Statistical modelling and computer simulation of indoor radio channel

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Indexing terms: Radiocommunication, Simulation, Propagation

Abstract: Multipath profiles obtained from radio propagation measurements at 910 MHz are used to analyse the statistical characteristics of the indoor radio channel. The data base is divided into two classes: manufacturing floors and college offices. In the manufacturing floors, there is plenty of open space without any presence of walls, as a result of which most of the received power is concentrated in the initial paths. The college office areas have a wider spread of power in delay, because of less open space and the frequent obstruction of the signal between the transmitter and the receiver by one or more walls. The statistical parameters required for computer simulation of multipath profiles in each environment are determined. The arrival of the paths is shown to fit a modified Poisson process and the amplitude of the paths follow a log-normal distribution. The mean and the standard deviation of the log-normal distribution are shown to decay exponentially with delay. To evaluate the performance of this simulation model, the distribution of the RMS delay spreads from the simulated profiles is compared with that obtained from the measured profiles.

1 Introduction

Indoor radio communications is currently studied for applications such as wireless PBX systems, wireless local area networks, universal portable phones and wireless security systems. These applications will be complemented by wireless communications between mobile robots, automatic guided vehicles (AGV) and other services unknown at the present time [1]. The dependence of a wireless system on effective radio propagation demands some measurement and modelling of the indoor channel characteristics. A model for the channel enables the system designers to simulate the channel for the purpose of performance predictions and enables comparative study of various alternative models.

Radio propagation in an office environment is very complex. The received signal usually arrives by several paths reflected by walls, ceilings, and other fixed and moving objects, around the transmitter and the receiver. The difference in the arrival time of the signal from various paths is proportional to the length of the path travelled, which is affected by the size and architecture of the office and the location of the objects around the transmitter and the receiver. The strength of the signal arriving by such paths depends on the attenuation caused by passage or reflection of the signal from various objects in the area. The deterministic analysis of propagation mechanisms in such an environment is not practical, and statistical analysis must be used. A mathematical model is formed for the channel. The statistics of the model parameters are determined using the channel impulse responses measured for various locations of the transmitter and the receiver.

One of the earliest statistical measurements of the amplitude fluctuations and distance-power law for indoor channels was reported by British Telecom [2]. Results of these measurements give the power law representing the signal attenuation as a function of the distance inside a building. The first wideband indoor radio delay spread measurements were reported by BellCore [3]. All the reported wideband measurements for indoor channels are concerned with the statistics of the multipath or the power in the received profiles [1-5]. The only attempt at modelling the indoor radio channel, was reported by the AT&T Bell Laboratories [6]. This model was based on Turin's model [7] for urban radio propagation and considers the rays of the multipath profile to have Poisson arrivals, independent Rayleigh amplitudes and independent uniform phases. Based on the observation of the channel profiles collected from a research laboratory in the AT&T Bell Laboratories, Saleh and Valenzuela [6] conclude that the paths arrive in clusters. The arrival of the clusters is also assumed to have a Poisson distribution. They suggest that the paths and the clusters both decay exponentially with a certain decay rate. The arrival rate of the paths and the clusters are determined from the statistics of the collected data. The distance-power relation and the multipath spread of the collected profiles was also reported.

In the present study a wider range of statistics for Turin's model [7] were collected and compared for two classes of buildings: manufacturing floors and college offices. Five different areas in manufacturing floors and two office areas in a college campus were used as the measurement sites. The discrepancies following the Poisson arrival assumption are reported based on the empirical data collected. It is shown that the modified Poisson process fits the arrival of the paths accurately for both environments. The Rayleigh, Weibull, Nakagami, log-normal, and Suzuki distributions are considered as potential models for the amplitudes of the arriving paths. Though the Suzuki distribution fits some of the data quite closely, the log-normal is shown to be the best dis-
tribution for all areas. The mean and the standard deviation of the log-normal distribution are shown to decay exponentially with the path delays. The statistics provided in either of the two environments, are used to reproduce the measured profiles using computer simulation. The distribution function of the RMS delay spread obtained from computer simulation closely fits that obtained empirically.

