Statistical characterisation of a partitioned indoor radio channel

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Indexing terms: Radio data communication, Multipath propagation, Wireless local area networks

Abstract: The relationship between behaviour of radio wave propagation and building architecture in a small indoor environment is examined. A site is divided into three partitions on the basis of number of walls between transmitter and receiver. Wideband radio propagation measurements are performed in each partition and the data analysed to compare channel characteristics in the partitions. Comparisons include the RMS delay spread values and its short time variations, values of the distance-power law gradient and short time fluctuations of received power. The statistics of path arrivals and amplitudes, used for simulation of the measured channel profiles, are also analysed and compared for the partitions. Simulation model parameters in a partition are described by mathematical fits and are related to the number of walls between transmitter and receiver.

1 Introduction

In recent years, the possibility of using radio for data and voice communications within offices, manufacturing floors, warehouses, hospitals, college campuses and convention centres [1, 2] has become an attractive proposition. Indoor radio communication is being studied for applications such as wireless local area networks (WLLANs) wireless PBX systems, universal portable phone and wireless security systems [3, 4]. Most of the studies in indoor radio propagation so far have involved one central base station to provide broad coverage. In such systems a direct line of sight to the base station antenna is often unavailable and studies have shown that channel characteristics differ in LOS (line of sight) and OLOS (obstructed line of sight) environments [5, 6]. Depending on the location of the user, significant multipath signal components with excess delays ranging to 480 ns can be received. It has been shown that these long-delayed paths might cause the RMS delay spread to increase more than 100 ns [5, 7], causing intersymbol interference and hence performance degradation for wideband communications. The channel parameters such as RMS delay spread and multipath power which are important in ISI and coverage considerations can vary significantly in LOS and OLOS environments on the same floor, even when the distances are of the same order of magnitude.

The demand for high-speed data transmission for WLLANs requires wideband communications. The existing wideband wireless local area networks provide short working ranges of the order of tens of metres, at data rates of several Mbit/s. The performance of such high-speed systems are dependent on the building architecture and number of walls between transmitter and receiver. The objective of this paper's to determine the changes caused in the channel parameters and characteristics by the number of walls between transmitter and receiver. A floor of a building is chosen and three partitions, one in LOS and two in OLOS environments, are identified on this floor on the basis of a similar geometry observed amongst all possible terminal locations in that partition. All the locations in the LOS partition had a direct line-of-sight between the transmitter and receiver. Multipath profiles of the received signal are gathered during three independent sets of wideband propagation measurements in the partitions. The data are analysed to study and compare the RMS delay spread, multipath power and statistics of path arrivals and path amplitudes for these partitions. A simulation model based on channel statistics for arrival and amplitude of paths [8] is used to regenerate multipath profiles in different partitions. The results of simulation are compared to those obtained empirically. Model parameters involved in simulation are fitted to mathematical equations and compared for the three partitions identified on this floor. The effect of the number of walls is determined on the model parameters. Short time variations in the indoor radio channel which occur frequently due to local movements of the terminals around a given location are also analysed from the data collected.

2 Description of the measurements

2.1 Measurement setup

The setup used for the multipath propagation experiments is described in Reference 5. It involves modulation of a 910 MHz signal by a train of 3 ns pulses with 500 ns repetition period provided by a pulse generator. The modulated carrier feeds a 45 dB amplifier and the output is transmitted with a quarter-wavelength antenna placed

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about 1.5 m above the floor level. The stationary receiver uses a similar antenna to capture the radio signal. This is followed by a step attenuator and a low-noise high-gain ($\simeq$60 dB) amplifier chain. The signal is demodulated using an envelope detector whose output is displayed on a digital storage oscilloscope coupled to a PC with instrument bus (GPIB). The components used in the measurement setup have a flat frequency response in the 0.9 GHz range. The dynamic range of the receiver display is limited to 25 dB owing to the linear scale on the digital storage oscilloscope. However, the actual dynamic range of the measurement setup is more than 100 dB, achieved by manually adjusting the step attenuators at the receiver. A coaxial cable was required to trigger the oscilloscope from the pulse generator of the transmitter to guarantee a stable timing reference. This measurement system is noncoherent and does not include the phase associated with the arriving paths [9, 10]. These phases are reasonably assumed *apriori* to be statistically independent uniform random variables over $[0, 2\pi)$ [9, 10]. The measurement system was tested by conducting a back-to-back test, in which the transmit and receive systems were connected by coaxial cable, to ensure that there were no noise or excess delay components resulting from imperfections in the measurement system [5].

