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Earth-Space Links and Fade-Duration Statistics

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Abstract

In recent years, fade-duration statistics have been the subject of several experimental investigations. A good knowledge of the fade-duration distribution is important for the assessment of a satellite communication system's channel dynamics: What is a typical link outage duration? How often do link outages exceeding a given duration occur?

Unfortunately there is yet no model that can universally answer the above questions. The available field measurements mainly come from temperate climatic zones and only from a few sites. Furthermore, the available statistics are also limited in the choice of frequency and path elevation angle.

Yet, much can be learned from the available information. For example, we now know that the fade-duration distribution is approximately lognormal. Under certain conditions, we can even determine the median and other percentiles of the distribution. This paper reviews the available data obtained by several experimenters in different parts of the world. Areas of emphasis are mobile and fixed satellite links. Fades in mobile links are due to roadside-tree shadowing, whereas fades in fixed links are due to rain attenuation.

Introduction

Digital radio communication systems are influenced by the dynamics of fade events, that is, fade rate, fade duration, and inter-fade duration. In a digital receiver, signal decoding and synchronization (timing and phase) can be affected by the distribution of fade events. For long fades, a receiver could lose lock, and reacquisition may become necessary. Therefore, fades and their statistical distribution influence service availability, receiver loss of lock probability, and decoder performance. We will examine fade-duration statistics on Earth-space links.

On satellite links, fade events can result from atmospheric causes (rain) or, in the case of mobile satellite links, from tree shadowing and blockage. The analysis of measured data has shown that both types of fade give rise to fade-duration statistics that can be approximated with a lognormal distribution [1–3].

The lognormal probability density function is given by

$$p_z(z) = \frac{1}{sz\sqrt{2\pi}} \exp[-\frac{(\ln(z)-m)^2}{2s^2}] \qquad (1)$$

where z denotes the random variable, and s and m are the standard deviation and the mean of ln(z). The cumulative distribution of z can be obtained by integrating the above function from Z to infinity resulting in the probability that z is larger or equal to Z:

$$P(z \geq Z) = \frac{1}{2} erfc[\frac{\ln(Z)-m}{s\sqrt{2}}] \qquad (2)$$

where *erfc* denotes the complementary error function. For convenience, Eq. (2) can be multiplied by 100 to express the probability as a percentage.

Fade-Duration Statistics in Mobile Satellite Links

Fade-duration statistics caused by tree shadowing were obtained from measurements made in south-eastern Australia at a frequency of 1.5 GHz and a path elevation angle of 51° [1]. The data were shown to fit the lognormal distribution with good accuracy when $m = -1.514$ and $s = 1.215$, for a 5-dB fade threshold. The distribution encompassed road types that exhibit moderate and extreme shadowing —see reference 1 for a description of shadowing types. This distribution is shown in Figure 1. Note that fade duration is given in meters rather than seconds. Distance durations may be converted to time durations by dividing the former by the speed of the vehicle, which was nominally 25 m/s in the Australian experiment.

For this example, 50 percent of all the fade events consisted of fades shorter than 0.22 m. At a speed of 25 m/s, this translates to less than 0.01 s. Ninety-nine percent of all fade events consist of fades with durations shorter than 4 m, which is equivalent to a time duration of 0.16 s. Therefore, it appears that, for this example, fade durations are generally short enough to avoid receiver synchronization problems (at least for most of the time). Other experimental data have shown that for tree shadowing, fade durations increase with decreased elevation angle. For instance, the fade duration for a 30° elevation angle has been observed to be twice that of a 60° elevation angle at the same probability level [1]. If this observation is applied to the data presented in Figure 1, the fade-duration distribution for an elevation angle of about 25° can be estimated by adding the constant $\ln(2)$ to m. The result is shown by the dashed curve in Figure 1.

Rain Attenuation

Fades due to rain attenuation have been investigated in several experimental campaigns. Signals propagating through the atmosphere experience both attenuation and scintillation effects. Since signal fluctuations due to scintillation contain higher frequency components than the ones caused by rain attenuation, low-pass filtering of the observed signal can remove the scintillation effect. To focus our discussion to fade events due to rain attenuation, only data with scintillation-induced fluctuations removed are considered.

Reference [2] reports on a four-year experiment in Texas, where the elevation angle is 6° and the signal frequency is 11 GHz. Fade-duration statistics for fade thresholds from 5 to 20 dB are shown to be approximately lognormally distributed with the 50% probability level corresponding to a fade duration of about 300 s. Figure 2 shows the lognormal fit to the data. In this example, 50% of all fades are shorter than 300 s, and 90% of all fades are shorter than 2500 s. For a threshold of 20 dB, measured fade durations are shorter than the lognormal model predictions at high duration values. The asterisk at the 2000 s duration value in Figure 2 shows the measured data for a threshold of 20 dB. This means that, for a fade threshold of 20 dB, fades longer than 2000 s are rare.

