Fading Characteristics of RF Signals due to Foliage in Frequency Bands from 2 to 60 GHz

Simon Perras
Communications Research Centre
Ottawa, Ontario, Canada
email simon.perras@crc.ca

Luc Bouchard
Communications Research Centre
Ottawa, Ontario, Canada
email luc.bouchard@crc.ca

Abstract

This paper compares the various temporal characteristics of radio channels for a broad range of frequencies, including 2.45, 5.25, 29 and 60 GHz, in various foliage and weather conditions. A substantial number of data points, in excess of 1.9 billions at 500 samples per second (equivalent to 45 days), was collected and analyzed for three particular types of channels: foliated deciduous trees, non foliated deciduous trees and coniferous trees. The radio channels are statistically analyzed and the resulting PDFs (probability density functions) and CDFs (cumulated density functions) are compared against existing models. Furthermore, wind speeds and rain precipitation are correlated with the power samples to consider RF propagation dependencies. Second order statistics are derived, including level crossing rate (LCR) and average fade duration (AFD). The power profile is analyzed for spectral components. Frequency characteristics of the RF propagation channel are evaluated. Finally, channel-specific RF propagation attributes are presented.

Keywords

RF Propagation, Millimeter Wave, Tree, Foliage, Rain, Channel Modeling, Fading Characteristics, Attenuation, Average Fade Duration, Level Crossing Rate, Spectral Component

INTRODUCTION

The demand for high bandwidth to the home continues to grow, with the last mile issue remaining the greatest obstacle. As most neighborhoods have some sort of vegetation that can expand or grow over the years it is not always possible to guarantee a clear Line of Sight (LoS) propagation path. Thus, a better understanding of the RF attenuation effects of vegetation will help in finding solutions to this problem.

A review of the literature [1-5] indicates that the effect of foliage on RF propagation has been studied to some extent, whereas in-depth studies over a large range of frequencies, type of foliage and path conditions remain to be done. This paper examines the fading characteristics versus foliage blocking on radio channels at 2.45, 5.25, 29 and 60 GHz. Various statistical models are used to characterize each of the scenarios investigated [6].

The paper is organized as follows. First, the test methods are described. The second section presents the results of the data analysis, including curve modeling for each type of RF channel, second-order statistics to better understand the behavior of the fades, and analysis to identify spectral components in the power profile of faded signals. Conclusions are provided at the end.

TEST METHODOLOGY

All radio channels are measured using a carrier wave centered at 2.45, 5.25 29 and 60 GHz. The lower frequencies are transmitted using a signal generator whereas higher frequencies require the use of up/down converters. In excess of 1.9 billion power measurement points were collected, equivalent to 45 days of continuous data acquisition. The carrier wave is sampled at 500 readings per second using a spectrum analyzer, multimeter, and a computer with GPIB (General Purpose Interface Bus) interface. For low frequencies the spectrum analyzer is centered at the carrier wave frequency, and at the down converted frequency for higher frequencies. Both methods use a 0Hz span, a sweep time of 1 μsec and a 10 kHz resolution bandwidth. The vertical axis of the video trace output is then connected to the multimeter, and voltages are sampled with the use of GPIB and a computer. The voltages are converted to their equivalent power values relative to the positioning of the trace on the display of the spectrum analyzer.

Three different types of foliated channels were studied. Table 1 outlines the site descriptions.

Table 1. Outline of Sites

Site Name	Link Distance	Foliage Depth	(Description)
Site 1	63.9 m	14.0 m 7.6 m	(3 foliated maple trees) + (1 foliated flowering crab tree)
Site 2	110.0 m	25.0 m	(Several spruce and one pine tree creating a wall)
Site 1 No Leaves	63.9 m	14.0 m 7.6 m	(3 leafless maple trees) + (1 leafless flowering crab tree)

The first site, populated with deciduous trees, is considered twice; when the trees are in full leaf and when the trees are leafless. Figure 1 shows the deciduous trees used for the analysis.