The mathematical formulation for the channel and the measuring system overview are presented. The mathematical parameters required to regenerate the channel impulse responses are described. The results of the data analysis on the path arrival times and amplitudes obtained from the two sets of measurements is discussed and the simulation procedure presented. The empirical and simulated results are then compared. The summary and conclusions are finally presented.

2 Mathematical model and measurement data base

The mathematical model used for the complex low-pass impulse response of the indoor radio channel was originally suggested by Turin [7] for the mobile radio and is given by

\[ h(t) = \sum_{k=1}^{L} \beta_k \delta(t - t_k)e^{j\theta_k} \]  

(1)

The transmitted impulse \( \delta(t) \) is received as the sum of \( L \) paths with amplitudes \( \{\beta_k\} \), arrival times \( \{t_k\} \) and phases \( \{\theta_k\} \).

Several statistics are required to regenerate a set of measured profiles with a computer simulation. The statistics of the arrival times are required to identify the existence of a path at a given delay. The fluctuations in the path amplitudes should be fitted to a known probability distribution, identified with a set of parameters (usually the mean and the standard deviation). The functions relating the mean and the standard deviation of the distribution to the path delay should be determined so as to accurately regenerate the path amplitude.

The channel impulse response has to be determined at all possible locations in various indoor environments to determine the required statistical parameters. There are three phenomena affecting the impulse response at any location in an indoor channel. The first is the fluctuations in the received power. The second is the effect of multipath propagation caused by fixed objects such as walls or ceiling. The third is the effect caused by moving humans or moving objects, close to the transmitter and/or the receiver. The effect of traffic and local antenna movements is reported in Reference 8. The phases \( \theta_k \) are assumed to be statistically independent uniform random variables over \([0, 2\pi]\) [6, 7].

The indoor radio measurements were performed at frequencies around 1 GHz. Very narrow pulses, which resemble an impulse, were transmitted. If the duration of these transmitted pulses is several times smaller than the largest multipath spread, the receiver will observe several isolated pulses for each transmitted pulse. In this case

\[ h(t) \approx \sum_{k=1}^{L} \beta_k p(t - t_k)e^{j\theta_k} \]  

(2)

where \( p(t) \) represents the narrow transmitted pulse.

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The measurement set-up used for the multipath propagation experiments is shown in Fig. 1. It involves modulation of a 910 MHz signal by a train of 3 ns pulses with a 500 ns repetition period [4] provided by a pulse generator. The choice of the 910 MHz carrier frequency is in compliance with the FCC band allocations in the United States for indoor radio transmission. The modulated carrier was input to a 45 dB amplifier. The output was transmitted using a quarter-wave dipole antenna placed about 1.5 m above the floor level. The stationary receiver used a similar antenna to capture the radio signal. This was followed by a step attenuator and a low-noise high gain (-60 dB) amplifier chain. The signal was then demodulated using an envelope detector whose output is displayed on a digital storage oscilloscope coupled to a PC with a GPIB instrument bus. The components used in the measurement set-up have a flat frequency response in the 0.9 GHz range. The dynamic range of the receiver display is limited to 25 dB because of the linear scale on the digital storage oscilloscope. The actual dynamic range of the measurement set-up was more than 100 dB. This dynamic range is 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 non-coherent and does not include the phase associated with the arriving paths [6, 7]. These phases are reasonably assumed a priori to be statistically independent uniform random variables over \([0, 2\pi]\) [6, 7].

The transmitter was moved to various locations in each site. The received multipath profiles were stored in the oscilloscope and then in the computer. Each stored profile is an average over time of 64 impulse responses collected during 15-20 s at one location. Care was taken to prohibit any movement close to the transmitter and the receiver during the measurement time. The distance between the transmitter and the receiver varied between 1 and 100 feet. A total of 472 profiles are collected from measurements made at different locations in five areas on three different manufacturing floors [4] and two office areas in the college campus.

