COMPARISON OF MICROWAVE PROPAGATION AT 13, 18, AND 28 GHZ

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ABSTRACT

Recent FCC regulatory proceedings have opened up the 18 and 28 GHz bands for certain types of multichannel television distribution. It is, therefore, of some interest to CATV operators to compare the atmospheric propagation characteristics of microwave transmissions at 18 and 28 GHz with the more familiar 13 GHz CARS band. The effects of multipath and rain attenuation at these frequencies are reviewed and the method of predicting path performance is summarized. Pertinent examples delineating performance limits of existing systems are given.

INTRODUCTION

The calculation of microwave system performance is relatively straightforward when applied to free space. Formulas are available to describe the free space attenuation and the antenna gains from which the received power is calculated when the transmit power is given. This net propagation loss can also be envisioned as a percentage of the transmitted beam energy which is intercepted by the receiving antenna. The transmit beam spreads with distance at an angle Θ. The area of the receiving antenna could then be compared to the transmit beam area for the path distance L. Further losses due to antenna inefficiencies and waveguide are then added to the net free space loss to predict the power at the input of the receiver.

The situation is somewhat more complicated when a terrestrial path is considered. Not only must one assure oneself that there is no actual blockage of the path, i.e., "line of sight" must be established, but also there must be adequate clearance so that interaction between the electromagnetic beam and an object close to the center line of the path will not lead to a significant modification of the free space propagation prediction. The required clearance to avoid diffraction effects is given by the Fresnel zone formula for $0.6F_1$, the radius of a narrow ellipsoid of revolution with the path center line as an axis. However, in the presence of large "flat" surfaces such as bodies of water or sides of buildings, one must also investigate the possibility of reflection in the area of overlap between the transmit beam and the "receive beam". Such a reflection would interfere with the direct, on-axis, propagation. For the very small angles of reflection typically encountered, the surface need not be very flat to be an efficient reflector. A common experience is the reflection of light from the asphalt as one is driving along the highway. Clearly, the surface is orders of magnitude rougher than the wavelength (1/2 micron) at optical frequencies, yet the mirage effect is very evident. Similarly, at microwave, even cultivated fields with near uniform height vegetation can act as a highly reflective surface at small angle of incidence.

Another consequence of the terrestrial environment is that the curvature of the earth's surface comes into play. If there were no atmosphere, the earth bulge would be simply accounted for just as any other potential obstructions along the path. The atmosphere, however, complicates matters further since it does not have a uniform density as a function of elevation. As a result, it acts as a lens which normally bends the electromagnetic beam slightly downward as it travels between the end points of the path. One speaks of an effective earth radius and a corresponding K-factor to describe this effect.

A more serious consequence of the atmosphere is that conditions change. The most obvious change is rain which causes a sharply increasing attenuation of the electromagnetic beam as the frequency increases. A not so obvious effect is caused by changes in the K-factor and the formation of atmospheric inversion layers which can lead to multipath propagation interference.

RAIN ATTENUATION

Attenuation due to rain is described by the equation

$$\gamma = kR^{\alpha} \qquad (1)$$

where γ is the specific attenuation expressed in dB/km, k and α are constants dependant on frequency and polarization, and R is the rain rate in mm/hr. Figure 1 shows the results at 13, 18.3, and 28 GHz for vertical polarization and also for horizontal polarization at 28 GHz.