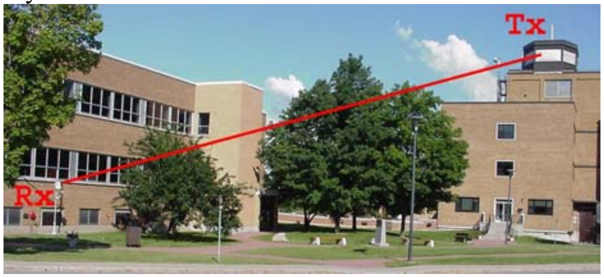

Figure 1. Site 1 – Deciduous Trees

The second site has several coniferous trees. The receiver sits behind a wall of trees and can barely see the transmitter area as shown in figure 2.

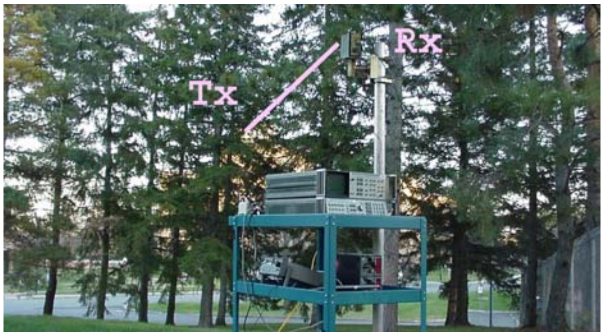

Figure 2. Site 2 – Coniferous Trees (Receiver view)

The transmit antennas are sheltered in a radar dome protected from any weather conditions. The loss from the fiberglass window of the radar dome is considered to be constant throughout the experiment. The receive antennas are mounted on a mast outside the laboratory for site 1 and are mounted on an equipment dolly for site 2.

Wind speed samples are collected to correlate the RF power samples with wind speed, in order to explore the possibilities of wind dependencies in the attenuation characteristics. The meteorological data is collected with a weather station that samples the wind speed (in m/s) every 5 seconds and the rain precipitation (in mm/hr) every 10 seconds.

ANALYSIS

Among a large quantity of acquired and analyzed data, only typical curves are shown in this paper.

Power Profile vs Wind Speed Profile

Typical examples of acquired power signal profiles versus their respective wind speeds are illustrated in figures 3 and 4 for single tone signals centered at 5.25 and 29 GHz respectively, for full leaf deciduous trees (site 1).

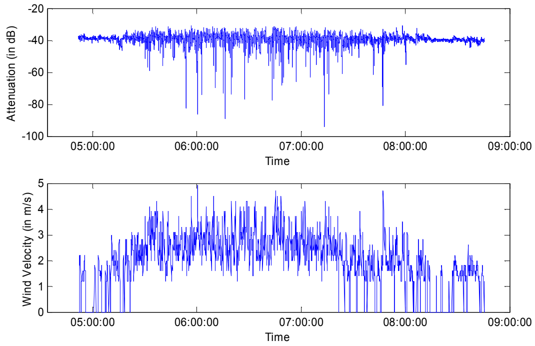

Figure 3. Typical Signal Power vs Wind Speed (5.25 GHz)

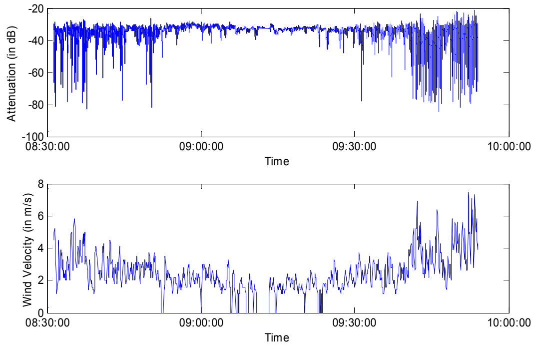

Figure 4. Typical Signal Power vs Wind Speed (29 GHz)

For both profiles, the power variations are clearly reduced during low wind speed periods, and augment as the wind speed increases. This observation is reproducible and indicates that a strong wind dependency exists for RF power transmission through trees.

