Standard deviation σ (dB)
Case 1			3.5
LOS conditions	–51.23	–1.15	
Case 2			3.8
Door closed	–54.80	–1.10	
Case 3			4.9
Personnel movement	–55.10	–1.16	

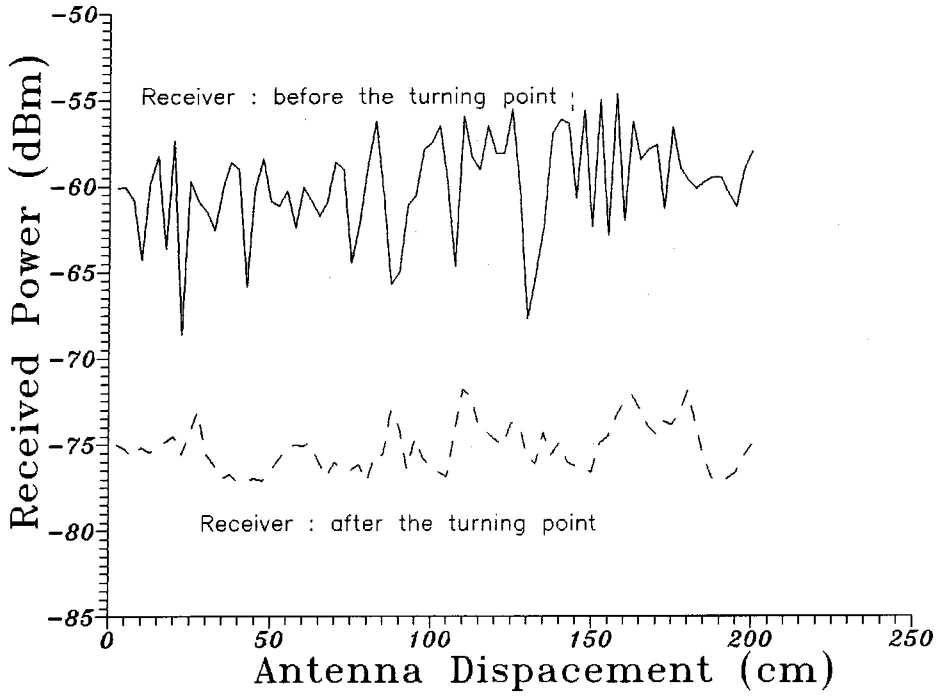


Figure 8. Comparison of envelope fading before and after the turning point in the corridor.

For the propagation measurements in the main corridor the power decay factor n was found to be smaller than in free space which is reported to be equal to 2. This is, because long and narrow corridors with walls up to the ceiling result in a strong wave guided effect.

The corner effect is shown in Figure 8. It has been observed that diffraction areas are important when turning from a corridor to an other corridor. The dynamic signal range drops from 10 dB (2 m before the turning point) to 5 dB (2 m after the turning point). The decrease of the average signal experienced when turning the corner is 15 dB. As it can be seen from Figure 8, the received signal 3 m after the turning point is almost continuous over small periods [9].

At the one floor separation case in Figure 9, there is strong evidence that signal is beign channeled up by stairwells and lift shafts.

The reduction of path loss exponent n could possibly be explained by the wave guided effect introduced by the stairs. The following should be taken in consideration: as the signal is crossing the different obstacles in order to be significant to the relative transmission, the building configuration provides ways to bring a strong signal near the receiving site. For the present case this can be the adjoining floors which are connected through staircases, along which the signal is transmitted [8].

Losses for the one floor separation (especially in the case of the transmitter away from the stairs) are significant, because of the leakage radiation along the line joining *Tx*-*Rx* [10].

5. Conclusions

Results at 1800 MHz propagation measurements on typical indoor environment were discussed. The signal behavior in corridors has been studied. During CW propagation experi-

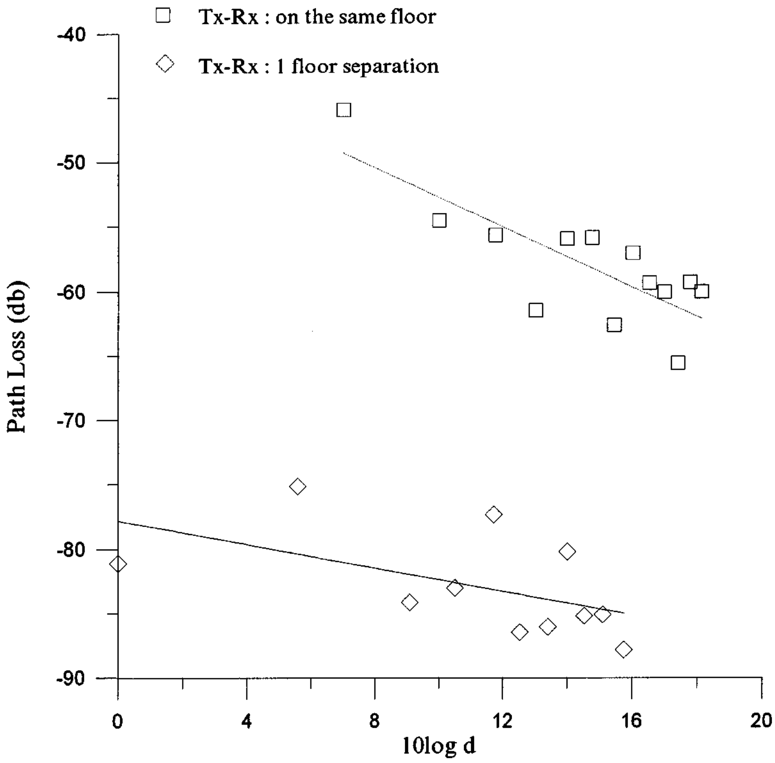


Figure 9. Comparison of measurement results for corridor and floor cases.

