Spatial Channel Model and Measurements for IMT-2000 Systems

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Abstract This paper presents a spatial channel model for IMT-2000 systems as well as measurement results for 1.2MHZ wide wireless channels using an eight element linear array at two different frequencies. The spatial channel model is a spatial extension of the commonly known IMT-2000 temporal (*i.e.,*delay profile) model. The measurement results are used to characterize the spatial aspects of the wireless channel and are used to verify the model.

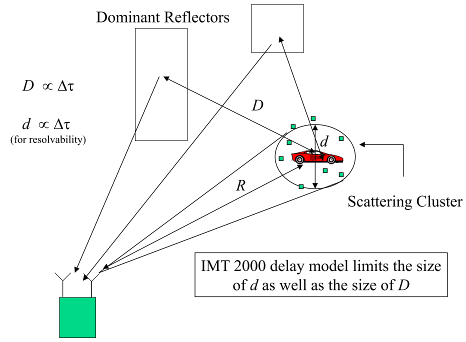

Figure 1: Geometry Assumed in Spatial Channel Model

1 Introduction

Modeling the wireless channel has been the subject of a significant amount of study and resulting literature over the last 20 years. Traditional models have focused on the frequency and time distortion caused by the mobile wireless channel. However, in recent years intelligent antennas [1] and space-time coding techniques have become the focus of a significant amount of research. Since antenna performance prediction requires modeling the spatial dimension of the mobile channel, new models have been formed which add the effect of angular spreading (spatial fading) [2]. The present work seeks to improve upon previous models by creating a model which is physically coherent across all three wireless distortion parameters. Additionally, we propose a model which is specifically relevant to third generation wireless systems by anchoring it to the IMT-2000 two-dimensional channel model.

2 Spatial Channel Model

The distortion caused by the wireless mobile channel can be described by three main parameters: (1) Doppler spread, (2) delay spread, and (3) angle spread. Doppler spread describes the dispersion the transmitted signal experiences in the frequency domain, or equivalently the temporal fading. The delay spread describes the temporal spreading observed at the receiver or equivalently the frequency dependent fading. Finally, the angle spread describes the angular spreading observed at the receiver or equivalently the spatial dependent fading experienced. Traditionally, wireless channel models have incorporated the first two parameters [3], but have ignored the third.

Recently, due to the increased interest in intelligent antennas, the spatial dimension of the wireless channel has received more attention [2]. In creating an appropriate model to be used for performance testing we have several requirements. Specifically, the model should (1) incorporate temporal, frequency, and spatial fading, (2) be physically coherent across all three types of fading, (3) collapse to a known 2-dimensional model, (4) allow both uplink and downlink modeling, (5) allow multi-input multi-output (MIMO) modeling, (6) allow both Rayleigh and Ricean fading, and (7) allow time evolution.

One of the goals in creating a spatial channel model is creating a model which is physically coherent across temporal, frequency, and spatial fading. Thus, spatial modeling of the scatterers is preferable

	Pedestrian A		Pedestrian B		
Tap	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Doppler Spectrum
1	0	0	0	0	Classic
2	110	-9.7	200	-0.9	Classic
3	190	-19.2	800	-4.9	Classic
4	410	-22.8	1200	-8.0	Classic
5	–	–	2300	-7.8	Classic
6	–	–	3700	-23.9	Classic

Table 1: IMT-2000 Pedestrian Test Environment Tapped-delay-line Parameters

	Vehicular A		Vehicular B		
Tap	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Doppler Spectrum
1	0	0	0	-2.5	Classic
2	310	-1.0	300	0	Classic
3	710	-9.0	8900	-12.8	Classic
4	1090	-10.0	12900	-10.0	Classic
5	1730	-15.0	17100	-25.2	Classic
6	2510	-20.0	20000	-16.0	Classic