Attenuation Characteristics and Curve Modeling

Samples of the analyzed data using probability density function (PDF) curves are shown for each frequency in figure 5, 6 and 7 for site 1, site 2 and site 1 without leaves respectively, for dry weather conditions.

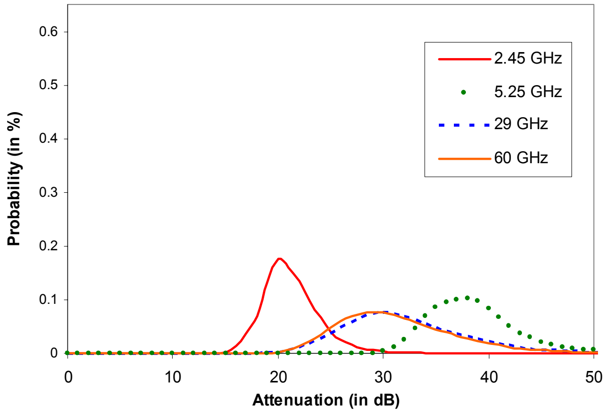

Figure 5. Typical PDF Results for leaved Deciduous Trees

Figure 5 displays flat curves with their mean attenuations centered at 20, 30 and 40 dB. For leaved deciduous trees, the flatter and wider curves represent more variation in the RF signal, hence being more susceptible to fading events. All the statistical curves differ from one another, but there is a strong resemblance between the 29 GHz and 60 GHz results. Furthermore, it is shown that the 5.25 GHz signal is greatly attenuated for this particular radio channel. This could be due to the wavelength of the frequency that is comparable in size with the physical components of the trees. The wavelength at 5.25 GHz is 5.7 cm which is approximately the size of the leaves in the flowering crab tree.

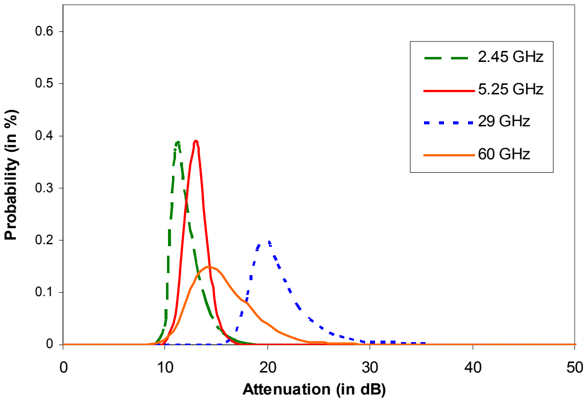

Figure 6. Typical PDF Results for Coniferous Trees

From the above plot, the spreading of the curves indicates less variation of the received RF signal when propagated through coniferous trees. For this type of channel it is the 29 GHz frequency that exhibits more loss. Its wavelength is approximately 1.0 cm, which is close to the length of a spruce tree needle, hence likely contributing to more loss.