It is clear from this result that rain attenuation is approximately twice as severe at 18 GHz as at 13 GHz and 3 to 4 times as severe at 28 GHz. Moreover, horizontal polarization results in 20 -

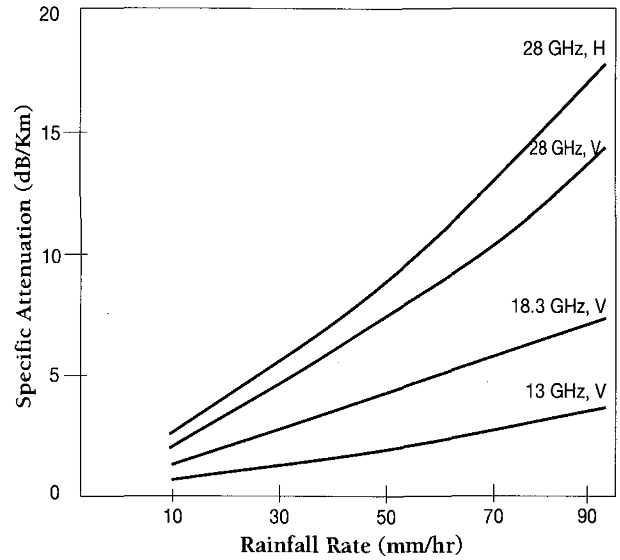

FIGURE 1
Specific Attenuation vs Rainfall

25% greater attenuation than vertical polarization. Note that these comparisons are in terms of dB/km, i.e., "twice the attenuation" is not just a factor of 3 dB, but a much larger number dependant on the total path attenuation. The constants used in plotting Figure 1 are derived from the rain model given by the International Radio Consultative Committee (CCIR)[1].

The path attenuation is obtained by multiplying the specific attenuation, equation (1), by an "effective" path length. This length differs from the actual path length because in actuality, the rain rate varies along the path. In particular, for very high rain rates, the storm diameter is usually less than the path length. In the CCIR model[2], the path length reduction factor is given by

$$r = L_{eff}/L = 1/(1 + L/L_o) \qquad (2)$$

where L_o is a parameter that depends only on $R_{0.01}$. Figure 2 shows the path length reduction plotted as a function of path length for three different rain rates.

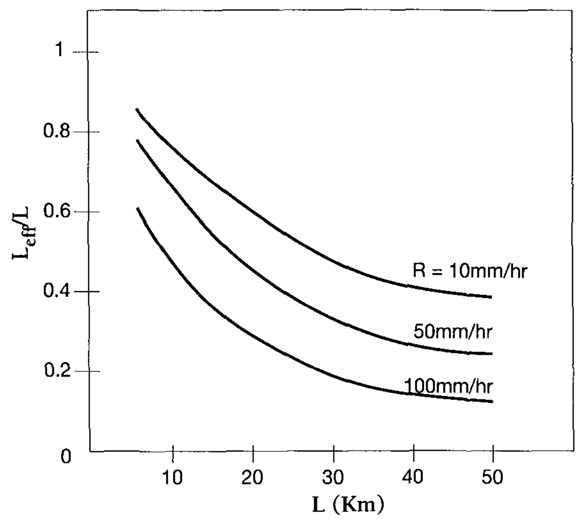

FIGURE 2

Path Length Reduction Factor vs Path Length

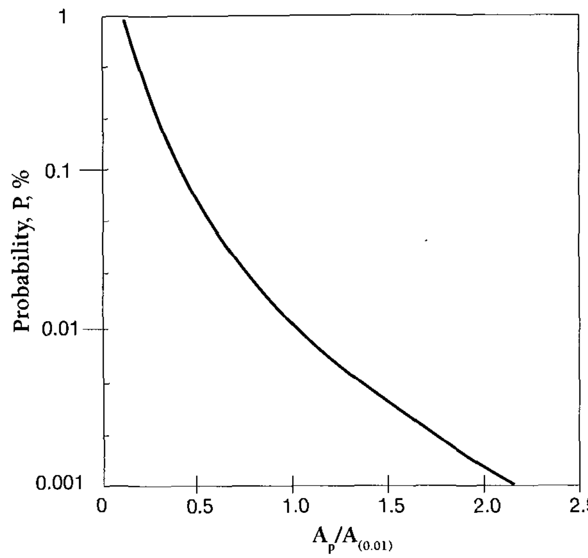

FIGURE 3

Fade Probability vs Normalized Rain Fade

The total path attenuation exceeded for 0.01% of the time is obtained by multiplying the specific attenuation in Figure 1 by the path length and the path length reduction factor from Figure 2. In general, the attenuation thus calculated is not equal to the available fade margin. To obtain the probability for a rain fade equal to or greater than the available fade margin, the equation

