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Radio Propagation Considerations for Local Multipoint Distribution Systems

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A local multipoint distribution system will essentially broadcast television signals (and perhaps more) to subscribers in small cells. It has been proposed to put such systems in the frequency band from 27.5 to 29.5 GHz where the wave length is only about 1 cm, and where equipment is not well established and propagation effects are not entirely known. In this report we discuss what is known about the expected behavior of the radio waves and we suggest areas that need more study.

Key words: atmospheric absorption; LMDS; millimeter waves; power budgets; rain attenuation; television

1. INTRODUCTION

It has been suggested that the band from 27.5-29.5 GHz be used for a local multipoint distribution system (LMDS). The notion is that one can essentially broadcast television signals into small cells and that the wide bandwidths available will compensate for the hazards that arise because of the high frequencies. Other services could also be accomodated and it has even been suggested that a type of two-way communication service could be established.

Since such a system would be competing with standard broadcast stations, with cable installations, and perhaps also with direct broadcast satellites, its signal must be reliable and of high quality. An important consideration is therefore whether this is technically feasible. One very suspect part of this question is the over-the-air transmission channel itself, and it is this part that is reviewed in this report.

In what is probably the most important scenario, the 2-GHz band would be divided into two sub-bands each 1 GHz wide. These in turn would be divided into 50 video channels each 20 MHz wide. These latter channels would carry the separate television signals. Using the present technology, a standard NTSC signal at baseband would be "FM'ed" into the proper subchannel. Assuming the video signal has frequencies up to 4 MHz, this would allow a modulation index β of less than 1.5.

In this same scenario, the service area of a single transmitter would be a small cell, perhaps 6 km in radius. If a larger area is involved, it would be divided into these smaller cells

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which are served by an alternation of the two different sub-bands and the two orthogonal (horizontal and vertical) polarizations. Highly directive antennas at the receivers would play an important role.

2. RADIO PROPAGATION

The commercial use of these proposed frequencies for over-the-air transmission would be something new, and whether the goals of the present proposal are technically achievable is not certain. The wave length is approximately 1 cm so that high gain antennas may be built that have small dimensions. But also such small wavelengths imply that almost any object in the radio path will have a strong effect on the transmission. In free space, the *basic transmission loss* (the loss in power between antenna terminals, assuming no-gain, isotropic, antennas) is

$$L_{bf} = 92.45 + 20 \log F_{GHz} \; D_{km} \quad dB$$

where F_{GHz} is the frequency in gigahertz and D_{km} the distance in kilometers. At 28 GHz and 6 km this becomes 137.0 dB. This (plus the other effects we discuss below) is the loss that must be countered by transmitter power, antenna gains, and modulation gains.

2.1 Clear Air Absorption

At frequencies above 10 GHz, radio waves propagating through the atmosphere are subject to molecular absorption. Although frequencies near 28 GHz are in a "window"—comfortably between the water vapor absorption line at 22 GHz and the band of oxygen lines near 60 GHz—there will nevertheless be some residual effects from the tails of these and other lines. Such effects can be evaluated using the Millimeterwave Propagation Model of Liebe [1, 2]; in Table 1 we have displayed the resulting specific attenuation as a function of temperature and humidity. Note that on a hot, muggy day, a 6-km path could suffer perhaps 5 dB additional attenuation.

Table 1. Clear Air Absorption at 28 GHz

	Relative Humidity			
Temp (C)	0%	50%	100%	
0°	0.02	0.05	0.08	(dB/km)
10°	.02	.08	.14	
20°	.02	.12	.25	
30°	.02	.20	.44	
40°	.01	.33	.79	

2.2 Effects of Rain

Absorption and scattering of radiowave energy, due to the presence of raindrops, can severely degrade the reliability and performance of communication links. Attenuation resulting from propagation through rain drops is often the most significant threat to EHF telecommunication availability. For many paths, predictions based on rain attenuation alone would be sufficient, with the error due to exclusion of the other propagation effects being much less than the normal year-to-year variation in rain attenuation. Note, however, dispersion (frequency selectivity) because of rain is not considered significant for bandwidths of less than 1 GHz [3].