There is evidence that the lognormal model also applies to a mix of data taken at different sites and different frequencies. Figure 3 taken from [3] shows an approximate lognormal fit to data obtained from three sites, one in the U.S. (Virginia) and two in Europe. The data include three frequencies of 12, 20, and 30 GHz, and fade thresholds in the range of 4 to 10 dB. The Virginia site[1] had the lowest path elevation angle of 14°. The 50 percentile value in this case is 200 s compared to 300 s in Figure 2. Another difference between these two cases is that the

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[1] One full year of data was acquired in the 1990–92 period using the Olympus spacecraft.

percentage of very long fades, that is, fades longer than 1000 s, is less in this case than in Figure 2. This may be attributed to the data in Figure 2 corresponding to the very low elevation angle of 6°.

Another subject of interest is the absolute number of fades at a given threshold. The absolute number of fades depends on the frequency of the signal. The number of fade events increases with increasing frequency. For the Virginia site, Reference [4] shows the number of fades as a function of fade duration for frequencies of 12, 20, and 30 GHz and an elevation angle of 14°. For example, at a fade threshold level of 5 dB the number of fade events with fades equal to or exceeding 1 minute is 108 at 12 GHz, 605 at 20 GHz, and 935 at 30 GHz. These values for a fade threshold of 15 dB are 6 at 12 GHz, 75 at 20 GHz, and 200 at 30 GHz. Clearly, the number of fade events decreases when the threshold level increases. Since system engineers use the fade threshold information to determine the required fade margin in a system, it is useful to further explore the relationship between the fade duration statistics and the fade threshold (attenuation level). The next section will address this topic.

Fade Duration and Attenuation Level

The probability of service availability is a very important parameter of link design in a satellite communication system. The availability of the service is directly related to the link margin. Therefore, it is important to examine the fade-duration distribution as a function of signal attenuation. Presenting fade duration in this fashion will enable system designers to conveniently plan the optimum value of the fade margin for a system. Note that too little margin will result in an unacceptable grade of service, whereas too much link margin will give rise to high system costs.

Reference [5] considers this issue by relating the occurrence of fades of a certain duration to attenuation level. Although the model presented in [5] is a preliminary one, it is noteworthy in that it addresses an important system need. In this approach, fade durations have been binned into predetermined intervals. For example the model for fade durations between 30–60 s is given by

$$FT_{12} = 8900\exp(-1.315A + 0.118A^2 - 0.004A^3) \qquad (3)$$

where FT_{12} denotes the cumulative fade time in seconds for a frequency of 12 GHz and A is the attenuation level in dB ($3 \le A \le 16$). Figure 4 shows a plot of Eq. (3) for attenuation levels from 3 to 16 dB. For example, at a margin of 9 dB all fades lasting for 30–60 s add up to 500 s of link outage in one year of observation. The data used for this model were also obtained from the Virginia site mentioned earlier with a path elevation angle of 14° to the satellite.

Because the database used to develop Eq. (3) also included 20 and 30 GHz data, this equation was extended to a model that predicts fade time for three frequencies [5]. This model is given as

$$FT_f = 8900(-8.899 + 0.915f - 0.008f^2)\exp(-1.315A + 0.118A^2 - 0.004A^3) \qquad (4)$$

where FT_f is the cumulative fade time in seconds for the 30–60 s fade duration interval at a given frequency, f is the frequency in GHz, and A is the attenuation in dB. The dashed curve in Figure 4 shows the above model for 20 GHz. An extension of the above model to other fade duration intervals, e.g., 60–120 s, is also given in [5].

Although Eq. (4) offers a powerful tool for determining fade-duration distribution as a function of attenuation, there is a caveat associated with this tool: The model was developed based on measurements at a single elevation angle and in a single rain climate zone. Therefore, its extension to other elevation angles and climate zones is not clear. The model may also be contaminated by statistical noise because it is based on only one year of observations. Measurements at different sites and for longer time durations will very likely contribute to the improvement of the model's accuracy and robustness.

Summary

Fade-duration statistics on satellite links can be approximated by the lognormal distribution. This distribution can be uniquely described by the mean and the standard deviation of the natural logarithm of the samples. This model applies to fades due to rain attenuation (fixed satellite) as well as fades due to tree shadowing (mobile satellite).

For shadowing-induced fades, fade-duration statistics seem to be insensitive to the amount of shadowing, i.e., light to heavy shadowing. However, a moderate dependence on elevation angle has been observed in field measurements. This dependence gives rise to longer fade durations with decreased elevation angle.

