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A FRACTAL ATTENUATION MODEL FOR THE Ka BAND

Nedo Celandroni, Francesco Potortì

CNUCE, Institute of CNR (Italian National Research Council)
Via S. Maria 36 - 56126 Pisa - Italy
Phone: +39-50-593207/593203
Fax: +39-50-904052 - Telex: 500371
E-mail: N.Celandroni@cnuce.cnr.it, F.Potorti@cnuce.cnr.it

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Abstract.

We propose a model that describes the rain attenuation process, which can be useful for designing atmospheric fade countermeasure systems for satellite communications. We analyzed a data set of up-link (30 GHz) and down-link (20 GHz) attenuation values averaged over 1 second intervals. The data are samples relative to 10 significant events, for a total of 180,000 s, recorded at the Spino d'Adda (North of Italy) station using the Olympus satellite.

Our analysis is based on the fact that the plot of attenuation versus time recalls the behaviour of a self-similar process. Starting from this observation, we make various considerations and propose a fractional Brownian motion model for modeling the attenuation process. We describe the model in detail, with pictures showing the apparent self-similarity of the measured data, then we show that the Hurst parameter of the process is a simple function of the attenuation.

In order to produce useful data for simulating fade countermeasure systems, one needs to interpolate the measured attenuation traces, which have 1 s granularity, so we describe a method for producing random data that interpolate the measured samples, while preserving some of their interesting statistical properties.

We conclude by suggesting a possible application for such a model, which is the subject of current research.

Introduction

Until recently it was thought that the introduction of fiber optics in high speed digital communications would dramatically reduce the employ of satellites. Since then, satellite communications systems have been reevaluated. This is not only due to the special features offered by satellites, such as broadcasting and the ease of creating new user installations regardless of geographical position, but also to recent progress in technology, which has made possible the use of satellites which in some cases are economically competitive with fibers. In particular, the fall in cost of solid state power amplifiers (SSPA) has allowed the use of personal systems in the Ka band, which offers noticeable advantages, such as a wide spectrum and a significant reduction in the size of on-board antennas. High gain multispot antennas make access possible for users equipped with 2 W SSPA and below 1 m dishes for multimedia applications such as videoconferencing. The situation improves considerably if on-board processing is employed. In this case multimedia applications are made accessible to mobile users as well.

In order to ensure an acceptable level of link availability (in the order of 99.9% for personal systems), however, using the Ka band entails dealing with signal attenuation due to rain and scintillation, since the amplitude of both these phenomena increases with frequency [11, 12]. Fade countermeasure systems, such as transmission power [9], bit and coding rates adaptation [1, 2], frequency [12, 13] or space diversity [10] are thus required to avoid loss of economy.

All these systems need a quick and accurate measurement of link degradation, due to atmospheric events, in order to reduce the power margins over the countermeasure's thresholds of intervention.

The estimation accuracy of both the attenuation or the signal to noise ratio (SNR) is generally inversely proportional to the measurement time. Furthermore, due to the satellite transmission delay and the algorithm used, there is an interval of time, in the order of one or two seconds, between the countermeasure application and the actual reception of data by the destination user. By observing a considerable sample of experimental attenuation data we revealed that linear regression methods were not useful for short term predictions of attenuation. This opinion is also shared in [5]. The short time attenuation fluctuactions (expressed in dB), in fact, seem to have a Gaussian distribution and a small autocorrelation. This phenomenon is mostly attributed to scintillation, i.e. signal amplitude variations due to tropospheric turbulence [20], rather than to raindrop absorption and scattering. Instead of trying to predict the attenuation value, our approach is to estimate its variance, which is due to the delay between measurement and data reception. Then, in order to compensate for such a variance and the measurement inaccuracy, we can introduce a suitable power margin. This paper presents a method to model attenuation behaviour, which is applicable for time intervals of a few seconds, in order to optimize both the attenuation measurement time and the needed power margin. This method is based on a fractal model which is also used to generate, at any desired time instant, synthetic attenuation data which can be used when simulating fade countermeasure systems.

First we give an overview of fractional Brownian motion, and describe our model. Then the interpolation method, based on the random midpoint displacement algorithm is introduced, followed by an explanation of some of the model's characteristics. We conclude with a brief outline on how the model can be used to optimize measurement times.