Rain attenuation is a function of drop shape, drop sizes, rain rate, and attenuation cross section. Classical rain attenuation models assume that the wave decays exponentially as it propagates through the volume of rain, the drops are spherical, and the contributions of each drop are additive and independent of the other drops. Typically, the specific attenuation through rain is approximated by

$$\alpha = aR^b \quad \text{dB/km}$$

where the rain rate R is measured in mm/hr and the parameters a and b depend on the distribution of drop sizes and on the radio wave frequency. Tables of these parameters for several raindrop size distributions have been computed by Olsen *et al.* [4]. This approximation has been shown to be in excellent agreement with Mie scattering calculations for spherical drops over a wide range of frequencies (up to 200 GHz at 0°C for the Law and Parsons distribution).

Several investigators have studied the distribution of rain drop sizes as a function of rain rate and type of storm activity. The most commonly used distributions are those of Law and Parsons (L-P), Marshall and Palmer (M-P), and Joss and Waldvogel (J-W). Law and Parsons, indeed, propose two distributions, the L-PL distribution for widespread rain (with rates less than 25 mm/hr), and the L-PH distribution for convective rain with higher rates. In general the L-P distributions seem to be favored for design purposes because they have been widely tested and compared to measurements (see, *e.g.,* [5]). The L-PL distribution gives approximately the same specific attenuation as the J- W thunderstorm distribution and the specific attenuation of the M-P and L-PH are approximately the same.

Allen [6] points out that at EHF there is a range of more than a factor of 2 in specific attenuation for different drop size distributions used by Olsen *et al.* and a range of a factor of 4 for the different climate regions used by Dutton *et al.* [7]. The resulting uncertainty is the most critical limitation to reliable prediction of EHF system availability. This would indicate that drop-size distributions dependent upon climate or type of rain will need to be developed to improve predictions of the cumulative distributions of EHF attenuation. For the geographical regions under consideration in this report (San Francisco and Los Angeles, California) the low rain rate distributions are applicable. In some sense, the L-PL distribution provides an upper bound on attenuation based on commonly used drop-size distributions for low rain rates (< 25 mm/hr) and was used for the link budget calculations provided in this report.

System availability (cumulative distribution of attenuation) is typically determined by using the Rice-Holmberg point rain rate distribution [8] and the point to path algorithm provided by Crane [9]. The Rice-Holmberg model gives the rain rate distribution in terms of commonly recorded climatological parameters (total precipitation and the fraction of rainfall from convective storms). The Crane model is widely used and has been shown by Dutton [10] to be one of the better models.

Data recorded at meteorological stations in Los Angeles and San Francisco were used to calculate the rain rate distribution and attenuation shown in Table 2 and in Figures 1 and 2. The attenuation is plotted as a function of path length for rain rates exceeded less than 0.1% of a year. Assuming a 6-km path in the San Francisco area, the results of this analysis indicate that a margin of approximately 15 dB is required to achieve an annual availability of 99.9% (13 dB for Los Angeles).

Table 2. Cumulative Distribution of Point Rain Rates
Based on the Rice-Holmberg Model

Percent	*Rain Rates* (mm/hr)	
of year	San Francisco	Los Angeles
0.001	27.6	26.2
0.01	18.6	17.3
0.1	9.7	8.4
0.2	7.0	5.7
0.5	3.5	2.4

The parameters a and b for specific attenuation provided by Olsen *et al.* [4] apply to spherical drops for which attenuation is independent of wave polarization. Coefficients for oblate spheroidal drops are given by CCIR [11]. At 30 GHz the horizontal and vertical polarization coefficients are:

$$a_h = 0.187, \quad a_v = 0.167, \quad b_h = 1.021, \quad b_v = 1.0.$$

Assuming a rain rate of 10 mm/hr, the specific attenuation for horizontally polarized waves is 0.3 dB/km more than that for vertically polarized waves.

