

A Model for the Multipath Delay Profile of Fixed Wireless Channels

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Abstract—This paper deals with the measurement and modeling of multipath delay on fixed wireless paths at 1.9 GHz in suburban environments. The primary focus is on the delay profile, which is the normalized plot of received power versus delay in response to an RF “impulse.” We describe measurement campaigns in the western suburbs of Chicago, IL, and in suburban north-central New Jersey. Our analysis of the data suggests to us that, for directive terminal antennas, the delay profile can be modeled as having a “spike-plus-exponential” shape, i.e., a strong return (“spike”) at the lowest delay, plus a set of returns whose mean powers decay exponentially with delay. This delay profile can be characterized by just two parameters (both variable over the terrain), namely, the ratio (K_o) of the average powers in the “spike” and “exponential” components and the decay time constant (τ_o) of the “exponential” component. No such simple structure appears to apply for delay profiles using omnidirectional antennas. For a directive antenna with a 32° beamwidth, we find that: 1) the statistical correlation between the profile parameters K_o and τ_o is negligible; 2) these parameters are relatively insensitive to antenna height and path length; and 3) over each measured region (Illinois and New Jersey), K_o and τ_o have median values close to 8 dB and just below 0.2 μ s, respectively. Moreover, we have found simple probability distributions that accurately portray the variability of K_o and τ_o over the terrain.

Index Terms—Delay profiles, directional antennas, fixed wireless, multipath, propagation, rms delay spread.

I. INTRODUCTION

TIME delay dispersion, a result of multipath scattering, is an inherent aspect of reception in most wireless systems, whether fixed or mobile. It is the time-domain dual of frequency-domain selectivity, i.e., the greater the time dispersion, the greater the frequency selectivity of the channel response.

The impact of time dispersion (or frequency selectivity) varies in kind and degree with the particular communication method. For example, in code division multiple access (CDMA) systems, it determines the amount of frequency diversity attainable and the effectiveness of Rake processing. In time division multiple access (TDMA) systems, it determines the amount of intersymbol interference and the extent to which

equalization is required. In multitone systems, it determines the frequency response variation across the tones and the value derived from coding across tones.

Regardless of the application, the preferred way to characterize multipath effects is in the time domain, i.e., through the so-called delay spectrum (also called the delay profile). This is the approach we take here. With an adequate representation of the delay profile, designers and analysts can simulate either time-domain or frequency-domain responses, whichever best suits the system at hand.

There are numerous publications on delay profiles, and also delay spreads, in the open literature [1]–[22]. Most of the published results, however, are for omnidirectional antennas; only a few give results for directive antennas [5], [8], [9], [22], and mainly at the base station. In this paper, we characterize the delay profile for fixed paths with directive terminal antennas, and we propose a statistical model. We also make a comparison with results obtained for omnidirectional terminal antennas.

Delay profile measurements were made in New Jersey (NJ) and Illinois (IL), using a commercial wideband channel sounder (8-MHz bandwidth). In both regions, two transmit sites (representing base stations) were used, and the number of downlink receive sites (representing terminal locations) for each was either 20 (NJ) or 12 (IL). The transmit-receive distances ranged from about 0.5 km to about 2 km in both regions. The New Jersey data were collected from both branches of a dual-polarized (slant 45°) antenna with a nominal half-power beamwidth (HPBW) of 32° at heights of 3 and 10 m. The Illinois data were collected using the same kind of dual-polarized antenna and also using an omnidirectional antenna, both at a height of 3 m only. The transmit antenna in all cases had a 65° HPBW.

The organization of this paper is as follows: Section II gives the theoretical background; Section III describes the measurement campaigns; Section IV presents preliminary modeling based on the data reductions; Section V gives numerical results; and Section VI summarizes the model and cites additional important issues.

II. THEORY

The complex envelope impulse response of a wireless channel with multipath can be denoted by the two-variable function $g(\tau; t)$ where: τ represents echo delay; g is the complex signal gain for the component received at delay τ ;

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and t is the time variable, reflecting the fact that the gain g for any delay τ can undergo variations. The value of τ is typically referenced to the time of arrival, at the receiver, of the original impulse traversing a line-of-sight path from the transmitter.

It is physically intuitive to envision $g(\tau; t)$ as a summation of impulses, i.e., a set of discrete echoes, each with its own delay and complex amplitude, which can be slowly time varying. In this representation, we could write the impulse response as

$$g(\tau; t) = \sum_i a_i(t) \delta(\tau - \tau_i) \quad (1)$$

where the set of delays $\{\tau_i\}$ is determined by the geometry of the environment of direct and scatter paths. Pursuing this one step further with the aid of sampling theory, the impulse response for a channel of strictly limited bandwidth W can be represented by the form (1), where $\{\tau_i\}$ is now the uniformly spaced set $(0, 1/W, 2/W, \dots, i/W, \dots)$. [In essence, the gain of the i th path is the complex sum of gains for all paths having delays between $(i-1/2)/W$ and $(i+1/2)/W$.] We will follow this latter approach in our data reductions and modeling.

Without regard to whether $g(\tau; t)$ is discrete in τ or continuous or some of both, we can say the following: the average over t of $g(\tau; t)$ represents the fixed part of the impulse response, and the remainder represents a zero-mean variable part. Thus

$$g(\tau; t) = g_V(\tau) + g_v(\tau; t) \quad (2)$$

where

$$g_V(\tau) = \text{Ave}_t\{g(\tau; t)\}; \quad \text{Ave}_t\{g_v(\tau; t)\} = 0. \quad (3)$$

The Fourier transform of $g(\tau; t)$ with respect to τ is the time-varying frequency response of the channel.