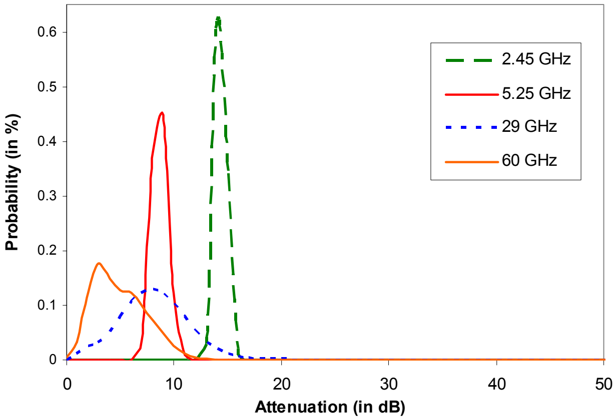

Figure 7. Typical PDF Results For Leafless Deciduous Trees

From Figure 7, it can be observed that leafless deciduous trees produce the curves with the smallest variations in the RF signal. The RF propagation through those trees is lossier at lower frequencies. Since the 29 and 60 GHz curves start at 0 dB of attenuation, it is also shown that there are some occurrences where there is no loss at those frequencies for leafless deciduous trees. Again this phenomenon could be explained by the wavelength of lower frequencies, such as 2.45 GHz (12.2 cm) being comparable to the length of small branches, and the RF signal thus more prone to being attenuated than a 60 GHz signal with a 0.5 cm wavelength.

In all cases, it is shown that the variance is typically small for lower frequencies and tends to increase with frequency. A summary of the typical mean attenuation and variance relative to the LoS measurement for all radio channels is outlined in table 2. The values are taken from the same plots shown in figures 5 to 7 above.

Table 2. Typical Mean Attenuation and Variance

	Freq. (in GHz)	2.45	5.25	29	60
Site 1	Mean (in dB)	-21.8	-39.1	-32.8	-32.1
	Variance (in dB)	7.9	19.6	37.4	34.8
Site 2	Mean (in dB)	-12.6	-13.5	-21.7	-16.2
	Variance (in dB)	1.9	1.1	10.0	9.7
Site 1 No Leaves	Mean (in dB)	-14.9	-9.2	-8.7	-5.5
	Variance (in dB)	0.2	0.5	10.9	6.0

Next, the curves are fitted with some known models: Rayleigh, Rician, Lognormal and Extreme Value. All of these models are commonly used for RF propagation modeling except for the Extreme Value distribution, which is used to describe extreme meteorological events, such as the size of floods or gust velocities encountered by airplanes. It is observed that the Extreme Value and Lognormal distributions best represent the data collected, each distribution proving better than the other in different scenarios. Figure 8 illustrates a sample of the curve modeling analysis, using the χ^2 test to evaluate the suitability of each model.

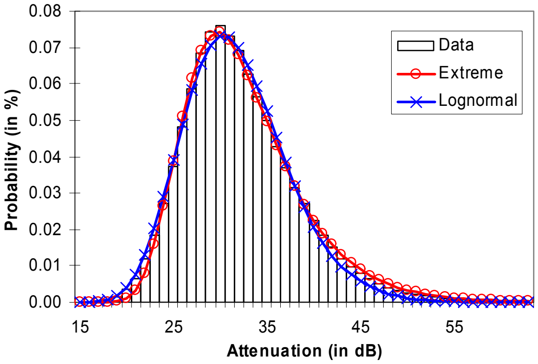

Figure 8. Typical Modeling – 29 GHz – Dry Weather

As shown, the Extreme Value distribution better fits the tail end of the curve, while the Lognormal distribution best represents the start of the curve. In this case, the χ^2 test yields 7.63E-7 and 1.35E-6 for the Extreme Value and Lognormal distribution respectively, which indicates a strong correlation between the model and measured data.

Further analysis was done to examine the effects of constant wind periods. Three wind speed ranges are considered and modeled; low (1.2 to 3 m/s), medium (3 to 6 m/s), and high (6 m/s and above). A comparison between wind speeds and RF signal behavior for dry deciduous trees (Site 1) at 60 GHz is shown in figure 9.