For rain-attenuation-induced fades, it appears that for temperate site locations, elevation angles above 14°, and frequencies between 12–30 GHz, the fade-duration statistics are not strongly dependent on site location, elevation angle, or frequency.

A simple model to relate fade time for a given fade duration to attenuation level is also discussed. This approach is useful for examining the impact of fades on the receiver, allowing for an estimation of total receiver downtime. Note that total downtime is the sum of the fade duration and system reacquisition time.

The models presented in this paper are based on a limited amount of experimental data. Further study is required to substantiate their application to specific slant path configurations.

Acknowledgment

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References

1. J. Goldhirsh and W. Vogel, *Propagation Effects for Land Mobile Satellite Systems,* NASA Reference Publication 1274, Feb. 1992, pp. 41–45.
2. M. Rice, et. al., "K-Band Land-Mobile Satellite Channel Characterization using ACTS," *International Journal of Satellite Communications,* will be published in late 1995.
3. W. Vogel, et al, "Rain Fades on Low Elevation Angle Earth-Satellite Paths: Comparative Assessment of the Austin Texas, 11.2 GHz Experiment," *Proc. IEEE,* vol. 81, no. 6, Jun. 1993, pp. 885–896.
4. J. Baptista, et al, ed., *Reference Book on Attenuation Measurement and Prediction,* ESA WPP-083, Nov. 1994, pp. 101–107.
5. W. Stutzman, et al, "Results from the Virginia Tech Propagation Experiment Using the Olympus Satellite 12, 20, and 30 GHz Beacons," *IEEE Trans. Antennas and Propagation, vol 43, no 1, Jan. 1995, pp. 54–62*
6. H. Ajaz and A. Saffaai-Jazi, *Fade and Inter-Fade Durations in Ku- and Ka-Band Frequencies Measured From the Olympus Satellite Beacons,* Satcom Report 93-17, VPI&SU, Oct. 1993.

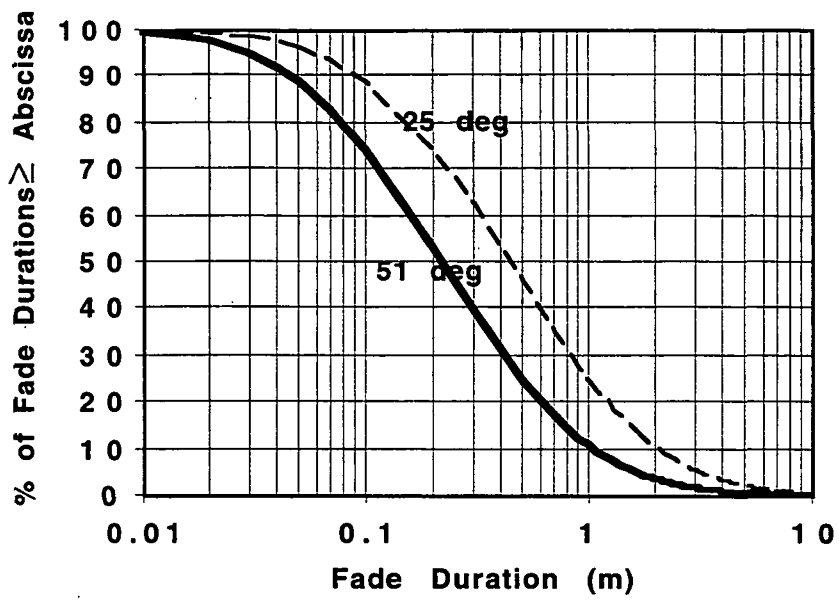

Figure 1. Fade Duration Distribution for Mobile Satellite Links (elevation angles 51° and 25°)

