Statistics of short time and spatial variations measured in wideband indoor radio channels

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Abstract: In an indoor environment, channel variations which occur most frequently are due to the movement of personnel near the transmitting or receiving antennas and/or local movements of the terminals around a given location. Such spatial and short time variations in the indoor radio channel are studied and determined by performing wideband propagation experiments in line of sight and nonline of sight environments at 910 MHz. The database is divided into two classes: spatial and short time variations. Spatial variations deal with the changes in the radio channel, observed over a short time and space, at different locations in an environment. The short time variations address changes induced over time, by human traffic close to the fixed transmitter/receiver or by manually shaking the antenna on its base. The statistics of RMS delay spread and the received power in the multipath profiles are computed and compared for these experimental variations.

1 Introduction

Design of radio communications systems within buildings requires an accurate study of multipath propagation characteristics of the indoor radio channel. The signal fading and multipath spread present a severe environment to digital radio systems. There have been attempts to study the statistics of signal attenuation and delay spread and to model the indoor radio channel [1–6]. However, human traffic around the transmitter or receiver and local movements of the terminals cause variations in delay spread and power. Previous research performed within buildings has not thoroughly investigated these short time variations. Bultitude's measurements [6] included periods of no movement with periods of local movements. His analysis of the movement data, which he filtered out of the total measurement duration, showed the channel to be wide sense stationary for time periods of at least 3.4 s. The dynamic range of fading was on average about 15 dB with occasional nulls below 25 dB. Rappaport [5] measured temporal fading of the received signal envelope over a 100-second period during the normal working hours of the factory. His analysis of the temporal fading data showed that the dynamic range is about 10 dB. Both researchers compared the temporal fading data to the Rayleigh and Rician distributions, and showed that the Rician distribution fits the data well.

The changes seen in the received profile as a result of such movements is that a few multipath rays appear, disappear or slowly change their arrival times or strengths. Such variations have drastic effects on the delay spread and the received power. This paper reports wideband radio propagation measurements made to determine these short time changes in rms delay spread and the received power, caused by local traffic close to the terminals and local movements of the terminals around a given location, in the indoor radio channel. The issues concerning the Doppler spread and the narrowband received power caused by such local disturbances are addressed [7].

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2 Description of the experiments

Since indoor radio communication behaves differently in line of sight (LOS) and obstructed LOS (OLOS) environments [1], experiments to induce short time and spatial variations in the channel are performed in both environments. All the 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 measurement setup used for the multipath propagation experiments is described [1, 3]. The variations studied in this paper are divided in two classes, described in the following Subsections.

2.1 Small spatial 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 induced by slowly moving the antenna around a 0.5 m square at various locations of the transmitter, in one LOS and two OLOS environments (see Fig. 1). The person moving the antenna, is a part of the scattering situation. For these experiments in the two environments, the receiver was located in the centre of the third floor,

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inside an electronics laboratory comprising typical equipment such as scopes, voltmeters, power supplies on wooden benches. The LOS environment consists of all person 'shaking' and 'wiggling' the transmitter antenna on its base, labelled as experiments B and D, in the LOS and OLOS environment, respectively. It should be noted

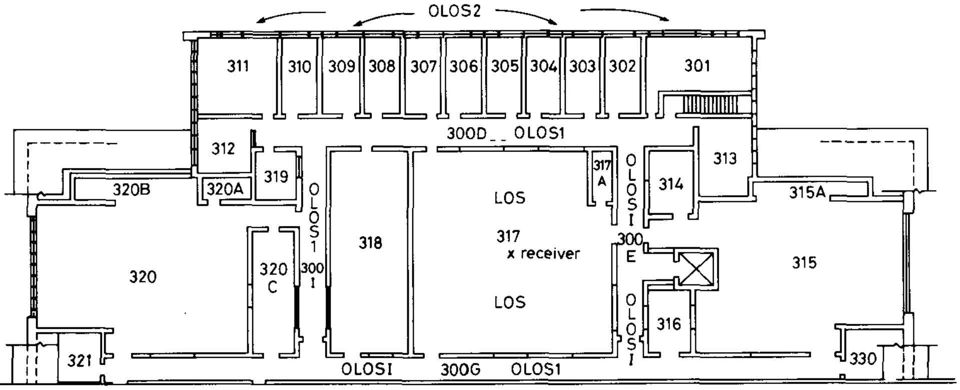

Fig. 1 *Plan of third floor of Atwater Kent building in Worcester Polytechnic Institute*
1" = 20'

the locations inside this electronics laboratory. The first OLOS environment 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 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 were 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 scope to be transferred later on into the computer. The number of measurement locations in the LOS, OLOS1 and OLOS2 partitions were 50, 40 and 70, respectively. For 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. It should be noted that RMS delay spread values change with this threshold value. Thus the threshold level was cautiously chosen to be 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. 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.

