A Discussion of Frequency Dependence of Multipath Fading and Enhancement on Line-of-Sight Radio Links

Terje Tjelta	Sofus Linge Lystad	Kenneth H. Craig
Telenor R&D	Norwegian Meteorological Institute	Rutherford Appleton Laboratory
terje.tjelta@telenor.com	sofus.lystad@met.no	k.h.craig@rl.ac.uk

Abstract

Prediction methods for multipath fading distribution on line-of-sight (LOS) radio links have suggested a radio frequency dependency since the 1970s. Usually a power-law form is indicated such that each predictor provides an estimate of a probability that deep mutlipath fading and strong enhancement takes place, and the product of the probabilities gives the overall likelihood. The method forms the basis for predicting performance of broadband as well as narrowband radio links. This paper discusses some of the basics and use full-wave calculations to investigate fading in the laminar atmosphere and also the condition where there is a transition from a laminar to turbulent atmosphere. The atmosphere is modelled using refractivity measurements obtained from high-resolution sondes in Norway where also a horizontal structure is introduced. The results suggest that the frequency term should not have a significant role in predicting the deep fading and strong enhancement distribution.

1. Introduction

Published prediction methods for multipath fading distribution on line-of-sight (LOS) radio links have suggested a radio frequency dependency since the 1970s. The methods usually suggest a power-law form such that each predictor provides an estimate of a probability that deep mutlipath fading takes place, and the product of the probabilities gives the overall likelihood of multipath fading of a certain fade depth. The deep-fade tail follows a Rayleigh distribution for a narrow-band system and forms the basis for predicting performance of broadband as well as narrowband radio links. The frequency term has traditionally been an important factor in the prediction methods; with a commonly used exponent of 1 in power law models. This gives, for example 10 times more deep fading for a 20 GHz links compared to a system operating at 2 GHz if everything else stays the same. It is fair to say that the theoretical basis for frequency dependency in deep multipath fading is rather week, but some possible causes have been suggested.

By contrast the scintillation effects due to small-scale variations of the refractive index in a turbulent atmosphere has a solid theoretical and statistical basis confirming a clear frequency dependency. Depending on the scales of eddies the theory predicts scintillation amplitudes depending on a frequency term raised to the power of 2 or so. It has been suggested that scintillation and deep multipath fading were both caused by the small-scale variation suggesting a Nakagami-Rice fading distribution, with a frequency dependency largely argued from scintillation theory. However, this does not explain deep fading or "median depression" leading to the deep fade tail of the distribution. The limitations are within scintillation theory to really create large amplitudes for a significant portion of the time, besides its inability to explain median depression.

This paper discusses some of the basics and use full-wave calculations to investigate fading in the laminar atmosphere and also the condition where there is a transition from a laminar to turbulent atmosphere. The atmosphere is modelled using refractivity measurements obtained from high-resolution sondes in Norway. The vertical resolution of such data is better than 10 m. The horizontal structure is varied partly based on two-dimensional refractivity data obtained by numerical modelling, using that maximum horizontal refractivity changes are around 1000 times less compared to strong vertical changes.

2. Clear-air propagation concerns for radio system dimensioning and operation

Clear air effects may have a major role in dimensioning radio systems and interference free operation. Radio links have to perform satisfactory and meet requirements, and the frequency spectrum has to be used in a best possible and efficient manner. For higher frequencies the precipitation effects dominate unavailability. In current prediction methods it is only the clear-air effects that are counted when error performance is considered irrespective of frequency, i.e., when a link is an available state. Also for efficient frequency reuse the enhancement is of concern; the stronger the enhancement is the poorer the spectrum utilisation becomes. The latter is very relevant for high frequency cellular and mesh networks in the range of 20-50 GHz. Since both deep fading and strong enhancement are caused by the same atmosphere structures, as also reflected in current predicting methods, it is important to use the correct frequency dependency.

Enhancement can cause unwanted signals interfering with users or base stations. For millimetre broadband radio access system the scenario to consider is the re-use distances of frequency at the 1/5 ratio suggested for millimetre systems, see for example [1]. Wanted path length for millimetre systems will due to propagation constraints be within a few kilometres [2], say the range 1-5 km, such the unwanted signals may come from path lengths in the range of 5-25 km. Coverage in the millimetre range requires LOS links and it drops off quickly with path length due to obstructions by buildings and vegetation. Therefore most potential interferers will be blocked and not cause any harm. The remaining visible ones may interfere and this should be accounted for in the network planning for base station locations. Interference caused by a user into a base station or between user terminals are also possible, but less likely than between base stations since these are located to provide best possible coverage.