The manufacturing floor environment is typically characterised by large open areas, containing various machinery and equipment of different sizes. There are usually no walls between the transmitter and receiver, and a 'direct' path is available for most of the locations. To adequately represent statistical behaviour of such an environment we selected five different manufacturing
areas for measurement. The first area was a typical electronics shop floor containing circuit board design equipment, soldering and chip mounting stations. The second area consisted of test stations and storage for common electronic equipment, partitioned by metallic equipment, soldering and chip mounting stations. The fourth measurement site was a car assembly line 'jungle' floor having dense welding and body shop equipment of all kinds. The last area was a vast open space with very little equipment, used for final inspection of the new cars coming out of the assembly line. The number of profiles collected from the five areas were 54, 48, 75, 45 and 66, respectively, resulting in a total of 288 profiles representing the manufacturing environment. Individual characteristics of these five areas as regards radio wave propagations were reported in Reference 4.

The office environment has less open space and for most of the locations, the 'direct' path is obstructed by the presence of one or more walls. The environment as presented to the radio waves, has considerable reflections from the walls and ceilings. The office areas discussed include several offices and a corridor, located on the third floor of the Atwater Kent Laboratories at the Worcester Polytechnic Institute. The offices are separated from the receiver located in a central electronics laboratory by two walls of sheet rock and some windowed glass on each wall. The superstructure and the size of all the rooms in this area are very similar. The corridor is around the electronics laboratory, separated by a sheet rock wall with metal studs and some windowed glass. The office rooms are located on the other side of this corridor. A total of 184 profiles were collected from these areas comprising 88 in the offices and 96 in the corridor.

Fig. 2a shows a profile of the received signal for a transmitted pulse of 3 ns (3 dB width) at 910 MHz, with minimum multipath spread and direct line of sight between the transmitter and the receiver, depicting the accuracy of the measurement set-up. Fig. 2b shows a sample profile, with considerable multipath spread.

![Profile of received signal](image)

**Fig. 2** Profile of received signal

a Minimum multipath spread; line of sight operation
b Considerable multipath spread

### 3 Statistics of the channel model parameters

The statistical parameters mentioned are derived from the measured profiles described. The statistics of the path arrival times $\tau_i$ are first discussed. The path amplitude $\beta_k$ associated with each $\tau_i$ is then fitted to a known probability distribution whose moments are functions of $\tau_i$. Results obtained from simulation of the model are then compared with those obtained empirically. As mentioned earlier, the data base is divided into two classes: manufacturing floors and college offices. 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 Arrival of the paths

A simple statistical model for the arrival of the paths would be a Poisson process [6], since the multipath propagation is caused by randomly located 'objects'. The path arrival distribution governed by a Poisson hypothesis was compared with the empirical data to find the degree of closeness. The number of paths $l$ in the first $N$ bins of each measured profile was determined. To determine the empirical path index distribution, the probability of receiving $l$ paths in the first $N$ bins $P_d(l = N)$ is plotted as a function of $l$. This procedure was repeated for $N = 5, 10, 15$ and 20 bins. The probability $P_d(l = N)$ for the theoretical Poisson path index distribution is given by

$$P_d(l = N) = \frac{\mu^l}{l!} e^{-\mu}$$

where $\mu$ is the path index, and $\mu$ is the mean path arrival rate, given by

$$\mu = \frac{N}{\sum_i p_i}$$

In this equation $r_i$ is the path occurrence probability for bin $i$ computed from the empirical data.

Figs. 3 and 4, show a comparison between the empirical path index distributions and the theoretical Poisson path index distributions [9] for $N = 5, 10, 15$ and 20. The Figures correspond to the manufacturing floor areas and the college offices, respectively. These are plotted as continuous curves for clarity, though they have values for
only integer path numbers. Considerable discrepancies are observed between the empirical and the Poisson distributions for all values of \( N \), irrespective of the environment. This discrepancy reflects a tendency of the paths to arrive in groups, rather than in a random manner. To explain similar discrepancies, a modified Poisson model was proposed by Suzuki for urban radio channel modeling [10].