2.1 *Short time variations*

This kind of variation deals with the changes in the radio channel, observed over a short time at a fixed location of the terminal. Such variations are induced by human traffic close to the fixed transmitter/receiver antenna, or by manually shaking the antenna on its stand, in one LOS and one OLOS environment (see Fig. 1). Two sets of experiments are performed to induce such variations, in each environment. The first set involves two people walking briskly around the transmitter and the receiver, labelled as experiments A and C, in the LOS and OLOS environment, respectively. The second set involves a

that the human experimenter involved in moving the antenna as before is part of the scattering situation. These experiments are made with both transmitter and receiver stationary on the third floor of the Atwater Kent Laboratories. For the LOS experiments, both the transmitter and the receiver are located in the central electronics laboratory. For the OLOS experiments, the receiver is located in the communications research lab,

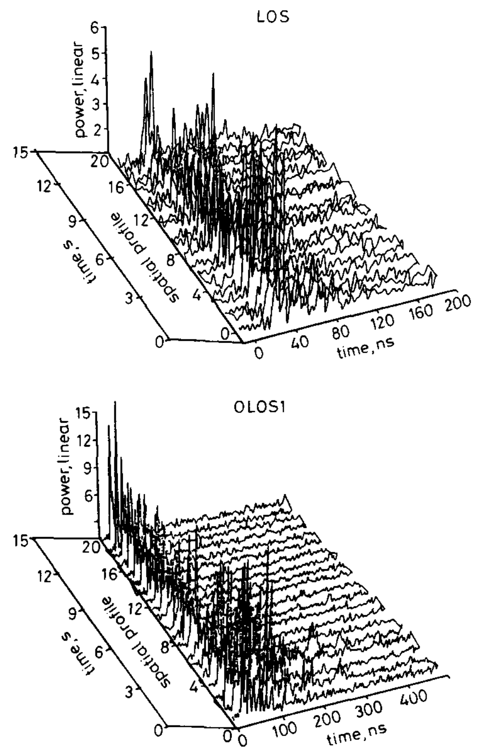

Fig. 2 *Three-dimensional plots of 20 multipath profiles obtained at one LOS and one OLOS location*
Ordinate axis has power on linear scale

comprising typical office furniture and computers among other radio communication equipment; the transmitter was located in a computer laboratory separated from the receiver by two walls having windowed glass. The walls were made of plasterboard with metal studs.

For all four sets of data, the distance between the transmitter and the receiver was fixed at 10 m. A total of 400 profiles are collected from the four experiments. An adequate sampling rate of 20 samples per second is used to properly sample such short time variations because, as shown [7], the Doppler spread of the indoor channel is less than 10 Hz. While the profiles were being stored during the experiment, care was taken to prohibit any other kind of activity or movement in the nearby vicinity. Similar to the spatial data set, the data from short time measurements was analysed by dividing the arrival times in a profile into 5 ns bins, and a threshold level was judiciously employed to detect a genuine path in any bin. Fig. 3 shows the three-dimensional plots of the multipath

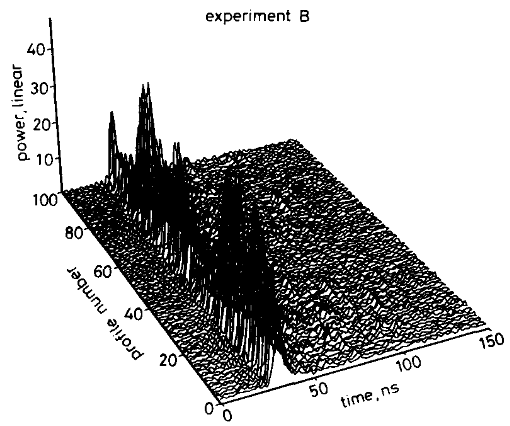

Fig. 3 *3-D plot showing multipath profiles received during local measurement B, in LOS environment*

profiles obtained during the duration of 5 seconds of experiment B, in the LOS environment. The ordinate axis has power on a linear scale. One can clearly see the strongest peak changing its stength as the antenna was 'wiggled' on its base.

