Finding the Right Small-Scale Fading Distribution for a Measured Indoor 2.4 GHz Channel

Alexander H. Henderson
Furman University
Greenville, SC, 29613

Christopher J. Durkin (Member IEEE)
Gregory D. Durgin (Senior Member IEEE)
Georgia Institute of Technology
Atlanta, GA 30332

Abstract
Accurate characterization of wireless small-scale fading is of growing interest to wireless modem developers who are using increasingly complicated multi-antenna signaling schemes and protocols that either mitigate or exploit multipath in the radio channel. This paper presents a measurement technique for (and subsequent characterizations of) small-scale fading for a realistic, indoor propagation environment at 2.45 GHz.

Introduction
Accurate characterization of wireless small-scale fading in typical local areas is of growing interest due to the proliferation of cell phones, wireless monitoring equipment, and other radio devices. It has typically been assumed that Rayleigh statistics, which assumes the absence of any large specular wave components in a local area, will be the worst-case distribution in terms of depth and occurrence of signal fades, while Ricean statistics, which assume the presence of a single specular component with diffuse, non-specular scattered waves, are a good approximation for line-of-sight situations, where the fading is less severe [1]. Work by Frolik indicates that certain situations experience “Hyper-Rayleigh” fading, though this has only been shown to occur in enclosed areas such as vehicles where strong resonance conditions hold [3].

There have been many measurement campaigns to characterize the wireless channel for large-scale fading. These include both studies inside buildings such as [4] and those for various outdoor or between-building environments as in [2]. However, far fewer studies have been performed on small-scale fading.

Methods and Results
For this experiment, a custom quarter-wavelength monopole antenna was used in combination with an amplifier and a bandpass filter to form a receiver, while a spectrum analyzer in conjunction with a computer system recorded data. A pure tone signal was generated and transmitted at a frequency of 2.43 GHz from an omnidirectional antenna located more than ten wavelengths from the receiver.
The receiver was mounted on a linear positioner, and measurements were taken at regular intervals as it was moved down the track. Measurements were conducted in a lab room containing a large number of scatterers distributed around the sides of the room. Of particular note are two large metal cabinets which were on the far side of the room facing back towards the transmitter.

As a check on the instruments and processing, data was taken on the noise present in the channel when no transmitted signal was present. The data taken in this manner revealed that the transmitted signal was strong enough that the noise in the system could be neglected. For the next set of measurements, Set 1, the transmitter was placed just outside of the room with a clear line-of-sight (LOS) through an open doorway. Data was also taken with the transmitter placed behind the wall adjoining the doorway, Set 2, and with the transmitter placed over 7 meters down the hallway with several walls and two offices between the transmitter and receiver on the direct LOS path, Set 3.

Subsequent analysis was performed using MATLAB and commonly known distribution types. Standard parameter finding methods were used to find the variance and mean for a Rayleigh fit to the data. In order to obtain an unbiased Ricean fit, a Maximum Likelihood (ML) estimator put forth by Sijbers et al. was used [5]. An ML estimator was also devised for use in fitting a Two-Wave-Diffuse-Power (TWDP) curve.

The data was first normalized such that the highest value was set equal to zero dB, then converted to a linear scale from logarithmic form, making the corresponding graphs more readable. Subsequently, histograms were constructed from the data, and probability density functions (pdfs) generated using ML estimators to obtain values for the various parameters. In order to obtain a TWDP fit, numerical techniques were found to be impractical. Consequently, the approximation formulated by Durgin et al. in [6] was used, to fifth order. This approximation is a formula in three variables, \( V_1, V_2, \) and \( r \), namely:

\[
F_R (r) = \frac{r}{\sigma^2} \exp\left( -\frac{r^2}{2 \sigma^2} \right) \sum_{i=1}^{M} a_i D \left( \frac{r}{\sigma^2} ; K, \Delta \cos \frac{\pi (i - 1)}{2 M - 1} \right)
\]

Where \( r \) is the magnitude of received voltage, \( \sigma^2 \) is the variance in the data, \( V_1 \), and \( V_2 \) are the magnitudes of the voltages of the specular components, and \( K, D, \) and \( \Delta \) are as defined in [6]. The ML estimator formulated work similarly to the method for the Ricean distribution in [5], whereby the function is evaluated at each data point, thus leaving three variables, then the natural logarithm of this function is taken and the resulting functions summed for all data point. The parameter values are then those at the absolute maximum of the summed function within the applicable range of values for the three variables.

It is worth noting that using ML theory, the log-likelihood function for this formula results in more than one local maximum in \( V_1, V_2, \) and \( r \) in the range for all three parameters \( \bullet 0 \), requiring one to compare the values at all such points to find the global maximum.
Figure 1 shows a histogram from one data run, with various probability density functions overlaid. For the data set in this figure, the K-value for the Ricean distribution was found to be 4.7 dB, using the ML estimator mentioned above. While a Ricean distribution was expected since there was a strong line-of-sight component, the fit for this distribution was bad, with a root-mean-squared (rms) error of 0.49 normalized counts, which was still significantly better than the Rayleigh fit, which had an rms error of 0.59 normalized counts, some 20% higher. For comparison, the rms error of a Ricean fit which was visually Ricean distributed, was 0.38 normalized counts, a good 22% lower. In all, for the Set 1, two data runs showed the expected Ricean distribution, one showed a Rayleigh distribution, and one did not adequately fit any of the standard pdfs. For Set 2, one trial showed a Ricean distribution, leading to suspicion that the wall was letting a significant amount of signal through, and one did not fit any of the standard pdfs. For Set 3, neither of the two data runs showed a Rayleigh distribution, as was expected, though of the pdfs tested, the Rayleigh distribution was the closest. It should be noted that the hallway in question was in use at the time of measurements, so the channel was time-varying during the taking of these measurements. For all data runs, the TWDP fit was visually indistinguishable from the Ricean fit. Furthermore, in all cases less time was spent in the region of low signal strength than in the case of the Rayleigh fit.

Figure 1: Histogram of received voltage magnitude measured in a local area with overlaid pdf models. The received envelope is normalized such that the highest value is set to 1. Note that the Ricean and TWDP PDFs are not visually distinguishable.

Conclusions
Rayleigh or Ricean distributions may not always be adequate in describing small-scale fading for indoor propagation environments. When designing an indoor network, one should be wary of this possibility. In particular, any fading model which has fewer undesirable drops in signal strength than a Rayleigh model should be used with caution. In addition, while TWDP fading may describe the most fading scenarios mathematically, in that it reduces to all other common distributions in different limiting cases [8], an indoor fading environment can be described just as accurately by a Ricean distribution in most cases.

Furthermore, the use of a linear positioner has been shown to provide a means of mapping small-scale fading phenomena in the wireless channel to a fairly high level of precision in the GHz range. Further investigation may result in more detailed characterization of small-scale scattering and fading.

References


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