Rain induced depolarization is produced from a differential attenuation and phase shift caused by nonspherical raindrops. The classical model for a falling raindrop is an oblate spheroid with its major axis canted to the horizontal and with major and minor axes related to the radius of a sphere of equal volume. For practical applications a semi-empirical relationship between rain attenuation and depolarization is provided by CCIR [12]:

$$\begin{aligned} XPD &= 20 \log E_{\|}/E_{\perp} \\ &= 30 \log F_{GHz} - 10 \log (0.516 - 0.484 \cos 4\tau) - 40 \log (\cos \theta) - 23 \log A \end{aligned}$$

where XPD is the "cross-polarization discrimination" showing the relation between the copolarized received field $E_{\|}$ and the cross-polarized field $E_{\perp}$, and where τ is the tilt angle

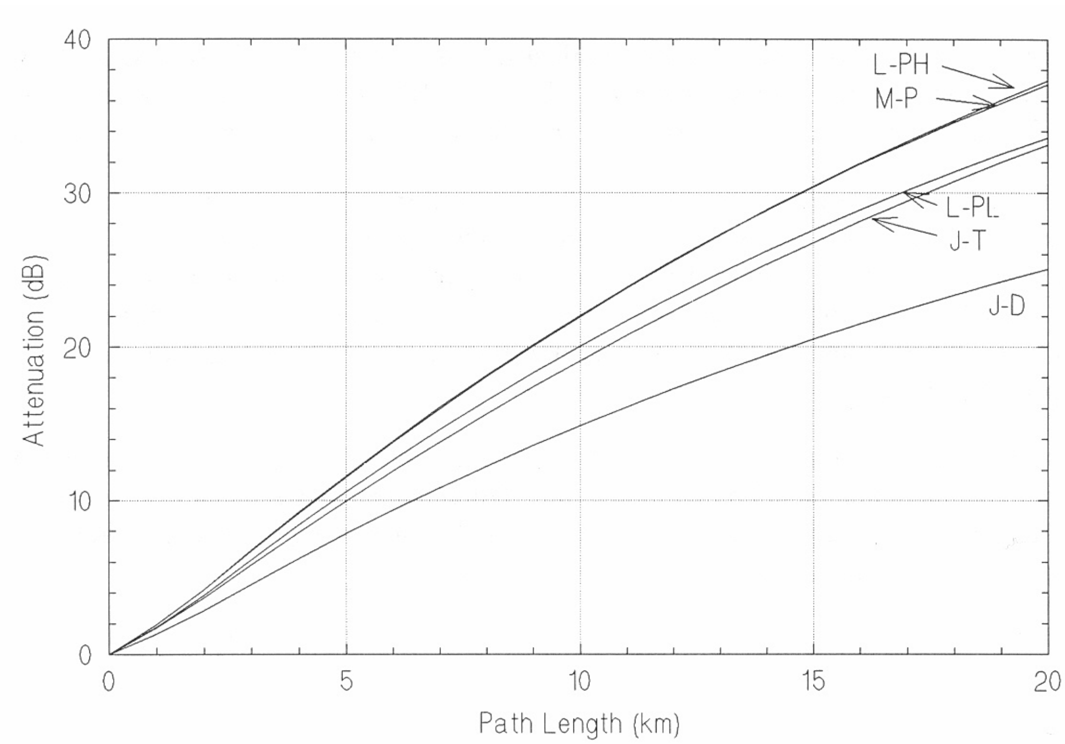

Figure 1. Rain attenuation *vs.* path length for 99.9% availability in San Francisco. Curves represent Law and Parsons (L-PL and L-PH), Marshall and Palmer (M-P), Joss Thunderstorm (J-T), and Joss Drizzle (J-D).