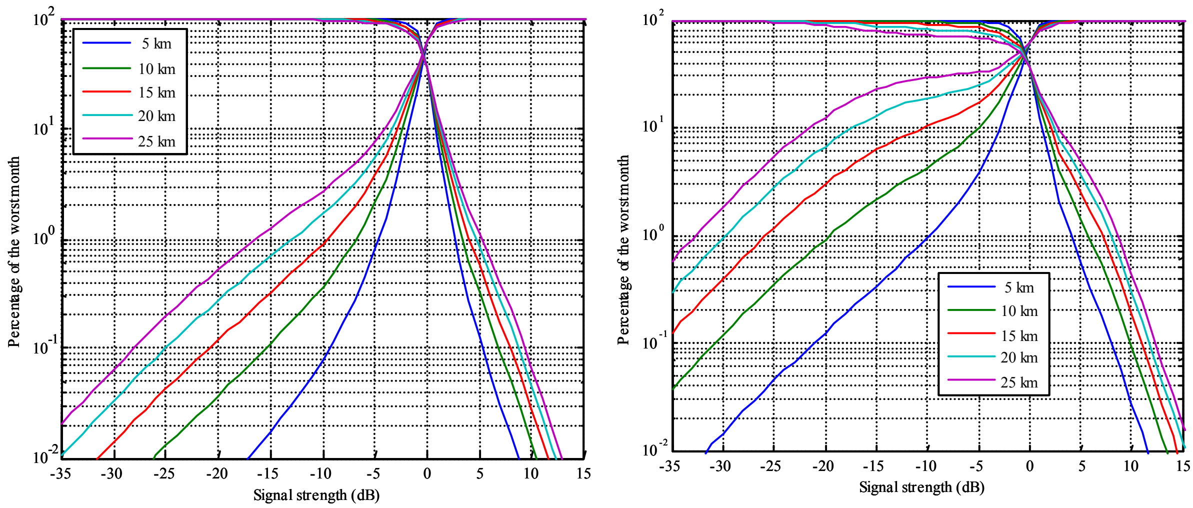
Either clear air ducting or scintillation can cause enhancement. Scintillation effects result out of a turbulent atmosphere. Under ducting the atmosphere has a layered structure. These two atmospheric conditions are connected, but do appear at different times. Under normal conditions there are neither significant scintillation nor ducting. The phenomena to be estimated happen only at a fraction of the time.

2.1. Deep fading and enhancement caused by ducting

The ITU-R has issued Rec. P.530 [1] to estimate the percentage of time a LOS path observes fading and enhancement. The method assumes that both deep fading and strong enhancement are caused by the ducting conditions, where strong enhancement is connected to the deep fading as suggested in [4]. The most important step is to establish the deep fading distribution tail and once this has been done the full distribution is easily calculated. The multipath activity, responsible for both fading and enhancement, is dependent on the factors path length, path inclination, path position, and climate characteristics including ducting and terrain features. Also frequency is suggested in prediction methods. Equation (1) gives the general expression for the tail part of the distribution for the percentage p that the deep fade exceeding A dB, or strong enhancement exceeding E dB

$$p = \begin{cases} c_A \prod_{i=1}^{N} g_i(x_i) 10^{A/10} \\ c_E \prod_{i=1}^{N} g_i(x_i) 10^{E/3.5} \end{cases} \tag{1}$$

where g are functions of predictors x, and c a constant. In the area between deep fading and strong enhancement, the percentage p is found by interpolation. Strong enhancement follows from the deep fade tail.



a) b

Figure 1. Worst month multipath distribution for a 42 GHz link with zero inclination, antenna heights at 150 m above sea, and a) the 1% value of dN/dz not less than –200 N-units/km and b) –700 N-units/km

It is accepted that the longer the path length the more likely it is to observe multipath activity. The activity is reduced with path angle through layers. The lower the lowest antenna is the more likely it will be found in a ducting structure. However, more multipath activity for higher frequency is not generally accepted as long as a layered atmospheric structure goes. For scintillation higher frequency creates large signal amplitudes.

The prediction method differentiate between contributions governed by the climate and the geographical area, such as refractivity gradient statistics and area surface roughness, and the specific link characteristics, such as path length, lowest terminal height above see, path inclination and radio frequency. The method for quick estimates only uses the refractivity gradient statistics, and it is this method that is used in the results provided in here. Figure 1 depicts two examples for link lengths ranging from 5 to 25 km. The frequency is 42 GHz and the other variables are 150 m above sea for the lowest antenna and zero path inclination. There are two family curves, one set represent the fading and the other enhancement.

