A COMPARISON OF PROPAGATION AT MILLIMETRIC, SUBMILLIMETRIC AND INFRARED WAVELENGTHS

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ABSTRACT

This paper reviews the propagation mechanisms which influence the reliability and availability of communications systems which are, or may be, under development for future applications. In particular, there is currently little commercial exploitation of the millimetric, submillimetric and infrared wavebands, and these offer the prospect of large amounts of spectrum, facilitating the possibility of extremely high data rates. However, various atmospheric phenomena contribute to impairments in reliability, for example, attenuation by hydrometeors and polar molecules in the atmosphere and scintillation caused by atmospheric turbulence. Comparisons are made of the effects of these phenomena in the different wavebands.

INTRODUCTION

The past decade has witnessed a prodigious growth in communications requirements associated with a variety of applications, for example transport systems, mobile telephone technology, data transfer, etc. As a direct consequence of this, communications link capacities have been, and continue to be, stretched both in terms of channel availability and bandwidth. For "hard-wired" links, increased capacity requirements have, to a large extent, been accommodated through the installation of optical fibre networks and improved data-coding techniques. With wireless links, however, the limited available spectral capacity in the conventional radio and microwave regions is rapidly becoming congested. It is thus becoming increasingly necessary to consider exploitation of much shorter wavelengths, extending into the millimetric, submillimetric and infrared regions, which have hitherto been regarded as unattractive, due either to the perceived technological difficulties or to limitations in signal propagation imposed by the Earth's atmosphere.

Methods of generating electromagnetic energy at millimetric wavelengths, and the coupling of this energy to any propagation medium, involve factors which scale with wavelength. Since the beamwidth of any antenna is related to the square wavelengths per unit area of antenna, a given antenna will confine the transmitted energy to a narrower beam as the wavelength is reduced. This implies better angular or pointing resolution, concomitant with lower overall loss of the signal along the propagation path, and favours the use of the highest possible frequencies.

However, the atmosphere imposes additional constraints on the propagation environment, and may thus set an upper practical limit to the range of frequencies which may be exploited. Atmospheric gases cause signal attenuation through molecular absorption in certain characteristic frequency bands. A very large number of gases exhibit resonant absorption features, although only a few have a major impact on signal propagation through the Earth's atmosphere in the wavelength range of interest – molecular oxygen and water vapour at millimetric and submillimetric wavelengths and additionally carbon dioxide in the infrared region. The theory of gaseous absorption is now fairly well-developed, and methods exist for the prediction of propagation conditions over a wide range of frequencies with good accuracy.

In addition to molecular absorption, scattering by particles in the atmosphere, especially condensed water-vapour particles – hydrometeors – in the form of fog, rain, snow and hail, has an important effect on signal propagation. When the radiation wavelength is much greater than the size of these precipitation particles, as in the case for conventional radio systems, the absorption cross-section is at least an order of magnitude greater than the scattering cross-section, and scattering can thus be neglected. However, this simplification is not valid in the millimetric region, since precipitation particles are comparable in size with the wavelength, nor is it valid in the infrared region where wavelengths are comparable in size with fog particles. As a result, scattering occurs, leading to attenuation of signals. Precipitation is a stochastic process, however, imposing limits to system availability and reliability, and thus its effects are generally treated on a statistical basis.

Atmospheric turbulence produces rapid variations in received signal strengths, resulting in scintillation phenomena, which can impact significantly on some communications systems, and also must be taken into account in system design.

It is relevant here to note that both molecular absorption and scattering can be advantageous in certain communications applications. For example, the transmission frequency can be selected for communications links such that the atmosphere imposes additional attenuation, thus minimizing unwanted interference from other co-frequency systems and improving the efficiency of spectrum usage.

The selection of a particular frequency band for new communications systems will therefore depend on a number of factors, including (a) the propagation environment, (b) the frequency bands available for a particular service and (c) the availability of appropriate technology.

This paper will examine the propagation conditions due to the Earth's atmosphere in the millimetric, submillimetric and infrared wavelength regions, addressing in particular the 1.6 μm band in the infrared, where much interest has recently been manifest because of existing technology.

MODELLING PROPAGATION PHENOMENA IN THE DIFFERENT WAVEBANDS

Atmospheric Gaseous Attenuation

The theoretical description of gaseous absorption is well-established and a number of models have been developed to calculate the transmission and attenuation through the Earth's atmosphere. These generally fall into two distinct categories – those which apply to the microwave and millimetre-wave regions of the electromagnetic spectrum, and which provide results with very high spectral resolution, and those which address the infrared regions, with somewhat lower spectral resolutions more appropriate to the requirements of the traditional instrumentation generally employed for telluric geophysical observations, for example. In the future, as communications applications begin to exploit these shorter wavebands, more emphasis may be placed on developing higher-resolution models.

