Path Loss, Delay Spread, and Outage 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 five representative microcellular environments in the San Francisco Bay area at 1900 MHz. Measurements were made with a wide-band channel sounder using a 100-ns probing pulse. 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 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 overbound 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 size.

I. INTRODUCTION

For efficient microcellular system design, it is necessary to characterize the radio channels in such a way that outage probabilities and other system performance measures can be estimated. In this paper, results of wide-band propagation path loss and multipath measurements are presented for five representative microcellular environments in the San Francisco Bay area (San Francisco and Oakland). Measurements were made using a wide-band channel sounder with a 100-ns probing pulse at 1900 MHz with base transmitter station antenna heights of 3.7 m, 8.5 m, and 13.3 m and a mobile receiver antenna height of 1.7 m. These antenna heights were used to cover the range of typical antenna heights that might be encountered in a microcellular system using lamp-post-mounted base stations at street corners. Measurement locations were chosen to coincide with places where microcellular systems will likely be deployed in urban and suburban areas.

The power delay profiles recorded at each receiver location were used to calculate path loss and delay spread. Path loss and delay spread are two important methods of characterizing channel behavior in a way that can be related to system performance measures such as bit error rate [4] and outage probability [7]. Path loss is a strong function of the propagation environment in the vicinity of the transmitter and receiver. Researchers have often used propagation models where the mean path loss decays as a function of the distance between transmitter and receiver raised to the power $n$, where $n$ is called the mean path loss exponent [5]. The distance-dependent power law model ($d^n$) has been applied in many circumstances where there may be more than two paths between the transmitter and receiver [5], [7], [9], [10].

For the simple case of a direct path and a single ground reflection between the transmitter and receiver, the distance power law model describes the mean path loss [6], [14], [16]. Theoretically, for transmitter-receiver separation distances less than the first Fresnel zone clearance, the mean path loss exponent will be two; beyond the distance for first Fresnel zone clearance, the exponent becomes four [6], [16]. In other words, if the path loss in decibels is plotted versus the logarithm of the distance between the transmitter and receiver, a dual-slope piecewise linear curve will result from the log-log plot. The piecewise linear curve will have one slope prior to the Fresnel zone clearance break point and a different slope after the break point, where the slopes of the lines are directly related to the path loss exponents. In this paper, it is shown that this dual-slope piecewise linear model can be used accurately to characterize the measured path loss data for line-of-sight topographies, even though, in many cases, more than two rays are likely to be present between transmitter and receiver.

The rms delay spreads have been compared for the three antenna heights. In general, delay spreads were found to increase significantly with antenna height. This is an important result that has implications on the data rates that can be transmitted through these channels. In this paper, it is also
shown that the delay spread increases markedly as a function of path loss. An exponential overbound model has been developed so that for any of the antenna heights a worst case estimate of delay spread can be obtained for a given path loss.

The dual-slope piecewise linear model for path loss and the exponential overbound model for delay spread have been applied directly to the problem of microcellular design. By developing appropriate statistical models for the probability of a given path loss conditioned on the propagation model parameters and cell size, it is possible to determine outage probabilities [7]. If a particular path loss or delay spread criterion is used to define a system outage, then a relationship between the outage probability and maximum cell size can be obtained. The ability to predict outage probability for a specified path loss or delay spread allows microcell sizes to be optimized for a particular propagation environment, thereby providing more predictable performance compared with systems where the microcell sizes are selected arbitrarily.

This paper shows that a model that determines the Fresnel zone break point based only on antenna height and frequency can model microcellular propagation as accurately as a minimum mean square error (MMSE) fit on the data. This model is general in that we present no conditions on its usage based on street width. When reflections from surrounding buildings are considered, the location of the break point may change [16]. This paper shows that the break point predicted by the two-ray model accurately models the measured data.

II. MEASUREMENTS

A. Measurement System

A time-domain channel sounder similar to the ones used in [5] and [7] was used to measure both time delay spread and path loss during summer 1991. Measurements were conducted in five microcell environments in urban and suburban areas of San Francisco and Oakland, California. A 20-MHz bandpass spectrum centered at 1900 MHz was used to transmit 100-ns-duration RF pulses with a repetition rate of 10 kHz, providing a multipath resolution of about 100 ft. The pulse train was amplified to a peak power of 10 W and fed into an omnidirectional vertically polarized antenna. The minimum measurable signal was −83 dBm for a maximum measurable path loss dynamic range of 123 dB.