$$A_p/A_{0.01} = 0.12\ P^{(0.546 + 0.043 \log P)} \quad (3)$$

is utilized. Figure 3 shows the relationship in graphical form. For instance, if the available fade margin, $A_p = 0.6\ A_{0.01}$ then the probability for such a fade is 0.04%. Note the steepness of the curve, i.e., a 10% change in attenuation in dB results in roughly 40% change in probability of occurrence. Equations (1), (2), and (3) constitute the present CCIR rain attenuation prediction method.

The notation $R_{0.01}$ denotes a rain rate which is equalled or exceeded 0.01% of the time during an average year. Since the attenuation is tied directly to the rain rate, it is important to distinguish between the total amount of rain which falls in an hour at a particular point, and the "instantaneous" rain rate expressed in mm/hr. For practical purposes, a 1 minute measurement interval is close enough to instantaneous to adequately describe the actual fluctuations of the path attenuation with time. Unfortunately, there are very few locations in the United States where 1 minute rain rate measurements have been made. In the absence of such long term statistical information, the CCIR offers either rain climate zones which are associated with a tabulated rain rate for various probabilities of exceedance, or 0.01% rain rate contour maps[3]. Figure 4 shows the CCIR contour map portion for the United States.

The above CCIR path attenuation calculation, into which the value of $R_{0.01}$ is entered, is considerably simpler than another model[4] which was cited in earlier CCIR reports and which was utilized until recently for predicting path attenuations. On a world-wide basis, the latest CCIR model appears to be most accurate[5]. However, comparison of the CCIR path attenuation prediction to measured path attenuation values is most accurate when the actual rain rates are used. Year to year rain rate variability as well as place to place variability within a relatively small local area can be expected to result in rms deviations of the probability in excess of a factor of 2. For this reason some caution is recommended in applying these formula. One way to build in conservatism into the calculation is to assume horizontal polarization even when the actual implementation will be with vertically polarized antennas.

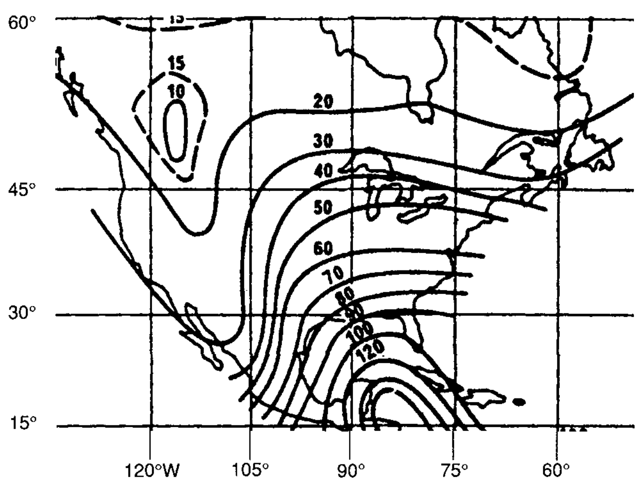

FIGURE 4
CCIR .01% Rainfall rate, mm/hr

MULTIPATH ATTENUATION

The general CCIR equation for the probability of multipath attenuation in the worst month is given by[2]

$$P = K_m Q f^B L^C 10^{-A/10} \qquad (4)$$

where A is the multipath attenuation in dB corresponding to the % probability, P, at which A will be equalled or exceeded. With B=1 and C=3, equation (4) takes on the form of the Barnett equation[6] which has been used heretofore for path reliability predictions. In equation (4), f is the frequency in GHz and L is the path length in kilometers. The CCIR suggests a form of the equation [2] which is

