RADIO CHANNEL MODELS IN MANUFACTURING ENVIRONMENTS

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Abstract

This work has developed statistical indoor radio propagation models for the analysis of factory communications systems. These models will permit research into the development of wideband wireless networks for AGVs, vision systems, and portable personal communications within factories. Models have been developed which characterize the discrete impulse response of indoor radio channels for both line-of-sight (LOS) and obstructed (OBS) topographies. In addition, the effects of transmitter-receiver (T-R) distance and receiver sensitivity are incorporated in the models.

Introduction

Models which characterize the impulse responses of factory radio channels are useful in the analysis of the maximum data rate which may be transmitted without requiring equalization, and are needed for the development of sophisticated high data rate digital communications systems. Factory radio channels may be divided into two basic categories. When there is a direct path between the transmitter and receiver, LOS topography exists. Absence of such a
path indicates an OBS topography [1]. Models have been developed for both LOS and OBS topographies which describe the distribution of the number of multipath components, the probability of receiving a multipath component at a particular excess delay, the distribution of the amplitude of multipath components at a particular excess delay, and the correlation between multipath component amplitudes over both space and time.

Results

The impulse response $h(t)$ of a linear system is a useful characterization since the output of the system can be computed through convolution of the applied input with the impulse response. In a multipath radio channel, the impulse response can be modeled statistically. Instead of measuring the impulse response, which requires an accurate measurement of the phase of multipath components, the multipath power delay profile $|h^2(t)|$ has been measured to provide data for amplitude and excess delay statistics for indoor factory multipath channels. An example of the measured data is given in Figure 1. Multipath components are resolved to 7.8 ns resolution [1].

Path Number Distribution

Knowledge of the number of multipath components is important for the simulation of modulation and equalization techniques. The distribution of the number of multipath components which exist above a certain threshold in LOS topographies is shown in Fig. 2 for received power thresholds of 30, 39, and 48 dB below a ten wavelength free space reference. These statistics have been computed from all profiles which have at least one multipath

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component existing above the particular threshold used. Note that a 48 dB threshold below a
10\lambda reference implies a path attenuation of about 86 dB, close to the 90 dB maximum dynamic
range of our system. Also shown is the Poisson distribution of the number of multipath
components with the same mean value as the measured data. One can see that for increased
receiver sensitivity, the Poisson distribution is a poor model for the number of discrete
multipath components. With a less sensitive setting, the Poisson distribution provides a better
fit to the data. The average number of multipath components per power delay profile was
computed over each local measurement area (in each local measurement area, 19 profiles were
measured over a 1-m track). The distribution of the average number of multipath components
over 25 LOS factory channels from 5 different factories is shown in Figure 3 along with the
normal distribution with the same mean and standard deviation as the measured data. It can
be seen from Figure 3 that a uniform distribution which ranges from 9 to 35 paths, or a normal
distribution with a mean of 22.4 paths and a standard deviation of 8.6 paths are good models
for the average number of multipath components in LOS topographies. In obstructed
topographies, the uniform distribution extends from 1 to 35 paths, or for the normal
distribution, the mean is 17.7 paths with a standard deviation of 11.0 paths. Intuitively, we
would expect fewer multipath components in OBS topographies due to shadowing. Given the
average number of multipath components for a particular receiver location, one needs to know
how that number changes as the receiver or transmitter is moved. The standard deviation of
the number of paths about the average is a linear function of the average of multipath
components. Figure 4 shows this model for LOS, and allows us to simulate how the discrete
number of multipath components changes as the receiver is moved over a local area.
Probability of Path Arrival

Once the number of multipath components is determined for a particular profile, it is desirable to know the probability that a component will exist within a particular excess delay interval. Figure 5, which has been computed from all of the 475 measured LOS profiles, shows the probability that a multipath component is received above a certain path loss threshold. Notice that as the threshold level is decreased (path attenuation is increased), the probability of receiving multipath components with excess delays greater than 50 ns increases more than the probability of receiving multipath components with excess delays less than 50 ns. The probability of path arrival in LOS topographies may be modeled as an exponentially decreasing function of excess delay. This assumes no correlation on the interarrival times of multipath components (i.e. the paths arrive independently).

In obstructed topographies, the probability of receiving a multipath component increases from 0.5 at an excess delay of 0 ns to 0.6 at an excess delay of 75 ns and then decreases exponentially with excess delay. The effect of received power threshold cannot be overlooked when determining the probability of path arrival. As seen in Figure 5, the shape of the probability of path arrival curve changes significantly as the received power threshold is changed. This shows that low power systems (for example, distributed antenna systems [8]) will experience less time dispersion than higher power indoor radio systems.