The base transmitter was located inside a van that 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 van. Measurements were made with transmitter antenna heights of 3.7 m, 8.5 m, and 13.3 m above the ground and a mobile receiver antenna height of 1.7 m above the ground.

B. Microcellular Path Loss Measurements

The stationary van containing the transmitter was parked as close as possible to an intersection of two streets that extended radially away from the intersection. The omnidirectional transmitter antenna was raised to a height of 3.7 m above the ground, and a car with the receiver traveled along streets in the vicinity of the transmitter where the path loss was within the dynamic measurement range of the receiver. At each measurement location, the receiver car would stop as closely as possible to an intersection, and the operator recorded snapshots of the power delay profile. Power delay profiles were computed as the time average of 16 instantaneous oscilloscope snapshots of the received probing signal over a 1-s averaging interval while both the transmitter and receiver were stationary. Measurements at intersections allowed the measurement positions to be located quickly on a topographic map of the area. Many of the intersections were obstructed from the transmitter (no direct line of sight (LOS)), which is representative of shadowed microcellular environments. Results for both LOS and obstructed topographies are presented in this paper. The transmitter antenna was then raised to 8.5 and 13.3 m, and the procedure was repeated.

III. DATA PROCESSING FOR PATH LOSS AND DELAY SPREAD ANALYSIS

A. Determining Path Loss

The time-domain channel sounder used in these tests records the magnitude squared of the complex envelope baseband pulse response of the channel [5]. That is, the measurement system records

\[ |r(t)|^2 = \sum_k \alpha_k^2 p^2(t - \tau_k), \tag{1} \]

where \( r(t) \) is the complex envelope baseband pulse response, \( p(t) \) the transmitted pulse shape, \( \alpha_k \) the amplitudes of the particular path components, and \( \tau_k \) the time delays of the individual path components. Each measurement record of this type is called a power delay profile because it represents the power entering the receiver as a function of the time delay. Because the transmitter used a sounding pulse with a finite temporal width, the resolution of the path time delays (\( \tau_k \)) is limited to 100 ns.

A relative measure of received power, \( G_r \), at the receiver antenna for a given power delay profile snapshot can be determined from the oscilloscope display and calibration curves

\[ G_r = \sum_k \alpha_k^2. \tag{2} \]

From (2) and a calibration power delay profile recorded with a known transmitter power through a short test cable, it is possible to calculate the path loss from the measured power delay profiles. Let \( PL \) denote the channel path loss, \( P_T \) the peak transmitter power, \( G_T \) the transmitter antenna gain, \( G_R \) the receiver antenna gain, and \( \Delta \tau \) the oscilloscope sampling time between consecutive \( \alpha_k^2 \) points. Then, \( PL \) is given by [5]

\[ PL(dB) = P_T(dBm) + G_T(dBi) + G_R(dBi) - P_R(dBm), \tag{3} \]
where
\[ P_R (\text{dBm}) = P_{cal} + 10 \cdot \log_{10} \left( \frac{G_r \Delta \tau_r}{G_{cal} \Delta \tau_{cal}} \right). \] (4)

To compute the wide-band path loss, it is necessary to compute the power received by integrating the area under the received power delay profile. The term \( G_r \Delta \tau_r \) is the integrated power (total power) in a given measured profile. For a calibration run where only one 100-ns pulse is present, the total integrated power is assigned the known input power, \( P_{cal} \). The term \( G_{cal} \Delta \tau_{cal} \) converts the total integrated power to an equivalent peak power in a 100-ns pulse.

A frequently used model [5], [7], [9], [11] indicates that mean path loss increases exponentially with distance, that is,
\[ \text{PL}(d) \propto \left( \frac{d}{d_0} \right)^n \] (5)

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 decibels is defined as the path loss in decibels from the transmitter to the reference distance \( d_0 \) plus the additional path loss described by (5) in decibels; thus,
\[ \text{PL}(d) \text{ dB} = \text{PL}(d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) \text{ dB}. \] (6)