Now suppose that, for modeling purposes, we represent both $g_V(\tau)$ and $g_v(\tau; t)$ in (2) by a discrete summation, as in (1), where $\{\tau_i\} = (0, 1/W, 2/W, \dots, i/W, \dots)$ and W is a suitably large bandwidth (e.g., $W = 8$ MHz). Suppose further that, for $g_v(\tau; t)$, the amplitudes are independent, zero-mean, complex Gaussian variables over time.¹ Then, a quite adequate description of time dispersion on a given radio link could be obtained by specifying two things: 1) The set of fixed complex amplitudes $\{A_i\}$ in $g_V(\tau)$ associated with the uniformly spaced delays in $\{\tau_i\}$ and 2) the set of mean-square amplitudes $\{\sigma_i^2\}$ in $g_v(\tau; t)$ associated with the same delays.

In traditional wireless channel modeling, the paths for all delays are treated as having complex Gaussian fading (no fixed part, so that $|A_i|^2 = 0$ for all i). This is the condition for Rayleigh fading magnitudes. In this case, the variation of σ_i^2 with τ_i is called the delay spectrum or delay profile. (Usually, each σ_i^2 is normalized by the sum of σ_i^2 over i , so that the "area" of the delay profile is one.) This approach is quite suitable to mobile channels, where complex Gaussian fading of the i th path, for all i , is reasonable to assume. For the fixed wireless environment, however, the component

$g_V(\tau)$ must also be considered. This is evident from previous investigations of Ricean K-factors, cf. [23], which showed that Rayleigh fading over time is not the norm in these channels.

We conclude that both $\{|A_i|^2\}$ and $\{\sigma_i^2\}$ are desired for a characterization of dispersion on fixed wireless channels. In addition, the time variation properties (e.g., fading rates, Doppler spectra) of the gain fluctuations at the various τ_i 's would be valuable for multipath modeling. Our measurement system, however, was not capable of sampling gain at each delay with sufficient periodicity to acquire such information.

What we were able to acquire with good accuracy is the mean power $|A_i|^2 + \sigma_i^2$ for all i . We call this sum, suitably normalized, the delay profile of the fixed wireless channel. Specifically, the delay profile is P_i versus τ_i , where

$$P_i = \frac{|A_i|^2 + \sigma_i^2}{\sum_j (|A_j|^2 + \sigma_j^2)}. \quad (4)$$

We are also able to estimate the rms delay spread τ_{rms} , which is the second central moment of the delay profile. Thus

$$\tau_{\text{rms}}^2 = \sum_j \tau_j^2 P_j - \left(\sum_j \tau_j P_j \right)^2. \quad (5)$$

This quantity (also called just delay spread) is an important parameter in characterizing time dispersion or frequency selectivity. The reciprocal of τ_{rms} (appropriately scaled) is a measure of the correlation bandwidth, which is the frequency interval over which the channel response does not change appreciably. We will compute the delay spread from our data and use it to assess the accuracy of our delay profile modeling.

III. DATA COLLECTIONS AND PROCESSING

A. Experiment Design

The measurement program consisted of recording numerous delay profiles in Illinois and New Jersey. In Illinois, measurements were made at 12 downlink (i.e., terminal) locations from a transmit site in Bellwood and at 12 downlink locations from a transmit site in Naperville. At each downlink location, the measurements were made from a van parked on the street. Delay profiles were recorded for an omnidirectional antenna and for each branch of a dual-polarized (slant 45°) antenna with a half-power beamwidth of 32°. All measurements were conducted for a receive antenna height of 3 m. In Naperville the terrain was flat with low tree density, while in Bellwood it was flat with moderate tree density. The measurements took place in the fall, with trees in full foliage.

In New Jersey, measurements were made at 20 downlink locations from a transmit site in Iselin and at 20 downlink locations from a transmit site in Whippany. At each downlink location, the measurements were made from a van parked on the street. Delay profiles were made for each branch of the dual-polarized antenna at heights of both 3 and 10 m. The terrain was hilly, with dense trees. These measurements took place in the late summer, with trees in full foliage.

¹The premise underlying the Gaussian assumption is that there are several fluctuating echoes associated with any delay interval of width $1/W$ so that their complex sum converges to Gaussian in the central limit.

The transmit/receive distances for all sets of measurements were roughly in the 0.5–2.0-km range. Specifically, the distances ranged from 0.35–1.51 km in Bellwood, from 0.60–2.03 km in Naperville, from 0.47–2.17 km in Iselin, and from 0.50–2.00 km in Whippany.

For each combination of transmit site, receive location, antenna type, and antenna height, the measurement consisted of a sequence of recorded snapshots of the delay profile (received power versus delay in response to a transmitted RF “impulse”). Each measurement was made over a 5-min time interval at a rate of about 7 snapshots/s.

B. Measurement Equipment

The equipment used for every measurement was a commercial transmit/receive set whose operation is based on a variation of the sliding correlator principle [2]. The transmitted signal was a repeated 255-length pseudorandom noise (PN) chip sequence, with a rate of 8 Mc/s and a frame period of 32 ms. The transmission was centered at 1985 MHz in a bandwidth of about 10 MHz.

The processed receiver response to each PN sequence, assuming no multipath, is a sinc-type pulse with symmetrical sidelobes about the main lobe. The first sidelobe pair is about 14 dB below the mainlobe, separated from it by about $\pm 0.18 \mu\text{s}$. Further sidelobe pairs are spaced by about $0.125 \mu\text{s}$ and decay slowly with distance from the main lobe.

When there are multiple echoes due to scattering, the processed receiver output is a linear superposition of sinc-type pulses, reflecting the relative delays and amplitudes of the echoes. Successive responses of this type were square-law-envelope-detected and post-detection-integrated over about 140 ms to produce the net delay profile. The receiver processor acts to identify the 13 strongest of the echoes it resolves and to report their powers and delays as its output. This set of power-delay samples constitutes the output data of a single snapshot. About 2100 such snapshots were recorded for each 5-min measurement interval.

