PATH LOSS AND DELAY SPREAD MODELS AS FUNCTIONS OF ANTENNA HEIGHT FOR MICROCELLULAR SYSTEM DESIGN

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ABSTRACT

This paper presents results of wide band path loss and delay spread measurements for two representative microcellular environments in the San Francisco Bay area in the 1900 MHz band. The results presented in this paper provide insight into the statistical distributions of measured path loss by showing the validity of a double regression model with a break point at a distance that has first Fresnel zone clearance for line-of-sight topographies. The variation of delay spread as a function of path loss is also investigated and a simple exponential over-bound model is developed. The path loss and delay spread models are then applied to communication system design allowing outage probabilities, based on path loss or delay spread, to be estimated for a given microcell radius.

1. INTRODUCTION

The particular nature of the radio communication channel directly impacts the performance of digital radio communications. For efficient microcellular system design, it is necessary to characterize the channels in such a way that outage probabilities and other system performance measures can be estimated. In this paper, results of wide band path loss measurements are presented for two representative microcellular environments in the San Francisco bay area (San Francisco and Oakland). Measurements were made with a wide band channel sounder with a 100 ns probing pulse at 1900 MHz so that received power delay profiles could be obtained at several test locations. Base station antenna heights of 3.7 m, 8.5 m, and 13.3 m were tested with a mobile receiver antenna height of 1.7 m to emulate a typical microcellular scenario. The results of this work indicate that a simple double-regression path loss model with a break point at a distance that has first Fresnel zone clearance can be accurately used to characterize the measured path loss data for line-of-sight topographies. The measured delay spreads, in general, were found to increase significantly with antenna height. It is also shown that delay spread increases as path loss decreases. An exponential over-bound model is developed which provides a worst case estimate of delay spread as a function of path loss. The dual slope piecewise linear model for path loss and the exponential over-bound model for delay spread are applied directly to the problem of microcellular design. A statistical model is developed to predict outage probability as a function of antenna height and maximum cell radius for a specified path loss or delay spread.

2. MEASUREMENTS

2.1 Measurement System

A time-domain bi-static radar system similar to one used in [1] was used to measure both time delay spread and path loss. Measurements were conducted in a total of five microcell environments in urban and suburban areas of San Francisco and Oakland, CA. A 20 MHz wide bandpass spectrum centered at 1900 MHz was used to transmit 100 ns duration radio pulses (10 W peak power). Omni-directional vertically polarized antennas were used at the transmitter and receiver. The base transmitter was located inside a van which remained parked on the side of a main street during measurements. The transmitter antenna height was changed by hoisting an antenna mast from the roof of the stationary van. The mobile receiver was located in a car.

2.2 Microcellular Path Loss and Delay Spread Measurements

The stationary van containing the transmitter was parked as close as possible to an intersection of two streets which extended radially away from the intersection. The omni-directional transmitter antenna was raised to heights of 3.7 m, 8.5 m, and 13.3 m above the ground and the mobile receiver canvassed areas around the transmitter where the path loss was within the 120 dB dynamic range of the receiver. Measurement locations were chosen to coincide with places where microcellular systems will likely be deployed in urban and suburban areas. At each measurement location, the car would stop as closely as possible to an intersection so that the operator could record a single data snapshot of the power delay profile. Power delay profiles were computed as the time average of sixteen instantaneous oscilloscope snapshots of the received probing signal over a one second interval while both the transmitter and receiver were stationary. Recording measurements at intersections allowed the measurement positions to be quickly located on a topo-
graphic map of the area. Many of the intersections were obstructed from the transmitter (no direct line-of-sight) which is representative of shadowed microcellular environments. Only the results for line-of-sight (LOS) topographies are presented in this paper.

The received power from the wideband measurements is determined by integrating the area under the power delay profile [1]. RMS delay spread, one method to characterize wideband multipath channels, is defined as the square root of the second central moment of the power delay profile [1].