For the results presented herein, we use a close-in reference distance \( d_0 = 1 \text{ m} \) from which to refer all measured path loss values. We assume \( \text{PL}(d_0) \) is due to free-space propagation from the transmitter to the 1-m reference distance. Assuming isotropic antennas, this leads to 38.0-dB path loss at 1900 MHz over a 1-m free-space path, as shown in (7)
\[ \text{PL}(d_0 = 1 \text{ m}) \text{ dB} = 20 \log_{10} \left( \frac{4 \pi (1 \text{ m})}{\lambda (\text{m})} \right) \text{ dB}. \] (7)

Because the 3-D propagation distance is larger than the 2-D ground separation when the transmitter and receiver are separated by less than 10 m, there will be some error in calculating path loss using only the 2-D ground separation. Since all measurements were made at distances greater than 10 m, we have measured separation distances using the 2-D ground separation between the transmitter and receiver, rather than the actual 3-D separation, with no loss in accuracy.

**B. Two-Ray Model and Fresnel Zone Theory**

In the two-ray model [6], [11], [14], [15] shown in Fig. 1, the direct ray travels from the transmitting antenna of height \( h_t \) to the receiving antenna of height \( h_r \) along the LOS path \( r_1 \). The second ray reaches the receiver antenna along the ground-reflected path \( r_2 \). This model is used commonly when the transmitting antenna is several wavelengths or more above the horizontal ground plane [6], [15]. The signal at the receiving antenna is the resultant vector sum of the direct and ground-reflected components. By using the method of images [6], [15], the received electric field can be expressed as
\[ |E|^2 = |E_1 - E_2|^2 = \left| \frac{1}{r_1} e^{-jkr_1} + \Gamma(\alpha) \frac{1}{r_2} e^{-jkr_2} \right|^2, \] (8)

where \( \Gamma(\alpha) \) is the Fresnel reflection coefficient, which is a function of the angle of incidence \( \alpha \) and the antenna polarization. This dependence on angle and polarization is expressed as [6]
\[ \Gamma(\theta) = \frac{\cos \theta - a \sqrt{\varepsilon_r - \sin^2 \theta}}{\cos \theta + a \sqrt{\varepsilon_r - \sin^2 \theta}}, \] (9)

where
\[ a = \begin{cases} 1/\varepsilon_r, & \text{for vertical polarization} \\ 1, & \text{for horizontal polarization} \end{cases} \]

and \( \theta = 90^\circ - \alpha \) and \( \varepsilon_r \) is the relative dielectric constant.

Fig. 2 is a plot of the path loss in decibels relative to the received power at a 1-m reference point as a function of T-R separation for the two-ray model shown in Fig. 1, with the Fresnel reflection coefficient assumed to be \( \Gamma = -1 \). Fig. 2 shows two distinct regions that are separated by a "break
point" there is a significant difference in the way the received signal strengths vary in these two regions. Prior to the break point, the signal strength oscillates due to the destructive and constructive interference combination of the phases of the two received rays. The mean path loss, determined by averaging out the fast fading [5], has an exponent for this region of $n = 2$. The oscillations in the signal strength cease after the break point, and the received power exhibits an $n = 4$ mean path loss exponent.

The "break point" shown in Fig. 2 can be related to Fresnel zone theory. The first Fresnel zone is defined as an ellipsoid whose foci are the transmit and receive antennas. The distance from either antenna to a point on the ellipsoid and back to the other antenna is $\lambda/2$ greater than the direct path distance, $r_1$, in Fig. 1. The break point will be considered as the distance for which the ground begins to obstruct the first Fresnel zone. When the propagation path has first Fresnel zone clearance, meaning that the particular obstacle does not impinge on the first Fresnel zone volume, then the signal attenuation with distance is purely due to the spherical spreading loss of the wavefront (the same mechanism as free-space propagation). Once the first Fresnel zone is obstructed, the path loss becomes greater than for free-space propagation. The distance, $d_f$, at which the first Fresnel zone becomes obstructed, is given by

$$d_f = \frac{1}{4} \sqrt{(\Delta^2 - \delta^2)^2 - 2(\Delta^2 + \delta^2)\left(\frac{\lambda}{2}\right)^2 + \left(\frac{\lambda}{2}\right)^4},$$

(10)

where $\Delta = h_t + h_r$ and $\delta = h_t - h_r$ [6], [15]. Equation (10) assumes a flat earth model between the transmitter and receiver. The Fresnel zone model is valid only for LOS cases where there is a direct signal path between the transmitter and receiver, and for this reason the model will be applied only to LOS topographies. For obstructed (OBS) topographies, a single regression path loss model is presented.