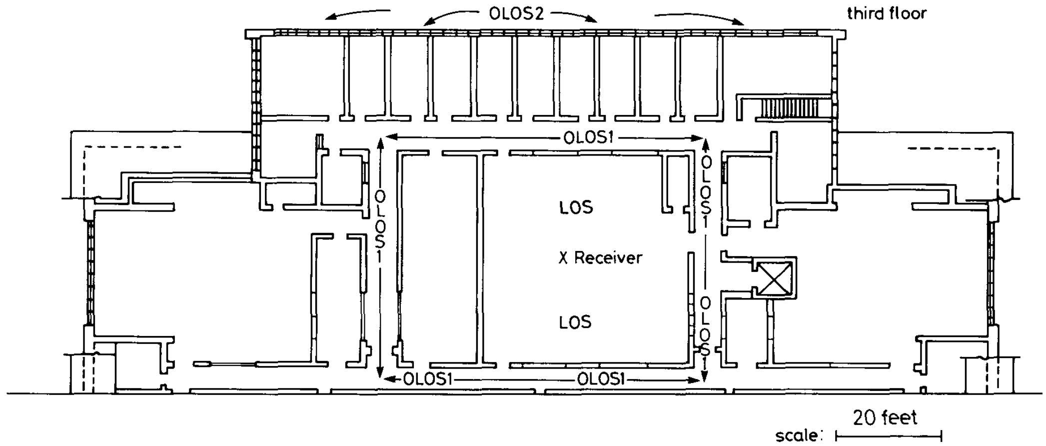

Fig. 1 *Plan of third floor of Atwater Kent building in Worcester Polytechnic Institute*

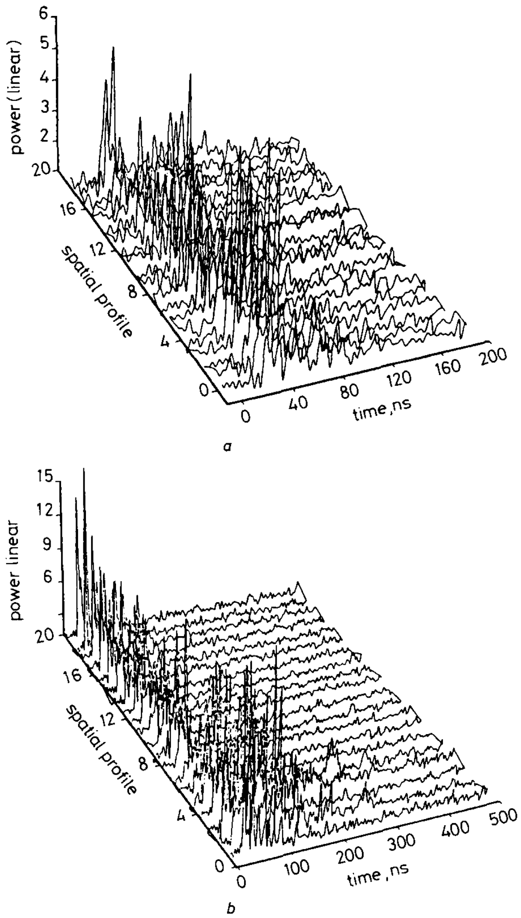

Fig. 2 *Three-dimensional plots of the 20 multipath profiles measured at one LOS and one OLOS location*

a LOS location
b OLOS location

2.2 Measurement sites and data base

All the partitioned measurements reported here are made with both transmitter and receiver stationary on the third floor of the Atwater Kent Laboratories at the Worcester Polytechnic Institute. The plan of the third floor of this building is shown in Fig. 1. The floor is divided into three partitions, one in LOS and two in OLOS environments, on the basis of a similar geometry observed amongst all possible terminal locations in that partition. A similar geometry means the number of walls between the base station and transmitting antenna and objects/interferers surrounding the locations. For all the measurements, the receiver was located in the centre of the third floor, inside an electronics laboratory comprising typical equipment such as oscilloscopes, voltmeters and power supplies on wooden benches. The LOS environment consists of the set of measurements made at all possible locations inside this electronics laboratory. The first OLOS environment (OLOS1) includes all the transmitter locations on the corridor separated from the electronics laboratory by at least one wall with some windowed glass. The second OLOS environment (OLOS2) consists of all the locations inside the office rooms located on the third floor, and separated from the electronics laboratory by at least two walls having windowed glass. The walls are made of plasterboard with metal studs.

