Quantification of the Performance Benefits of Receiver Diversity in Mitigating Scintillation on Ka Band Downlinks

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Abstract

This paper quantifies, through the use of a multiple phase screen (MPS) simulation model, the benefits of using two receive antennas to mitigate tropospheric-induced scintillation on Ka band (20-30 GHz) satellite downlinks. Two representative turbulence profiles are considered, and cumulative distribution curves for scintillation-induced attenuation are generated for selection and maximal ratio combining schemes and compared to those for a single antenna. The results indicate that, in the two representative cases considered, there can be significant diversity gains achieved by combining two antennas. Also, a comparison of simulation results with the results predicted by the *basic Rytov* approximation shows that, at elevation angles greater than 10 degrees, Rytov theory can accurately predict performance benefits of antenna combining, but at elevation angles less than 10 degrees it is better to use simulations to make the performance predictions.

1 Introduction

The desire for higher data rates and the need for available bandwidth has pushed satellite communications into the Ka band (20-30 GHz). At these higher carrier frequencies the effects of scintillation due to turbulence-induced index of refraction irregularities in the troposphere is known to become more prevalent, particularly on slant paths. Mitigation of scintillation can be very important for certain links such as those operating at a low-margin along a low elevation path in a dry climate, where scintillation, rather than rain, is the key link factor. As our primary goal in this paper, we will quantify, for two representative cases, the benefit of using two receive antennas to mitigate the deleterious scintillation effects on a satellite signal in the Ka band. As a secondary goal, we will establish some guidelines to determine in what situations *basic Rytov* theory, which is applicable in weak scattering conditions, can be used and in what situations simulations should be used in determining possible antenna combining benefits. We will use the multiple phase screen (MPS) model to simulate the effect of the troposphere on the Ka band satellite signal. In years past the MPS method has been used to model the effects of the ionosphere on the propagation of satellite signals at less than 10 GHz, see for example [1]. Also, in recent years it has been used extensively by the optical communications community to model the effects of the troposphere on laser signals, and by at least two researchers to model the effects of the troposphere on Ka band signals [2] and [3].

2 Background

This section presents some results derived from scintillation theory. The interested reader may wish to consult the classic text by Tatarski [4] or the more recent text by Wheelon [5] for more details. Using the *basic Rytov approximation* (i.e. the approximation based on the first term in the series representation of the surrogate function), it can be shown that 1) the received signal's amplitude has a log-normal distribution, and thus that the log of that amplitude, χ, has a Gaussian distribution and that 2) the variance of χ, can be found from [4, 5],

$$\sigma_\chi^2 \quad = \quad 0.563 k^{\frac{7}{6}} \csc^{\frac{11}{6}}(\theta) \int C_n^2(h) h^{\frac{5}{6}} dh \,(\mathrm{Np})^2 \tag{1}$$

In this equation 1) $C_n^2(h)$ describes how C_n^2, the index of refraction structure function constant, varies with altitude h, 2) θ is the elevation angle of the slant path, 3) $k = \frac{2\pi}{\lambda}$ is the wave number and 4) λ the wave length of the signal. C_n^2 quantifies the turbulence strength, for this reason C_n^2 is also often simply termed the *turbulence strength*. Fig. 1 shows a typical turbulence profile when 1) clouds are present and 2) when clouds are not present. The cloud-present profile was determined from radio-sonde measurements taken in Belgium on a summer day (August 14, 1990) [6]. The no-cloud profile was developed in [7]. It is based on the ITU-R C_n^2 profile model, with a modification to take into account water vapor. The version shown assumes a standard summer atmosphere for European latitudes. These two profiles represent what might be expected on a summer day in European latitudes.