Table 2: IMT-2000 Vehicular Test Environment Tapped-delay-line Parameters

to statistical modeling of the channel parameters. Such an approach forces the coherence of the three parameters. The goal then is to determine how we should distribute scatterers in the environment to model the spatial channel. First, we assume that the first arriving resolvable multipath component (typically the dominant path) arises due to local scattering about the mobile. This will cause either Rayleigh or Ricean fading (depending on the presence of a line-of-site component) within that single discrete path. Multiple discrete paths (*i.e.,*taps in the delay line model) are modeled as reflections of the original scattering cluster as shown in Figure 1. This is opposed to modeling each path as separate clusters of scatterers which are illuminated by the mobile unit. This has impact on the Doppler spectrum as will be discussed later. For now we note that the IMT-2000 models considered specify classic cosine Doppler spectra for each path.

Examining the scatterers which are local to the mobile unit, we must determine the distribution of these scatterers. Extensions of the classic Jakes model [3] have proposed modeling the scatterers as existing on either a circle about the mobile [2] or on spokes emanating from the mobile [3]. Other proposals include uniform distribution of scatterers about the mobile [4] and a bi-variate Gaussian distribution of scatterers [5]. Of the different distributions of scatterers examined, a bi-variate Gaussian distribution is preferred. The justification for this is three-fold. Firstly, a bi-variate Gaussian distribution provides a classic cosine spectrum (due to uniform angle distribution about the mobile) which is generally preferable due to the large amount of results in existence which assume a cosine spectrum. Secondly, a Gaussian distribution provides an angle-of-arrival distribution at the base station which is more consistent with the scarce measurement information than uniform distributions or enhanced Jakes models. Thirdly, a bi-variate Gaussian distribution of scatterers is more intuitively satisfying.

Thus, we model the first (or dominant) path of the channel as being the result of S scatterers distributed with a bi-variate Gaussian distribution about the mobile location with a standard deviation σ_Δ. Other discrete taps are reflections of the original cluster. Since they are reflections each scatterer will have an independent phase shift from the original cluster. Further, they will appear to the base station as arriving from a different direction. The location of each apparent cluster will be related to the excess delay of each tap as we will show.

The number of taps (*i.e.,*clusters) and excess delays of each in the tap delay model were chosen according to the IMT-2000 propagation model [6]. The IMT-2000 propagation model for outdoor environments is summarized in Tables 1 and 2. The model specifies 4-6 taps with specified delays and average powers. The first arriving path is composed of a set of waves due to S scatterers distributed about the mobile with a bi-variate Gaussian distribution. The standard deviation of that distribution is determined as $\sigma_\Delta = \frac{1}{10}\mathrm{E}\left\{\Delta\tau\right\}$ where $\Delta\tau$ is the difference in excess delay between successive paths. This results in a distribution in which 95% of the scatterers are within the resolvability of the channel $\tau_{res} = \frac{1}{5}\Delta\tau$. Further, it is assumed that all other resolvable mulitpaths are due to reflections from dominant scatterers as shown in Figure 1. The locations of each scattering cluster are determined according to the relative delays of the taps. The difference in excess delay is assumed to be directly related to the difference in location. Specifically, the cluster center of each path is defined to be $\left\langle x^m + \cos(\psi)\frac{c\Delta\tau_i}{1+\sin\psi}, y^m + \sin\psi\frac{c\Delta\tau_i}{1+\sin\psi}\right\rangle$ where c is the speed of light, ψ is the angle made by the new cluster center location with respect to the mobile location $< x^m, y^m >$ and is assumed to be

Model	Clusters	Base-Mobile Separation (m)	σ_τ (ns)	σ_Δ (deg.)
Veh A	6	3000 – 5000	370	2
Veh B	6	3000 – 5000	4000	10
Ped A	4	300 – 500	45	2
Ped B	6	300 – 500	750	20

Table 3: Parameters for Spatial Channel Models Derived from IMT-2000 Specifications

on $[0, \pi]$. The exact value of ψ is somewhat arbitrary but should be consistent between simulations to guarantee repeatability. We have assumed $\psi_i = [0, 0, \pi, \pi/4, 3\pi/4, \pi/2]$. The resulting delay spread ($\sqrt{\overline{\tau^2} - \overline{\tau}^2}$) and angle spread ($\sqrt{\overline{\phi^2} - \overline{\phi}^2}$) for each model are given in Table 3.