Interpolation of a set of measured attenuation values

Experimental traces of atmospheric attenuation are typically available with a measured value every second, an interval which is usually much longer than the frame time of a satellite communication system operating in TDMA, and also about four times a typical satellite round trip time. As we have noted previously, fade countermeasure systems need a quick and accurate measure of the attenuation value, and this estimate must be disseminated as soon as possible, for the satellite network to apply the adaptive countermeasure.

Our approach to the problem of simulating rain fade events is to take a rain attenuation trace and interpolate it, in order to synthetically compute attenuation samples at a rate higher than the measurement rate.

By looking at the traces, it is quite clear that any kind of elementary interpolation method would lead to a behaviour of the process which is quite far from reality. Linear or spline interpolation, for example, would create at small scales — i.e. between measured samples — a smooth graphic that is not similar at all to what is observed at coarser scales. This discrepancy is important for the problem at hand, because we need to check the behaviour of the prediction algorithms when the samples are noisy. We therefore took a different approach, which was inspired by the apparent statistical self-affinity of the measured attenuation. In Figure 2, the same rain event is magnified and properly rescaled. One can see what appears to be the footprint of a rescaled self affine random process: without the help of the numbers on the horizontal axis, it would be difficult to tell whether any one picture is taken on a greater or smaller scale than the others.

Fractional Brownian motion and statistical self-affinity

A stochastic process A(t) is said to be statistically self-affine if, for any given positive real number r, its statistics are the same as those of the process $kA(t/r)$, where k depends on r. This means that, if the process is stretched along the time axis, a suitable magnification along the ordinate yields a new process with the same statistics as the original one. One such process is the Brownian Gaussian motion, that is, a process with stationary independent Gaussian increments.

Let us denote this process by B. If we consider discrete times t_i, $B_{i+1} - B_i$ is, by definition, a Gaussian random variable with null mean and variance σ^2. The increment $B_{i+1} - B_i$ is stationary, that is, it does not depend on the index i. Moreover, it is independent of other increments as well, that is, different increments $B_{i+1} - B_i$ are i.i.d. variables. Given these properties, the increment process

$W(i,j) = B_i - B_j$ is only dependent on the difference $k = i-j$, so that it can be written as $W(k)$. From these properties, a consequence is that $W(k)$ is a Gaussian random variable with null mean and variance equal to $k\sigma^2$. In fact $\mu(W(k)) = k\mu(W(1)) = 0$, and $\sigma^2(W(k)) = k\sigma^2(W(1))$.

The same concepts can be applied to the continuous time domain, where $W(\tau) = B(t)-B(t+\tau)$ is the difference process, which is independent of t, but only depends on τ. As with the discrete case, $W(\tau)$ has a null mean and a variance proportional to τ. $B(t)$, in the continuous domain, can be viewed as the integral of white Gaussian noise, or even as the output of a linear system with transfer function G such that $|G(f)|^2 \propto f^{-2}$ whose input is fed with white Gaussian noise. Hereafter, unless otherwise specified, we will refer to Brownian motion without distinguishing between discrete and continuous time.

Gaussian Brownian motion, as defined above, is a statistically self-affine process such that $B(t)$ is statistically indistinguishable from $\sqrt{r}B(t/r)$. This property will be central to the following discussions. It means that stretching the stochastic process $B(t)$ along the horizontal axis by r times and along the vertical axis by $\sqrt{r}$ times yields a new stochastic process which has the same statistics as $B(t)$ or, more precisely, $B(t)$ and $\sqrt{r}B(t/r)$ have the same finite dimensional joint distributions. The reason is that $B(t)$ is completely defined by the variance of the null-mean, Gaussian increments $W(\tau) = B(t)-B(t+\tau)$ and, since the variance of $W(\tau)$ is proportional to τ, $B(t)$ has increments that are distributed like those of $\sqrt{r}B(t/r)$. This fact can also be expressed by saying that the "slowed" process $B(t/r)$ is *properly rescaled* by magnifying it by $r^{0.5}$ times.

Fractional Brownian motion (fBm, for short) is an extension of these concepts. Gaussian fBm can be defined as a process with stationary Gaussian increments such that $B(t)$ has the same statistics as $r^H B(t/r)$, where $H \in [0; 1]$ is known as the *Hurst parameter* of the process. The same process can be obtained by filtering white Gaussian noise through a linear system with transfer function G such that $|G(f)|^2 \propto f^{-\beta}$, where $\beta = 1+2H$, hence $\beta \in [1; 3]$ [4, §1.4.2]. The increments of fBm are correlated, apart from the case H = 0.5, when fBm is reduced to "ordinary" Brownian motion, whose increments are uncorrelated.