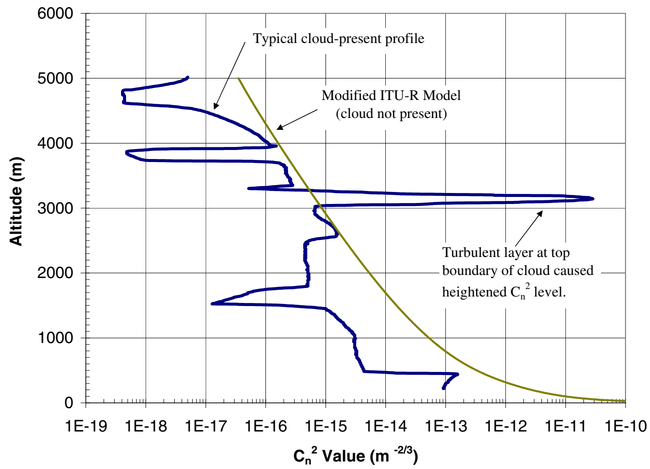


Figure 1: Two typical C_n^2 profiles during summer in European latitudes.

The above formula from *basic Rytov* theory was used to calculate, for a given turbulence profile, the anticipated value of σ_χ^2. Which in turn was used along with a log-normal distribution to predict the benefits of using antenna combining. These values, based on the *basic Rytov* approximation, were then compared with the values generated from simulations.

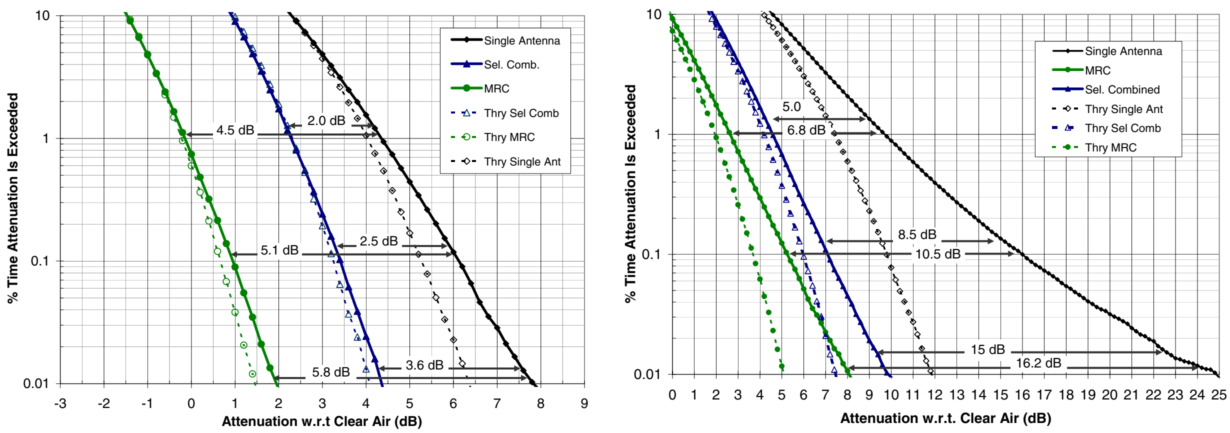
We will consider the following antenna configurations in this study: 1) a single antenna, 2) maximal-ratio-combining (MRC), in which the received signals from two separate antennas are scaled by the conjugate of their channel gains and then added and 3) selection-combining, in which the signal from the antenna with the best signal-to-noise ratio (SNR) is used. It is well known that the MRC method of combining results in the best SNR, but that selection combining is less complicated to implement. Let $|a_i|$ be the magnitude of the signal at antenna i, then the relative output SNRs can be expressed as, 1) $\mathrm{SNR}_{\mathrm{single}} = |a_1|^2$, 2) $\mathrm{SNR}_{\mathrm{MRC}} = (|a_1|^2 + |a_2|^2)$ and 3) $\mathrm{SNR}_{\mathrm{SC}} = max(|a_1|^2, |a_2|^2)$.