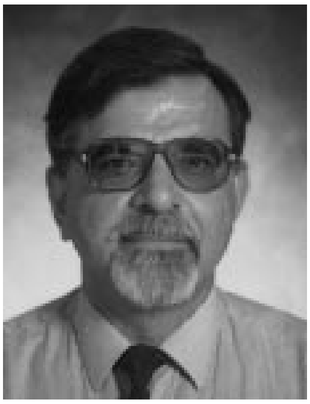
ments described in this paper, a number of important characteristics of indoor radio channels were determined. The spatial fluctuations of received signal envelope were measured. The temporal fading, when people were moving along the corridor was observed. Path loss models have been derived in LOS and NLOS cases. A summary of the best fitting parameters is given and quantitative models are proposed. Finally, the statistical analysis based on the empirical data indicate that Rayleigh and Rician distributions describe the indoor short term fading data. In clear LOS conditions K factor up to 10 dB was estimated. Short term fading was found to be approximated by lognormal distribution with average $\sigma = 4.5$ dB. People in indoor propagation environments can cause a substantial amount of fading to the received signal. Fades with more than 10 dB magnitude were observed in our measured data sets. The standard deviation of the fading signal correlates with the amount of people activity in the vicinity of the radio wave propagation. The distribution of the fading signal can be approximated with Rayleigh and Laplacian distributions. Furthermore, steeper fading is caused when personnel activity increases.

References

1. F.C. Owen and C.D. Pudney, “Radio Propagation for Digital Cordless Telephones at 1700 MHz and 900 MHz”, Electronic Letters, Vol. 25, No. 1, 1989.
2. Robert J.C. Baltitude, “Measurement Characterization and Modeling of Indoor 800/900 MHz Radio Channels for Digital Communications”, IEEE Communications Magainze, Vol. 25, No. 6, 1987.
3. William C.Y. Lee, “Mobile Communications Design Fundamental”, Wiley-Interscience Publication, 1993.
4. H. Hashemi, “The Indoor Radio Propagation Channel”, Proceedings of the IEEE”, Vol. 81, No. 7, 1993.

5. J.M. Keenan and A.J. Motley, "Radio Coverage in Buildings", British Telecom Technology Journal, Vol. 8, No. 1, pp. 19–24, 1990.
6. J.D. Parsons, "The Mobile Radio Propagation Channel", Pentech Press, Publishers, London, 1992.
7. Jean-François Lafortune and Michael Lecours: "Measurement and Modeling of Propagation Losses in a Building at 900 MHz", IEEE Transactions on Vehicular Technology, Vol. 39, No. 2, 1990.
8. Purification Bartolome and Gema Vallejo, "Site Measurements for Installation of an Indoor Radio Communication", Proceedings of the 43th Vehicular Technology Conference 1993, pp. 57–60.
9. Theodore S. Rappaport and Clare D. McGillem, "UHF Fading in Factories", IEEE Journal on Selected Areas in Communications, Vol. 39, No. 2, 1990.
10. S.E. Alexander, "Characterizing Buildings for Propagation at 900 MHz", Electronics Letters, Vol. 18, No. 21, pp. 313–314, 1982.
11. H. Hashemi, "A Study of Temporal and Spatial Variations of the Indoor Radio Propagation Channel", Proceedings of 5th Personal Indoor Mobile Radio Conference 1994, The Hague, pp. 127–134.
12. C. Tovernik, J.-E. Berg and F. Lotse, "900 MHz Propagation Measurements and Path Loss Models for Different Indoor Environments", Proceedings IEEE Vehicular Technology Conference 1993, New Jersey, U.S.A.

Nikolaos Papadakis received the Diploma in Electrical Engineering from the National Technical University of Athens, Greece, in 1992. He is currently working towards the Ph.D. degree. He has participated in RACE II and COST projects. His main fields of interest involve mobile radio propagation channel modelling and simulatiion in indoor and outdoor environment. He is also a member of the Technical Chamber of Greece.



Dr. Philip Constantinou received the Diploma in Physics from the National University of Athens in 1972, the Master of Applied Science in Electrical Engineering from the University of Ottawa, Ontario, Canada in 1976 and the Ph.D. degree in Electrical Engineering in 1983 from Carleton University, Ottawa, Ontario, Canada. From 1976 to 1979 he was with Telesat Canada as Communications System Engineer. In 1980 he joined the Ministry of Communications in Ottawa, Canada where he was engaged in the area of Mobile Communication. From 1984 to 1989 he was with the National Research Centre Demokritos in Athens, Greece where he was involved in several research projects in the area of Mobile Communications. In 1989 he joined the National Technical University of Athens where he is currently Professor. His current research interests includes Personal Communications, Mobile Satellite Communications and Interference Problems on Digital Communications Systems.

Anastasia Economou received the Diploma in Electrical Engineering from the National Technical University of Athens, Greece, in 1995. She is currently involved in Digital Communication Systems and Mobile Radio links. She is a member of the Technical Chamber of Greece.

Ioanna Fotinopoulou received the Diploma in Electrical Engineering from the National Technical University of Athens, Greece, in 1995. She is currently involved on propagation modelling in mobile radio systems and Simulation on Communication Systems. She is a member of the Technical Chamber of Greece.