3 Variations in RMS delay spread

The RMS delay spread is the normalised value of the square root of the second central moment of the average multipath profile [9]. When designing communication links, the RMS delay spread gives a measure of performance degradation in the system, caused by intersymbol interference. In this Section, we discuss the measured variations in RMS delay spread caused by human traffic around the transmitter/receiver and local movements of the terminals. Note that these variations refer to the changes in the instantaneous values of RMS delay spread of the measured multipath profiles during the duration of each experiment. A common rule of thumb, adopted while designing a communication system to operate at a certain data rate with negligible performance degradation, is to use a symbol period much greater than the average RMS delay spread [12]. Typically, the symbol period used is about five times greater than the average RMS delay spread of the radio channel. As an alternative to this thumb rule using average RMS delay spreads, we believe that the maximum variations in instantaneous RMS delay spread studied in this paper could be used to determine data rate limitations in a more accurate manner.

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.

3.1 Small spatial variations

The channel parameter RMS delay spread is computed for each received profile at every location of the transmitter in the three environments. As reported [9, 11] the maximum RMS delay spreads measured in the LOS, OLOS1, OLOS2 environments were 36 ns, 58 ns, and 80 ns, respectively. The median values of RMS delay spread in the LOS environment was 8.3 ns, as compared to median values of 14.1 ns and 22.3 ns for the OLOS1 and OLOS2 environments, respectively. The variations in RMS delay spread amongst the twenty received profiles around a 0.5 m square, was calculated at every location. Fig. 4 shows the complementary cumulative distributions

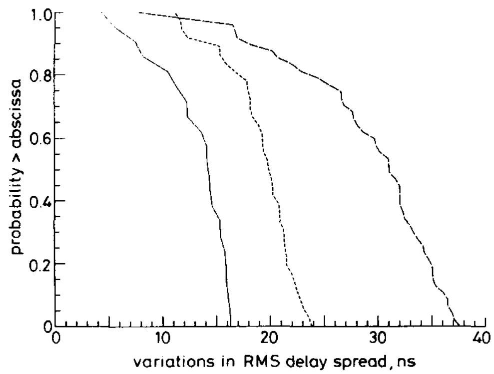

Fig. 4 *Measured complementary cumulative distributions of spatial variations in RMS delay spread for three environments*

.... LOS
------- OLOS1
– – – – OLOS2

of the variations in RMS delay spread for the three environments, respectively. The maximum variations in RMS delay spread for the LOS environment were about 17 ns while, for the OLOS1 and OLOS2 environments, they were about 24 ns and 38 ns, respectively. The average variations in rms delay spread for the LOS environment was 12.9 ns while, for the OLOS environments, they were 19.2 ns and 29.0 ns, respectively. This indicates that OLOS channels are subject to higher spatial variations in RMS delay spread caused by movement of the terminal around a small area. This could be attributed to the presence of more number of scatterers (and hence more paths) in OLOS than in LOS environments. Fig. 5 shows the variations in RMS delay spread versus the distance between the transmitter and receiver. Though some increase in the variations with distance can be observed, no definite correlation of the variations with distance could be established.

3.2 Short time variations

The channel parameter RMS delay spread was computed for each of the 100 profiles obtained during the duration of every experiment. The values of average RMS delay spread measured at the site of the four experiments A, B, D and D were 12 ns, 16 ns, 22 ns and 29 ns, respectively.

Fig. 6 and Fig. 7 show the variations and the complementary cumulative distributions of RMS delay spread for the four experiments, respectively. The variations in RMS delay spread for the LOS experiments A and B, were 16 ns and 24 ns, respectively, while for the OLOS experiments C and D, they were 32 ns and 17 ns, respectively. The standard deviations of RMS delay spread for the LOS sets A and B were 3.5 ns and 5.6 ns, while for the OLOS sets C and D they were 6.2 ns and 3.6 ns. Thus short time variations of RMS delay spread, caused by human traffic were higher for OLOS than LOS channels. In case of experiments involving 'shaking' and 'wigging' the antenna on its base, the plane of polarisation of the omnidirectional antenna changes. The effects of this, as shown in Fig. 3, is that the direct path in LOS channels undergoes the maximum amount of fluctuations. However, in OLOS profiles, power is distributed over more paths rather than one direct path and, when the antenna is 'shaken', the fluctuations observed are smaller in all the paths. This leads to smaller variations in delay spread for OLOS than LOS channels. The measured short time variations in delay spread, for fixed terminal locations, were however always less than 35 ns.