C. Multiple Regression Models for Line-of-Sight Topography

Path loss is often considered to be log-normally distributed about the mean power law described in (6) [9], [11]. The two-ray model discussed in Section III-B has been used to model propagation in many urban and suburban environments [14]-[16]. Because of the simplicity of the dual region linear curve that results from a log-log plot of path loss versus distance, the model is an excellent candidate for use in environments where a direct path and one or more reflection paths may occur. If a simple analytical model can be developed, the results can be applied directly to solving microcellular system design problems [14]. In this paper, we show that for LOS topographies a double regression model gives good results, whereas for OBS topographies a single regression model is more appropriate.

The path loss results presented in this paper for LOS topographies were obtained using two different forms of a double linear regression to compute values of the path loss exponents $n_1$ and $n_2$ for the two regions and the standard deviation $\sigma$ in decibels about the best fit mean power law model in an 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 [15]. If a logarithmic distance axis is used, then the double regression model becomes a piecewise linear model with different slopes on either side of the break point. This double regression piecewise linear model generally provides an overall MMSE best fit curve with a smaller standard deviation than a simple single linear regression model for LOS cases.

One form of the piecewise linear model forces the break point between the two linear regions to occur at a distance that has first Fresnel zone clearance, such as shown in Fig. 2. The alternate form of the model allows the break point to float so that the MMSE best fit curve on all the measured data determines the least-mean-squared error break point distance. 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 analytically derived first Fresnel break point is very close to the mean squared error for the measured MMSE break point, then there is not much advantage to using the MMSE break point. In this case, the Fresnel break point, which is based on the physical heights of the antennas, can be computed easily by (10) for any microcellular LOS system. We now show that, indeed, for LOS microcell channels, the first Fresnel zone break point is an excellent parameter for determining the break point for a piecewise linear path loss model.

In the first form of the double regression model, the break point between the two linear regions is fixed at the first Fresnel zone clearance distance determined from (10) based on the antenna heights and wavelength. The first double regression piecewise linear model for path loss $PL_1$ in decibels and $d$ in meters is then

$$PL_1(d) = \begin{cases} 
(10n_1)\log_{10}(d) + p_1, & \text{for } 1 < d < d_f \\
(10n_2)\log_{10}(d/d_f) + (10n_1)\log_{10}(d_f) + p_1, & \text{for } d > d_f,
\end{cases}$$

(11)

where $p_1 = PL(d_0)$ is the path loss in decibels at the reference distance of $d_0 = 1$ m (at 1900 MHz, $p_1 = 38.0$ dB). The unknown parameters $n_1$ and $n_2$ are the power law exponents for the two regions of the model that are optimized for MMSE with measured data [9], [5]. The power law exponents are a function of the choice of reference distance $d_0$ [14]. The break point between the two regions, $d_f$ in meters, is fixed at the first Fresnel distance defined by (10). Thus, there are two unknown coefficients in this model ($n_1$, $n_2$) that completely define the slope and intercept of the line segments in the two linear regions. These two unknowns can be determined in closed form based on the MMSE criterion, where the variance or mean squared error $\sigma^2$ is the quantity to be minimized. For a
total of $N$ measurement locations, the mean squared error is

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (PL_i - PL_1(d_i))^2,$$

(12)

where $PL_1$ is the measured path loss in decibels for the $i$th path loss measurement and $PL_1(d_i)$ in decibels is (11) evaluated at the T-R separation distance $d_i$ in meters for the $i$th measurement. The distances $d_i$ were determined from maps and the known locations of the mobile receiver at street intersections near the base station transmitter. The two model parameters are calculated so that the mean squared error defined in (12) is minimized given the model in (11).

In the second form of the double regression model, the break point between the two linear regions is not fixed, but is instead an unknown parameter to be determined in the curve fit. Thus, the break point is the one that minimizes the mean squared error between the model and the measured data. The alternate double regression piecewise linear model for path loss $PL_2$ in decibels is

$$PL_2(d) = \begin{cases} 
(10n_1^*) \log_{10}(d) + p_1, & \text{for } 1 < d < d_b \\
(10n_2^*) \log_{10}(d/d_b) + (10n_1^*) \log_{10}(d_b) + p_{1}, & \text{for } d > d_b, 
\end{cases}$$

(13)

where the break point $d_b$, $n_1^*$, and $n_2^*$ are unknown parameters. Again, $n_1^*$ and $n_2^*$ are the path loss exponents for the model. Since the break point is allowed to float, an MMSE curve fit will produce the break point $d_b$, which minimizes the mean squared error. An iterative routine is used to minimize the mean squared error as defined in (12) as a function of the three unknown parameters.