The refractivity gradients chosen, -200 N-units/km and 700 N-units/km, represent the median and 2 % of the percentage of area of the Earth, see Figure 2. For a normal area of the Earth it is noted that for 0.1 % of the time the enhancement is between 5 and 9 dB for path lengths in the range of 5 to 25 km, for an area with significant more multipath activity the enhancement range from about 8 to 12 dB. Cleary, if such a transmitter is visible and allowed to use the same frequency and polarisation, it has to be accounted for in the design. It should be noted that multipath activity of this kind, has not been reported for shorter links than 7 km, but cannot be ruled out. Nevertheless, the wanted link of up to 5 km will most likely not fade at all. If multipath activity occurs the wanted link may be enhanced or it may fade at the same time as the unwanted signal is enhanced. Careful design will have to assume that the wanted signal stays as is whilst the unwanted signal is enhanced.

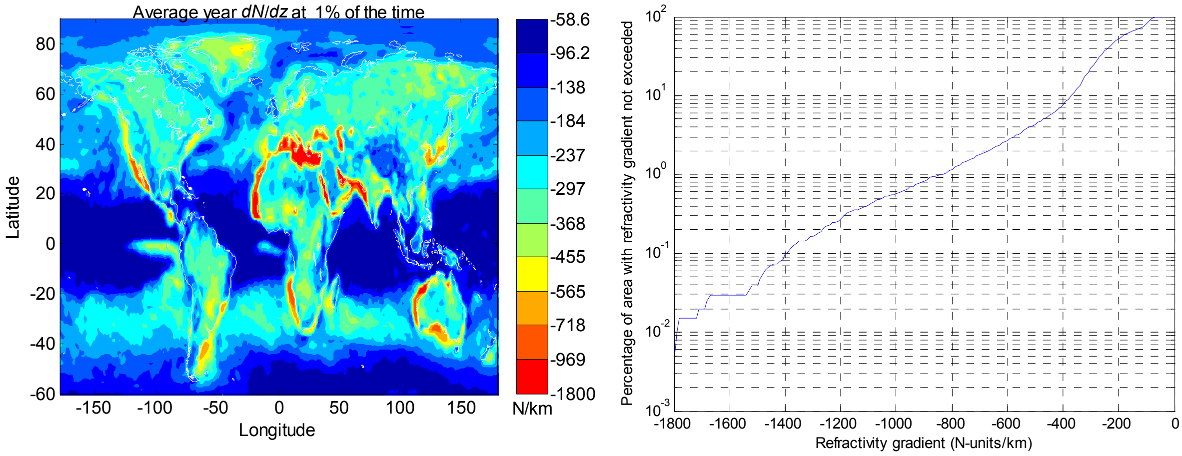


Figure 2. Lowest 65 m refractivity gradient not exceed at 1 % of the time shown as a) global map, and b) distribution of surface of the Earth

One reason for the uncertain frequency dependency is the lack of experimental data. There are some data and the CRABS project did point out the dependency is weak, if it is there at all [2].

2.2. Full-wave calculations of loss variability

To investigate the frequency dependency further an illustrative situation have been simulated using full wave calculations, a parabolic equation methods [5], and software [6].

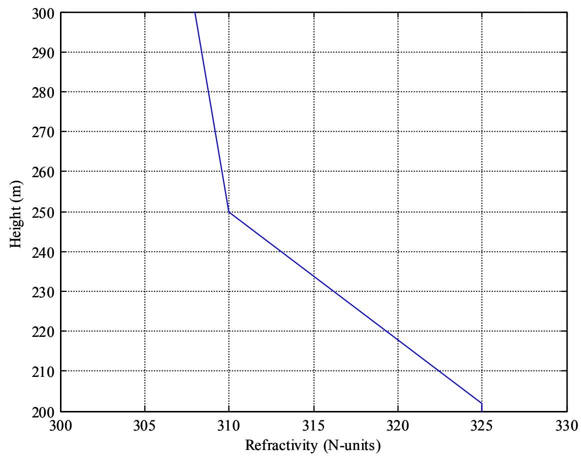


Figure 3. Refractivity and modified refractivity profiles used for the simulation example

The parabolic equation method referred to is restricted to paraxial propagation parallel to the Earth, which is the case for the study done. However, the software does handle non-paraxial cases in a hybrid manner. The calculation used a 100 mW vertical polarised signal transmitted using a Gaussian antenna with 1° beam width located 50 m above a flat terrain, 250 m above sea. The transmitter is positioned at 250 m above sea. The refractivity profile is given in Figure 3.
The path loss calculations at frequencies ranging from 10 GHz to 40 GHz are presented in Figure 4, the actual frequency identified above each plot.