C. Processing of the Recorded Data

The set of recorded data was preprocessed to make it suitable for our analysis. There were noise level, resolution, and other issues that had to be addressed. Therefore, we performed the following steps prior to data reduction.

1) *Noise-Level Setting*: In each snapshot, the 13 most significant echoes were recorded by the instrument. Some noise peaks may, by random chance, be large enough to appear as weak echoes. Therefore, a threshold referenced to the noise floor had to be set above which the echoes are counted and below which they are ignored. We chose a threshold 6 dB above the mean noise floor, which translates into a 1.8% probability of false echo detection. The mean noise floor was found by linearly averaging echo-free noise samples over many data records.

2) *Data Binning*: We assigned each echo to the nearest value of delay equal to a multiple of $0.125 \mu\text{s}$. No significant echoes were observed beyond $1 \mu\text{s}$ in our data files, and so we processed only echoes between $\tau = 0$ and $\tau = 1 \text{ Ms}$.

3) *Data Screening*: A key step in the data reductions was to estimate the delay profile, obtained from the linear power versus delay, averaged over all the snapshots in a 5-min period. Another key step was to estimate the rms delay spread from appropriate moments of the delay profile. Some delay profiles obtained from data artificially produce small estimates of delay spread because of an inadequate signal-to-noise ratio. In cases where the strongest echo is close to the noise floor, for example, other echoes may not be detected because they are below the threshold we set (6 dB above the noise floor). This leaves only the strongest echo in the rms delay spread calculation, yielding $\tau_{\text{rms}} = 0$. To avoid this false result, we kept only the delay profiles where the strongest echo was at least 15 dB above the mean noise floor, thus leaving a reasonable margin for detecting other echoes.

4) *Combining the Two Polarizations*: The experimental data were collected at two orthogonal polarizations for each location and antenna height. We noted that, in most cases, the delay profiles at the two polarizations were roughly the same. Therefore, we obtained our net delay profiles by averaging the delay profiles for the two polarizations.

IV. MODELING THE DELAY PROFILE SHAPE

We computed the average of all the snapshots for each combination of transmit site, receive site, antenna type, and antenna height. In the case of the dual-pol antenna, this included averaging of the snapshots on the two branches. The result in each case was a power-delay representation like the one shown in Fig. 1 for a receive location in New Jersey (antenna height = 10 m). In this case, we give the results for the two polarizations individually, to demonstrate their similarity. Examples for a location in Illinois are shown in Fig. 2, where we give results for the two polarizations individually and also for the omnidirectional antenna.

The plots of Figs. 1 and 2 actually show relative path gain versus delay. To be consistent with the conventional notion of a delay profile, a specific normalization is required, namely, one that makes the sum of the linear path gains equal to unity, as in (4). This was done for all the cases treated.

A. Directive Antennas

The power-delay plots of Figs. 1 and 2 show a trend that was observed in nearly all of our data for directive antennas: a strong return at the lowest delay (defined as $\tau = 0$), followed by a sharp drop and a more-or-less linear decrease in decibel path gain with delay. Since a linear falloff on a decibel scale is equivalent to a decaying exponential on a linear scale, this suggests a delay profile of the form

$$P(\tau) = A\delta(\tau) + B \sum_{i=0}^{\infty} e^{-i\Delta\tau/\tau_o} \delta(\tau - i\Delta\tau) \quad (6)$$

where A , B , and τ_o are constants to be determined from data, and $\Delta\tau = 0.125 \mu\text{s}$ is the spacing between discrete terms of the delay profile. We shall call $A\delta(\tau)$ the *main* component and the remaining term the *exponential* component. Note that the total value of $P(\tau)$ at $\tau = 0$ is $A + B$, i.e., this average path

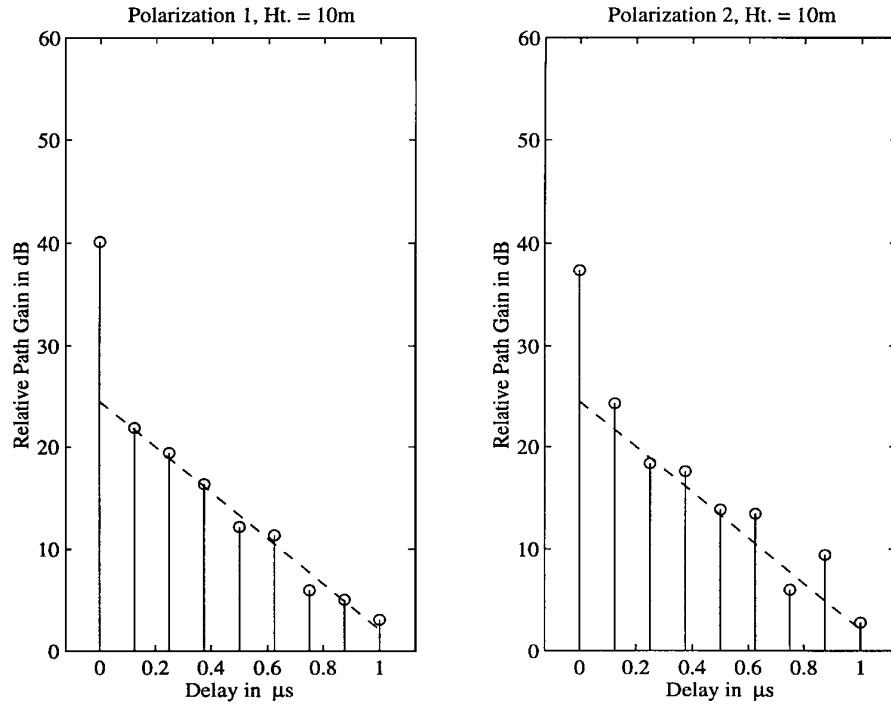


Fig. 1. Sample plots of decibel path gain versus delay, showing the “spike plus exponential” nature of the delay profile shape (New Jersey data).

gain has contributions from both the main and exponential components.