The distance between the transmitter and receiver varies between 1 and 10 metres in the LOS environment and between 7 and 20 metres in the OLOS environments. At each of the transmitter locations the antenna is moved slowly around a 0.5 m square and 20 multipath profiles are stored in the digital oscilloscope to be transferred later to the computer. The number of measurement locations in the LOS, OLOS1 and OLOS2 partitions were 50, 40 and 70, respectively, resulting in a total of 3200 profiles. Care was taken so that direct line-of-sight was not broken for any of the 20 profiles collected from an LOS location. Fig. 2 shows the three-dimensional plots of the 20 multipath profiles obtained at one LOS and one OLOS location. The ordinate axis has power on a linear scale.

2.3 Data analysis

In measurement systems, noise or equipment imperfections could be mistakenly identified as excess delay components in the multipath profile. For this reason, measured data from the profiles must be run through a thresholding technique to ensure that noise and other errors are not erroneously considered in the analysis. For the measurements presented in this paper, an upper limit was chosen for the observation window, after ensuring that there were no genuine paths beyond this limit. This limit was 500 ns for the OLOS environments and 200 ns for the LOS environment. For data analysis, the arrival times in a measured profile is divided into 5 ns bins and a threshold level is employed to detect a genuine path in any bin. Since the RMS delay spread values are very sensitive to this threshold level, care was taken to ensure that the threshold value chosen was above the noise level in each profile. Any received profile in which only one path could be detected leading to a zero RMS delay spread value was hence discarded from the analysis. Thus, a total of more than 2000 profiles are considered from the three regions.

3 Preliminary results

3.1 RMS delay spread calculations

For radio communication in the indoor environment, the RMX delay spread of the channel gives a measure of performance degradation in the system, caused by intersymbol interference. It is an important parameter for determining data-rate limitations of standard and equalised modems [11]; it is used for performance prediction of spread spectrum modems [12] and it can be shown that it is important in coverage considerations [13]. The RMS delay spread is the normalised value of square root of the second central moment of the multipath profile. This parameter was calculated, for all profiles collected from each partition. Fig. 3 shows the complementary CDFs of the computed RMS delay spreads of all the measured profiles from the three partitions. The Figure shows that the LOS environment exhibited lower values for the RMS delay spread than the OLOS environments. This could be attributed to the presence of more number of scatterers (and hence more paths) in OLOS than in LOS environments. The minimum, median and maximum values of the RMS delay spread observed in the OLOS environments were all greater than those seen in LOS environments. The median RMS delay spread in the LOS partition was 8.3 ns, as compared to median values of 14.1 and 22.3 ns for the OLOS1 and OLOS2 partitions, respectively.

The standard deviation of the RMS delay spread values were 7.14, 10.36 and 15.12 ns for the LOS, OLOS1 and OLOS 2 partitions, respectively. The higher standard deviation values in the OLOS partitions are an indication that coverage by an operational system in such locations, would be less uniform. Even at the worst locations in the OLOS environments, the RMS delay spread did not exceed 80 ns.

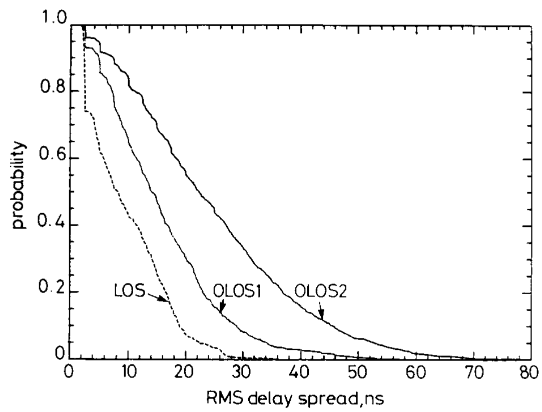

Fig. 3 *Measured complementary distribution functions of RMS delay spreads in the three partitions*

3.2 Multipath power calculations

For a given location of the transmitter and receiver, the total received power in a multipath profile is described [9, 14] by the multipath power. The multipath power is the sum of all the powers contained in all the detected paths in a profile. The received multipath power is plotted against the distance between transmitter and receiver and the slope of the best-fit line gives the distance-power law gradient α. This gradient is useful in characterising the signal decay or the path loss, inside buildings (α is reported to be between 1.8 and 5.0 for indoor environments [6, 15]). Measurements in hallways of office buildings with both the transmitter and receiver located in the hallway have yielded gradients between 1.2 and 1.3 [9].