3 Simulation Results

As mentioned in the introduction, the MPS method was used to simulate the effects of the troposphere in creating scintillation. For a description of the MPS method see [1] and [3]. Simulations were run with frequencies of f_c= 20 GHz and f_c= 30 GHz assuming the presence of two receive antennas separated by various distances and using each of the following spectrums for the index of refraction irregularities: 1) Kolmogorov, and 2) von Karman, with an outer scale of 100 m. The antennas were assumed to act like point receivers. (It is worth noting that simulations run assuming an antenna dish diameter of 3.4 m yielded almost identical results). Both 1) the typical cloud-present and 2) the cloud not-present (i.e. the modified ITU-R model) turbulence profiles shown in Fig. 1 were used in the simulation. In order to save space, only the 30 GHz results will be presented in the figures.

The simulation results showed that the use of two antennas can provide diversity benefits, particularly for slant paths of less than 20 degrees of elevation. From analyzing the combing gain values obtained at various antenna spacings it was determined that a separation of only 30 m is required to obtain sufficiently independent scintillation fades. Increasing the spacing beyond 30 m led to no additional gain. The determination of the required spacing is an important result in that it can be quite difficult to obtain theoretically for a general turbulence profile ([5], ch. 4.2).

For the typical cloud-present turbulence profile, Fig. 2 portrays the cumulative distribution function (CDF) curves, determined by simulation, for the scintillation-induced attenuation at 30 GHz for the various antenna schemes for elevation angles of a) 10 and b) 5 degrees. The CDF curves generated using the *basic Rytov* theory results are also shown. The 0 dB level represents the attenuation level for a single antenna if no scintillation is present, in other words these attenuation values are with respect to clear air. The results shown are for the von Karman spectrum, with a realistic outer scale length of 100m. The results for the Kolmogorov spectrum were slightly more dramatic, but probably not as realistic since the Kolmogorov spectrum does not limit the outer scale length to a realistic value [8]. These results show that there can be significant advantage to using receiver diversity to mitigate scintillation.



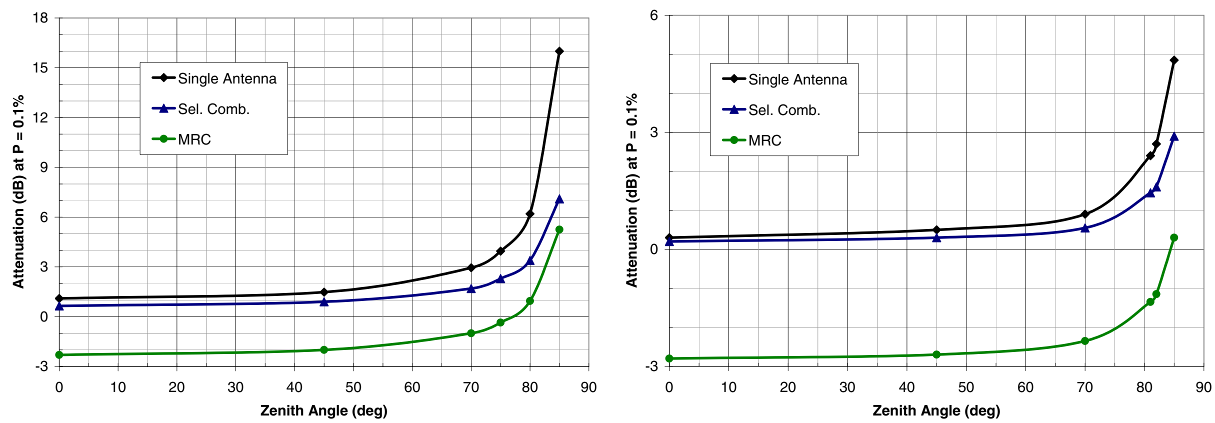
(a) 10 deg (b) 5 deg

Figure 2: CDFs from simulation and from Rytov theory for attenuation due to scintillation for cloud-present turbulence profile for a) 10 degree and b) 5 degree elevations.