For convenience, we choose to cast $P(\tau)$ in (6) in terms of two delay profile parameters, K_o and τ_o , where K_o is the ratio of the power in the main component to the power in the exponential component. Since $P(\tau)$ has a total “area” of one, it is easy to show that

$$A = K_o/(1 + K_o); \quad B = (1 - e^{-\Delta\tau/\tau_o})/(1 + K_o). \quad (7)$$

Since the power in the main component is A , the power in the exponential component (for the normalized delay profile) must be $1 - A$. We can therefore estimate K_o from the data by: 1) determining B via linear regression of $\ln P(\tau)$ over all $\tau_i \neq 0$; 2) computing A as $P(0) - B$; and 3) computing K_o as $A/(1 - A)$. The estimation of the second parameter (τ_o) from the data is discussed in Section IV-C.

B. Observations and Omnidirectional Antennas

The “spike-plus-exponential” shape model for directive antennas applies to both the New Jersey and Illinois databases. The steady power decline with delay of the multipath components is consistent with intuition: echoes at longer delays tend to arrive at angles farther from the direct path and are thus more attenuated by the antenna sidelobes.

We found the exponential falloff of $P(\tau)$ to be more consistently adhered to in the New Jersey population than in the Illinois population, as exemplified by the comparison between Figs. 1 and 2. Nevertheless, we applied the same shape model to both databases and found K_o and τ_o to have very similar statistics for the two populations.

The “spike-plus-exponential” shape model does not hold up well for omnidirectional antennas. This is exemplified in Fig. 2 and is further illustrated later. In the absence of azimuth sidelobes, which impose some “structure” on the falloff of $P(\tau)$, the pattern of echo strength versus delay becomes more dependent on the vagaries of the local scattering environment. We therefore have no shape model to postulate for omnidirectional antennas.

C. RMS Delay Spread and the Parameter τ_o

There are several ways that τ_o in (6) can be estimated from data. An obvious way is regression fitting to the data plots of decibel power versus delay, as was done to obtain B in (6). The approach we prefer, however, is to compute the rms delay spread of the exponential component, using moment calculations on data, and then relating τ_o to that computed quantity.

For notational convenience, we denote by T_{rms} the rms delay spread of the exponential component of $P(\tau)$, to distinguish it from the rms delay spread, τ_{rms} , of the entire delay profile. We proceed by normalizing the exponential component to have unit area, leading to the profile

$$P_{\text{exp}}(\tau) = (1 - e^{-\alpha}) \sum_{i=0}^{\infty} e^{-i\alpha} \delta(\tau - i\Delta\tau) \quad (8)$$

where we define

$$\alpha \equiv \Delta\tau/\tau_o. \quad (9)$$

Applying (5), the defining relationship for delay spread, to (8), we can show that

$$T_{\text{rms}} = \frac{\Delta\tau}{(e^{\alpha/2} - e^{-\alpha/2})}. \quad (10)$$