By modeling the scatterers directly we allow the modeling of MIMO channels as well as simultaneous uplink and downlink channels. The former is important for space-time coding applications while the second is important for beamforming algorithms which use uplink data to estimate the downlink steering direction. The channel seen by receive antenna m due to path p from transmit antenna k is determined as

$$h_{p,m,k}(t) = \sum_{s=1}^{S} \sqrt{G_r(\theta^A_{p,s})}\sqrt{G_t(\theta^D_{p,s})}\, e^{j 2\pi f_{p,s} t} \dots e^{j\phi_{p,s}}\, e^{j\frac{d_k}{\lambda} 2\pi \sin\left(\theta^D_{p,s}\right)}\, e^{j\frac{\delta_m}{\lambda} 2\pi \sin\left(\theta^A_{p,s}\right)} \quad (1)$$

where G_t and G_r are the power patterns of each transmit antenna and receive antenna respectively, $\theta^A_{p,s}$ and $\theta^D_{p,s}$ are the angle-of-arrival and angle-of-departure respectively of the sth scattering component of the pth path measured with respect to the array normals, $\phi_{p,s}$ is the random phase of each scattering component assumed to be uniformly distributed on $(0, 2\pi]$, $f_{p,s}$ is the Doppler shift associated with each scattering component, d_k and δ_m are the distance of the kth transmit and mth receive antennas from their respective reference points, and λ is the carrier wavelength. Further, if we define $< x^b, y^b >$, $< x^m, y^m >$,$< x^s_i, y^s_i >$, to be the positions of the base station, mobile and ith scatterer respectively, then $\theta^D_i = \tan^{-1}\left(\frac{y^s_i - y^m}{x^s_i - x^m}\right)$, $\theta^A_i = \tan^{-1}\left(\frac{y^s_i - y^b}{x^s_i - x^b}\right)$, $f_i = \frac{v}{\lambda_{up}} \cos\left(\theta^D_i\right)$ on the uplink and $\theta^D_i = \tan^{-1}\left(\frac{y^s_i - y^b}{x^s_i - x^b}\right)$, $\theta^A_i = \tan^{-1}\left(\frac{y^s_i - y^m}{x^s_i - x^m}\right)$, $f_i = \frac{v}{\lambda_{dn}} \cos\left(\theta^A_i\right)$ on the downlink. Once equation (1) has been used to calculate the channel for each path at each receive antenna, each path is weighted according to Tables 1 or 2 and paths which are non-resolvable according to the signal bandwidth are summed together. This provides a composite channel for each resolvable path and receive antenna. To generate simultaneous uplink and downlink channels, we assume that the scatterer positions are the same, but the phases are independent between uplink and downlink. Further, the wavelength and Doppler frequencies must be adjusted as mentioned.

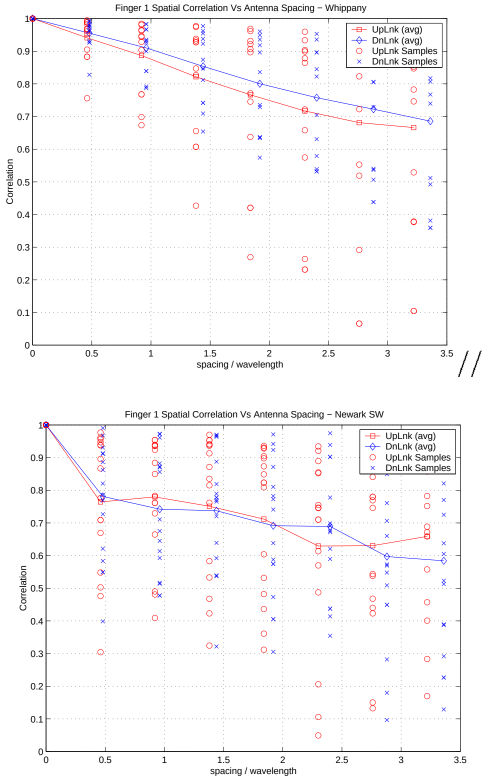

Figure 2: Scatter Plots of the Correlation Between Each Antenna and Antenna 1 for Suburban (top) and Urban (bottom) Environments on Uplink and Downlink Frequencies