For the modified Poisson process, the probability of having a path in bin \( i \) is given by \( \lambda_i \), if there was no path in the \((i-1)th\) bin, or by \( K_N \lambda_i \), if there was a path in the \((i-1)th\) bin. The 'underlying' probabilities of path occurrences \( \lambda_i \) have the following relation with the empirical path occurrence probabilities \( r_i \):

\[
\lambda_i = \frac{r_i}{(K_N - 1)\lambda_{i-1} + 1} \quad i \neq 1
\]

where \( \lambda_1 = r_1 \).

The modified Poisson path index distribution is related to \( \lambda_i \)'s, by the following recursive equations [10]:

\[
P_1(L = l) = P_{1,1}(L = l) + P_{1,2}(L = l)
\]

\[
P_{2,i+1}(L = l) = P_{2,i}(L = l - 1)K_N \lambda_{i+1}
\]

\[
+ P_{1,i}(L = l - 1)\lambda_{i+1}
\]

\[
P_{1,1}(L = l) = P_{2,i}(L = l) = \lambda_1
\]

\[
+ P_{1,1}(L = l) = \frac{1}{1 - \lambda_1}
\]

where \( P_1(L = l) \) is the probability of having \( l \) paths in the first \( i \) bins, \( P_{1,1}(L = l) \) is the probability of having \( l \) paths in the first \( i \) bins conditioned on having no path in the \( i \)th bin and \( P_{2,i}(L = l) \) is the probability of having \( l \) paths in the first \( i \) bins conditioned on having a path in the \( i \)th bin. The process begins in bin 1 where \( P_{1,1}(L = 0) = 1 \) - \( \lambda_1 \), \( P_{2,1}(L = 1) = \lambda_1 \), \( P_{1,1}(L = 0) = 0 \) for \( i \geq 1 \) and \( P_{2,i}(L = 0) = 0 \) for \( i \geq 2 \) or \( i \leq 0 \). Starting with a small value of \( K_N \) and minimising the mean square error between the empirical and theoretical modified Poisson path index distribution found using eqns. 5 to 8, optimum values of \( K_N \) are found from the data for \( N = 5, 10, 15 \) and 20. To aid simulation, the optimal values of \( K_N \) which are functions of the 'number of bins' are replaced by new parameters \( K_i \) (i = 1, 2, ..., 20), which are functions of the bin numbers \( i \) [11]. The \( K_i \)'s are determined by linear interpolation. For the final calculation of the modified Poisson path index distribution,

\begin{table}[h]
\centering
\caption{Measured parameters}
\begin{tabular}{|c|c|c|c|}
\hline
& \text{Manufacturing} & \text{College} & \text{} \\
\hline & \text{floors} & \text{offices} & \text{} \\
\hline \text{Bin} & \text{Measured} & \text{parameters} & \text{parameters} \\
\hline 1 & 0.984 & 0.4513689 & 0.697 & 0.3636364 \\
2 & 0.932 & 0.5418162 & 0.666 & 0.5406464 \\
3 & 0.900 & 0.5271417 & 0.634 & 0.6288999 \\
4 & 0.868 & 0.4926500 & 0.602 & 0.7164743 \\
5 & 0.836 & 0.5146308 & 0.570 & 0.7313251 \\
6 & 0.804 & 0.5442811 & 0.539 & 0.7230882 \\
7 & 0.772 & 0.5848987 & 0.507 & 0.7350161 \\
8 & 0.740 & 0.5170877 & 0.475 & 0.8171411 \\
9 & 0.708 & 0.5711024 & 0.443 & 0.7717200 \\
10 & 0.676 & 0.3649115 & 0.411 & 0.6645216 \\
11 & 0.340 & 0.3444129 & 0.589 & 0.6733878 \\
12 & 1.440 & 0.2928486 & 0.595 & 0.6594670 \\
13 & 1.540 & 0.3592564 & 0.602 & 0.6470692 \\
14 & 1.636 & 0.2762416 & 0.608 & 0.6743552 \\
15 & 1.732 & 0.1192904 & 0.614 & 0.4608082 \\
16 & 5.796 & 0.1300228 & 1.056 & 0.4402852 \\
17 & 6.388 & 0.1044048 & 1.117 & 0.4432586 \\
18 & 6.980 & 0.1019357 & 1.177 & 0.3890308 \\
19 & 7.572 & 0.0901229 & 1.238 & 0.3261777 \\
20 & 8.164 & 0.0810876 & 1.299 & 0.3297661 \\
\hline
\end{tabular}
\end{table}