The difference process of a Gaussian fBm is called Gaussian *Hurst noise* [3, pg.249], or fractional Gaussian noise (fGn for short). For $H = 0.5$, fGn is the ordinary white Gaussian noise, which exhibits no persistence, that is, its values at different points are uncorrelated. For $0.5 < H \leq 1$, fGn is *persistent* (positively autocorrelated), while it is *antipersistent* (negatively autocorrelated) for $0 \leq H < 0.5$. The power spectrum of fGn is proportional to $f^{-\beta+2}$.

Measure of the parameters of the scintillation process

We started from a data set chosen from the results of the propagation experiment, in Ka band, carried out on the Olympus satellite by the CSTS (Centro Studi sulle Telecomunicazioni Spaziali) Institute, on behalf of the Italian Space Agency (ASI). The up-link (30 GHz) and down-link (20 GHz) attenuation samples considered were 1 second averages. The samples relate to 10 significant events for a total of 180,000 s recorded at the Spino d'Adda (North of Italy) station, collected from August to October, 1992. The slant path elevation angle was 30.6° and the antenna diameter was 3.5m.

The attenuation versus time plot recalls the behaviour of a self-similar or self-affine process. However, our purpose is to look at the characteristics of the process in the range of a few seconds at the most, so we do not consider the overall shape of the trace of attenuation event, but we only look at the details that lie in that time range. In practice we analyze the scintillation process, which is commonly identified for frequencies above a few hundredths of Hertz (0.02-0.03 Hz in [20]). We expect to find a characterization of the scintillation process which depends on the instantaneous value of the attenuation. To this end, we analyzed the difference process of the attenuation using the following procedure.

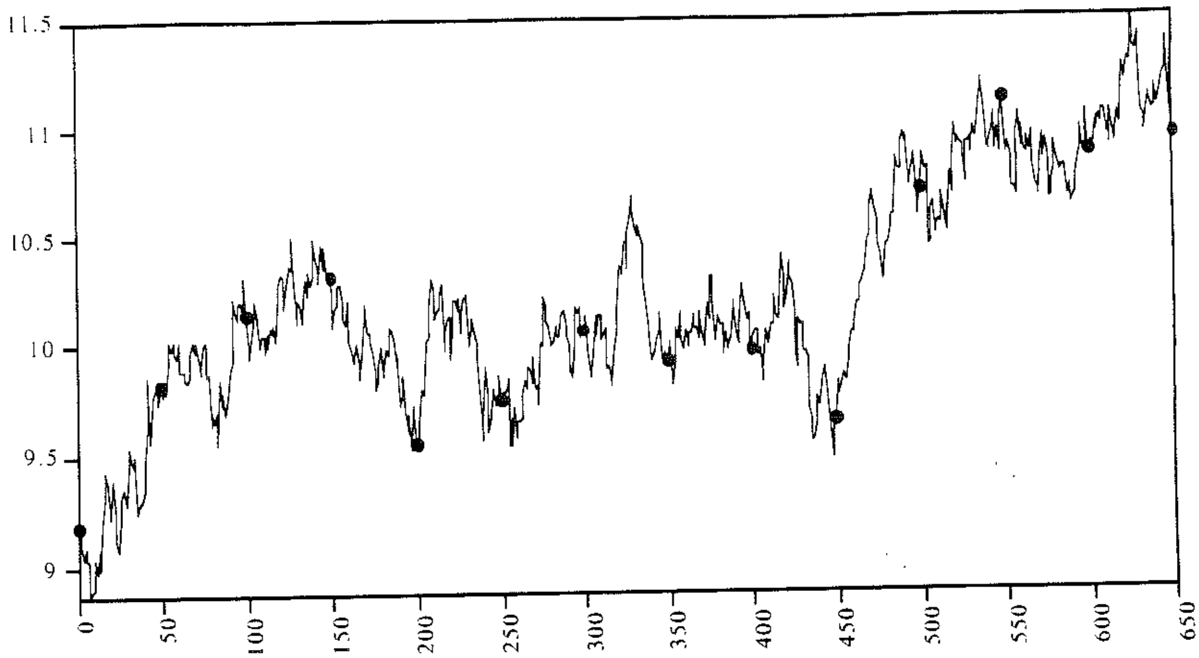

Figure 3: An example of the interpolation procedure. Starting from 14 1 s-spaced points we randomly compute 50 values per second. Values on the horizontal axis are 1/50-th of second, values on the vertical axis are attenuations in dB.