$$P = K_m L^{3.6} f^{0.89} (1 + \varepsilon)^{-1.4}\, 10^{-A/10} \qquad (5)$$

where ε is the absolute value of the inclination angle between transmit and receive antennas in milliradians. The value of K_m for overland paths in non-mountainous terrain is

$$K_m = 10^{-6.5}\, P_L^{1.5} \qquad (6)$$

where P_L is the percentage of time that the average refractivity gradient in the lowest 100m of the atmosphere is less than -100N units/km. Maps of P_L for four different months are given in Reference (3). For the USA, worst month values of P_L range from about 8 to 30% depending on location. To convert from worst month to yearly probability, one still has to multiply equation (5) by a climate and terrain related factor b which ranges from 1/2 to 1/8.

Aside from the variability of the parameters, the most striking attributes of equation (5) are the steep dependence on path length and the fact that a 10 dB change in fade depth corresponds to a factor of 10 change in probability (a 3 dB change in A would result in a factor of 2 change in P). True atmospheric multipath is therefore a concern only on relatively long paths. Equation (5) is valid only for fades in excess of 15 dB. The deeper the fade, the more frequency dependant it typically becomes. This can be understood by multi-ray models in which the rays interfere with each other through phase cancellation. Since even small atmospheric changes would affect the relative phase shifts, one can expect that deep fades will vary rapidly with both time and frequency.

By contrast, defocussing or beam bending phenomena can result in shallow fades which are relatively slowly varying and independent of frequency. These take place at the same time as the true multipath. The direct beam energy is thereby reduced and makes the signal more susceptible to phase cancellation by reflected beams either from atmospheric inversion layers or the ground.

When the reflected beam comes from the ground, K_m in equation (6), increases. A minimum factor of 3 increase is suggested. The same holds true for over-water paths. On the other hand, in mountainous terrain, a factor of 4 decrease applies to equation (6).

For broadband signals typical in multichannel AML applications, the best way to overcome multipath type phenomena is through careful path engineering which avoids ground reflections even under unusual K-factor conditions. Another technique, which has been proved useful in the past when fading was in fact encountered, is to tilt the antennas slightly upward. This sacrifices a few dB of fade margin, but matches better the propagation conditions during fade-prone atmospheric conditions. As a result, the path availability was greatly improved. In general, however, AML applications have encountered multipath in only a very small percentage of cases and the path predictions have been too conservative. It is expected that the use of equation (5) will more accurately incorporate local factors and thereby avoid costly over design.

REPRESENTATIVE SYSTEM EXAMPLES

Figure 5 is a schematic representation of a CATV system utilization of AML. In this simple example, there are 4 paths, each 30 km (18.6 miles) long. The single rack AML-SIBT-121 transmitter[7], the highest power broadband unit available, has been used in a number of CATV system upgrade applications of a similar nature. Generally, the paths are of unequal lengths and the splitting network associated with the broadband transmitter is optimized to take this factor into account, thereby providing additional power to the longest path. Thus, the example given in Figure 5 is in one sense a worst case 30 km application.

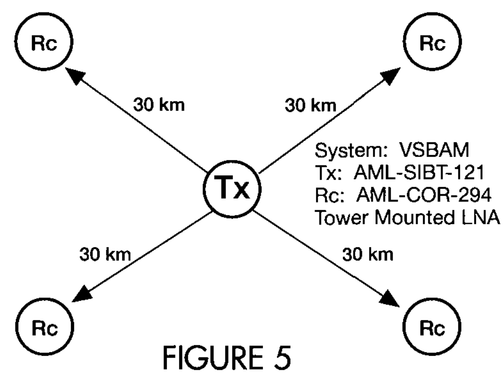

FIGURE 5

Typical 13 GHz CATV Application

It is assumed that the application involves carriage of 49 channels even though the same AML system could, of course, accommodate up to 79 6-MHz-wide channels as well as the FM broadcast band within the 12.7 - 13.2 GHz band. The assumed channel loading is selected to match that of the assumed LMDS 28 GHz system so that a more valid comparison can be made. In actuality, SIBT's are presently utilized to carry up to 77 channels in systems previously serviced by a lesser channel count AML-STX-141 high power array.