Figs. 5 and 6, show a comparison between the empirical and theoretical modified Poisson path index distributions found using eqns. 5 to 8.
path index distributions and the modified Poisson distributions, for the manufacturing floors and the college office areas, respectively. The curve fittings show considerable improvement over those of the Poisson model shown in Figs. 3 and 4. This suggests that the paths do not arrive randomly but in groups, and the presence of a path at a given delay is greatly influenced by the presence or absence of a path in the earlier bins. The modified Poisson model utilises the empirical probability of occurrence for each bin. The Poisson model just uses the sum of the probabilities of occurrence for all bins.

3.2 Path amplitudes

Rayleigh, Weibull, Nakagami-m, log-normal and Suzuki distributions were considered as potential models for the path amplitudes. In the indoor environments fluctuations in the signal amplitude are quite high because of fading, so the signal amplitude level was converted to decibels, and treated as a random variable. Using the method outlined in Reference 12, the parameters of the theoretical distribution functions were determined from the measured amplitudes of the signal in the bins. Figs. 7 and 8 show the comparisons between the theoretical and the

Fig. 7 CDF of path amplitude in bin 1 in manufacturing floor areas

- actual  LOG  NAK  RAY  SUZ  WEI

Fig. 8 CDF of path amplitudes in bin 5 for college offices

- actual  LOG  NAK  RAY  SUZ  WEI
experimental distributions for bin 1 in the manufacturing floor areas and bin 5 in the college office areas, respectively. The horizontal axis is normalised to the median value of the data in decibels.

The error criterion of the Cramer-Von Mises test [10] was used to compare the goodness of fit among the five distribution functions. This criterion is defined as

$$
\omega^2 = \int_{-\infty}^{+\infty} [P(x) - P^*(x)]^2 \, dP(x)
$$

where \( P(x) \) is a theoretical CDF and \( P^*(x) \) is an experimental CDF. Table 2 shows \( \omega^2 \) for various distributions for bins 1, 2, 3, 5, 7, 15 and 20, in the manufacturing floors and the college offices. Both log-normal and Suzuki distributions cause close fits, but the log-normal provides a better overall fit to the empirical distributions. It is also easier to simulate log-normal than Suzuki random variables to represent path amplitudes.

The inhomogeneities of the indoor channel result in variations in the mean and variance of the amplitudes for different delays. To simulate these changing parameters, the distribution for their variations should be known. The scatter plots of mean and standard deviation of the log-normal distribution as a function of the delays were fitted to decaying exponentials of the form \( A e^{-\gamma \tau} + B \) where \( \gamma \) is the decay rate, \( \tau \) is the delay and \( A \) and \( B \) are constants. Figs. 9 and 10 show the mean and the standard deviation for the received power with delay. The college office areas exhibited a wider spread of power in delay and thus a slower decay of the received power with delay. The decay rate \( \gamma \) was 35.5 for the mean and 28.3 for the standard deviation in the college offices. The scatter plots give the values of the mean and standard deviation for the path amplitude, given the existence of a path at that delay. The modified Poisson process decides whether or not a path exists at a given delay.