The multipath power was calculated for every received profile in a partition and the distance power law gradient α estimated for every partition. This value was 1.6 for the LOS, 2.1 for the OLOS1, and 4.5 for OLOS2 regions. The OLOS partitions were separated from the receiver by at least one wall and thus path attenuation was more than in case of the LOS partition. This caused α to increase. The standard deviation of the multipath power values were 2.5, 3.1 and 4.75 dB for the LOS, OLOS1 and OLOS2 partitions, respectively. As in case of the RMS delay spread, the higher standard deviation values of multipath power, in the OLOS partitions are an indication that coverage by an operational system in such an area, would be less uniform. In such instances, transmitter power could be raised or operating ranges reduced.

4 Short time variations

This kind of variations deal with the changes in the radio channel, observed over a short time around a given area, at different locations of the terminal. Such variations are studied by analysing the data collected from the partitioned measurements [16]. The channel parameters investigated are the RMS delay spread and the total multipath power. For the purpose of comparison, absolute values of the power are not required; so it has not been determined for the data presented and only relative values of the multipath power are given.

4.1 Variations in RMS delay spread

The RMS delay spread is computed for each received profile at every location of the transmitter in the three environments. The variations of the RMS delay spread amongst the 20 received profiles from around each square location of side 0.5 m was calculated. Fig. 4 shows the complementary cumulative distributions of the variations in RMS delay spread observed at every location, for the three environments. The maximum variations in the RMS delay spread for the LOS environment were about 17 ns, while for the OLOS1 and OLOS2 environments, they were about 24 and 38 ns, respectively. The average variations in the RMS delay spread for the LOS environment were 12.9 ns, while for the OLOS environments they were 19.2 and 29.0 ns, respectively. Note that the values for the variations in RMS delay spread, mentioned above, are absolute.

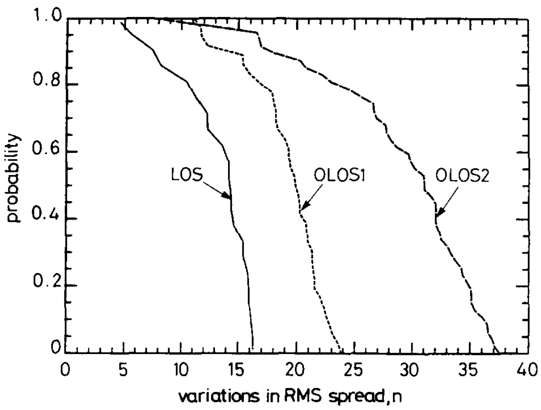

Fig. 4 *Measured complementary cumulative distributions of short time variations in RMS delay spread for the three partitions*

A better understanding is gained by computing the variations as a fraction of the average RMS delay spread determined at every test location. Fig. 5 shows the complementary cumulative distributions of the ratio of variations in RMS delay spread to the average RMS delay spread determined at every test location, for the three environments. The ratios, indicating spatial variations in RMS delay spread around each square location, vary from about 0.6 to 2.0 for both the OLOS channels and from 0.3 to 3.8 for the LOS channel. Note that though the LOS channel exhibits higher ratios, the absolute values of the RMS delay spread observed in the LOS channel are lower than in the OLOS channels (see Fig. 3). The behaviour of the variations in RMS delay spread with distance between transmitter and receiver was also studied. Though there was some increase in the variations with distance, no definite relationship could be established.

