FEDERAL COMMUNICATIONS COMMISSION

OFFICE OF ENGINEERING AND TECHNOLOGY

Bulletin Number 70

July, 1997

Millimeter Wave Propagation: Spectrum Management Implications

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ABSTRACT

The spectrum between 30 GHz and 300 GHz is referred to as the millimeter wave band because the wavelengths for these frequencies are about one to ten millimeters. Millimeter wave propagation has its own peculiarities. This paper reviews the characteristics of millimeter wave propagation, including free space propagation and the effects of various physical factors on propagation. It was created to provide an easy to understand reference explaining the characteristics of radio signal propagation at millimeter wave frequencies and their implications for spectrum management.

The information presented should be useful to frequency managers, system designers, policy makers, and users of millimeter wave communications.

Prepared by New Technology Development Division, OET

INTRODUCTION

The millimeter wave spectrum at 30-300 GHz is of increasing interest to service providers and systems designers because of the wide bandwidths available for carrying communications at this frequency range. Such wide bandwidths are valuable in supporting applications such as high speed data transmission and video distribution.

Planning for millimeter wave spectrum use must take into account the propagation characteristics of radio signals at this frequency range. While signals at lower frequency bands can propagate for many miles and penetrate more easily through buildings, millimeter wave signals can travel only a few miles or less and do not penetrate solid materials very well. However, these characteristics of millimeter wave propagation are not necessarily disadvantageous. Millimeter waves can permit more densely packed communications links, thus providing very efficient spectrum utilization, and they can increase security of communication transmissions. This paper reviews characteristics of millimeter wave propagation, including free space propagation and the effects of various physical factors on propagation.

FREE SPACE, BENIGN PROPAGATION CONDITIONS

The frequency and distance dependence of the loss between two isotropic antennas is expressed in absolute numbers by the following equation:

$$L_{FSL} = (4\pi R/\lambda)^2 \quad \text{Free Space Loss}$$

where R: distance between transmit and receive antennas; λ: operating wavelength.

After converting to units of frequency and putting in dB form, the equation becomes:

$$L_{FSL\ dB} = 92.4 + 20 \log f + 20 \log R$$

where f: frequency in GHz; R: Line-of-Sight range between antennas in km.

Figure 1 shows the Free Space Loss, or attenuation, incurred for several values of frequency. For every octave change in range, the differential attenuation changes by 6 dB. For example, in going from a 2-kilometer to a 4-kilometer range, the increase in loss is 6 dB. Note that even for short distances, the free space loss can be quite high. This suggests that for applications of millimeter wave spectrum, only short distance communications links will be supported.

MILLIMETER WAVE PROPAGATION LOSS FACTORS

In microwave systems, transmission loss is accounted for principally by the free space loss. However, in the millimeter wave bands additional loss factors come into play, such as gaseous losses and rain in the transmission medium. Factors which affect millimeter wave propagation are given in Figure 2.

Atmospheric Gaseous Losses

Transmission losses occur when millimeter waves traveling through the atmosphere are absorbed by molecules of oxygen, water vapor and other gaseous atmospheric constituents. These losses are greater at certain frequencies, coinciding with the mechanical resonant frequencies of the gas molecules. Figure 3 gives qualitative data on gaseous losses. It shows several peaks that occur due to absorption of the radio signal by water vapor (H_2O) and oxygen (O_2). At these frequencies, absorption results in high attenuation of the radio signal and, therefore, short propagation distance. For current technology the important absorption peaks occur at 24 and 60 GHz. The spectral regions between the absorption peaks provide windows where propagation can more readily occur. The transmission windows are at about 35 GHz, 94 GHz, 140 GHz and 220 GHz.

The H_2O and O_2 resonances have been studied extensively for purposes of predicting millimeter propagation characteristics. Figure 4 [3] shows an expanded plot of the atmospheric absorption versus frequency at altitudes of 4 km and sea level, for water content of 1 gm/m^3 and 7.5 gm/m^3, respectively (the former value represents relatively dry air while the latter value represents 75% humidity for a temperature of 10^{o}C).

An additional set of curves for *total* one-way attenuation through the atmosphere, including attenuation due to water vapor and oxygen, is given in Figure 5. This is shown for several angles from the vertical, or zenith. Clearly, the greater this angle Φ, the more atmosphere the signal goes through and, consequently, the more the signal is attenuated.

Figure 6 [1] shows the one-way attenuation through the atmosphere for *oxygen only*. The attenuation increases as the off-zenith angle Φ, increases, due to the longer distance atmospheric penetration. As one would expect, the loss is highest around the 60 GHz oxygen absorption peak for all elevation angles.

Figure 7 shows the gaseous attenuation for oxygen absorption and for water vapor absorption as a function of range, over and above the free-space loss given in Figure 1. The resonances for frequencies below 100 GHz occur at 24 GHz for water vapor and 60 GHz for oxygen.

Figure 8 depicts total attenuation, including free space loss and gaseous attenuation, for three typical frequencies. There is no significant increase in attenuation due to gaseous absorption above the free space loss given in Figure 1, except for the 60 GHz band. Above a distance of about 9 km, the composite loss (FSL + Absorption) increases significantly from free space loss alone.

Figure 9 indicates the frequency reuse possibilities, based on atmospheric gaseous losses, for typical digital fixed service systems operating in the vicinity of 60 GHz. Note that at the 60 GHz oxygen absorption peak, the working range for a typical fixed service communications link is very short, on the order of 2 km, and that another link could be employed on the same frequency if it were separated from the first link by about 4 km.