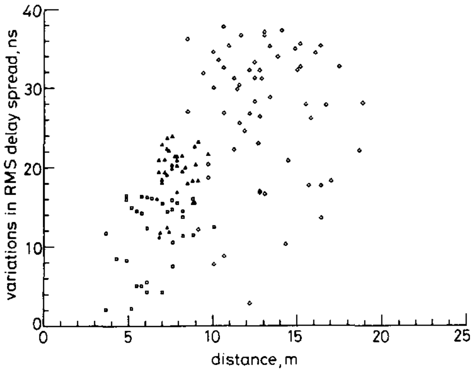

Fig. 5 *Spatial variations in RMS delay spread versus distance between transmitter and receiver, for three environments*

□ LOS
△ OLOS1
◇ OLOS2

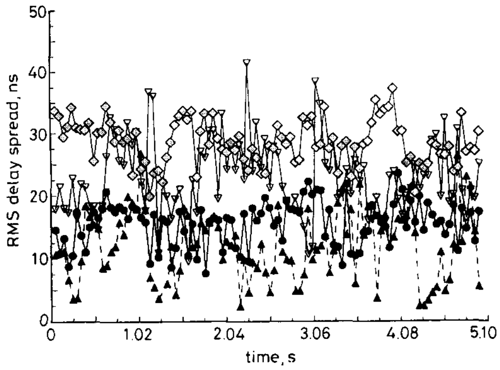

Fig. 6 *Short time variations in RMS delay spread measured during duration of four experiments*

● Exp A
▲ Exp B
▽ Exp C
◇ Exp D

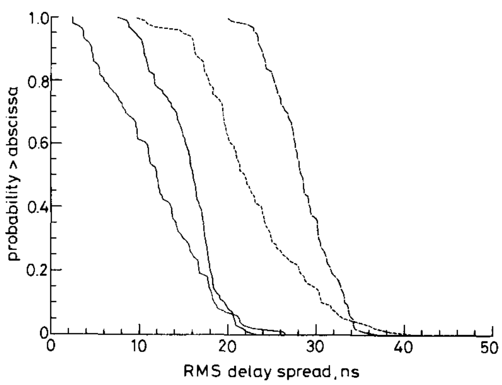

Fig. 7 *Measured complementary cumulative distributions of short time variations in RMS delay spread for four experiments*

—— A
······ B
------ C
- - - - D

4 Fluctuations in multipath power

The multipath power is the sum of all the powers contained in all the detected paths in a profile. 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 Small spatial fluctuations

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, were calculated at every location. Fig. 8 shows

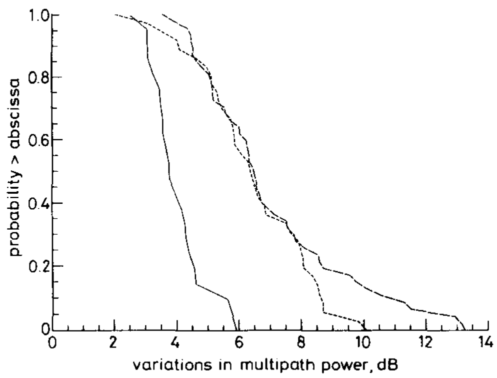

Fig. 8 *Measured complementary cumulative distributions of short time fluctuations in received multipath power for three environments*

······ LOS
------ OLOS1
- - - - OLOS2

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. Though for fixed locations of terminals the multipath power is highly correlated [1] with distance, no definite correlation between such spatial fluctuations in multipath power and distance could be established.