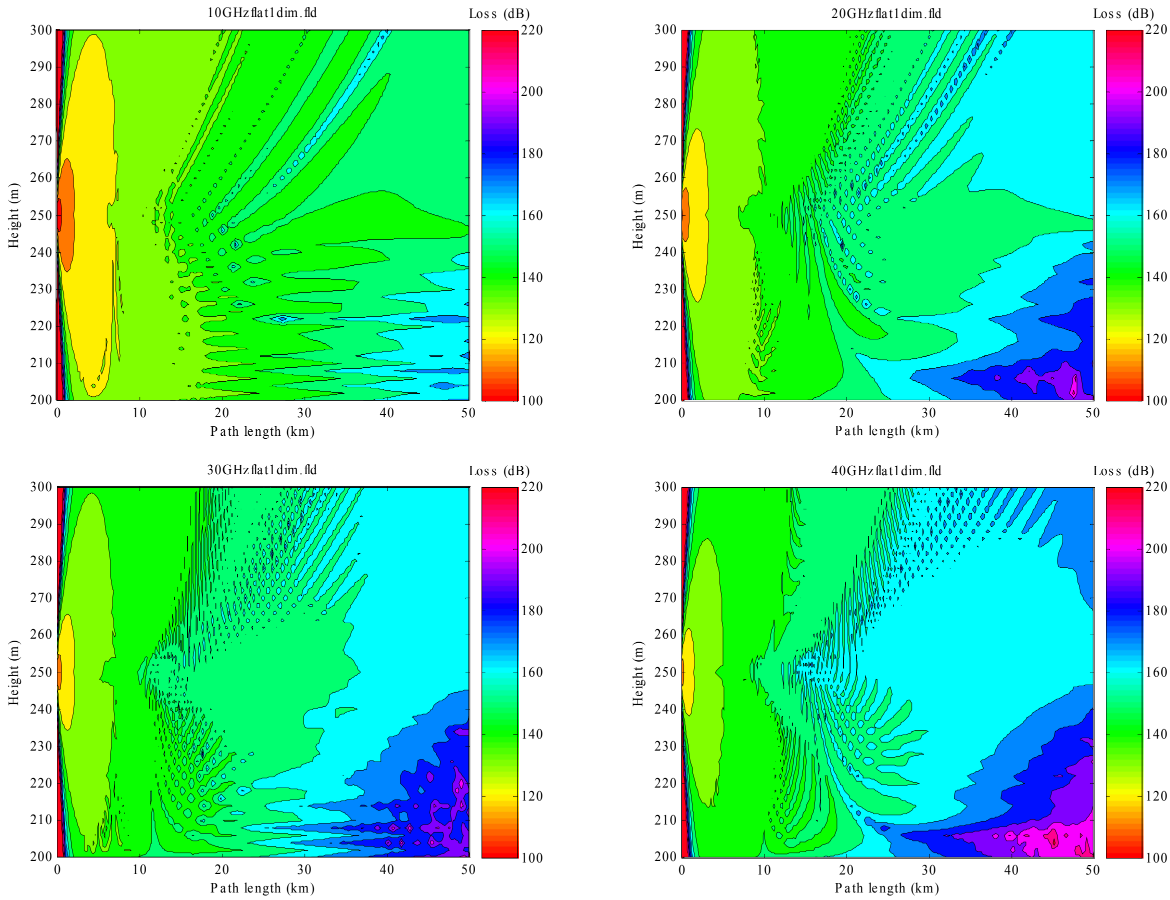


Figure 4. Calculated path loss for transmitter in the middle of a surface-elevated duct

It is observed that all loss examples vary across the vertical cut. The variability itself is of interest as the large this is the more likely it will be to observe both deep fading and enhancement. The study was performed to investigate the frequency dependency.