Certain applications (*e.g.*,beamforming) require modeling the large scale movement of the mobile to accurately predict tracking performance. A goal of the current model is to provide a means for modeling this movement. The scatterer positions are modeled as a bivariate Gaussian random variable. We choose to model the position coordinate system as being consistent with the direction of mobile movement. Further, we model the Gaussian distribution along the direction of movement as the sum of several Gaussian distributions with slightly different mean values. While the sum of Gaussian *distributions* is by no means guaranteed to be Gaussian, we find that if the mean values are very close relative to the standard deviation, the sum approximates a Gaussian distribution provided that the variance of the component distributions is $\sigma^2 = \sigma_\Delta^2 - \frac{(\Delta x)^2}{12}(N^2-1)$ and the mean values are $\mu_i = x^m - \left(\frac{N}{2}+i-1\right)\Delta x$ where σ_Δ^2 is the variance of desired scatterer distribution, N is the total number of component distributions, and Δx is the distance traveled by the mobile in one update period. We have found that the match to a Gaussian distribution is good to approximately 10^{-4} provided N and Δx are chosen such that $\sigma_\Delta > \Delta x N$. To model movement we must remove and add scatterers in a distribution periodically. If we change all of the scatterers at once, we will introduce radical phase and amplitude discontinuities in the channel. By using several component distributions, we can minimize the discontinuities in the channel by replacing the scatterers in the trailing distribution and adding a leading distribution.

3 Measurements

Field measurements were taken in suburban and urban environments at 1.9GHz and 1.98GHz with a 1.2MHz bandwidths. The results of these measurements were used to compare actual physical channels with the proposed model. The field experiment apparatus consisted of a mobile transmitting a wideband signal at both an uplink and downlink carrier frequency. The signals were received by a fixed BTS antenna array. The wideband signal was created using a repeating Pseudo-Noise (PN) sequence (length 63) with BPSK modulation and a transmission rate of 1.2Mbps.

At the cellsite, the signal was received through an 8-column vertically polarized antenna array.[1] The columns of the array were linearly spaced approximately 0.46λ at the uplink carrier frequency. The array had, in addition, 2 pairs of parasitic elements on the ends of the array to help minimize column-to-column pattern mismatch. The 3dB beamwidth of a single column was approximately 110^o in azimuth. From the array, eight RF paths were individually down-converted to low IF, oversampled by a factor of 8, and recorded. In addition, calibration signals, which were used for compensation of receiver path differences, were embedded on the received signal and recorded for use during post-processing.

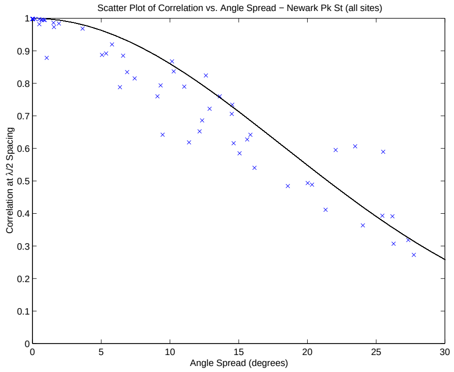

Figure 3: Measured and Theoretical Element Correlation vs. Angular Spread

A primary set of measurements was the correlation between antennas. Figure 2 presents measured correlation values for the array in suburban and urban environments. The suburban measurements show higher element correlation which is consistent with lower $(2^o - 10^o)$ angle spreads. This is in agreement with the Vehicular/Pedestrian A models which have small delay spread and low angle spread. Eigenvalue analysis of the suburban data is also consistent with narrow angle spread with a single dominant eigenvalue. The urban measurements given in Figure 2 show that less correlation exists between adjacent antennas consistent with larger angle spreads $(10^o - 20^o)$. This is in general agreement with the Vehicular/Pedestrian B models. In Figure 3 we plot sample correlation values between adjacent elements (separated by $\frac{\lambda}{2}$) for the first arriving multipath versus the measured angular spread in degrees. Also plotted is a theoretical curve for correlation vs. angle spread assuming a Gaussian scatterer distribution [5]. We see that the Gaussian model is a good predictor of the relationship between correlation and angle spread.