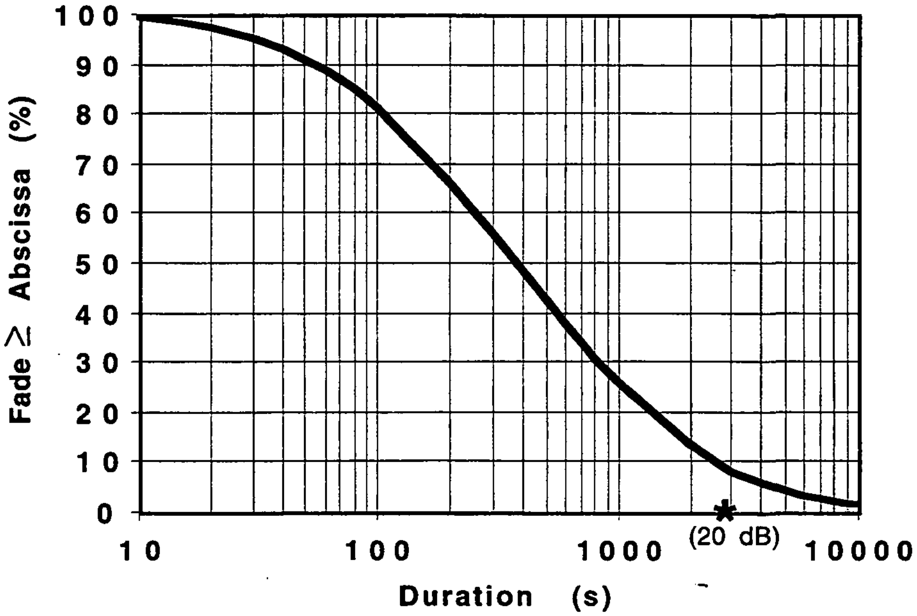

Figure 2. Texas 11-GHz Data

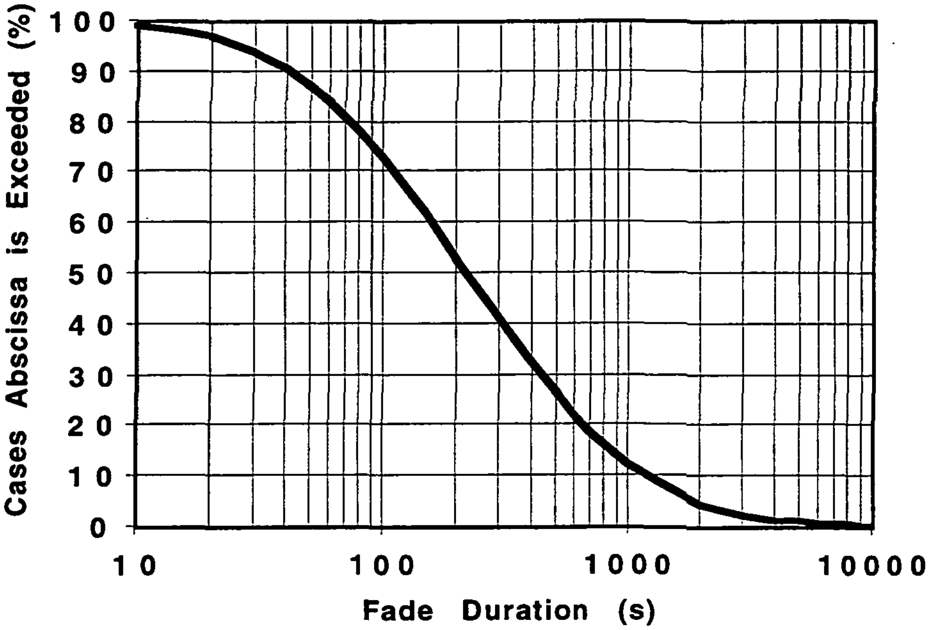

Figure 3. OPEX 12-, 20-, and 30-GHz Data

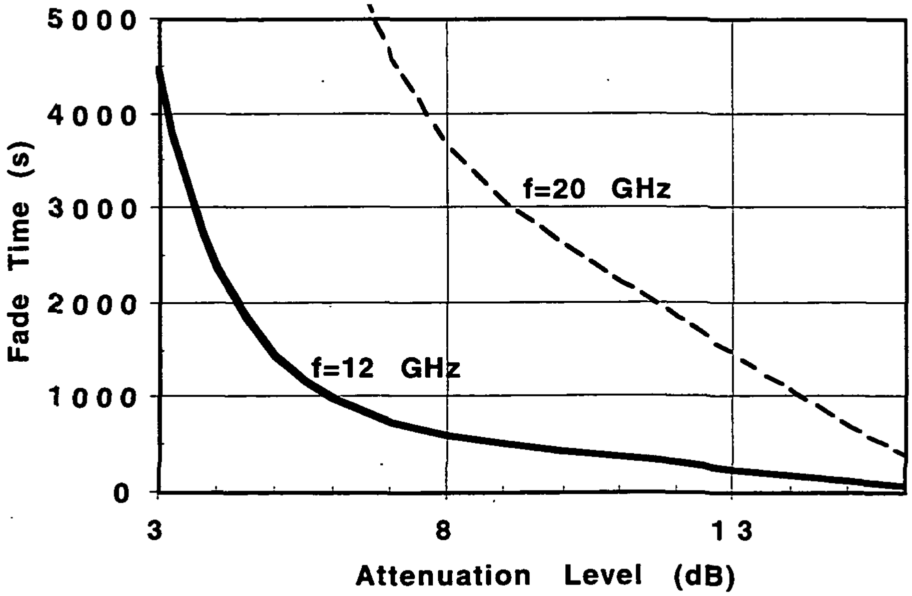

Figure 4. Annual Fade Time for 30–60 s Fade Durations