4.2 Short time fluctuations

Fig. 9 and Fig. 10 show the fluctuations and the cumulative distributions of the received multipath power for the four experiments. The range of fluctuations were 7.3 dB

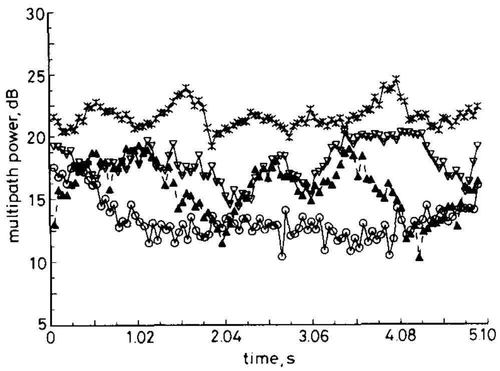

Fig. 9 *Short time fluctuations in received multipath power (relative) measured during duration of four experiments*

○ Exp A
▲ Exp B
▽ Exp C
* Exp D

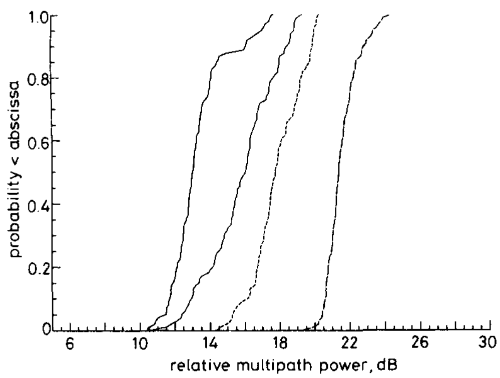

Fig. 10 *Measured cumulative distributions of short time fluctuations in received multipath power (relative) for four experiments*

—— A
······· B
-·-·-·- C
- - - - D

and 9 dB for the LOS experiments, while they were 5.9 dB and 5.3 dB for the OLOS experiments. The standard deviations of fluctuations in multipath power for the LOS data sets were higher than those for OLOS data sets. Most of the power in LOS profiles is contained in the main path and, when this path is obstructed by traffic, as in experiment A, multipath power also decreases significantly. In case of OLOS profiles, there are more paths to begin with and power is distributed wider in delay, and any traffic near the transmitter, as in experiment C, causes only small fluctuations in power. In case of experiments involving 'shaking' and 'wiggling' the antenna on its base, the plane of polarisation of the omnidirectional antenna changes. The effects of this, as shown in Fig. 3, is that the direct path in LOS channels, which contains most of the power, undergoes the maximum amount of fluctuations. However, in OLOS profiles, since power is distributed wider in delay, all paths undergo smaller fluctuations in amplitude, leading to correspondingly smaller fluctuations in received multipath power. Thus short time fluctuations in multipath power are higher for LOS than for OLOS channels.

The cumulative distribution functions (CDF) of the received signal amplitudes collected from any experiment was compared to the theoretical CDFs of Rayleigh and log-normal distributions [8]. The Rayleigh distribution showed a poor fit to the data, while the log-normal distributions provided a closer fit. This conclusion was the same for all the four experiments. For narrow band measurements, most of the time, fluctuations of power are larger which results in a better fit for the Rayleigh distribution [7].

5 Autocorrelation function

To define the channel characteristics in the indoor environment, the complex low-pass impulse response of the channel is often described by

$$h(\tau, t) = \sum_{k=1}^{L} \beta_k(t) p(\tau - \tau_k(t)) e^{j\theta_k(t)} \tag{1}$$

where $p(\tau)$ represents the narrow transmitted pulse, and the sets β_k, τ_k and θ_k describe the amplitudes, arrival times and the phases of the L arriving paths, at time t, respectively. Then we define the autocorrelation function of $h(\tau, t)$ during the short time variations in the channel as

$$\Phi(\tau; \Delta t) = \tfrac{1}{2} E[h^*(\tau, t) h(\tau, t + \Delta t)] \tag{2}$$

Figs. 11 and 12 show $\Phi(\tau; \Delta t)$ for experiments A and C,

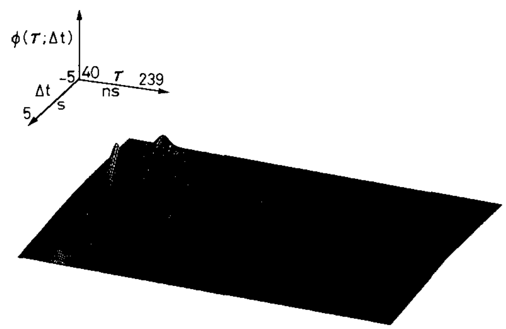

Fig. 11 *Autocorrelation function $\Phi(\tau; \Delta t)$ for short time variations of experiment A*