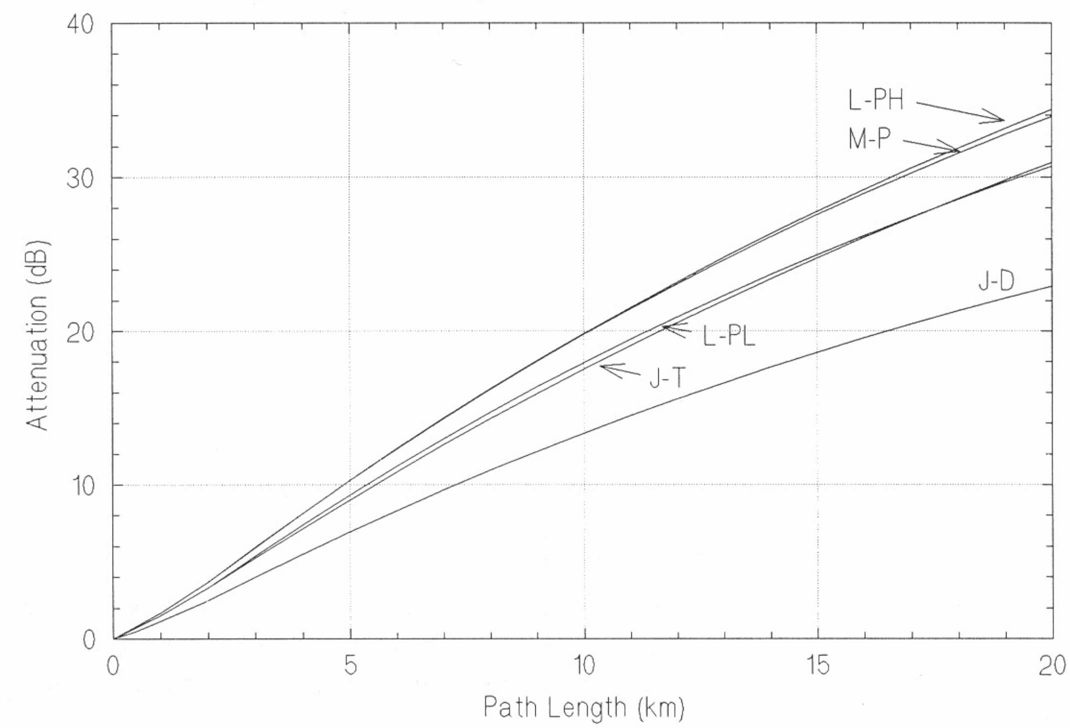

Figure 2. Rain attenuation *vs.* path length for 99.9% availability in Los Angeles. Curves represent Law and Parsons (L-PL and L-PH), Marshall and Palmer (M-P), Joss Thunderstorm (J-T), and Joss Drizzle (J-D).

of the polarization with respect to horizontal, θ is the elevation angle of the path, and A is the rain attenuation in decibels. Figure 3 shows XPD as a function of attenuation for $\theta = 0$ and for either horizontal polarization ($\tau = 0$) or vertical polarization ($\tau = \pi/2$).

Fog results from the condensation of atmospheric water vapor into water droplets that remain suspended in air. There are two main types of fog. Advection fog is coastal fog that forms when warm, moist air moves over colder water. Liquid water content of advection fog does not normally exceed 0.4 g/m^3. Radiation fog forms inland at night, usually in valleys and low marshes, and along rivers. Radiation fog can have a liquid content up to 1 g/m^3.

Specific attenuation for fog was calculated using a model developed at the Institute for Telecommunication Sciences (ITS) by Liebe [2]. Worst case calculations assuming 1 g/m^3 water result in a specific attenuation of 0.5 dB/km. For a homogeneous fog path of 6 km, the resulting attenuation is 3 dB.