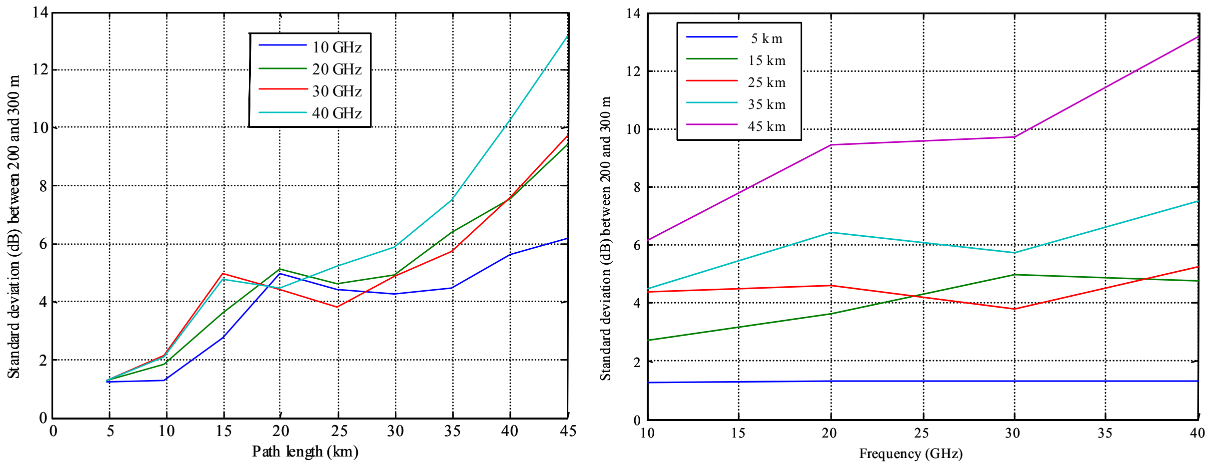


Figure 5. Variability of the vertical 100 m cuts shown in Figure 4 as a function of path length and frequency

Although it is a quick analysis, and should be done with much more examples, the results shown in Figure 5 confirm conventional knowledge with respect path length. The variability as a function of path length, increase noticeably. However, the variability as function of frequency show little or none dependency. Apparently, ducting caused fading and enhancement do not depend much on frequency. This may not be seen surprising for a stratified atmosphere.

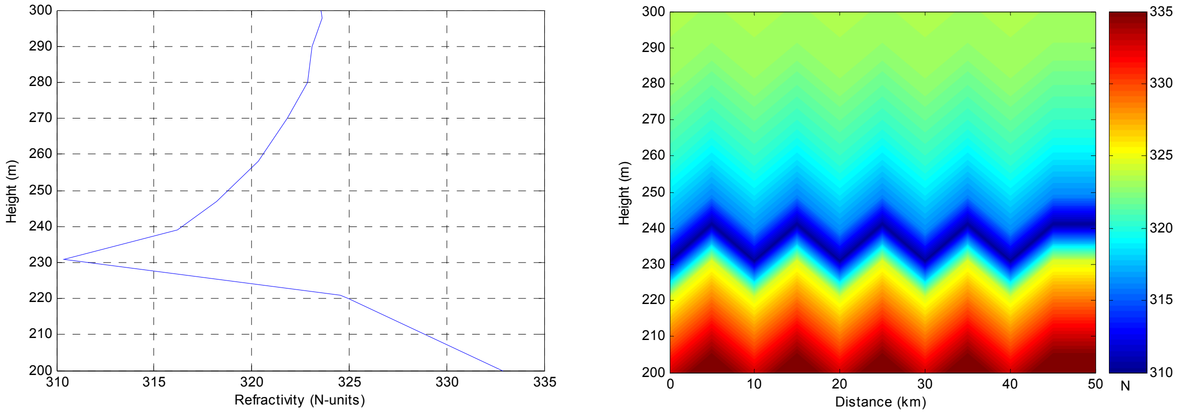


Figure 6. Observed refractivity profile over Gardermoen and simplified two-dimensional structure

Another calculation uses observed high-resolution (10 m) radiosonde data from Gardermoen shown in Figure 6, the left part. The observed data are those from 220 m and above, although the actual station height is lower the top of the duct is position at 230 m above sea. Below 220 m a fairly strong gradient of –400 N-units/km, is kept right to the actual terrain height. In the right part of Figure 6 a simplified horizontal variability is introduced along the path under consideration.