For an elevation angle of 10 degrees (Fig.2a), in this typical cloud-present example, the results show gains ranging from 2.0 dB for selection combining and 4.5 dB for MRC combining at a desired link availability of 99% to 3.6 dB for selection combining and 5.8 dB for MRC at a link availability of 99.99%. Also, the *basic Rytov* theory accurately predicted the CDF curves for probability values greater than 1% (i.e. link availabilities less than 99%). At probabilities less than 1% the values obtained using the *basic Rytov* approximation produced values for attenuation that were too optimistic for the single antenna case. These single-antenna theoretical values would result in values that were 1 to 2 dB too low in estimating the mitigation benefit of antenna combining.

For an elevation angle of 5 degrees (Fig.2b), in this typical cloud-present example, the results show large gains ranging from 5.0 dB for selection combining and 6.8 dB for MRC combining at a desired link availability of 99% to 15 dB for selection combining and 16.2 dB for MRC at a link availability of 99.99%. At this elevation, the scintillation is so strong that the *basic Rytov* theory fails to accurately predicted the CDF curves for any of the antenna configurations, showing that simulations need to be used to obtain accurate estimates. It is interesting to note that although equation 1 from basic Rytov theory produced a value of σ_χ^2 in close agreement with that found by simulation (0.13 compared to 0.12) for the single antenna case, the CDF curves were very different, indicating a substantial difference in amplitude distributions. As mentioned above, *basic Rytov* theory predicts that the received amplitude will have a log-normal distribution. Under weak scattering conditions this does hold true. However, in actuality, as the scintillation increases that distribution will become skewed towards lower amplitude values. The *second order Rytov* solution can predict this skew up to a point ([5], ch. 10), but the amount of skew is difficult to predict analytically and the analysis holds over a limited range, yet this skew can greatly influences the link margin values (as seen in Fig.2b), making simulation methods valuable.

Fig. 3 portrays the attenuation values that were exceeded 0.1% of the time for various elevation angles for both the a) cloud-present and b) cloud-not-present profiles. In other words, these are the link margin values that would be required in order to obtain a link availability of 99.9% under the type of turbulent conditions pictured in Fig. 1. As the elevation angle decreases (zenith angle increases) the signal traverses more of the troposphere, and the scintillation-induced attenuation becomes more pronounced, drastically increasing, particularly for the cloud-present profile, as the elevation angle decreases below 20 degrees (increases above 70 degrees zenith). At a given elevation angle, the vertical distance from the single antenna curve to the curve for either selection combining or MRC provides the value for combining gain that could be expected to be obtained under this type of turbulence profile when receiving a signal at that elevation angle. As expected, the turbulence profile without the cloud produces significantly less scintillation, which is evidenced by the much lower attenuation levels of Fig. 3b relative to those of Fig. 3a. For the no-cloud-present case, it should be noted that the lower altitude portion of the profile contributes significantly to the scintillation and that this is a section of the model that is open to debate. For an elevation angle of 20 degrees (70 degree zenith) the results in Fig. 3 show a gain of 1.2 dB for selection combining and 4 dB for MRC for the cloud-present case and 0.5 dB for selection combining and 3.2 for MRC for the no-cloud-present case. For an elevation angle of 5 degrees (85 degree zenith) the results in Fig. 3b show a gain 2 dB for selection combining and 4.6 for MRC for the no-cloud-present case.



(a) Results with cloud-present

(b) Results with cloud not-present

Figure 3: Attenuation values exceeded 0.1% of the time with a 30 GHz signal for various zenith angles (elevation angle= 90 deg - zenith angle)for the two turbulence profiles shown in Fig. 1: a) cloud-present and b) cloud-not-present (modified ITU-R model) .

4 Conclusions

According to MPS simulations of tropospheric scintillation effects on Ka band satellite signals, used in conjunction with 1) a typical summer cloud-present turbulence profile and 2) typical summer no-cloud-present profile, there can be a substantial diversity benefit in from using multiple antennas for links with elevation angles less than 20 degrees. At elevation angles greater than 10 degrees the potential benefit can be adequately estimated by *basic Rytov* theory for link availability percentages up to 99%. At elevations less than 10 degrees one should use simulations in order to adequately ascertain the potential benefits of using receive antenna diversity to mitigate scintillation at Ka band.

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