The time of arrival of each multipath component is determined from the probability that a multipath component exists at particular excess delay. A simple recursive algorithm, which generates a uniform random number and compares it with the probability of path occupancy (e.g. Figure 5) for each excess delay interval, is used to determine the initial excess delays at which components exist. The algorithm halts on the first pass when a sufficient number (as determined by the path number distribution) of multipath components are found. On subsequent passes, the probability of path occupancy model is normalized to account only for
the remaining possible excess delays. This technique for generating the excess delays has provided excellent agreement with the measured profiles, and is easily implemented on computer.

Path Loss

The total power contained in a received multipath profile at a particular transmitter-receiver (T-R) separation of d meters is well described by the log-normal distribution (normal distribution with values in dB) about a mean path loss law of the form $d^n$ [2]. Free-space path loss is assumed for the first 2.3 meters (10 ft) and mean values of n range from 1.8 to 2.8 [1,2]. In [1], it is shown that if multipath components have random phases, then ensemble averages of wide band and narrow band (CW) measurements will fit the same $d^n$ path loss law and will have a log-normal distribution about the fit. It is shown here that not only is the total received signal power log-normally distributed about the mean, but the path loss of discrete multipath components is also log-normally distributed about some mean $d^{n(\tau)}$ path loss law. Generally $n(\tau)$ increases with $\tau$ (i.e. path loss is greater for components that arrive later in the profile). Figure 6 is a scatter plot of path attenuation with respect to distance for the excess delay interval 0-7.8 ns ($\tau = 0$ns) and shows that a mean path loss law of the form $d^n$ may be assumed for individual multipath components which arrive within a particular excess delay interval. For this case, $n(0) = 2.6$. The best mean square fit of the $d^n$ path loss model and one standard deviation about the mean are shown. The distribution of the power received in a particular excess delay interval is log-normal about $d^{n(\tau)}$, as shown in Fig. 7. In [3], we showed the log-normal distribution is a good model for multipath power arriving in any excess delay interval.

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Figure 8 shows how the power law exponent $n$ changes with excess delay for LOS and OBS topographies. In obstructed topographies, the power of multipath components with small excess delay obeys a path loss power law in which the signal attenuates ($n$ increases) more rapidly than in line-of-sight topographies. This is expected since shadowing due to obstructions causes attenuation to be greater than in unobstructed topographies. We found the standard deviation about the mean path loss law is relatively insensitive to excess delay and is approximately $4 \text{ dB}$ for LOS and $5 \text{ dB}$ for obstructed topographies. The standard deviation for obstructed topographies is slightly larger than in LOS topographies since the effects of shadowing cause greater variation in path attenuation as the receiver is moved from one local area to another.

Multipath components fade as the receiver is moved over a local area (i.e. 1 meter track). It is important to understand the amount of fading which can occur as a result of small changes in receiver location. Since a characterization of all the individual scatterers in an indoor channel is futile, a statistical channel model is sought. We have found that individual multipath components have signal strengths that are log-normally distributed over small scale distances. Figure 9 is the cumulative distribution function (CDF) of the measured signal level and the CDF of the log-normal distribution fit to the mean and standard deviation of the measured signal level. We have found that over the ensemble of local measurements, although the mean signal level is highly dependent upon excess delay, the amount of fading (standard deviation) about the mean is not. Thus, where some LOS components at $\tau = 0$ undergo very slight, if any, fading over a 1 meter track, at other locations, the LOS signal fades as much as signals arriving later in the profile. Similarly, at some locations, signals which arrive later in the profile do not fade (they are specular reflections from walls, etc.) whereas at other locations, signals with large excess delay fade rapidly.
RMS Delay Spread

Figure 10 shows how the rms delay spread of LOS factory channels changes with respect to received power threshold. The average rms delay spread and one standard deviation about the average are shown. Notice that rms delay spread increases as the received power threshold is decreased. The interpretation of multipath parameters such as rms delay spread are very much conditioned upon the type of noise thresholding used.

Autocorrelation Coefficient Function

Inspection of the empirical data leads us to believe that some of the amplitudes of multipath components which exist at various locations and time delays are correlated. This has been found to be the case for urban mobile radio channels [4,5]. We assume that over distance separations greater than several wavelengths, channels become uncorrelated over space. Over excess delay differences greater than 100 ns, we have found multipath signal strengths on the average become uncorrelated. Assuming independence between time and space, autocorrelation coefficients (ACC) for received signal levels are estimated individually over time and space.