### D. Multiple Regression Results for Line-of-Sight Topography

Figs. 3-5 show measured path loss data as a function of T-R separation for the low, medium, and high antenna heights, respectively, for LOS topographies. Each point represents measured path loss with the mobile at a particular street intersection. Along with the experimental data points, the two forms of the double regression model that give the lowest mean squared error described in (13) with the floating MMSE break point ($d_b$) and (11) with the fixed Fresnel zone break point ($d_f$) are shown on each figure.

Table I compares the curve fit parameters and standard deviations for the two double regression models for each antenna height. From the table it can be seen that the rms errors ($\sigma$ in decibels) for the two curve fits do not differ more than 0.65 dB for all three antenna heights. This indicates that the error introduced by forcing the break point at the first Fresnel zone is quite small; therefore, the double regression model with the fixed break point at the first Fresnel zone gives good results compared with the model using the MMSE optimum break point based on actual field measurements, and is based solely on operating frequency and the antenna heights. It is worth noting that, for all three antenna heights, the Fresnel break point model has $n_1$ consistently near two and $n_2$ at approximately three to four.

The results from Table I indicate that the flat earth Fresnel break point model can be used to characterize the path loss as a function of distance. 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 variability in the path loss exponent for the region beyond the Fresnel break point, with values of $n_2$ from two to seven being typical. Values for the path loss exponent beyond the break point will depend on the particular physical environment, such as building locations, terrain characteristics, and street widths.

From Table I, there is a significant trend toward higher path loss exponents beyond the break point for the higher antennas than for the lower antennas using the Fresnel best-fit model. The model parameter $n_2$ changes from 3.29 to 3.36 to 4.16 for the low, medium, and high antennas, respectively. It is important to note that the first Fresnel zone clearance distance (break point) for the high antenna is much larger than for the low 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, whereas 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 important when considering microcellular systems where the cell size may be anywhere from a few meters to about 2000 m. The 100–2000-m T-R separation range is the most critical region for microcellular applications where low-power, small-radius cells are to be implemented. For microcells, the difference in first Fresnel zone clearance distances can more than offset the difference in path loss exponents for the high versus low antennas. Although the path loss exponent beyond the break point is greater for the high antenna, the path loss values in the 100–2000-m range are significantly less for the high antenna than for the low antenna because of the increased first Fresnel break-point distance. This important observation indicates that the value of the path loss exponent is not nearly as important as the break-point location for microcellular applications. Fig. 6 illustrates the influence of the break-point location on the path loss curves for high and low antennas. The two curves in the figure were obtained by using the Fresnel best fit model parameters for high and low antennas from Table I in the double regression linear model of (11). From the figure, it is clear that the higher antenna provides a lower path loss over the typical microcellular coverage range, although the higher antenna has a larger path loss exponent beyond the first Fresnel zone break point.

E. Single Regression Model for Obstructed Topography

For obstructed topographies, where no direct path exists between the transmitter and receiver, a single regression power law model relating path loss to T-R separation has been used. The single regression power law model is identical to evaluating the double regression model of (11) with the break-point distance set equal to infinity ($d_f = \infty$) and the path loss exponent $n_2$ selected to minimize the mean squared error. By fitting the models to experimental data, results indicate that the single regression rms error is usually within 0.2 dB of the rms error for an MMSE double regression model fit using (13) for the same obstructed topography data. Because the mean squared errors are comparable for the single and double regression models, the simpler single regression can be applied without a significant loss in accuracy.

F. Single Regression Results for Obstructed Topography

Fig. 7 shows the measured path loss data as a function of T-R separation and the single regression curve fit for the high antenna height in obstructed topographies. Table II lists the single regression curve fit parameters for each antenna height in obstructed topographies. The rms error values (σ = standard deviation of the data about the mean power law model) for the obstructed topographies with a single regression model are generally between 7 and 10 dB. These results are similar to the values obtained for the LOS data presented in Section III-D. The rather large standard deviations indicate the need for research into more accurate LOS and OBS propagation models. The rms errors are generally larger for the obstructed cases; this observation reflects the larger degree of variability.