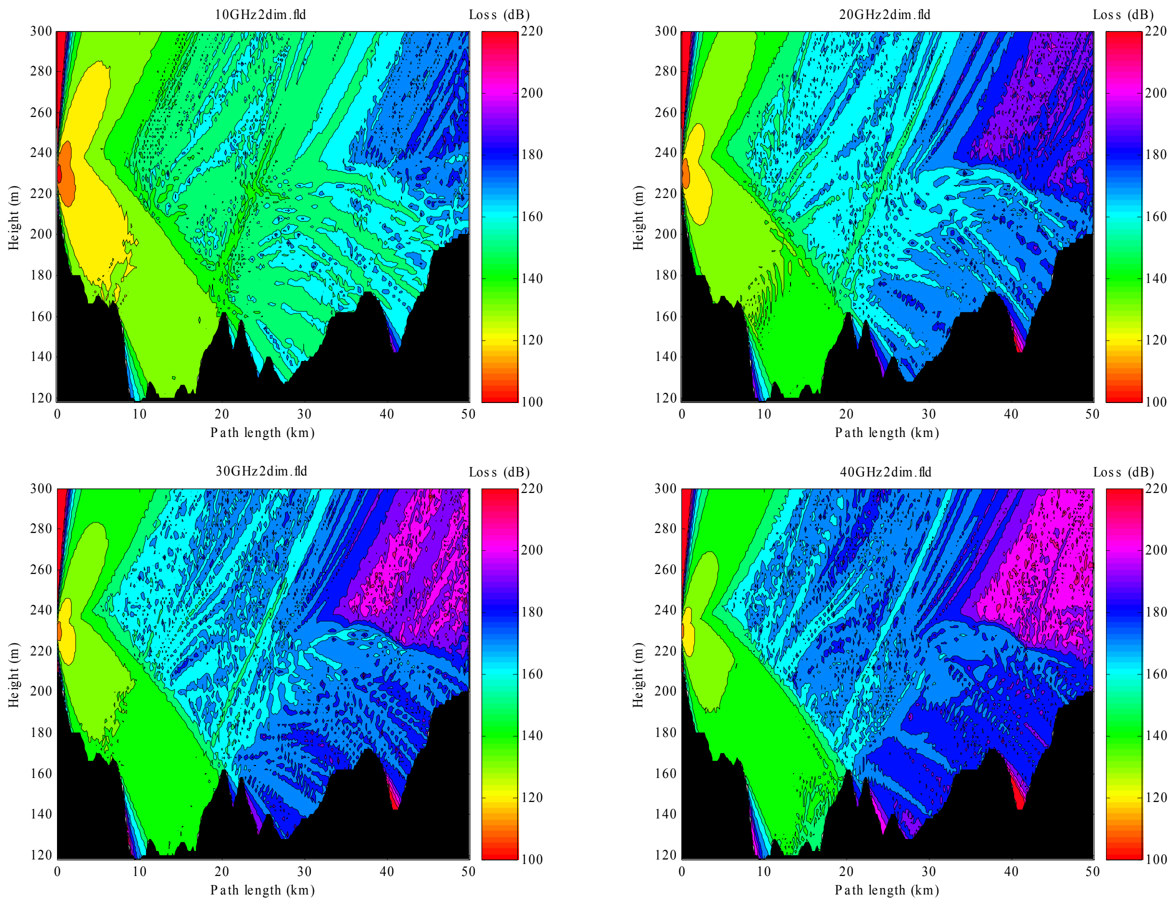


Figure 7. Path loss estimated for 10, 20, 40 and 40 GHz systems using the simplified two-dimensional refractivity structure

Taking a typical terrain from the region and a transmitter at 230 m above sea, path loss becomes as shown in Figure 7. The fields are not so smooth as in the flat terrain with a 1-dimensional layer in Figure 4. It seems that the terrain and also the very strong duct and sub-refractive layer above increase the variability. The images look similar irrespective of frequency, but loss increase loss with frequency naturally.

Again the variability along the path and for the four frequencies is given, Figure 8. It is noted an increase with path length and little variability with frequency. The local maximum at 10 km seems strange, but may have to do with the particular features of the terrain profile and the atmosphere shown. However, a weak tendency of the same was also seen in Figure 5 leading the plausible effects of interference form ground reflections giving strong variability due to phase variation between direct and reflected path as the values in the 100 m vertical area are analysed.