Gaseous attenuation is thus readily assessed, relying primarily on data on temperature, pressure and humidity, all of which are widely available.

In this paper, gaseous attenuations in the different wavebands are compared using (a) the Millimetrewave Propagation Model (MPM), developed by Liebe [1,2] and adopted by the International Telecommunications Union in Recommendation ITU-R P.676 [3], for the longer wavelengths and (b) LOWTRAN 7 [4] for the infrared wavebands. Other models which may be considered include the Atmospheric propagation Model (APM) [5] and EOSAEL NMMW module [6] for the longer wavelengths and MODTRAN [7] and FASCOD2 [8] for the infrared regions.

Attenuation by Hydrometeors

Rain, clouds and fog form the most prevalent forms of hydrometeor encountered in the atmosphere, and rain, in particular, plays a dominant role in determining the availability and reliability of communications systems operating at frequencies above about 10 GHz. Rain is a stochastic process, and its effects can be predicted, in general, only on a statistical basis. Frozen precipitation, in the form of sleet, snow and hail, do not, statistically, have a significant influence on the statistics of propagation. In fact, snow, hail and ice have vanishingly small dielectric constants, and frozen hydrometeors interact with electromagnetic radiation only when melting is taking place within the particles. Modelling such phenomena, however, is not trivial, since sleet especially is a very complex mixture of ice, water and air in varying proportions, and is beyond the scope of this paper.

Assuming spherical raindrops, the attenuation by rain can be calculated using classical Mie scattering theory from a knowledge of the distribution of rain drop sizes, their terminal velocities and the complex refractive index of water. For non-spherical drops, more complex methods are available, and, because these are non-trivial, simple approximations have been developed in terms of power-law relationships between attenuation and rainfall rates, i.e. $\gamma = aR^b$ [9-11]. In developing these simpler models, particular attention has been given to the validity of the various hypotheses and to the experimental data on the microstructure of rainfall used to calculate specific attenuation and to the applicability of these calculations to real rainfall situations [12].

Such models have been found to be effective and reliable at frequencies up to about 40-50 GHz. Above this, however, the simple models begin to underestimate measured rain attenuations, and a number of reasons are currently being investigated. There is some evidence that the dropsize distribution employed in the calculation of coefficients in the power-law relationship may underestimate the number of small raindrops, while the influence of wind on the capture efficiency of raingauges is being investigated [13].

Notwithstanding this, the estimation of rainfall attenuation is greatly facilitated by the prevalence of data on rainfall rates, especially from meteorological bureaux worldwide.

At frequencies below about 1000 GHz, the size of fog and cloud particles is considerably smaller than the wavelength, and the attenuation by fog/cloud can be modelled using a simple double-Debye model for the dielectric permittivity of water [14], based on the total liquid water content. At infrared wavelengths, this is no longer true and the distribution of fog particles must be considered. Assuming modified gamma function distributions of fog particles, models such as LOWTRAN permit the calculation of attenuation by advection and radiation fogs as a function of visibility, and these are compared with fog attenuations in the millimetric regions of the spectrum.

Scintillation Effects

Naturally-occurring turbulence in the atmosphere creates small-scale inhomogeneities in refractive index which are manifest in rapid fluctuations in the amplitude, phase and angle-of-arrival of radio waves. Such fluctuations are generally called scintillations, and there are two main regions in the atmosphere in which scintillation effects are likely to be strong: (a) the lower regions of the troposphere (the surface boundary layer) where turbulent fluctuations produce mixing of air and are responsible for vertical transport processes near the Earth's surface, and (b) in clouds, where turbulence results from entrainment of air.

The problem of wave propagation through a turbulent medium has been considered extensively in the literature. First developed by Tatarskii [15] for optical propagation, the theory has been further extended to the microwave region [16,17]. The most easily measured feature of scintillation is the amplitude of fluctuations, generally characterized by the log-amplitude, χ, in dB, which is the ratio of the instantaneous amplitude of the received signal to the mean amplitude, expressed in decibels. Using these theories, the general characteristics of a stationary scintillation event, such as the scintillation variance, σ_χ^2 in dB, can be related to the structure parameter C_n^2, which is a measure of the turbulent-induced inhomogeneities in the refractive index.

However, there is currently a paucity of data on this structure parameter, and empirical models have accordingly been developed which are based generally on surface parameters such as temperature and humidity, and which can hence be applied to the design of communications systems.

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