3. PATH LOSS AND DELAY SPREAD ANALYSIS

3.1 Determining Path Loss

A frequently used model [1,2] indicates that mean path loss increases exponentially with distance, that is

\[ \text{PL}(d) \propto (\frac{d}{d_0})^n \]

where \( n \) is the mean path loss exponent which indicates how fast path loss increases with distance, \( d_0 \) is a reference distance, and \( d \) is the transmitter-receiver (T-R) separation distance. When plotted on a log-log scale, this power law relationship is a straight line. Absolute mean path loss in dB is defined as the path loss in dB from the transmitter to the reference distance \( d_0 \) plus the additional path loss described by (1).

\[ \overline{PL}(d) \text{[dB]} = \text{PL}(d_0) + 10 \times n \times \log_{10} \left( \frac{d}{d_0} \right) \text{[dB]} \]  

For the results presented in this paper, a 1 meter reference distance is used, and we assume PL\((d_0)\) is due to free space propagation. Assuming isotropic antennas, this leads to a calculated value of 38.0 dB path loss at 1900 MHz over a 1 m free space path. Note that this technique of calculating the 1 m reference path loss is not valid for measurements within about 10 m because the actual propagation distance between transmit and receive antennas of different heights above ground will be larger than the 1 m ground separation. Since all measurements were taken at distances greater than 10 m, the results are valid.

3.2 Multiple Regression Models for Line-of-Sight Topography

The two-ray model has been used successfully to model propagation in many urban and suburban environments [4], [5]. The model is an excellent candidate for use in environments where a direct path and one or more multipath reflections may occur. In this paper, we show that for line-of-sight cases a double regression model based on the two-ray model and Fresnel zone theory [4] gives good results.

In order to test the validity of using the double regression model with a break point at the first Fresnel zone distance [4], two modeling techniques are used. A model using a fixed point at the first Fresnel zone break point \((d_0)\) is compared to a model using a break point determined in a minimum mean squared error (MMSE) sense \((d_0)\). If the meanquared errors for the two model curve-fits are similar, then the first Fresnel zone break point model can be used without much loss in accuracy compared to the MMSE break point model.

The results presented in this paper for line-of-sight topographies are obtained using two different forms of a double linear-regression to compute values of the path loss exponent \( n \) and the standard deviation \( \sigma \) in dB about the best fit mean power law model in a minimum mean square error (MMSE) sense for the measured data. The two multiple regression techniques divide the overall data into two subsets with a different power law exponent for each of the subsets [5]. If a logarithmic distance axis is used, then the double regression model becomes a two-line model with different slopes on either side of the break point distance. This double regression piecewise linear model provides a MMSE best-fit curve with a smaller standard deviation than a simple single linear regression method for line-of-sight cases.

The first form of the piecewise linear model forces the break point between the two linear regions to occur at the theoretical Fresnel break point distance \((d_f)\). The alternate form of the model allows the break point to float so that the MMSE best-fit curve determines the least mean squared error break point distance \((d_0)\). By comparing the mean squared error for the two curve fits, it is possible to determine the difference in accuracy between the two methods of calculating the break point. If the mean squared error for the first Fresnel break point is close to the mean squared error for the MMSE break point, then there is not much advantage to using the MMSE break point. Therefore, the break point can be easily be computed as the first Fresnel zone clearance distance based on the transmit and receive antenna heights along with the transmitter-receiver separation.

3.3 Multiple Regression Results for Line-of-Sight Topography

Figure 1 shows the measured path loss data as a function of transmitter-receiver separation for the high antenna height (13.3 m) for line-of-sight (LOS) topographies. Along with the experimental data points, the two forms of the double regression model with the floating MMSE break point \((d_0)\) and with the fixed Fresnel zone break point \((d_f)\) are shown on the figure. All LOS measurement locations in San Francisco and Oakland with the high antenna have been recorded on the plot. The Fresnel zone break point and the MMSE break point differ by 383 meters but the overall root mean squared errors for the two models, as defined as the rms error between the model and the measured data, differ by only 0.43 dB. This indicates that the Fresnel zone break point model gives a mean squared error very close to that of the optimum MMSE break point model, even though the break points may differ by hundreds of meters.
The fact that a large $n_2$ value occurs when $d_b$ is much larger than $d_r$ prior to the Fresnel break point. There is much more variation antenna heights reveals that the path loss exponents for the antennas are very close for the region prior to the first Fresnel break point, but after the break point the exponents for the higher antenna are larger than the corresponding exponents for the lower antennas. This implies that the path loss decays more rapidly after the break point for the higher antenna than for the lower antenna.