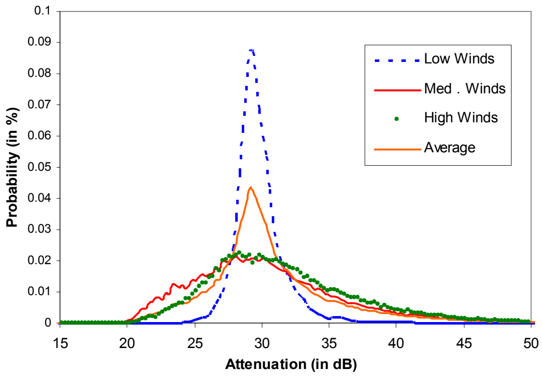

Figure 9. Typical PDF Results for Various Wind Speeds 60 GHz – Dry Weather

The RF signal behavior is similar for medium and high wind speeds. However, it is clearly shown that the curve representing low wind speeds differs a lot from the medium and high wind speed curves, indicating strong wind dependence in the RF signal behavior on these wind speeds.

Second Order Statistics

Second order statistic can provide crucial information in order to predict and manage fades. First, samples of the Average Fade Duration (AFD) normalized to the Root-Mean-Square (RMS) level curves for medium wind speeds are shown in figure 10 for all studied frequencies.

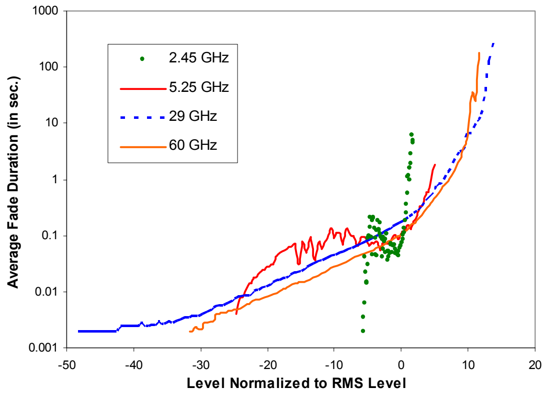

Figure 10. Typical AFD – Dry Weather

The lower frequencies, 2.45 and 5.25 GHz, curves follow an interesting “S” shape curve with their inflection point near the normalized level. This indicates a large dynamic range where the RF signal behavior remains the same. However, the continuous exponential growth of the 29 and 60 GHz curve indicates a constant change within the RF signal behavior. Figure 11, further investigates the effect of wind speed at 29 GHz.

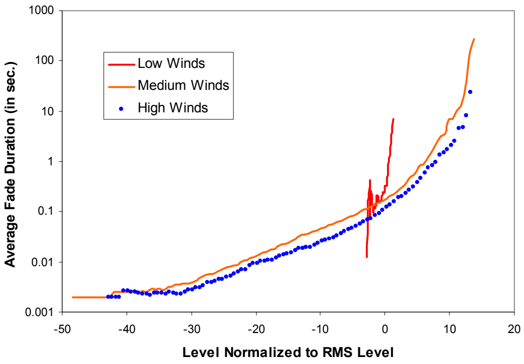

Figure 11. Typical Wind Speed Comparisons with the AFD – 29 GHz – Dry Weather

From this figure it is observed that the wind speed affects the signal as seen in figure 9 above. Medium and high wind speed produced similar AFD curves while low wind speed produced a different type of curve with a much sharper increase in the average fade duration.

All these curves clearly demonstrate a log-exponential or a 2nd order growth, which could be modeled itself to predict the duration of fades.

Next, samples of the Level Crossing Rate (LCR) normalized to the RMS level are shown in figure 12. The LCR plot is displayed in a linear format.

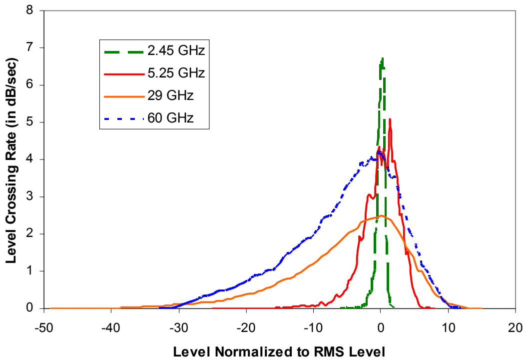

Figure 12. Typical LCR –Dry Weather

All the peaks of the LCR plots are near the normalized value (i.e., 0), indicating that there is more signal activity near the mean attenuation.