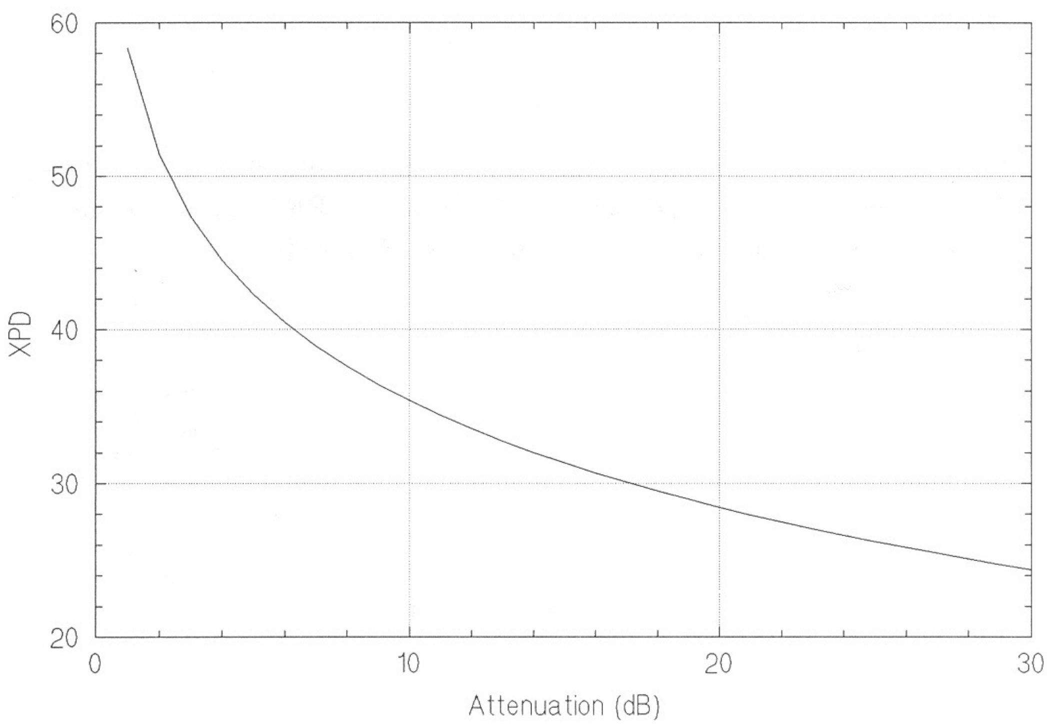

Figure 3. Rain depolarization at 28 GHz *vs.* attenuation.

2.3. Diffraction

Service at EHF frequencies will be almost entirely a line-of-sight service. Any large object that obstructs the path—even the house across the street—will introduce further large losses. Diffraction around such objects is nearly nonexistent, since the higher the frequency, the sharper the shadow.

To make an actual analysis, the standard approach is to suppose that the *diffracting edge* can be represented as a perfect "knife edge." Then there exist good approximations to the theoretical solutions, and these have been validated experimentally many times. For example, consider a scenario in which a wave is transmitted for some distance and would reach a particular receiving antenna, except that it is interupted by the rooftop of a nearby building. Knowing the radio frequency, the horizontal distance from the diffracting edge to the receiving antenna, and the vertical depth below the grazing ray, it is possible to derive the consequent additional attenuation that the wave will suffer. In Figure 4 we have plotted such attenuations for a variety of plausible configurations. As shown, attenuations of 20-30 dB are obtained with depths of only a meter or two.

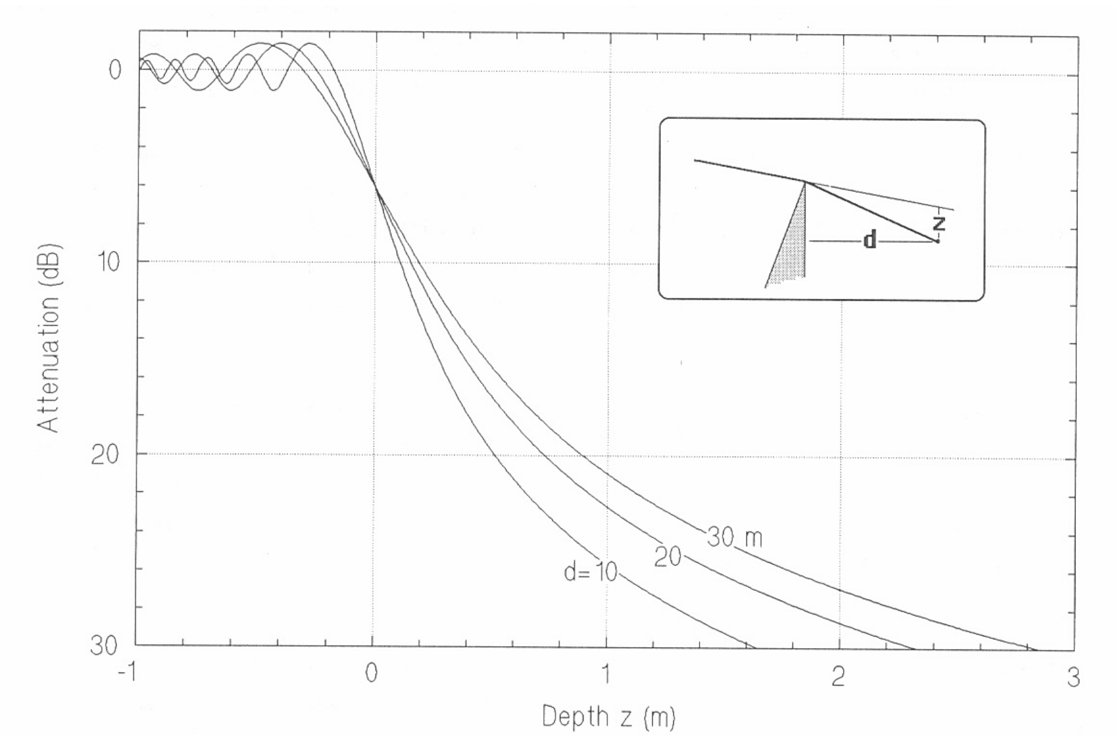

Figure 4. Diffraction attenuation at 28 GHz as a function of the depth of a receiver below the grazing ray. As in the inset, *d* is the distance behind the diffracting edge and *z* is the depth.