4.2 Fluctuations in multipath power

The multipath power was computed for each received profile at every location of the transmitter in the three environments. The fluctuations of the received multipath power amongst the 20 received profiles around a 0.5 m square, was calculated at every location. Fig. 6 shows the cumulative distributions of the fluctuations in multipath power for all the environments. The range of fluctuations were about the same and less than 14 dB for both the OLOS environments, while they were less than 6 dB for the LOS environment. Such spatial fluctuations in multipath power is thus more in OLOS than in LOS channels. This is because there are usually more paths in an OLOS than in an LOS profile and hence, fluctuations also occur in more paths in an OLOS profile. Fig. 7 shows the fluctuations of the received multipath power against the distance between the transmitter and receiver. Though for

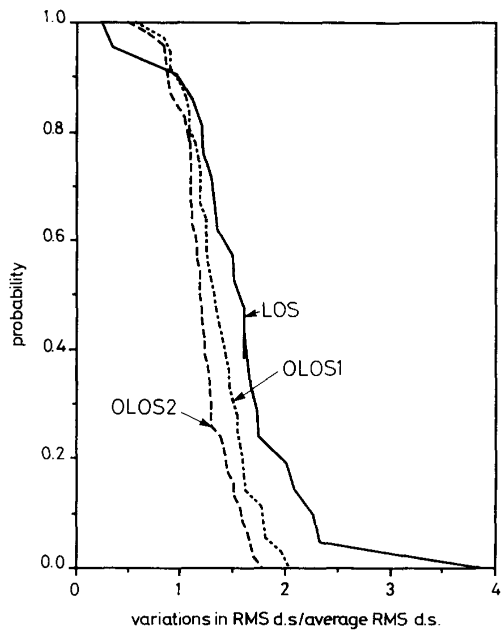

Fig. 5 *Measured complementary cumulative distributions of ratio of short time variations in RMS delay spread to average RMS delay spread at each location, for the three partitions*

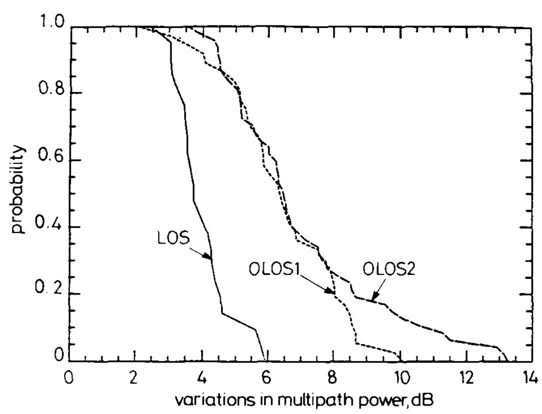

Fig. 6 *Measured cumulative distributions of short time fluctuations in multipath power for all environments*

fixed locations of terminals, the multipath power is highly correlated [9, 14] with distance, no definite correlation between such global fluctuations in multipath power and distance could be established.

5 Statistical parameters for modelling and simulation in the partitions

To regenerate channel multipath profiles with a computer simulation, statistics for the path arrivals and amplitudes should be analysed. It is shown in Reference 8 that there are considerable discrepancies in comparing the empirical arrival of the paths to a Poisson process.

However, the modified Poisson process is shown to closely fit the arrival of the paths. For the modified Poisson process, the presence of a path in a given bin is greatly influenced by the presence or absence of a path in

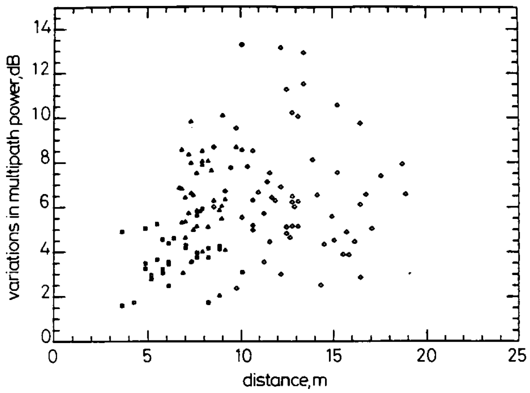

Fig. 7 *Short time fluctuations of received multipath power against distance between transmitter and receiver*

□ LOS
△ LOS1
◇ OLOS2

the earlier bins [17, 18]. The probability of having a path in bin i is given by λ_i, if there was no path in the $(i-1)$th bin, or by $K_i \lambda_i$, if there was a path in the $(i-1)$th bin. The optimised parameters K_i and λ_i can be computed from the empirical data and then be used to regenerate the path arrival times.