The conditional distribution of \( A(\xi_2) \) given the value of \( A(\xi_1) \) can be calculated by assuming both random variables are from a jointly log-normal distribution with a conditional mean

\[
A(\xi_2) | A(\xi_1) = \bar{A}(\xi_2) - r_{aa}(A(\xi_1), A(\xi_2)) (A(\xi_1) - A(\xi_1)) \frac{\sigma_{A(\xi_2)}}{\sigma_{A(\xi_1)}}
\]

(1a)

and a conditional variance

\[
\sigma_{A(\xi_2) | A(\xi_1)}^2 = (1 - r_{aa}(A(\xi_1), A(\xi_2))) \sigma_{A(\xi_2)}^2
\]

(1b)
where $A$ is a multipath amplitude for a particular location $\xi$. $\xi$ is a function of spatial location $x$ and excess delay $\tau$. $r_{aa}$ is the space or time correlation [3]. In (1), means and standard deviations have dB values. The previous general equations have been specialized for application to spatial and temporal correlations over local areas [6]. The local distances and excess delay values at which multipath signal amplitudes become uncorrelated are important in the analysis of antenna diversity, burst errors, and fading.

We have shown that individual multipath components obey a log-normal fading distribution [see Fig. 9] as a mobile is moved over a local area. We assume that multipath amplitudes are also jointly log-normally distributed over local areas. If the amplitude of a multipath signal which occurs at a particular excess delay at one location is known, then the conditional amplitude of the multipath signal amplitude at a distance $\Delta x$ away with the same excess delay is log-normally distributed with mean and variance as derived from (1a) and (1b). When (1) is used for spatial correlations, $\xi_1$ and $\xi_2$ represent two different physical locations which are within 1 meter of each other, and the means and variances on the righthand side are determined from the statistics of the empirical database. In the spatial correlation case, the excess delay is identical for all multipath components of interest; thus, $\sigma_A(\xi_2)$ will be equal to $\sigma_A(\xi_1)$ and $\mu_A(\xi_1)$ is equal to $\mu_A(\xi_2)$ as determined from a log-normal distribution about the mean $d^m(\tau)$ path loss. The computed spatial correlations of multipath amplitudes at a particular excess delay are based only upon multipath components existing in at least 5 of the 19 profiles measured along a 1 meter track. In addition, only those amplitudes of components which exist are used in the computation of correlation coefficients.

Because the autocorrelation coefficient function (ACCF) varies widely from local area to local area, and factory to factory, we have calculated an average ACCF based upon the individual ACCF's found at each local area. Curves have been fit to the data based on a combination of inspection and least-squares fit criteria. Figure 11 shows the average spatial ACCF in LOS topographies as a function of spatial separation and excess delay. The function
is piecewise exponential with respect to separation and is exponential with respect to excess delay. This function accurately approximates the average spatial ACCF for the measured data.

A similar method is used to compute average LOS temporal ACCF, except that now, $\xi_1$ and $\xi_2$ represent different excess delay times within the same multipath delay profile (i.e. same location). In (1), $\overline{A(\xi_1)}$ and $\overline{A(\xi_2)}$ have different values because multipath components at different excess delays have different distributions of the means [e.g. Fig. 8]. The standard deviations on the right hand side are independently determined from an empirical distribution of $\sigma$ values. The result is shown in Figure 12. Note that the first few components which arrive early in a profile have strengths which are anti-correlated from the LOS signal. Components which arrive later in the profile decorrelate rapidly without regard to excess delay value. We have found that there is virtually no correlation between multipath component amplitudes in obstructed topographies.

Conclusion

We have presented statistical models for wideband power delay profiles inside factory buildings. These models are based on the only known propagation measurements from factory buildings. Although indoor radio channels cannot be completely characterized by first and second-order statistics, they provide a more complete model of multipath propagation inside buildings than the first order models that have recently appeared [7,9]. Models have been presented here which quantify the number of multipath components which exist within a local area, the probability of receiving multipath components within a particular excess delay interval, the distribution of multipath component amplitudes, and the correlation between multipath component amplitudes which exist at various spatial locations and excess delays over a local one meter area. We have made good progress towards the development of channel models.
which can be incorporated in computers to analyze the performance and design tradeoffs of indoor radio networks of the future. An example of a computer generated power delay profile is shown in Fig. 13 and may be compared to the actual data shown in Fig. 1. Excellent agreement between computer generated profiles and actual measurements has been achieved, although measurements in additional factories are needed to fully validate and refine our models.

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