2.4. Effects of Vegetation

A millimeter-wave link near ground level may run through vegetation over part of its path. Woods and forests are structurally very complex with constituents, such as leaves and pine needles, that are often much larger than a wavelength. In addition, the type and density of vegetation is likely to vary significantly over the transmission path. As a consequence it is expected that propagation through vegetation will cause attenuation, depolarization, and beam broadening.

For several years, ITS has conducted a variety of experiments in an effort to characterize the propagation of millimeter-wave signals through vegetation. These experiments include the measurement of received strength of narrowband signals propagated through both coniferous [13] and deciduous vegetation [14] at 28.8 GHz. In support of this work, Schwering *et al.* [15] presented a theory of millimeter-wave propagation in woods and forests. More recent work includes wideband propagation measurements at 30.3 GHz through a pecan orchard in Texas [16].

The experiments cited above were conducted in a regularly planted, well groomed stand of trees of the same species and about the same growth. This allowed for well-defined reproducible experimental conditions. Basically, it was found that there is a high attenuation rate at short distances into woods and a much reduced attenuation rate at large distances. In the transition region, substantial beam broadening occurs. For trees without leaves, the transition occurs after about eight trees as opposed to three trees when leaves are present. Attenuation in the foliated state was found to be as high as 12-20 dB per tree for the first three trees but is only about 0.5-0.7 dB per tree at larger vegetation depths.

Since many trees only partially obstruct a given path, Violette *et al.* [14] have estimated signal loss versus foliage depth for coniferous and deciduous trees. The foliage depth is calculated by tracing the direct path between the transmitter and receiver terminals on an orchard layout diagram and then summing the portions of the path that are intercepted by trees. Foliage depth can be expressed as an equivalent number of whole trees through division by the average tree width.

In general, the results of these studies indicate that for the first 30 m of foliage depth, the increase in vegetation loss is nearly linear at a rate of 1.3-2.0 dB/m, depending on frequency; beyond 30 m, the curve decreases at a rate that averages only 0.05 dB loss per meter. Propagation through the deciduous orchard (in the foliated state) resulted in less loss than propagation through the conifer orchard for any given combination of frequency, transmitter height, and foliage depth.

Measurements of multipath delays and depolarization are also given in the works cited above. In summary, impulse response measurements at 30.3 GHz showed the presence of multipath signals at delays as long as 15 ns for foliated deciduous trees. Measurements of depolarization in the conifer orchard show that at 28.8 GHz, cross-polarization discrimination is 12 dB for a foliage depth of 20 m and decreases to 9 dB after about 60 m.

2.5. Multipath

Because the wavelength is so small, the waves will reflect or scatter from almost any exposed object. Thus most receiver locations will almost surely be subject to multipath. The different multipath components, however, will arrive from different directions and a high gain antenna will render most of them invisible. The only components that would be seen are those that lie almost directly along the path to the transmitter. They might include, for example, a simple ground reflection. In such a case the path length difference (the difference between the path length of the multipath ray and that of the straight line direct ray) would be fairly small. Using a simple scenario for ground reflection on a 5-km path we have computed differences of perhaps 16 cm. This amounts to a *delay spread* of about 0.5 ns, which is much too short to cause any effect such as intersymbol interference. On the other hand, this path length difference is about 16 wavelengths; if the components are large enough, one can expect “flat” fading in which an entire 20-MHz channel disappears.

2.6. Passive Repeaters

Passive repeaters have been successfully used in microwave applications to overcome obstructions and reduce the number of active repeaters required. They also allow for more convenient placement of active repeaters (*e.g.*, near roads and utilities). The obvious advantages of passive repeaters are that they require no access or power lines and are virtually maintenance free.