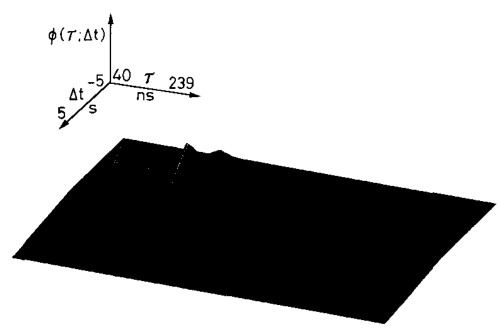

Fig. 12 *Autocorrelation function $\Phi(\tau; \Delta t)$ for short time variations of experiment C*

respectively, where Δt is between $-T$ and T seconds where T is the duration of the experiment. For $\Delta t = 0$ the resulting autocorrelation function $\Phi(\tau; 0)$ is the average power of the path at delay τ, which is sometimes referred to as the delay power spectrum [10]. The values of τ at which $\Phi(\tau; 0)$ is significant can be related to the existence of a path at τ. Figs. 13 snd 14 show $\Phi(\tau; 0)$ versus τ for experiments A and C, respectively.

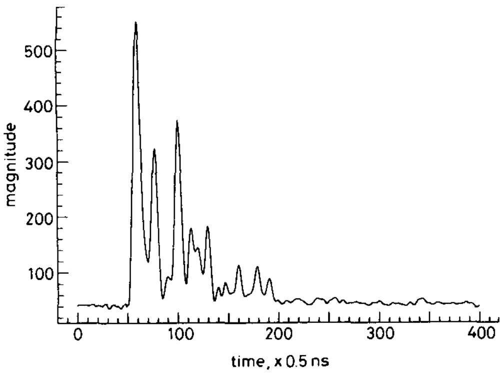

Fig. 13 *Average 'delay-power spectrum' $\Phi(\tau; 0)$ versus τ for experiment A*

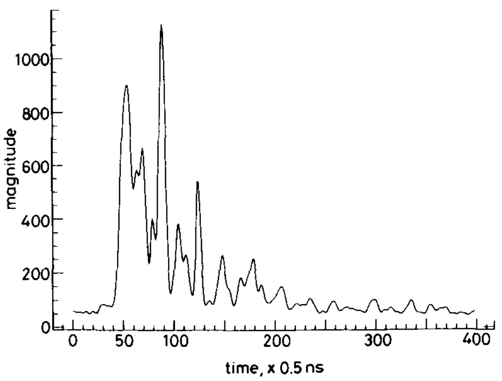

Fig. 14 *Average 'delay-power spectrum' $\Phi(\tau; 0)$ versus τ for experiment C*

For the LOS experiment A, maximum fluctuations in $\Phi(\tau; \Delta t)$ can be seen in the main path, while all the other paths show a linear decay of the autocorrelation with time. In the case of the OLOS experiment C, small fluctuations of the autocorrelation function is observed for all the paths.

6 Summary and conclusions

Results of 910 MHz, pulsed multipath propagation experiments to determine the effects of short time variations in the indoor radio channel were presented. The variations were studied in two classes: small spatial variations observed around a 0.5 m square at different locations of the terminal; and short time variations caused by human traffic close to the fixed terminal location. The spatial variations in RMS delay spread were found to be more in OLOS than those in LOS environments. On the other hand, the short time variations in RMS delay spread in OLOS environments were found to be less than those in LOS environments, for experiments involving change in plane of polarisation of the antenna. However, both spatial and time variations in RMS delay spread were found to be less than 40 ns in any environment.

Spatial fluctuations in received multipath power were found to be more in OLOS than in LOS environments. The short time fluctuations in multipath power for fixed terminal locations, however, were higher for LOS than OLOS environments. The range for both spatial and short time fluctuations were found to be less than 14 dB, in any environment. The log-normal distribution was shown to best fit the short time fluctuations in the received signal amplitudes. For the LOS short time experiments, maximum fluctuations in the autocorrelation function were observed for the main path, while all the other paths showed a linear decay of autocorrelation with time. In the case of the OLOS experiments, small fluctuations of the autocorrelation function were observed for all the paths.

7 References

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