By contrast, at 55 GHz, the working range for a typical fixed service link is about 5 km, but a second link would have to be located about 18 km away to avoid interference. Other factors must be considered in determining actual frequency reuse such as antenna directivity and intervening obstacle path loss.

Rain Losses

Millimeter wave propagation is also affected by rain. Raindrops are roughly the same size as the radio wavelengths and therefore cause scattering of the radio signal. Figure 10 [1,2] shows the attenuation per kilometer as a function of rain rate. The rain rate in any location in the continental United

States can be determined by referring to a map of Rain Rate Climate Regions and a chart of associated rainfall statistics, which are shown in Figures 11(a) and 11(b) respectively. For example, from Figure 11(b), for 0.1% of the year (99.9% availability) the rain rate is about 14.5 mm/hour for the sub-region D_2 (Washington region) shown in Figure 11(a).

An increase in the rain factor reduces the communications signal availability. A measure of this availability and the corresponding communications outage is shown in Figure 12. For example,for an availability of 99.99%, the outage is 8.8 hours a year or 1.44 minutes on a 24 hour basis.

Foliage Losses

Foliage losses at millimeter wave frequencies are significant. In fact, the foliage loss may be a limiting propagation impairment in some cases. An empirical relationship has been developed (CCIR Rpt 236-2), which can predict the loss. For the case where the foliage depth is less than 400 meters, the loss is given by

$$L = 0.2\, f^{0.3}\, R^{0.6} \quad \text{dB}$$

where f: frequency in MHz;

R: depth of foliage transversed in meters,
and applies for R< 400 meters.

This relationship is applicable for frequencies in the range 200-95,000 MHz. For example, the foliage loss at 40 GHz for a penetration of 10 meters (which is about equivalent to a large tree or two in tandem) is about 19 dB. This is clearly not a negligible value.

Scattering/Diffraction

If there is no line-of-sight (LOS) path between the transmitter and the receiver, the signal may still reach the receiver via reflections from objects in proximity to the receiver, or via diffraction or bending. The short wavelengths of millimeter wave signals result in low diffraction. Like light waves, the signals are subject more to shadowing and reflection. (Shadowing makes it easier to shield against unwanted signals in communications systems.) Normally, for non-LOS, the greatest contribution at the receiver is reflected power.

Reflections and the associated amount of signal diffusion are strongly dependent on the reflectivity of the reflecting material. Shorter wavelengths (higher frequencies) cause the reflecting material to appear relatively "rougher," which results in greater diffusion of the signal and less specular (*i.e.*, direct) reflection. Diffusion provides less power at the receiver than specular reflected power.

SKY NOISE (BRIGHTNESS TEMPERATURE) IN MILLIMETER BANDS

Anything that absorbs electromagnetic energy is also a radiator. Constituents of the atmosphere that cause attenuation, such as water vapor, oxygen and rain, radiate signals which are noise-like. When these signals impinge on a receiver antenna, they degrade system performance.

An earth station antenna aimed at a satellite at a high elevation angle will pick up sky noise emanating from atmospheric constituents (and other sources). This is referred to as the sky noise temperature or brightness temperature. For low elevation angles, the dominant noise will be mostly from terrain and will be picked up by the antenna sidelobes.

Figures 13 and 14 [5] show the sky noise temperature as a function of frequency. The sky noise peaks at the millimeter wave gaseous molecule resonance bands; and this phenomenon also affects the suitability of millimeter wave spectrum region for communications applications.

The noise entering a receiver from the antenna is commonly referred to as the antenna noise temperature and it includes components of sky noise. The antenna noise temperature adds to the receiver noise temperature to form the system noise temperature:

$$T_s = T_{ANT} + T_{RCVR}$$

(To be strictly correct the system noise temperature stems from several sources, which are depicted in Figure 15.)

MILLIMETER WAVE APPLICATIONS

Communication systems operating at millimeter wave frequencies can take advantage of the propagation effects described in the preceding sections. For example [7]:

- Propagation ideally suits short range (<20 km) communications;
- Limited range permits a high degree of frequency reuse;
- In the absorption resonance bands, relatively secure communications can be performed.

On the other hand, propagation effects impose restrictions:

- High attenuation in a rain environment;
- Limited communications range, typically <20 km.;
- Poor foliage penetration.

System designers can take advantage of the propagation properties manifested at millimeter wave frequencies to develop radio service applications. The windows in the spectrum are particularly applicable for systems requiring all weather/night operation, such as vehicular radar systems; or for short range point-to-point systems such as local area networks. The absorption bands (*e.g.*, 60 GHz) would be applicable for high data rate systems where secure communications with low probability of intercept is desirable; for services with a potentially high density of transmitters operating in proximity; or for applications where unlicensed operations are desirable.

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FREQUENCY BAND DESIGNATIONS

Q : 33-50 GHz

U : 40-60 GHz

V : 50-75 GHz

E : 60-90 GHz

W : 75-110 GHz

F : 90-170 GHz

D : 110-170 GHz

G : 140-220 GHz

GLOSSARY OF TERMS

DIFFRACTION: Change in direction (bending) of propagating energy around an object cause by interference between the radiated energy and induced current in the object. There is no line of sight between the transmitter and receiver.

FREE SPACE LOSS: The amount of attenuation of RF energy on an unobstructed path between isotropic antennas. Basically, dilution of energy as the RF propagates away from a source.

ISOTROPIC ANTENNA: An antenna which radiates in all directions (about a point) with a gain of unity (not a realizable antenna, but a useful concept in antenna theory).

REFRACTION: Change in direction of propagating radio energy caused by a change in the refractive index, or density, of a medium.

RESONANT ENERGY: Frequencies in the band where attenuation peaks. In contrast to windows, where the attenuation bottoms out and is lower.