It is important to note the first Fresnel break point distance for the higher antenna is much larger than for the lower antenna; for example, for a receiver height of 1.7 m the high antenna (13.3 m) has a break point at $d_f=573$ m, while the low antenna (3.7 m) has a break point at $d_f=159$ m. The difference in the first Fresnel zone break point distances is critically important when considering microcellular systems where the cell size may be anywhere from a few meters out to about 2000 meters. The 100 to 2000 meter T-R separation range is the most critical region for microcellular applications where low-power small-radius cells are to be implemented. For small-radius microcells, the difference in first Fresnel point distances can more than offset the difference in path loss exponents for the high versus low antennas. Even though the path loss exponent beyond the break point is greater for the high antenna, the coverage areas in the 100 to 2000 meter range are significantly less for the high antenna than for the lower antenna because of the increased first Fresnel break point distance.

### 3.4 Delay Spread Analysis

For this study, rms delay spread is analyzed as a function of antenna height and path loss. The measurements indicate the overall average rms delay spread increases as a function of the base station antenna height. The low antenna at 3.7 m had an average rms delay spread of 136.8 ns and a standard deviation of 138.0 ns (maximum delay spread of 1011.16 ns) while the high antenna at 13.3 m had an average delay spread of 257.9 ns and a standard deviation of 352.0 ns (maximum delay spread of 1859.5 ns). As discussed in Section 3.3, a higher base station antenna generally offers a lower path loss for a given distance, but the higher base station antenna will also cause a larger delay spread. Therefore, a trade-off between path loss and delay spread for a given antenna height exists for LOS microcell systems.

Figure 2 is a plot of rms delay spread versus path loss for all LOS and OBS measurement locations and for all three antenna heights. From the plot, it is clear delay spread increases with path loss. This has also been observed by Devasirvatham for indoor environments [6]. For system design purposes, an upper-bound on rms delay spread as a function of path loss is developed using a simple exponential model.

<table>
<thead>
<tr>
<th>Fresnel Best-Fit</th>
<th>MMSE Best-Fit</th>
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<tr>
<td>$n_1$</td>
<td>$n_2$</td>
</tr>
<tr>
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<tr>
<td>Med</td>
<td>2.17</td>
</tr>
<tr>
<td>High</td>
<td>2.87</td>
</tr>
</tbody>
</table>

Table 1: Path loss exponents, standard deviations, and break points for 1st Fresnel zone and MMSE break point curve fits for each antenna height.

The results from Table 1 indicate that the flat earth Fresnel break point model can be used to characterize the path loss as a function of distance in LOS channels. If the transmit and receive antenna heights are known, along with the T-R separation, then path loss can be computed based on the two path loss exponents $n_1$ and $n_2$. From these results, letting $n_1=2$ is a very reasonable assumption for the region prior to the Fresnel break point. There is much more variation in the path loss exponent for the region beyond the Fresnel break point, with values of $n_2$ from 2 to 7 being typical. However, when averaged over several transmitter locations, the best-fit exponent for $n_2$ is consistently about 3 or 4. An important observation about Figure 1 and Table 1 is the fact that a large $n_2$ value occurs when $d_b$ is much larger than $d_f$, but the best fit models offer very similar standard deviations. Thus, the break point location is critical in interpreting path loss for system design when best-fit exponents are used. Values for the path loss exponent beyond the break point will depend on the particular physical environment.

Figure 1: Path loss vs. T-R separation for high antenna height.
model of the form \( \sigma_d = e^{0.065PL(d)} \), where \( \sigma_d \) is the rms delay spread in nanoseconds and \( PL(d) \) is the path loss in decibels as a function of the T-R separation \( d \).

\[ \sigma_d = e^{0.065PL(d)} \] (ns)

Figure 2: Path loss vs. rms delay spread for all antenna heights and an exponential over-bound model.

4. MICROCELLULAR SYSTEM DESIGN

4.1 Calculation of Outage Probability due to Path Loss

By using the path loss models presented in Section 3, along with some basic assumptions concerning user density within a microcell, approximations can be developed for the probability of path loss for any point in the cell [7]. The microcell is assumed to be a circular region with a minimum radius of \( r_{\text{min}} = 1 \) m. The path loss over a microcell is assumed to follow a log-normal distribution about the mean power law path loss Fresnel break point model presented in Section 3.3. The probability density function (pdf) of path loss conditioned on the propagation model parameters \((n_1, n_2, \sigma_1, \sigma_2)\) and the cell radius \( r \) can be written in terms of the Gaussian distribution as [7]