The 13 GHz application, as well as the 18 and 28 GHz applications, assume that the propagation factors are average, i.e. $R_{0.01}$ = 50 mm, P_L = 19%, ε = 2 mr, and b = 1/4 are the parameter values inserted in the rain and multipath attenuation equations.

Figure 6 shows the result of the calculation. The fade margin to 35 dB C/N is 22.5 dB when a 65 dB C/CTB requirement is imposed on the overall microwave system. As seen, multipath and rain probabilities are nearly equal at 0.016% each. At larger path attenuation, rain dominates. The two probabilities are additive since multipath type phenomena are precluded during rainfall when the atmosphere is well mixed.

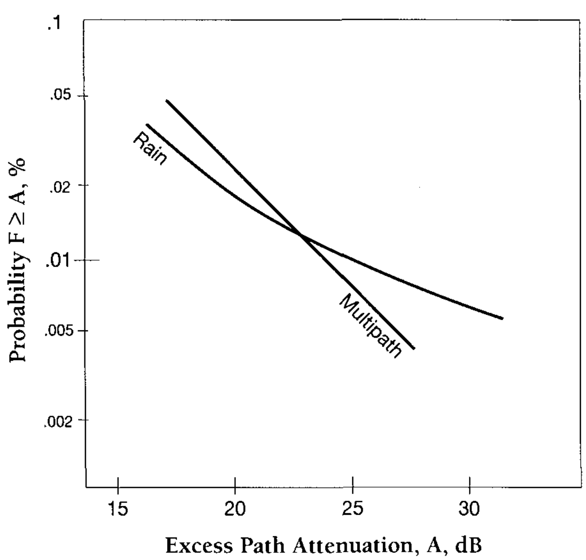

FIGURE 6

Average Rain and Multipath on 30 km path at 13 GHz

Figure 7 illustrates a typical SMATV application. A cluster of nearby sites is serviced directly by the high power outdoor transmitter. One path, however, is 10 km long, and a repeater is used to feed the signals to a second cluster of receive sites. This is the performance limiting path. The regulatory limitation sets the number of available 6 MHz-wide channels to 72, but 49 channel loading is again assumed to match the LMDS system. The SMATV system need not drive a large cable plant. As a result, the specification for the microwave system is relaxed and a 58 dB C/CTB is acceptable. The clear weather C/N, fade margin to 35 dB C/N, and path availability are also less than for the previous CATV application. Because the path is much shorter, multipath plays a near negligible role but the probability of rain fade is significantly higher.

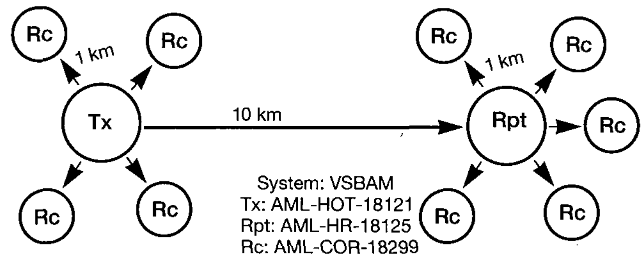

FIGURE 7

Typical 18 GHz SMATV Application

Figure 8 shows the 28 GHz LMDS application. In this case, the transmit antenna broadcasts the signal in all azimuth directions and only the receiver utilizes a directional antenna. Table I summarizes the antenna and microwave path parameters for the three systems. Note that the antenna beamwidth angle at 28 GHz is significantly larger (37 mr vs 8 mr) than for the 13 and 18 GHz point to point links. This makes the receiver more vulnerable to interference from nearby transmitters utilizing the same frequency band. Of course, the fact that the system is FM helps ameliorate the potential interference problem.