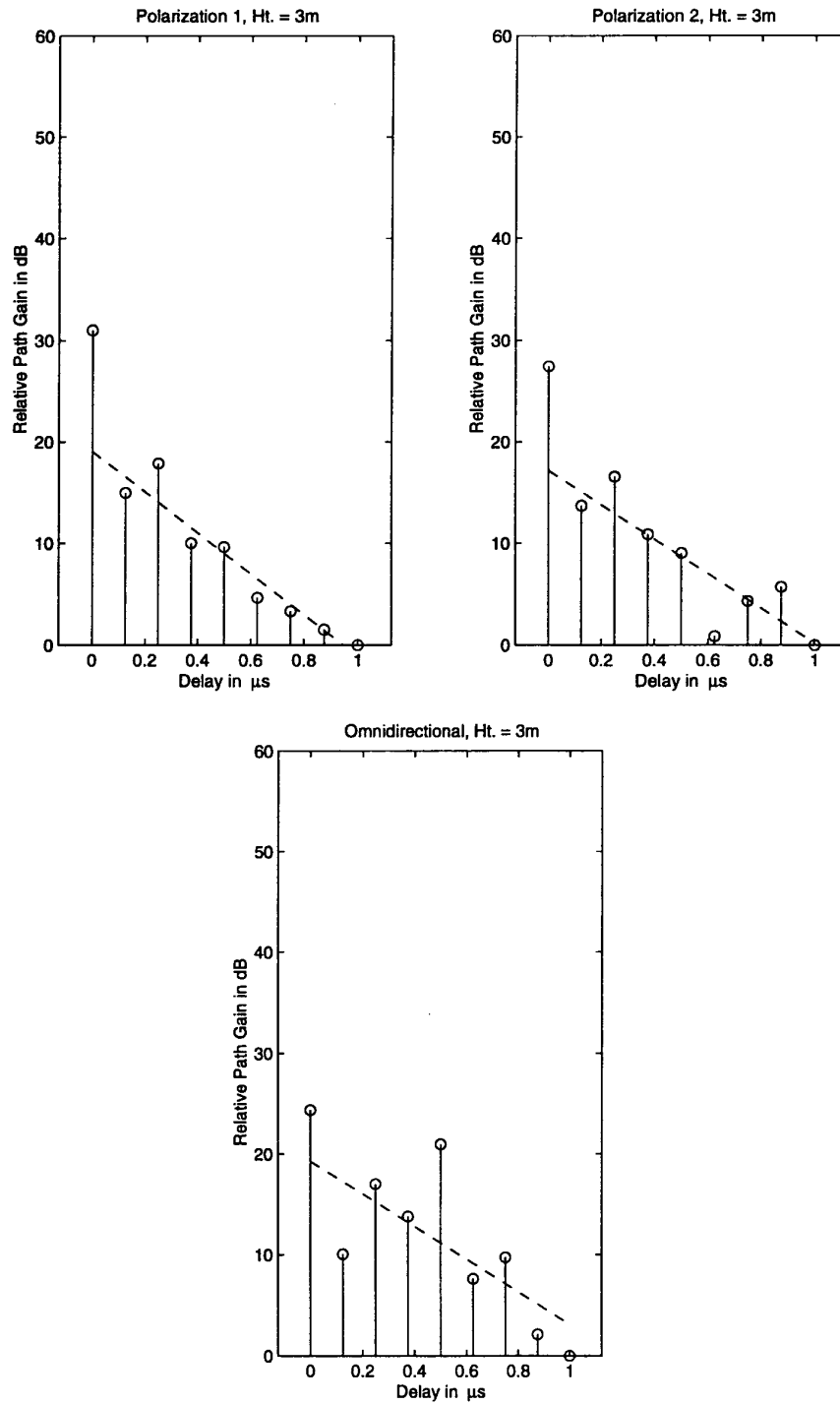


Fig. 2. Sample plots of decibel path gain versus delay, showing the “spike plus exponential” nature of the delay profile shape (Illinois data).

Combining (10) with (9) yields the solution

$$\tau_o = T_{\text{rms}} \left[\frac{\beta}{2 \ln \left(\frac{\beta}{2} + \sqrt{1 + \left(\frac{\beta}{2} \right)^2} \right)} \right] \quad (11)$$

where

$$\beta \equiv \Delta\tau / T_{\text{rms}}. \quad (12)$$

Clearly, when $\Delta\tau$ is small compared to T_{rms} , τ_o and T_{rms} are virtually the same, as they are in the limit of a continuous exponential ($\Delta\tau = 0$). Indeed, even when $\Delta\tau = T_{\text{rms}}$, there is only a 4% difference between τ_o and T_{rms} . In any case, τ_o

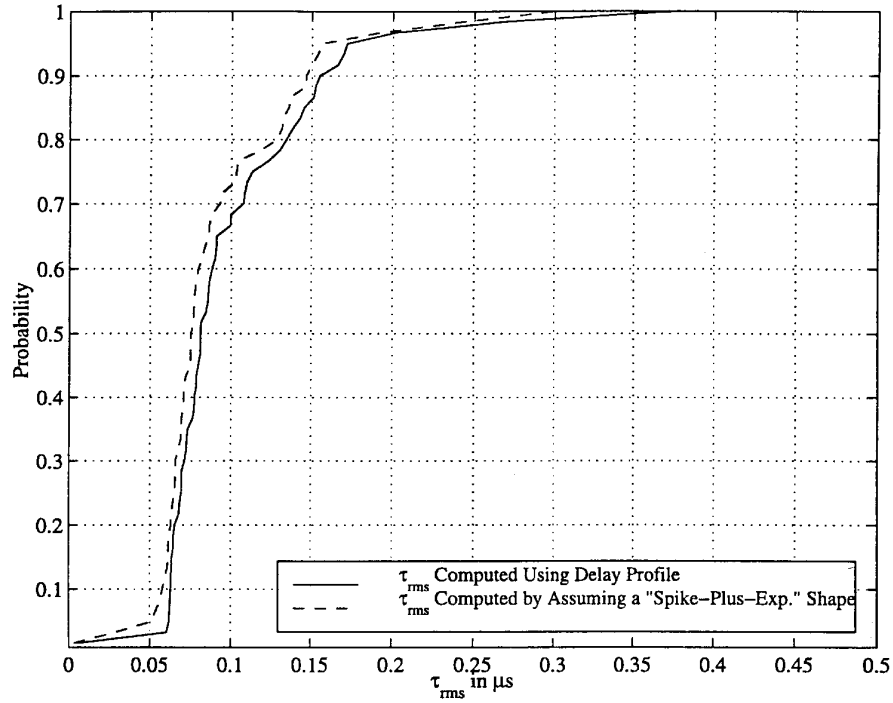


Fig. 3. CDF's of computed and estimated rms delay spread with a directive antenna (New Jersey data).

is easily computed using (11) and (12), where T_{rms} is derived from data via moment calculations (5), and $\Delta\tau$ is a fixed value of $0.125 \mu\text{s}$.

D. Confirming the Proposed Shape of $P(\tau)$

If the proposed shape of $P(\tau)$ is valid, it should be possible to predict the rms delay spread τ_{rms} given just K_o and T_{rms} . The relationship of τ_{rms} to these two parameters is sensitive to the shape, which suggests the following test. Predict τ_{rms} by first computing K_o and T_{rms} from data and then applying the presumed shape. Next, compute τ_{rms} directly from the data-derived profiles by applying (5). Finally, obtain and compare the cumulative distribution functions (CDF's) of τ_{rms} obtained both ways.

To predict τ_{rms} from K_o and T_{rms} , we apply (5) to (6) and, after some algebraic manipulation, we obtain

$$\tau_{\text{rms}}^2 = \frac{T_{\text{rms}}^2}{1 + K_o} \left[1 + \frac{K_o e^{-\alpha}}{1 + K_o} \right]. \quad (13)$$

Through (10), $e^{-\alpha}$ can be related to T_{rms} . We can therefore compute T_{rms} and K_o from data and then predict τ_{rms} using (13).

We followed this procedure over the population of locations in New Jersey and obtained a CDF. For the same population, we computed τ_{rms} directly from data via (5) and obtained another CDF. Both results are shown in Fig. 3. The extreme closeness of the two CDF's attests to the validity of our assumed shape for $P(\tau)$.