\[ f(PL|n_1, n_2, \sigma, r) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left( -\frac{1}{2} \frac{(PL - \overline{PL}(n_1, n_2, r))^2}{\sigma^2} \right) \] (2)

where \( p_1 \) is the 1 meter reference path loss in dB, \( \sigma \) is the standard deviation about the mean path loss in dB, and \( \overline{PL}(n_1, n_2, r) \) is the mean path loss model in dB as a function of distance \( r \) \((r > 1 \) m\) and power law exponents \( n_1 \) and \( n_2 \). For distance \( r \) less than the Fresnel break point \((r < \Delta p)\), \( \sigma = \sigma_1 \), and beyond the break point \((r > \Delta p)\), \( \sigma = \sigma_2 \), based on the two different regions of the path loss model. The probability can be integrated from \( r_{\text{min}} \) to \( r_{\text{max}} \) to determine the pdf conditioned solely on the model parameters \((n_1, n_2, \sigma_1, \sigma_2)\) and independent of the radial distance \( r \) [7]. The result is [7]

\[ f(PL|n_1, n_2, \sigma) = \int_{r_{\text{min}}}^{r_{\text{max}}} f(PL|n_1, n_2, \sigma, r)f(r) \, dr \] (3)

where \( f(r) \) is the pdf of users over a circular cell of radius \( r \).

To determine the pdf of users \( f(r) \), first assume that the users are uniformly distributed over the circular cell coverage area. Using the theory of functions of a single random variable, the pdf of users with a uniform density is easily derived as a function of \( r_{\text{max}} \) [7],

\[ f(r) = \frac{2r}{r_{\text{max}}^2} \] (4)

Substituting (4) and (2) into (3), a closed form expression for the pdf of path loss conditioned on the model parameters \( f(PL|n_1, n_2, \sigma) \) can be obtained. The resulting probability density function can be integrated to obtain a cumulative distribution function (cdf) which gives the probability that path loss is within a particular decibel range. From the cdf, the probability of an outage can be calculated by obtaining the probability that the path loss will be lower than the outage threshold.

4.2 Results for Outage Probability due to Path Loss

Figures 3, 4, and 5 show percent outage probability versus maximum cell size based on the LOS first Fresnel break point model parameters shown in Table 1 for each antenna height. The term outage means that the path loss exceeds a specified level at which point communications are assumed lost over the particular channel. The outage probability curves are plotted for various outage thresholds in steps of 10 dB of absolute path loss.

Once the model parameters for a particular environment are determined or estimated, the outage probabilities due to path loss can easily be obtained. System designers can use these results to optimize cell size.

Figure 3: Outage probability vs. maximum cell size as a function of path loss for low antenna and LOS topography.
4.3 Calculation of Outage Probability due to Delay Spread

The relationship between delay spread and path loss, which was developed in Section 3.4, can be used to estimate worst case outage probabilities based on delay spread. The exponential over-bound model shown in Figure-2 can be used to determine path loss for a specified worst case delay spread. Therefore, based on a particular delay spread outage threshold, the outage probability can be computed indirectly from path loss estimates based on antenna height and T-R separation. The system designer is then able to use either path loss or delay spread to define an outage.

5. CONCLUSIONS

Double-regression path loss models using both a Fresnel zone break point and an MMSE optimum break point have been examined for outdoor line-of-sight microcellular environments. The standard deviations of the resulting best fit models indicate the Fresnel zone fit is as accurate as the optimum minimum mean squared error break point (which was calculated iteratively). Thus, for specified transmit and receive antenna heights and T-R separation, the mean path loss can be estimated based on two path loss exponents and the computed Fresnel break point.

Measured rms delay spreads were found to be a strong function of the antenna height. As the antenna height increased, the standard deviation and mean values of the rms delay spread increased. This result indicates a trade off between coverage area and delay spread considerations when choosing a microcellular base station antenna height. An exponential over-bound model has been used to give a worst case estimate of rms delay spread as a function of path loss.

The models for path loss as a function of transmitter-receiver separation and for rms delay spread as a function of path loss have been incorporated into the design of microcellular systems. If a specific path loss outage criteria is established, then an outage probability can be determined for a given cell radius. Outage probability can also be determined based on a delay spread outage criteria. Microcellular system designers can use these techniques to design an optimal cell size for a particular propagation environment based on outage probability and path loss or delay spread criteria.

6. REFERENCES


7. ACKNOWLEDGEMENTS

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