Using the parameters of modified Poisson process for each partition, the path arrival times were simulated. The path occurrence probability indicates the likelihood of existence of a path in a bin or at a given delay. The probability of path occurrence as obtained from these simulated profiles is compared to that obtained from the empirical data. Fig. 8 shows the comparison for one of

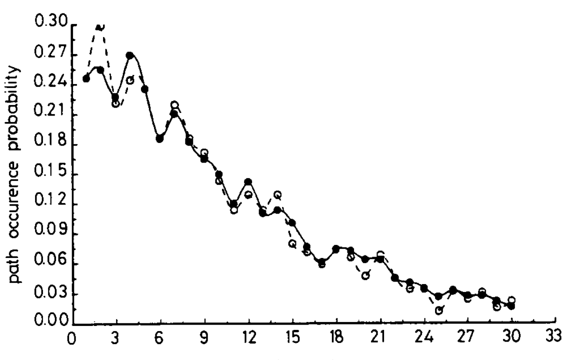

Fig. 8 *Comparison between empirical and simulated path occurrence probabilities for OLOS2 partition*

● empirical
○ simulated

the three partitions. The probabilities are plotted as continuous curves for clarity, though they have values at only integer bin numbers. The experimental and the simulated path occurrence probabilities are shown to be very close. If the path arrival times were simulated according to a Poisson process, the path occurrence probabilities would be a horizontal line at the mean path arrival rate. It should be noted that the path arrival statistics, collected in this study, are based on the measurement system's time resolution of 5 ns. This was estimated from the base width of the received profile, when the transmitter and receiver were connected by coaxial cable in a back-to-back test of the measurement system.

The amplitude of the arriving paths in a given bin of the profile was compared with a few distribution functions. As shown in Reference 8, the log-normal distribution provides a better overall fit to the amplitudes in any bin collected from the empirical data. The mean and the standard deviation of the log-normal distribution, required to simulate the amplitude for an existing path were computed from the empirical data for each partition. Next, the path amplitudes were generated using the parameters for the log-normal distribution for each bin with a path. To complete the picture, the phase angles could be chosen from a uniform distribution and added to each path.

The RMS delay spread was used as a performance parameter for this simulation model. Using the empirically determined parameters for each partition, channel multipath profiles were simulated. The number of simulated and empirically collected multipath profiles were the same in each partition. To evaluate the performance of this simulation model, the cumulative distribution of the RMS delay spreads as computed from the simulated profiles was compared with that obtained from the measured profiles. Fig. 9 shows this comparison for the

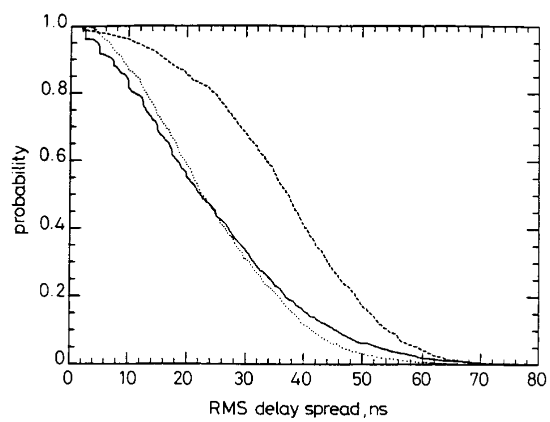

Fig. 9 *Empirical distribution of RMS delay spreads (solid line) compared to simulation results (broken lines) using empirical values for model parameters for OLOS2 partition*

------- Poisson/Rayleigh
······· modified Poisson/log normal
——— empirical

OLOS2 partition. The broken lines in this Figure are the cumulative distributions of the RMS delay spreads computed from simulation. The path amplitudes are simulated based on empirically determined values of means and standard deviations. The solid line in the Figure represents the actual cumulative distribution of the RMS delay spreads measured from the partition. The match between the empirical and the simulated distributions can be seen to be very good.

The statistical model given in Reference 9 considers Poisson path arrivals and Rayleigh amplitudes. For comparison, simulation was also carried out for this Poisson/

Rayleigh combination. For the Poisson arrivals, the mean path arrival rate was used to determine the presence or absence of a path in any bin. The measured powers in each bin were used to determine the Rayleigh amplitude of an existing path. The RMS delay spread was computed for each of these simulated profiles and their distribution function is shown in Fig. 9, for the OLOS2 partition. The match between the modified Poisson log-normal simulation and the empirical results is significantly better than that provided by the Poisson/Rayleigh simulation. The weakness of the Poisson/Rayleigh simulation was true for all the three partitions.