**TABLE I**

<table>
<thead>
<tr>
<th>FRESNEL ANTENNA HEIGHT FOR LINE-OF-SIGHT TOPOGRAPHIES</th>
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<tbody>
<tr>
<td>Low (3.7 m)</td>
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<tr>
<td>Med (8.5 m)</td>
</tr>
<tr>
<td>High (13.3 m)</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Antenna Height</th>
<th>n</th>
<th>σ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (3.7 m)</td>
<td>2.58</td>
<td>9.31</td>
</tr>
<tr>
<td>Med (8.5 m)</td>
<td>2.56</td>
<td>7.67</td>
</tr>
<tr>
<td>High (13.3 m)</td>
<td>2.69</td>
<td>7.94</td>
</tr>
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</table>
observed in non-LOS circumstances. An important result from Table II is that the path loss exponents for the low, medium, and high antennas are all $n_1 = 2.6 \pm 0.1$, indicating that in obstructed cases there is no real path loss advantage for the higher antennas. The results also indicate that path loss exponent values in the $2 < n < 3$ range accurately represent real-world measurements for microcell channels as suggested in [14]. It is also significant to note that the obstructed cases do not exhibit a pronounced break point, in contrast to the LOS cases.

G. Delay Spread Analysis for Line-of-Sight and Obstructed Topographies

One method of characterizing wide-band multipath channels is by calculating their rms delay spread ($\sigma_d$) [5]. Many researchers have shown that time delay spread can have detrimental effects on digital communications for certain portable radio channels [2], [4], although Fung and Rappaport have shown that delay spread alone does not determine the actual bit error rate at any instant [4]. The rms delay spread is the square root of the second central moment of the power delay profile and is calculated as in [5].

For this study, rms delay spread has been analyzed as a function of antenna height and path loss. Table III shows the maximum, mean, and standard deviations of the rms delay spread values as a function of the three antenna heights for all measured profiles. From the table it is clear that the mean rms delay spread increases as a function of the base station antenna height. The low antenna at $3.7 \text{ m}$ had an average rms delay spread of $136.8 \text{ ns}$, whereas the high antenna at $13.3 \text{ m}$ had an average rms delay spread of $257.9 \text{ ns}$. We also studied the standard deviation of the rms delay spread to determine the variability as a function of antenna height. The standard deviation of the rms delay spread increased as a function of antenna height. The delay spread increases as antenna height increases because as the antenna is raised it becomes visible to more scattering objects at greater distances. This observation brings up an interesting application to the design of microcellular systems. As discussed in Section III-C, in general a higher base station antenna provides a lower path loss for a given distance, but the higher base station antenna will also cause a larger delay spread. There will then be a tradeoff between path loss and delay spread for a given antenna height, and for a particular environment an optimum base station antenna height may be found.

Fig. 8 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, there is clearly a trend toward increasing delay spread as path loss increases. The increasing delay spread as a function of path loss has also been observed by Devasirvatham [13] for indoor environments. As path loss increases, delay spread increases because as the LOS component becomes weaker, multipath components with larger excess delays and weaker power levels can be detected by the measurement equipment. As a result of the limited dynamic range of the measurement system display, these weak multipath components cannot be detected when a strong direct path signal is present. For system design purposes, an overbound on the path loss can be obtained by using a simple exponential model of the form $\sigma_d = 0.065^{PL(d)}$, where $\sigma_d$ is the rms delay spread in nanoseconds and $PL(d)$ is the path loss in decibels (referred to the 1-m reference distance), as a function of the T-R separation $d$. The exponential model offers a simple model for delay spread as a function of path loss and distance. The exponential overbound curve is shown in Fig. 8 along with the measured data points for all measurement locations and antenna heights.