Physical considerations about the fractal characterization

The interpolation criterion we have described so far is based solely on geometrical considerations. Indeed, all parameters are deduced from the analysis of the values of the measured samples. It would be interesting to find some kind of justification for this procedure, that builds on physical findings and theories. In this section we will try to suggest some possible explanations and analogies, most of which should be taken as ideas for further research in this potentially fertile field.

The fundamental relationships we found are that the scintillation power σ^2 and its Hurst parameter are both dependent on the attenuation. As far as the scintillation power is concerned, most authors would admit that it should be considered constant with respect to the attenuation value. However, recent findings [20] suggest that a relationship exists, and it has the same sign as our statistics show.

As far as the variability of the parameter H with the attenuation value is concerned, we will refer to the spectral analysis of the scintillation process. In fact, it is commonly accepted [20, 22] that the power spectrum of the scintillation in log-log scale follows an f^{-1} slope followed by an $f^{-8/3}$ slope, and that the corner frequency f_c is dependent on many parameters. To our knowledge, no studies exist on the dependence of the corner frequency upon the attenuation value. Anyway, f_c is usually assumed to lie in a range compatible with the time range 1-3 s of our analysis. If f_c lies within this range, then its dependence on the attenuation, whose laws are as yet unknown, can be reasonably thought to cause the dependence of the Hurst parameter on the attenuation. In fact, as outlined above, the power density specrtum of an fBm process exhibits a slope of $f^{-\beta}$, where $\beta = 1+2H$. It is commonly assumed that the slopes of the power density spectrum of the scintillation process around f_c are f^{-1} for $f < f_c$ and $f^{-8/3}$ for $f > f_c$, which implies that H should lie in the range [0; 0.83]. This observation is noteworthy, because the range we found is compatible both with the allowed range of H, which is [0; 1] and with our measures, which give a range of approximately [0.2; 0.6]. Here we suggest that the dependence we observed of the Hurst parameter on the attenuation can be attributed to the variability of the scintillation power spectrum with the attenuation. If the spectrum is approximated by two asymptotes with slopes f^{-1} for $f < f_c$ and $f^{-8/3}$ for $f > f_c$, then H can be thought of as a function of f_c, which in turn depends on the attenuation.

Use of the model to optimize measurement times.

The methods to estimate the signal degradation reported in [14-16] produce a variance of the estimation which is inversely proportional to the number of inspected bits and thus to the measurement time interval. Considering that the variance of the attenuation increases with time according to our model, expressed by relation (1), it is possible to optimize the measurement times.

Let us denote by t_Δ the interval of time between the estimation of the signal degradation and the instant the destination user receives data sent with the adaptive countermeasure chosen according to the estimation. Let t_m be the measurement time, and let us assume that the measurement error and the attenuation difference process are independent and both Gaussian. The total error on the signal quality estimation is then Gaussian with a variance σ_q^2 given by

$$\sigma_q^2 = \sigma_m^2(t_m) + \sigma_\Delta^2(t_m + t_\Delta)$$

where σ_m^2 is the measurement error variance and σ_Δ^2 is the evolution of signal quality variance at the time $t_m + t_\Delta$, computed according to our attenuation model. Since t_Δ depends on the fade countermeasure system adopted, and can be assumed to be constant, σ_q^2 can be minimized with respect to t_m, given that σ_m^2 decreases, while σ_Δ^2 increases with the measurement time. Once the minimum σ_q^2 is obtained, a suitable power margin can be computed in order to guarantee the bit error rate (BER) required by the user. This margin is generally dependent on the characteristic of the BER versus the SNR and is thus dependent on the modulation/coding scheme. This topic needs further investigation, which will be the subject of future work.

Conclusions

The model we have presented characterizes the short time evolution of the attenuation process, mostly due to scintillation. We considered attenuation sample data, spread over a two-month period, at a fixed frequency, and with a fixed elevation angle and antenna size, so no attempt was made to consider the dependency of the process on these factors. We made the fundamental assumption that the process is to be considered as stationary in the same bulk rain attenuation belt.

It is well known [21] that the amplitude of rapid level fluctuations of the attenuation depends on a lot of factors such as elevation angle, antenna gain, season and latitude of the earth station. Corrections to apply for different elevation angles and antenna sizes can be found in [22], while reference [23] gives some ideas about the dependence on season and on some other factors in clear air conditions alone. We conclude therefore that the derivation of a model which has a more general validity needs a much deeper study and a much larger sample of attenuation data.

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