Figure 4 plots the pdf of the measured AOA in a urban environment for two fingers on both uplink and downlink frequencies. We can note a few things. First, we see good agreement between uplink and downlink frequencies. Thus, using uplink information to steer the downlink in this environment will be useful. Note that this does not guarantee that the instantaneous phase relationship between elements will be the same between links, which is dependent on the angle spread of the environment. However, it says that the average DOA is consistent between uplink and downlink. Also notice that

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[1] The array was manufactured by Celwave/RFS Systems.

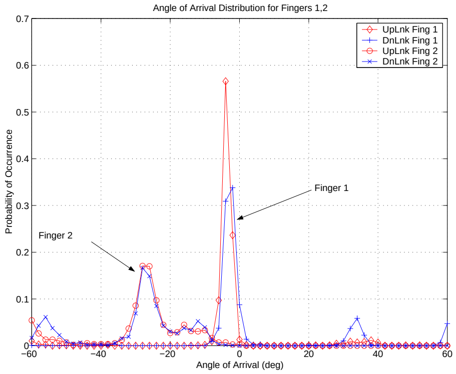

Figure 4: Angle-of-Arrival Measurements for Urban Environments for Fingers 1 and 2 (Uplink and Downlink Frequencies)

different fingers (*i.e.*,resolvable paths) are coming from different directions (within 10 degrees of the mobile's physical DOA). These observations are also in good agreement with the proposed models.

Another assumption of the model given here is that resolvable multipath is due to reflections of the main path. As such, the model predicts that each path will have similar Doppler spectrum since the Doppler spectrum is related to the location of the *original* cluster of scatterers relative to the mobile's movement. In Figure 5 we present measured Doppler spectra for two fingers in an urban setting. We see that both fingers provide very similar Doppler spectra, each with a classical shape and maximum Doppler spread of about 70Hz (consistent with the mobile speed of 25mph). These measurements are typical of the measurement results and provide support for the model as well as the IMT-2000 specifications for Doppler spectra.

4 Conclusions

In this paper we have presented a spatial channel model for IMT-2000 systems for the evaluation of multi-antenna transmit-receive systems. We have also presented measurement results which verify key aspects of the model.

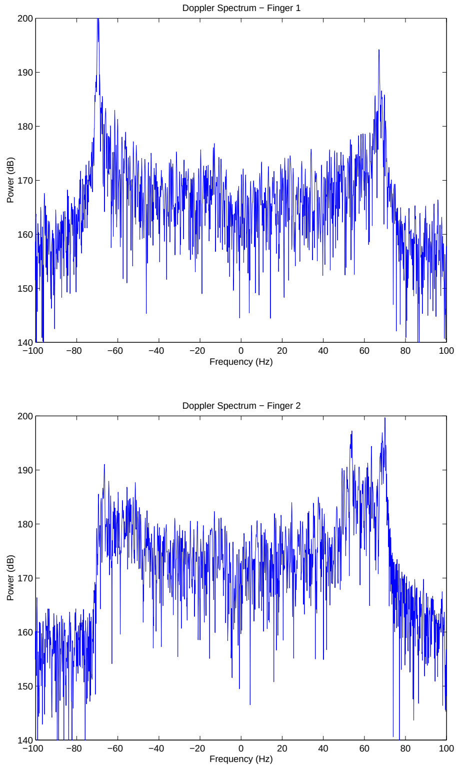

Figure 5: Doppler Spread for Urban Measurement Fingers 1 and 2 (speed = 25mph)

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