IV. MICROCELLULAR SYSTEM DESIGN

A. Calculation of Outage Probability due to Path Loss

By using the path loss models presented in Section III, along with some basic assumptions concerning user density within a microcell, approximations can be formulated 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 $r_{\text{min}} = 1 \text{ m}$. The path loss over a microcell is assumed to follow a log-normal distribution about the mean Fresnel break-point path loss model presented in (11). A log-normal distribution corresponds to a Gaussian distribution about the mean path loss with the values in decibels. Therefore,
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]

\[
f(PL|n_1, n_2, \sigma, r) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left\{ -\frac{1}{2} \left( \frac{p_1 - PL(n_1, n_2, r)}{\sigma} \right)^2 \right\}
\]

where \(p_1\) is the 1-m reference path loss in decibels, \(\sigma\) is the standard deviation in decibels given in (12), and \(PL(n_1, n_2, r)\) is the path loss model of (11) in decibels as a function of distance \(r\) \((r > 1 \text{ m})\) and power law exponents \(n_1\) and \(n_2\).

For distance \(r\) less than the Fresnel break point \((r < d_f)\) then \(\sigma = \sigma_1\), and beyond the break point \((r > d_f)\), then \(\sigma = \sigma_2\), based on the two different regions of the path loss model. The probability can be integrated from \(r_\text{in}\) to \(r_\text{out}\) to determine the pdf conditioned solely on the model parameters \((n_1, n_2, \sigma_1, \sigma_2)\) and independent of the radial distance \(r\) [12].

The pdf of path loss over a coverage area is [7]

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

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

To determine the pdf of the density of users in users per meter \(f(r)\), first assume that the users are distributed uniformly over the circular cell coverage area. Using the theory of functions of a single random variable, the following equation for the pdf of users with a uniform density is derived easily as a function of \(r_\text{max}\), the cell radius [7], [12]

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

Substituting (16) and (14) into (15), 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 integration over the radius range from \(r_\text{min}\) to \(r_\text{max}\) in (15) can be calculated by using a numerical integration algorithm. The resulting pdf can be integrated to obtain a cumulative distribution function (cdf), which gives the probability that path loss is within a particular decibel range throughout the microcell. From the cdf, the probability of an outage can be calculated by obtaining the probability that the path loss will be greater than the outage threshold. The outage probability curves presented in Section IV-B were generated in this manner, using values of \(r_\text{max}\) from 100 to 1500 m.

B. Results for Outage Probability due to Path Loss

Figs. 9-11 show the percent outage probability versus maximum cell size based on the LOS first Fresnel break-point model parameters shown in Table I for the low, medium, and high antennas. The term “outage” means that the path loss exceeds a specified level, and it is then assumed that communication is lost over the particular channel. The path loss values are with respect to the path loss at the 1-m reference distance; the actual path loss between the transmitter and receiver would be 38 dB greater than the contour values shown for a frequency of 1900 MHz. The outage probability curves are plotted for various outage thresholds in steps of 10 dB by using the method presented in Section IV-A, where each curve represents a different outage threshold. System designers can use the results obtained in Section IV-A to optimize cell sizes based on outage probabilities determined for a particular environment. Once the model parameters for a particular environment are determined or estimated, the outage probabilities due to path loss can be obtained easily.

From Figs. 9-11, several important observations can be made. The first Fresnel zone break point is clearly evident on the curves as the abrupt change in slope. Recall that, at the break point, the path loss exponent changes discontinuously from \(n_1\) to \(n_2\), causing the integration in (15) to change abruptly. If the standard deviation spread about the measured path loss \(\sigma = \text{rms error}\) beyond the break point is greater than
the rms error prior to the break point, the outage probability curve will exhibit a positive increase in slope (increased outage), as seen in Figs. 9 and 11. If the rms error beyond the break point is lower than the rms error prior to the break point, then the outage probability curve will exhibit a negative change in slope (decreased outage) as seen in Fig. 10. Based on the experimental models presented in Table I, our results are inconclusive with regard to a positive or negative increase in slope beyond the break point. This is because there is no clear trend for the rms error as a function of antenna height. The low and high antenna path loss models each exhibit higher rms errors than the medium antenna path loss models.

For microcellular design, it would be advantageous to have an abrupt positive change in the slope of the outage probability curve to delineate clearly the microcell boundaries. For example, in Fig. 11, if the microcell boundary were selected at the first Fresnel zone distance of 573 m, then with a path loss outage criteria of 80 dB with respect to a 1-m reference distance, an abrupt increase in outage probability is observed at the cell boundary. In other words, the microcell boundaries are defined clearly in terms of outage probability.

This observation gives microcellular systems designers the ability to fine-tune the microcell sizes to the propagation environment. Based on estimated path loss exponents, standard deviations, and transmit/receive antenna heights, it is then possible to determine the proper choice of cell radius to achieve a certain outage probability for given path loss.