Spectral Components

Further work has been accomplished to characterize the spectral components within the power profiles of the received RF power signals. A sample curve is shown in figure 13.

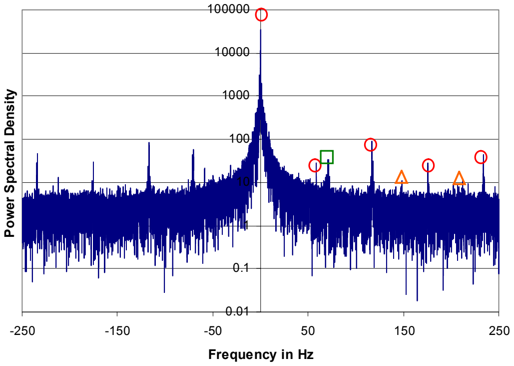

Figure 13. Typical Low Wind Speed Spectral Component – 29 GHz – Dry Weather

Due to its symmetry only the positive frequencies are investigated. The results show the presence of a strong DC component (centered at 0 Hz) and the presence of AC current of 60 Hz and its harmonics at 120, 180 and 240 Hz. All these components have been identified by a circle (○). A moderate spectral component is identified at approximately 70 Hz (identified by a square, □). This could be caused by a very fast shuffle of leaves, for example during a strong gust of wind. Other minor spectral components are present and identified by a triangle (△). The plot illustrated in figure 14 is obtained by taking the same spectral component plot but concentrating in the vicinity of 0 Hz.

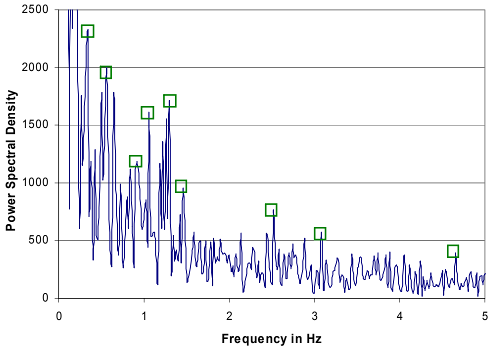

Figure 14. Typical Low Wind Speed Spectral Component (Vicinity of 0Hz) – 29 GHz – Dry Weather

These slower movements can be contributed to slower constant leaf movement, branches swaying or a combination of both. It is difficult to observe spectral components at medium and high wind speed, where spectral plots have a strong DC component with the rest resembling to noise-like behavior. This is likely produced by the random variation of the RF signal caused by repetitive and spurious foliage blockage.

CONCLUSION

This work explored several attenuation characteristics for a wide range of RF frequencies including 2.45, 5.25, 29 and 60 GHz. The objective is to better understand the behavior of RF fading characteristics of a foliated radio channel in order to contribute to the development of suitable broadband wireless solutions for the last-mile problem. Some of the key findings are:

- It is not possible to use a single distribution model to fit the various attenuation characteristics through foliage measured at 2.45, 5.25, 29 and 60 GHz. The Extreme Value and Lognormal models best represent RF attenuation characteristics through trees.
- It is shown that RF propagation transmission through trees between 2 and 60 GHz is strongly frequency and wind speed dependent.
- The amount of RF signal attenuation through trees is larger when the size of the obstructions in the foliated path and the wavelength are similar in size.
- The AFD and LCR can be statistically modeled, and the results can be used to characterize the duration and the rate of fades.
- Spectral components are present in the power profile of the transmitted signal. These components are more easily observed during low wind speed periods. Future work is required to reproduce these results for several different other foliated radio channels.

Finally, this work presented several RF propagation characteristics that could for example be used to design a smart receiver/transmitter that compensates or pauses the data transmissions when a fade is detected. Such algorithms capable of predicting and managing fades as they occur could typically be designed based on the statistical data reviewed in this work.

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