The parameters used for simulating the multipath profiles were determined from the empirical data. The scatter plots of the modified Poisson parameter K_i against bin number i, used to generate the path arrival times, showed good agreement to linear best-fit lines, for all the three partitions. The slopes of the best-fit lines were 0.0951, 0.1315 and 0.2134 for the LOS, OLOS1 and OLOS2 partitions, respectively. The slope was the highest in the OLOS2 partition which was separated from the receiver by at least two walls. The LOS partition had the least slope.

The scatter plots of the modified Poisson parameter λ_i, used in conjunction with K_i to generate path arrival times, exhibited good agreement with exponential fits of the form $A \exp(-i/\tau)$, for all the three partitions. The decay rate τ of the best fit exponentials was 3.155, 5.136 and 9.814 for the LOS, OLOS1 and OLOS2 partitions, respectively. The decay of λ_i with bin number i was fastest for the LOS and slowest for the OLOS2 partition. In generating the path arrival times, the path occurrence probability (shown in Fig. 8) is given by the product $K_i \lambda_i$, if there exists a path in the earlier bin. In small LOS environments, the number of paths in the received multipath profile are few and most of the received power is concentrated in the initial paths. Hence the likelihood of receiving any path at high delays, indicated by a small product probability $K_i \lambda_i$ for the LOS partition, is relatively low. On the other hand, the OLOS partitions usually have more scatterers leading to more number of paths in the received multipath profile. This is indicated by higher values of the product probability $K_i \lambda_i$ for any bin number i, for the OLOS than that in LOS partitions.

The parameters required to simulate a path amplitude, given the existence of a path at a given delay or a bin are the mean and standard deviation for the log-normal distribution. The scatter plots of mean and standard deviation of the log-normal distribution versus the bin number i, exhibited good agreement with exponential fits of the form $A \exp(-i/\tau)$, for all the three partitions. The decay rate τ of the best fit exponentials for the mean, was 25.1, 57.8 and 81.34 for the LOS, OLOS1 and OLOS2 partitions, respectively. Note these values are linear with respect to the bin number i. The decay of the mean with bin number i was fastest for the LOS and slowest for the OLOS2 partition. The decay rate τ of the best fit exponentials for the standard deviation, was 10.3, 37.5 and 51.9 for the LOS, OLOS1 and OLOS2 partitions, respectively. The decay of the standard deviation with bin number i was fastest for the LOS and slowest for the OLOS2 partition. In LOS environments there are usually no walls between the transmitter and receiver and hence most of the received power is contained in the direct and initial paths. The OLOS partitions, on the other hand, exhibit a wider spread of power in delay, because of frequent obstruction of the signal between transmitter and receiver. This is indicated by the slower decay rates for the mean and standard deviation in case of the OLOS partitions.

The four model parameters K_i, λ_i, $(\text{mean})_i$ and $(\text{stdev})_i$ are required to regenerate a path in a channel profile, in any partition. In the preceding Section, the empirical values of these parameters for a given partition were used to simulate profiles. However, each of these parameters have been shown to follow either a best linear or exponential fit. Using these best fits for the parameters for each partition, channel multipath profiles were again simulated. The number of simulated and empirically collected multipath profiles were the same, in each partition. To evaluate the performance of this simulation model, the cumulative distribution of the RMS delay spreads as computed from the simulated profiles was compared with that obtained from the measured profiles. Fig. 10 shows

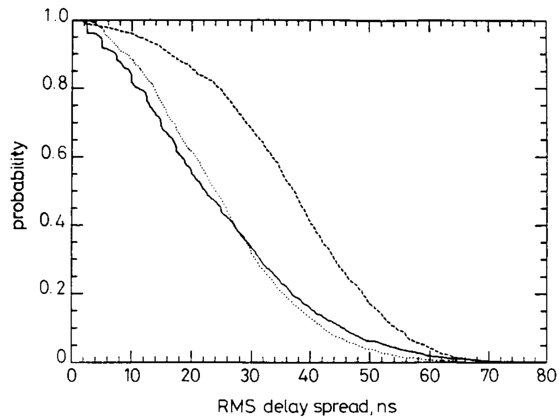

Fig. 10 *Empirical distribution of RMS delay spreads (solid line) compared to simulation results (broken lines) using best fits for model parameters for OLOS2 partition*

------ Poisson/Rayleigh
······ modified Poisson/log-normal
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this comparison for the OLOS2 partition. The broken lines in this Figure are the cumulative distributions of the RMS delay spreads computed from simulation. The path arrivals are simulated based on best-fit values of the parameters for the modified Poisson process. The path amplitudes are simulated based on best-fit values of means and standard deviations. The solid line in the Figure represents the actual cumulative distribution of the RMS delay spreads measured from the partitions. The match between the empirical and the simulated distributions can be seen to be very good.