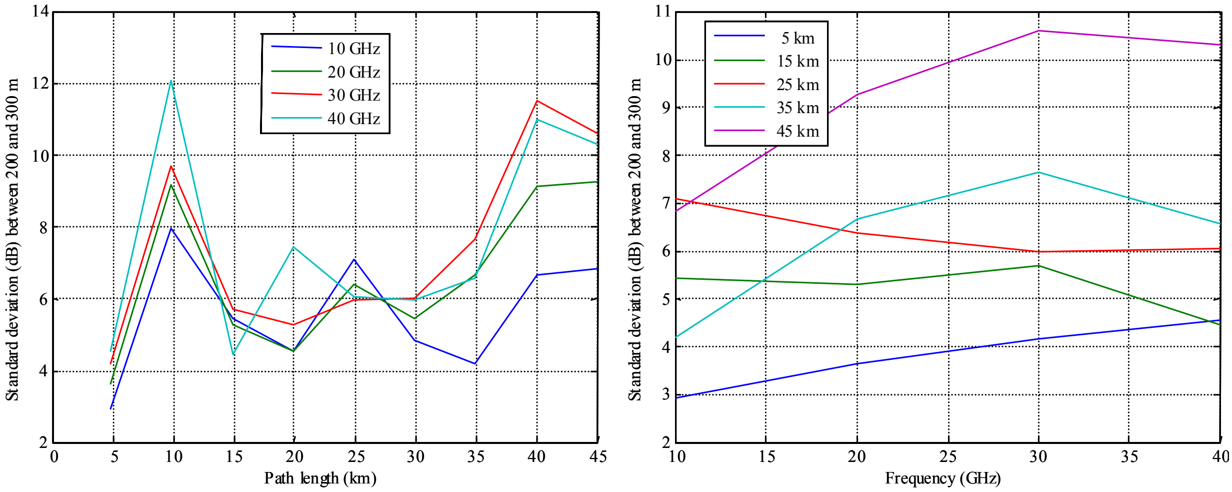


Figure 8. Vertical variability in the range from 200 to 300 m as function of path length and frequency

2.3. Frequency importance in multipath activity

However, there have been suggested several coefficients or dependencies, for the frequency part clear air fading. Several factors of the frequency dependency have been suggested, in part based on global studies or regional based prediction methods [7][8][9]. In the multivariate studies the frequency term have not generally shown up with a strong statistical significance. But it should be added due to correlation between predictors an estimated factor for one variable may be compensated by factor for another. The graphs in Figure 9 shows that the variation between the models is significant. Since the multipath fading and enhancement prediction method does not differentiate between ducting and scintillation, there are physical reasons for keeping it in. However, for the deep fading and strong enhancement regime, the frequency term should be considered removed.

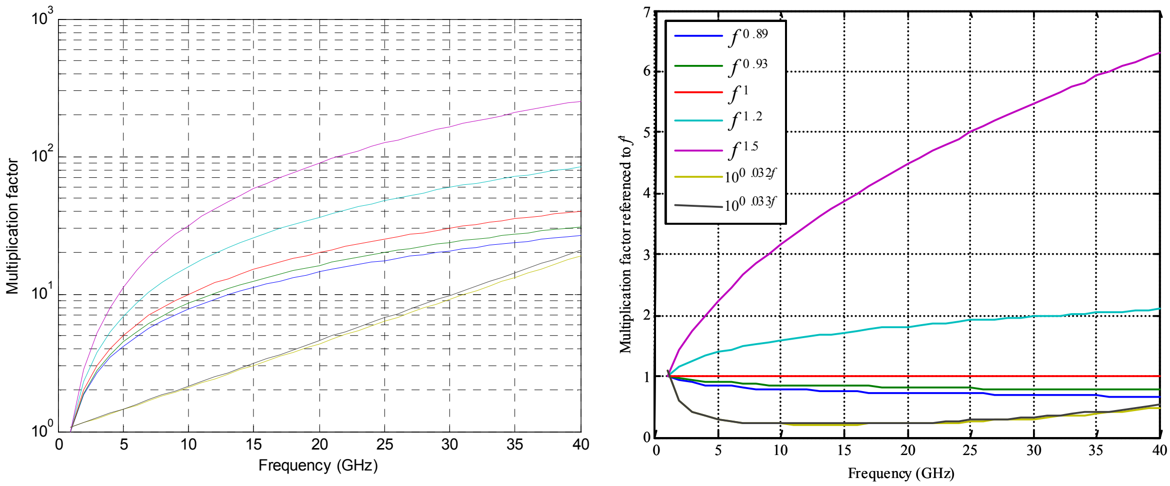


Figure 9. Relative importance of the frequency term in prediction the worst month multipath occurrence (legends apply to both figures)

Enhancement due to a layered atmosphere is a slowly varying phenomenon. If deep fading and strong enhancement vary more with frequencies below 10 GHz than found here above, a frequency dependency of power-law should be chosen with an exponent less than 1 actually smallest possible.

2.4. Scintillation

Under normal conditions due to small-scale refractive index variations, the signal fluctuates with amplitude typically within a few dBs. The condition is described statistically for a turbulent atmosphere, and under signal variation may also increase for small percentage of the time. The signal variation under turbulence increases with frequency as well as distance. If the atmosphere can be considered isotropic such that the structure function is the same independent of direction, the theoretical approach would be applicable for both terrestrial and satellite paths. However, the impact of clouds is significant and makes the two cases different.