We repeated the above procedure for the population of locations in Illinois, for both the dual-polarization and omnidirectional antenna. The results for the dual-polarization antenna, shown in Fig. 4, are also quite close; as expected, the results for the omnidirectional antenna, shown in Fig. 5, are not. We conclude that the "spike-plus-exponential" shape model is a valid one for directive antennas, i.e., the kind likely to be used in fixed wireless systems.

Although we cannot offer a shape model for omnidirectional antennas, we can make an interesting numerical comparison between such antennas and the 32° beamwidth antennas studied here. The median τ_{rms} in both the New Jersey and Illinois populations was approximately 75 ns (Figs. 3 and 4), while the median τ_{rms} for the omnidirectional antenna was approximately 175 ns (Fig. 5). This represents a 2.3:1 reduction in rms delay spread by virtue of using a directive antenna in these environments.

V. MODELING THE DELAY PROFILE PARAMETERS

A. New Jersey Data

In this database, we pooled all the data for the two transmit sites (Iselin and Whippany) and the two antenna heights (3 and 10 m). We did so because no important differentiation based on transmit site or antenna height was found. We now report on numerical results for the CDF's of K_o and τ_o , the correlation between K_o and τ_o , and their distance dependences.

1) *CDF's of K_o and τ_o :* Fig. 6 shows the CDF of K_o for the New Jersey locations. The median is about 6.7, or just over 8 dB. The dashed curve is for an analytical CDF that reasonably well matches the empirical one. The pdf

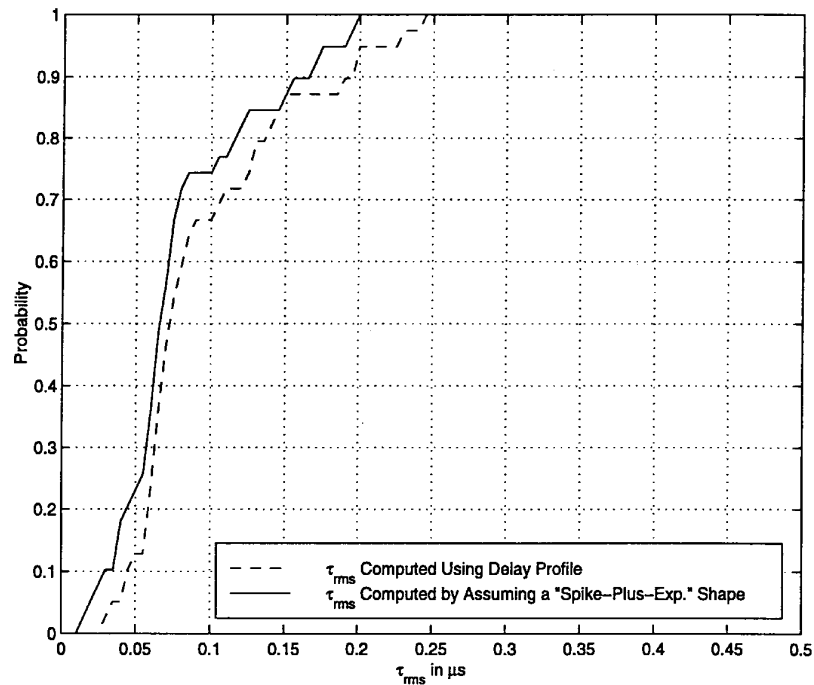


Fig. 4. CDF's of computed and estimated rms delay spread with a directive antenna (Illinois data).

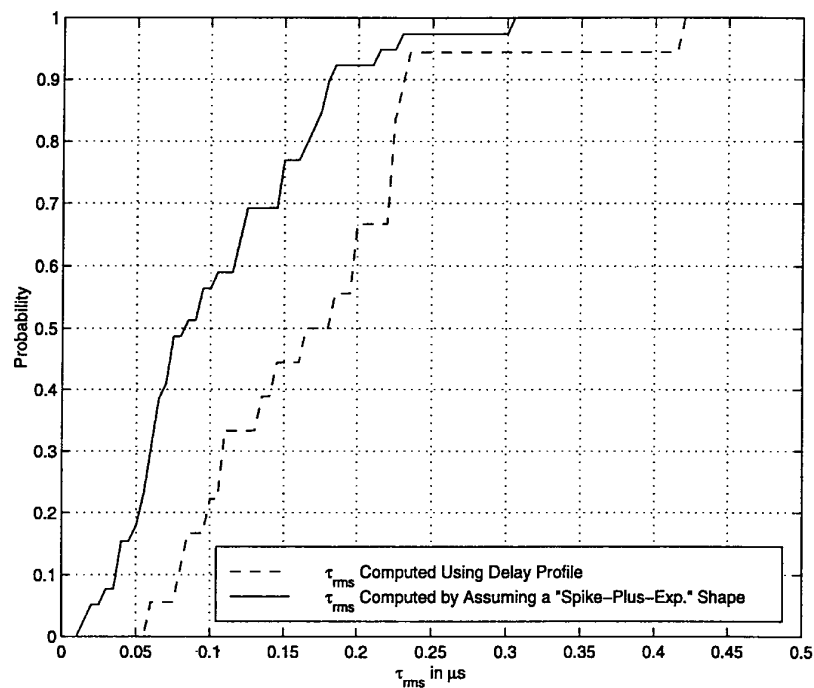


Fig. 5. CDF's of computed and estimated rms delay spread with an omnidirectional antenna (Illinois data).

corresponding to this approximation is shown in the inset. Random variables having this pdf are quite easy to simulate.

Fig. 7 shows the CDF of τ_o for the New Jersey locations. The median is about 0.19 μs . The dashed curve is for an analytical CDF that well matches the empirical one, especially in the large central region (10–90%). The associated pdf is

shown in the inset. Random variables having this pdf are also quite easy to simulate.