Typically, passive repeaters are in the far field of the transmitter. When it is assumed that the phase and amplitude of the incident field are uniform over the repeater surface, the directivity is equivalent to an aperture with a uniform field. The maximum directivity (in the direction of the reflected wave) is given by:

$$D = \frac{4\pi A \cos\alpha}{\lambda^2}$$

where λ is the wavelength, A is the area, and α is the angle between the incident ray and the normal to the repeater. The normalized power pattern is

$$p(u) = \left(\frac{\sin u}{u}\right)^2$$

where

$$u = \frac{\pi a}{\lambda}\sin\theta$$

and where a is the "effective width" equal to the actual width of the repeater multiplied by cos α. Here, θ is the observation angle measured with respect to the reflected ray. At 28 GHz, beamwidths corresponding to half and 10 dB down power points are given by

$$2\theta_0 = \frac{0.5}{a},\quad \frac{0.84}{a} \text{ degrees}$$

with the effective width a measured in meters. For a square repeater (with reflection in the principal plane), the area and half power beamwidth are related by:

$$2\theta_0 = \frac{0.5}{\sqrt{A}\cos\alpha}$$

The gain (20 log D) is given by

$$G = 102 + 20\log A\cos\alpha \quad dB$$

which for beamwidths of more than a few degrees and incident angles of less than 40° can be reasonably approximated as

$$G \approx 90 - 40\log 2\theta_0 \quad dB$$

relative to an isotropic radiator located at the center of the reflecting face fed with power equal to that accepted by the passive receiver. Thus the gain can be expressed approximately as a function of the desired beamwidth.

For a given beamwidth, the required area and orientation (*e.g.,* tilt) of a rectangular repeater are easily calculated. For example, if a beamwidth of 3° was desired, the reflector would need to be about 60 cm square, and the resulting gain would be 70 dB.

Narrow beamwidths improve discrimination and reduce the possibility of interference. A potential problem associated with narrow beam repeaters is that proper alignment is difficult. Also, the narrow beam repeater may not provide sufficient coverage for all households in a shadow zone.

3. EXAMPLES OF MEASURED DATA

There have been many radio propagation measurements made at frequencies near 28 GHz. Most of them have explored situations resembling satellite-earth paths or land-mobile links in which path elevation angles are high or the subscriber terminal has a broad beam antenna. Some, however, do treat situations approximating that of the proposed LMDS.

A report by Violette *et al.* [17] summarizes a series of such measurements that were designed to study propagation characteristics for paths between mobile terminals in urban and suburban environments. In particular, much of the experimental work involves narrow beam receiving antennas (typically 1.2°) and EHF frequencies in the range of interest for LMDS. Results from this study that are relevant to LMDS are discussed below. Unless otherwise indicated, the measurements described in this section are for narrowband 28.8-GHz signals using a 10°-beamwidth transmitting antenna and a 1.2°-beamwidth receiving antenna.

Reflections from various environmental surfaces are important since they may act as a primary signal source (nonline-of-sight) and/or an interfering source (multipath). Normal incidence reflection measurements involving structures composed of common building materials (*e.g.,* brick or concrete) show that losses of 7-15 dB (relative to free space) can be expected. In addition there is significant variation depending on path length and spatial position. Presumably this is due to surface roughness.

Reflections from street surfaces are another important source of reflected energy. Measurements of signal amplitude as a function of transmitter to receiver offset for a rural and an urban setting are shown in Figure 5. Here both the transmitter and receiver are near ground level. Multipath interference as discussed in Section 2.5 of this report is clearly evident. The rural measurements show deep fades between 0.2 and 0.6 km. Fading is not evident for distances of less than 0.2 km due to the narrow beamwidth of the receiver. The urban path also shows deep fades, although the pattern is quite different. This difference is most likely due to multipath interference from buildings or other scattering objects (*e.g.,* traffic blocking the ground reflections).