The signal variability is described by its variance σ^2, in [dB^2], see [11] and [12]for the basic theory, and [13] for a brief summary applicable to terrestrial paths,

$$\sigma^2 = \begin{cases} 23.17 k^{7/6} C_n^2 d^{11/6} & d_0 >> \sqrt{\lambda d} \\ 29.49 k^2 C_n^2 d d_0^{5/3} & d_0 << \sqrt{\lambda d} \end{cases} \tag{2}$$

where k is the wave number (k=2π/λ), C_n^2 the atmospheric structure parameter (variability in refraction), and d the path length. The structure parameter C_n^2 will be in the range of 10^{-15} to 10^{-10} [m$^{-2/3}$] near the surface of the Earth [14], increasing with increasing turbulence. The condition here is that the size of the turbulent eddies are within outer-scale larger than $d_0=(\lambda d)^{0.5}$. For 42 GHz this factor becomes 3-12 m for path length ranging from about 1 to 25 km. This is within the scales anticipated for the atmosphere for link lengths considered, is the outer-scale suggested by [13] range from 10 to 100 m. For lower frequencies or smaller outer-scales the frequency dependency becomes f^2.

Equation 15 suggests the higher the frequency the larger the scintillation amplitudes. In [2] a fairly shallow scintillation of 1.1 dB is estimated for 0.01 % of the time, for a 42 GHz link over 5 km. However, this would be significantly larger for a 25 km link. Taking Equation (15) into and assuming that the turbulent atmosphere last for two or three times a 5 km path the value to account for would be 3 dB.

The scintillation will follow a lognormal distribution with mean attenuation equal to 0 dB and a standard deviation given by Equation 15. Boithias [14] suggests a Nakagami-Rice distribution for propagation through some turbulence, but points out it will become Gaussian for shallower amplitudes.

For satellite links a prediction method has been adopted [15] based on suggestion found in [16]. The particular method connects the standard deviation with the wet term of refractivity, N_{wet}, available from [17]. However, there is no prediction method yet available for terrestrial paths.

Following [18] Equation (3) provides an expression for the refractive structure parameter C_n^2

$$C_n^2 = \frac{D}{2.8 \cdot r^{4/3}} \tag{3}$$

where $D = \langle N_1 - N_2 \rangle^2$ is the estimate of the structure function of the medium and N_1 and N_2 is the refractivity values taken at r m distance from each other.

Taking Equation (3) and using N from Figure 6 along the horizontal path, the structure variable D becomes 152 N-units over r=5000 m giving C_n^2 around 10^{-15}. This value does not describe a very turbulent atmosphere and therefore not a significant change in frequency dependency from a 1-dimensional refractive structure where the horizontal C_n^2 is zero.

The onset of turbulence is characterized by a critical Richardson number of approximately 0.25, or in the range from 0.15 to 0.5 [12]. The Richardson number is defined as the dimensionless ratio of buoyant suppression of turbulence (by a temperature gradient) to. The atmosphere is thus a layered structure with changing stable and turbulent layers. In the turbulent layers we have scintillation whereas ducting structures may take place in the stable layers.

3. Conclusions

Judged on signal strength variability along a 100 m vertical cut full wave analyses show a weak dependency on frequency in the range 10 GHz to 40 GHz. This suggests that frequency in this range has no important role in radiowave propagation mechanisms resulting in deep fading and strong enhancement. At shallower fading and enhancement scintillation effects are present suggesting a prediction method for the full distribution dominated by scintillation and also use of frequency around 0 dB and no or weak frequency dependency for the distribution tails.

Applied to millimetre broadband radio access systems the likelihood of getting unwanted LOS signal path lengths ranging from 5-25 km is small. However, if this is the case the current prediction method indicate enhancement of 5-9 dB or 8-12 dB, depending on climate. If there is little frequency dependency the estimates of enhancement might be reduced tot the ranges 3-6 dB or 5-8 dB. The level of scintillation to take into account could within 1-3 dB for the path length in questions.

It should be noted that more has to be done in the area for predicting the signal variation due to turbulence and to estimate the amount for terrestrial paths. The figures suggested to include in interference calculation for frequency reuse in the case there is line of sight paths are to some degree guessed.

A cautious method would be to avoid base station interferers at the 1/5 path length ratio as much as possible. For paths including users the likelihood to interfere is much smaller due to the lower antenna heights above ground. If the path length ration is doubled, 1 to 10, another 6 dB is gained in signal to interference ratio.

The duct caused enhancement and scintillation do not occur at the same time. It is therefore only necessary to account for the ducts caused enhancement in order to increase path length for protection. However, to establish the total time a signal is enhanced the two percentages have to be added.

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