Real microcells will not be circular with LOS to all portions of the coverage area, but will have very irregular shapes [17]–[19]. A circular cell approximation for determination of the maximum cell radius based on an LOS model provides a realistic estimate of the length of a microcellular coverage region where LOS can be maintained between the transmitter and receiver. The calculation for outage probability may be repeated for obstructed locations. The resultant coverage areas may be superimposed to provide the true coverage area that incorporates both LOS and OBS propagation models, as conceptually shown in Fig. 12. In Fig. 12, the circular boundaries represent the maximum cell radii for the LOS and OBS models. The coverage area is indicated by the shaded region.

C. Calculation of Outage Probability due to Delay Spread

The relationship between delay spread and path loss, which was developed in Section III-G, can be used to estimate worst case outage probabilities based on delay spread. The exponential overbound model shown in Fig. 8 can be used to determine path loss for a specified worst case delay spread. The overbound model provides a one-to-one mapping of path loss to rms delay spread and thus represents a worst case scenario for rms 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, T-R separation, and LOS/OBS topography. The same technique discussed in Section IV-A is used, where the path loss is obtained from the overbound model evaluated for the specified rms delay spread outage level. The system designer...
is thus able to use either path loss or delay spread to define an outage.

**D. Results for Outage Probability due to Delay Spread**

The exponential overbound model in Fig. 8 has been used to obtain a worst case relationship between path loss and delay spread. The resulting relationship can be used in the method described in Section IV-A to calculate outage probability as a function of delay spread. Figs. 13–15 give the delay spread outage probability versus maximum cell size for LOS cases as a function of delay spread with low, medium, and high antennas, respectively. A delay spread outage occurs when the delay spread on a particular channel exceeds the threshold level. Again, because of the dual regression model, the slope changes abruptly at the first Fresnel zone boundary. The microcellular system designer can select optimum cell sizes based on delay spread as well as path loss outage criteria. For example, in Fig. 15, if the microcell size is chosen as 573 m, then the delay spread should increase abruptly beyond that point. The delay spread outage probability results represent a worst case scenario, since they were derived using the exponential overbound model.

**V. CONCLUSIONS**

In this paper, measurement results have been presented for five typical microcellular-type environments in urban and suburban sections of the San Francisco Bay area. These measurements were made for three different transmit antenna heights that represent typical heights for lamp-post-mounted microcell base stations. In LOS cases, path loss as a function of T-R separation has been modeled using a double regression curve fit with both a break point at the first Fresnel zone clearance distance and an MMSE optimum break point. The standard deviations of the resulting best fit models indicate that the Fresnel zone fit can be used with excellent accuracy with respect to the optimum MMSE break point, which can be found iteratively. Thus, for specified transmit and receive antenna heights and T-R separation, the mean path loss can be estimated based on power law exponents and the computed first Fresnel zone break point.

In general, there is a trend toward higher power law path loss exponents after the first Fresnel break point for the high antennas compared with the low antennas. For microcellular systems, where cell sizes are typically in the range from tens of meters to approximately 2000 m, the difference in path loss exponents is more than offset by the change in first Fresnel zone distance. As the antenna height becomes higher, the first Fresnel zone distance becomes larger. Since the path loss exponent prior to the Fresnel break point is approximately two, and the exponent beyond the break point is greater than two, the distance at which the exponents change is very important for system design. For T-R separations of 50–2000 m, the high antenna generally observed a lower path loss than the low antenna. We found that beyond the Fresnel break point, path loss exponents were typically approximately three or four.

The rms delay spread was found to be a strong function of antenna height. As the antenna height increased, the standard deviation and mean values of the rms delay spreads increased...
markedly. This result indicates that there is a trade-off between path loss and delay spread considerations when choosing a microcellular base station antenna height. As the antenna height increases, path loss is reduced, but delay spread increases as well. An exponential overbound 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 T-R separation and for rms delay spread as a function of path loss have been incorporated into the design of microcellular-type systems. By developing an expression for the pdf of the path loss conditioned on the propagation model parameters and the cell radius, it is possible to get an expression for the outage probability as a function of cell size. If a specific path loss outage criterion 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 criterion. Microcellular system designers can now select an optimum cell size for a particular propagation environment based on an outage probability using a path loss or delay spread outage criterion.

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REFERENCES


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