2) *Correlation Between K_o and τ_o* : The correlation coefficient between K_o and τ_o was computed to be 0.06. This very low correlation is consistent with physical intuition: K_o is largely determined by conditions on the most direct path,

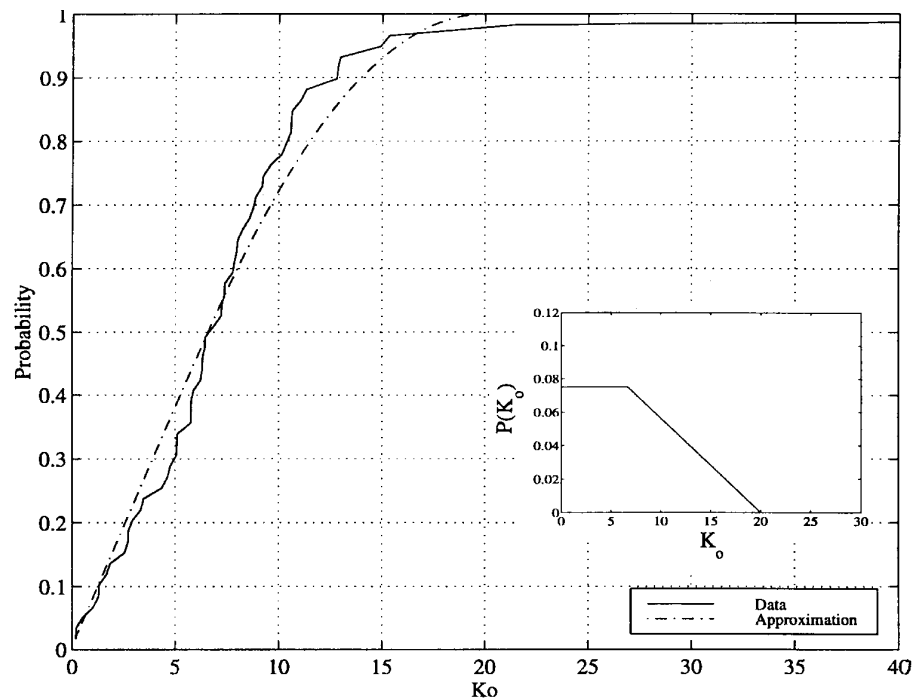


Fig. 6. CDF of K_o with a directive antenna (New Jersey data).

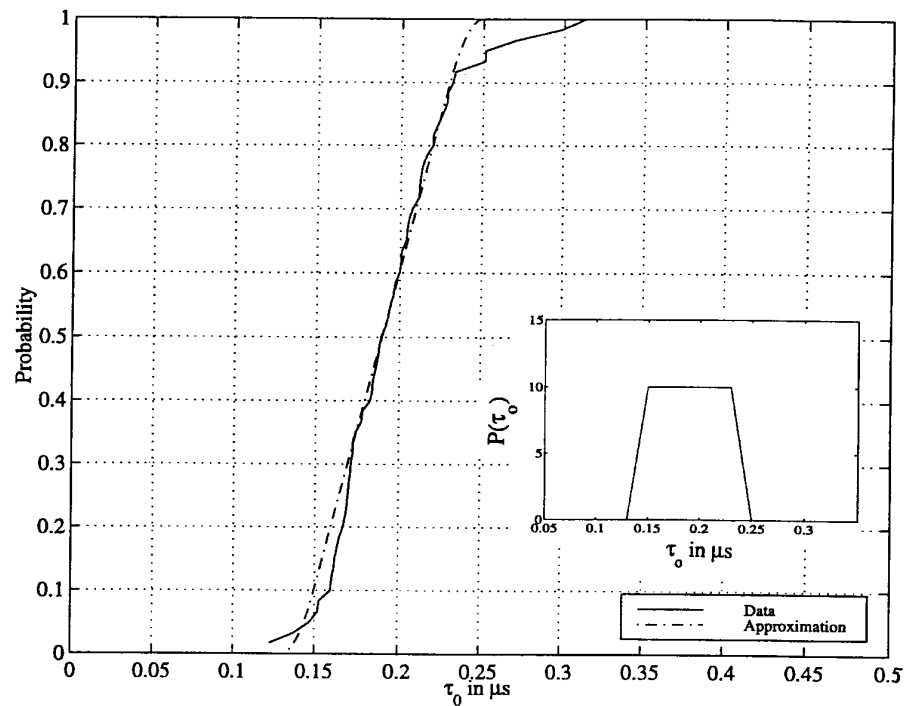


Fig. 7. CDF of τ_o with a directive antenna (New Jersey data).

while τ_o is determined by the number and locations of off-path scattering objects. We conclude that K_o and τ_o are statistically independent random variables.

3) *Distance Dependencies:* We developed scatter plots of K_o versus distance d (both in decibels) and τ_o versus d

(both in decibels) and did regression fits for each. In both cases, we saw weak trends that, given the sample size and the distance range, were not statistically significant. We tentatively conclude, therefore, that there is no strong influence of distance on either K_o or τ_o .