6 Summary and conclusions

Time-domain multipath propagation measurements were performed and analysed to determine the changes in the channel parameters and characteristics on a floor of an office building. The floor was divided into three partitions, on the basis of building architecture and number of walls between transmitter and receiver. One of the partitions was in an LOS environment and the other two partitions were in OLOS environments, separated from the base antenna by at least one wall. Such a classification method is useful in determining coverage ranges and system capacity in a cellular office communication system. The RMS delay spread, multipath power, path arrival and amplitude statistics were presented and compared for the three partitions on this floor. For the LOS partition, the RMS delay spread values were the lowest and were less than 22 ns, for 95% of the locations. The OLOS1 partition which was separated from the receiver by at least one wall, exhibited higher values of the RMS delay spread, less than 42 ns, for 95% of the locations. The OLOS2 partition, separated from the base station by at least two walls, exhibited highest values of the RMS delay spread, less than 55 ns, for 95% of the locations. The distance-power law gradient α was less than that for free space, for the LOS partition. Both the OLOS partitions exhibited values of α greater than that for free space. The standard deviations of the RMS delay spread values and wideband multipath power values were the lowest for the LOS partitions and the highest for the OLOS2 partitions. The higher standard deviations indicate that coverage by an operational system in such an area, would be less uniform. In such case, adaptive equalisation or antenna diversity techniques would have to be used to improve performance.

The simulation model based on channel parameters for arrival and amplitude of paths described in Reference 8, was used to regenerate multipath profiles in the three partitions. The results of the simulation were compared to those obtained empirically. The criteria of comparison was the distribution function of the RMS delay spreads. The parameters for the path arrivals described by a modified Poisson process were determined empirically. The path amplitudes were simulated using empirically determined parameters for the mean and standard deviation of the log normal distribution. The modified Poisson/log-normal combination showed a closer fit to the empirical distribution than the Poisson/Rayleigh combination, for all the partitions. The model parameters involved in the simulation were compared for the three partitions. Best-fit curves were plotted for each of the four parameters used for simulation, in each partition. By comparing the model parameters amongst the three partitions, it was shown that in case of OLOS partitions, more paths are likely to exist in a received profile and a wider spread of power in delay is expected. This would cause the RMS delay spread values to be higher in an OLOS location than that at a similar LOS location. In case of LOS partitions, most of the received power is concentrated in the initial few paths and there is a faster decay of power with delay. Because long-delayed multipath components are less likely to exist in a LOS profile, the RMS delay spread values are also lower.

A majority of office buildings can be divided into such partitions, based on the number of walls between the transmitter and receiver. To regenerate a wideband channel profile, the mathematical equations representing the four model parameters in the given partition could be used. As the number of walls increases between the transmitter and receiver antennas, the slope of the linear fit for K_i also increases. The rate of decay of the exponential fits for the remaining three parameters, became slower as the radio waves had to propagate more number of walls.

While a central base station covering the entire floor would require a lot of power, a distributed antenna system could be implemented in each of the suitably identified partitions of any medium-sized office building. This is likely to reduce delay spreads and power loss at any location. For large office buildings or several floors of a building, such cellular partitioning coupled with frequency reuse [19, 20] would be an attractive proposition. As no other research work presenting results of wideband propagation between floors of a building has appeared in the open literature, the channel partitioning results presented here could be enhanced further by extending the partitioning to include various floors of a building.

In conclusion, it is emphasised that the results presented here are intended to be preliminary and that additional research in other indoor buildings is required for confirmation. However, it is anticipated that this simulation technique can be extended to other office building scenarios, by suitably adjusting the slope or the decay rate for the parameters. As with any other simulation model, it can be effectively used in the design, testing and performance evaluation of various wireless communication system alternatives.

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