### 4 Results of simulations

Using the statistics given for the path arrivals and amplitudes, the channel multipath profiles can be regenerated with a computer simulation. This simulation capability can be used in the design and testing of communication systems as a substitute for costly hardware experiments. The results of the simulation are compared with those obtained empirically. The criteria for comparison is the distribution function of the RMS delay spreads. For radio communication in the indoor environment, the RMS delay spread of the channel [4] gives a measure of performance degradation caused by intersymbol inter-

### Table 2: Mean square error \( \omega^2 \)

<table>
<thead>
<tr>
<th>Bin</th>
<th>Manufacturing floors</th>
<th>College offices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOG</td>
<td>NAK</td>
</tr>
<tr>
<td>1</td>
<td>1.11 x 10^{-4}</td>
<td>1.32 x 10^{-3}</td>
</tr>
<tr>
<td>2</td>
<td>8.57 x 10^{-4}</td>
<td>1.04 x 10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>1.37 x 10^{-4}</td>
<td>5.53 x 10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>1.81 x 10^{-4}</td>
<td>1.02 x 10^{-3}</td>
</tr>
<tr>
<td>7</td>
<td>2.22 x 10^{-4}</td>
<td>4.96 x 10^{-3}</td>
</tr>
<tr>
<td>15</td>
<td>7.22 x 10^{-4}</td>
<td>1.27 x 10^{-3}</td>
</tr>
<tr>
<td>20</td>
<td>2.34 x 10^{-3}</td>
<td>6.50 x 10^{-4}</td>
</tr>
</tbody>
</table>
ference, in the system. It is an important parameter for determining data rate limitations of standard and equalised modems [13]. It is also used for performance prediction of spread spectrum modems [14].

The first step in simulation is to generate the path arrival times. The basic model for simulation of the arrival times is the modified Poisson branching process of Fig. 11. The delay axis is divided into bins of length 5 ns. The simulation for each profile starts with bin 1. The presence or absence of a path in each bin is determined using Table 1 and Fig. 11. Figs. 12 and 13 compare the path occurrence probabilities as obtained from these simulated profiles with those obtained from the measured profiles in the manufacturing floors and the college office areas, respectively. These probabilities are plotted as continuous curves for the purpose of clarity, although they only have values at integer bin numbers. The experimental and the simulated path occurrence probabilities are shown to be very close. The path occurrence probability would be a horizontal line at the mean path arrival rate if the path arrival times were to follow a Poisson process.

The path amplitudes were generated from the log-normal distribution for each bin with a path. The means and the standard deviations of the log-normal distribution were determined from the associated exponential fits in Figs. 9 and 10. The phase angles could be chosen from a uniform distribution and added to each path to complete the picture.

To evaluate the performance of the simulation model, the cumulative distribution of RMS delay spreads as computed from the simulated profiles was compared with that obtained from the measured profiles. Figs. 14 and 15 show these comparisons for the manufacturing floors and
It was shown that the arrival of the paths from a modified Poisson process and the amplitude of the paths fit a log-normal distribution. The mean and the standard deviation of the log-normal distribution were shown to fit decaying exponentials. The simulation procedure was detailed and the parameters determined from the modified Poisson process and log-normal distribution were used to regenerate the indoor radio channel multipath profiles. The distribution of the RMS delay spreads computed from simulation was shown to closely fit the empirically obtained distribution. Channel profiles were also simulated with Poisson arrivals and Rayleigh amplitudes and the distribution function of the RMS delay spreads computed from such simulated profiles had a weaker fit to the empirical data. The modified Poisson/log-normal combination was shown to provide a better model for simulation.

Although additional research is required for confirmation, it is anticipated that this simulation technique can be extended to other kinds of environment by adjusting the value of its parameters. As with any other simulation model, it can be effectively used in the design and testing of communication systems as a substitute for costly hardware experiments. System designers can use it for performance predictions and comparative study of various alternatives. Alexander [15] has shown the effect of different types of building construction on the distance/power law gradient. The relationship of the parameters in this simulation model with the building construction materials is a subject worth exploring.

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7 References