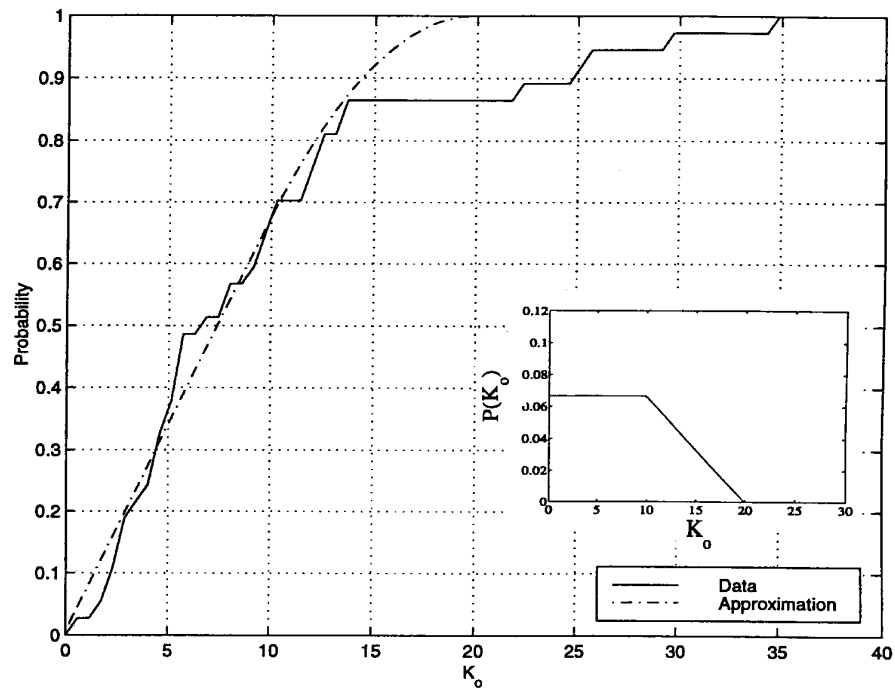


Fig. 8. CDF of K_o with a directive antenna (Illinois data).

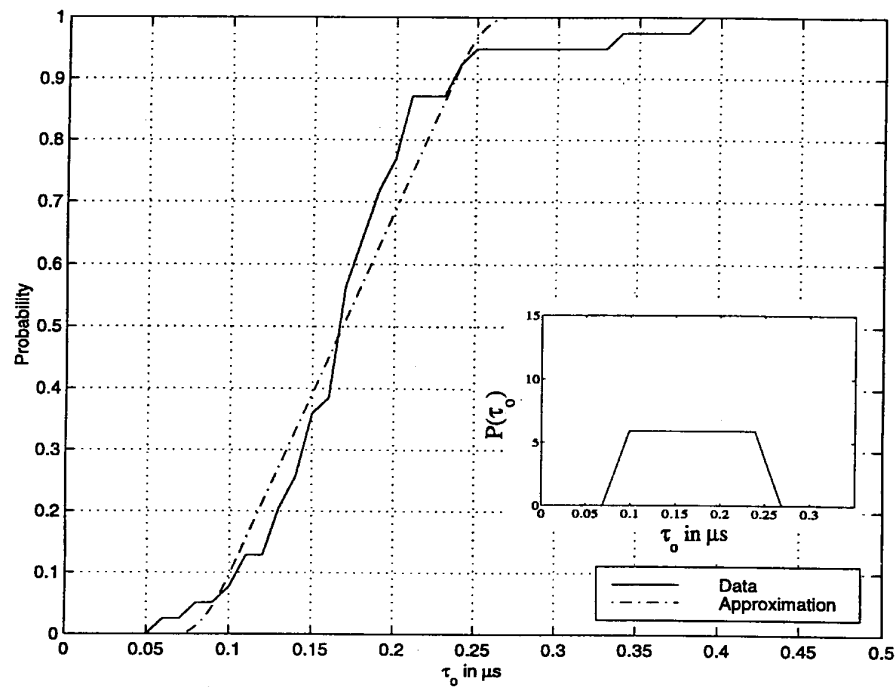


Fig. 9. CDF of τ_o with a directive antenna (Illinois data).

B. Illinois Data

As in the New Jersey case, we pooled all the data for the two transmit sites (in this case, Bellwood and Naperville). Here, all of the data were collected with the receiving antennas at a height of 3 m. We present results now for the directive antenna only.

1) CDF's of K_o and τ_o : Fig. 8 shows the CDF of K_o , using a directive antenna, for the Illinois locations. The median is about 5.9, or just under 8 dB. The dashed curve is for an analytical CDF that reasonably well matches the empirical one. The simple pdf which corresponds to this approximation is shown in the inset.

Fig. 9 shows the CDF of τ_o , using a directive antenna, for the Illinois locations. The median is about 0.16 μ s. The dashed curve is for an analytical CDF that reasonably well matches the empirical one. The associated pdf is shown in the inset.

2) *Correlation Between K_o and τ_o* : The correlation coefficient between K_o and τ_o was computed to be 0.07. Since the correlation is very low and consistent with the intuition described above, we again conclude that these parameters are statistically independent random variables.

3) *Distance Dependencies*: As described in Section V, we developed scatter plot of K_o versus d (both in decibels) and τ_o versus d (both in decibels) and did regression fits for each. Once again, we did not see any particularly strong trends. In light of the limited sample size and distance range, we again tentatively conclude that neither K_o nor τ_o are strongly influenced by distance.

VI. CONCLUSION

We have established, through extensive measurements in multiple fixed wireless environments, that a "spike-plus-exponential" delay profile shape is valid to use when the terminal antenna is directive. For a beamwidth of 32°, the two parameters we have defined for this shape, K_o and τ_o , are found to be essentially uncorrelated over a service environment and to have median values of close to 8 dB and just under 0.2 μ s, respectively. In addition, they can be characterized using easy-to-simulate pdf's; they show no strong dependence on antenna height or transmit/receive distance (over the limited range studied), and all these findings apply to the suburban environments measured in both New Jersey and Illinois. These results should be useful to systems engineers seeking models of multipath in fixed wireless scenarios.

Other issues remain to be addressed. Foremost among them are the fading distributions and time-variation characteristics (e.g., Doppler spectra) of the individual path gains. Another is the dependence of the multipath behavior on a range of possibly relevant parameters, such as season (not just full foliage), antenna beamwidth (not just 32°), and type of terrain (not just suburban).

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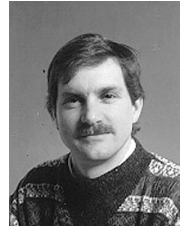
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