In all three cases, the possibility of ground and nearby building reflections must be taken into account as indicated by the beam diameter for the path length L. Actually, for the 13 GHz and 18 GHz point-to-point links the largest diameter of interest is at distance L/2 since the receive beam and transmit beams must overlap, but the diameters, although then somewhat smaller than the 28 GHz case, would still dictate care in path design.

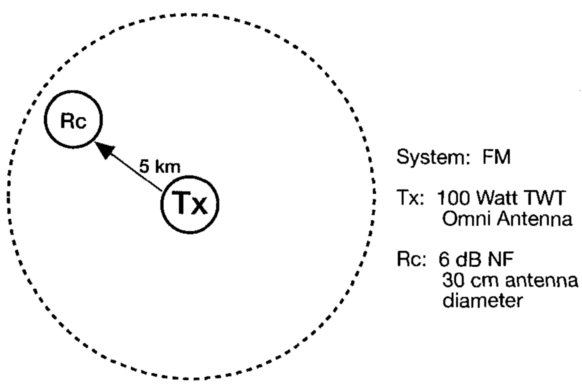

FIGURE 8
Typical 28 GHz LMDS Application

The comparison of far field distances shows that with only 30 cm aperture at 28 GHz, the distance at which the beam begins to spread with angle $\Theta = \lambda/D$ is quite small. As a consequence, any passive reflectors utilized to establish line of sight between the transmit antenna and the receive antenna must be significantly larger to avoid further propagation loss. At the same time, a small passive reflector beam width in the near field is normally too small to service more than a single receiver.

The Fresnel zone clearance criteria are not particularly onerous in any of the three examples.

TABLE I
Antenna/Path Characteristics

Frequency (GHz)	13	18.3	28
Wavelength, λ(cm)	2.3	1.6	1.1
Ant. Diameter, D(m)	3	1.8	0.3*
Path Length, L(km)	30	10	5
Beam Width, $\Theta=\lambda/D$(mr)	7.6	8.9	37
Beam Diameter, ΘL(m)	228	89	185*
Far Field, D^2/λ(m)	391	202	8.2*
$0.6F_1$, at midpoint (m)	7.9	3.9	2.2

*Receiver only

Table II summarizes the system performance for the three cases under consideration. Obviously, the CATV application has much greater range, but it also results in a higher quality signal and better system availability. The quality comparison is made in terms of baseband S/N to be able to compare to the 28 GHz FM system performance and includes all sources of noise including intermodulation noise (CTB) and phase noise. As previously indicated, atmospheric multipath plays a significant role only for the 30 km CATV example. At 18 GHz, and especially at 28 GHz, it is entirely insignificant. Rain, however, is a serious problem at the highest frequency. Note also that the availability limit for FM represents loss of signal, while for the VSBAM 13 and 18 GHz systems, the pictures are noisy, but still watchable even below 35 dB C/N.

TABLE II
System Parameters

Frequency (GHz)	13	18.3	28
Range (km)	30	10	5
C/CTB	65	58	56(1)
S/N	55	51	51(2)
Fade Margin (dB)(3)	22.5	14.5	17.5
Availability, %(3)	99.97	99.91	99.92

(1) Equivalent value with FM improvement
(2) Limited by CTB
(3) To 35 dB CN for VSBAM. To FM threshold for 28 GHz system.

SUMMARY

All three multichannel microwave video distribution systems can deliver good quality pictures, but the best path reliability and signal quality are possible with the 13 GHz system despite its use at greater distance. This result not only reflects the availability at this frequency of high power solid state broadband transmitters utilizing advanced dual feed forward linearization technology, but also illustrates the serious increase in rain attenuation, particularly at 28 GHz. Multipath plays a role only for longer path distances, but uncontrolled reflections from the ground or nearby buildings can cause interference in any of the systems. This, and the question of near-by frequency reuse in broadcast systems, needs further assessment for 28 GHz systems. Small size passive repeater utilization is only possible at very short distances and must then be limited to single receivers unless additional propagation loss can be accommodated.

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