The strength of reflections from building walls in an urban setting were investigated by pointing the 10°-beamwidth transmitting antenna away from the direct path in a series

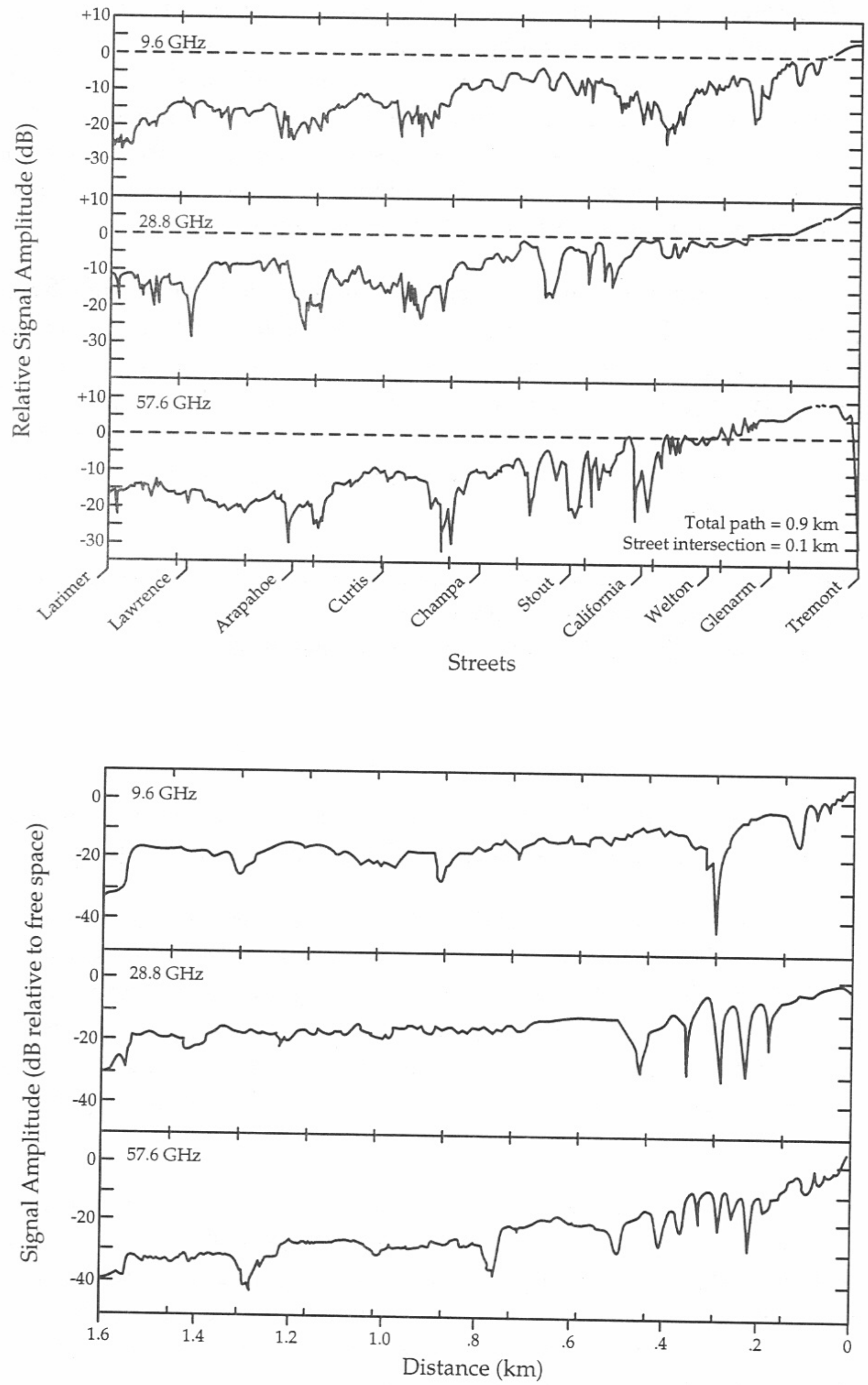

Figure 5. Signal amplitude as a function of range for two environments in and around Denver, Colorado: the top graph shows measurements along 17th Street in downtown Denver, the bottom along a rural asphalt road. The antennas were about 2 m above ground. These plots are reproduced from [17].

of 10° steps. A receiver scan (azimuthal) was made to detect reflected signals for each step. This more closely simulates the effects that may be expected for an omnidirectional transmitter and narrow beam receiver. The results clearly show significant reflected signals for both vertical and horizontal polarization (see for example, Figure 6). Reflections with amplitudes 10-20 dB below the direct ray are present. The reflections are oblique, however the amplitudes seem consistent with normal incidence reflections discussed above. It should be noted that the measurements do not include elevation scans.

Multipath, by introducing frequency selective fading, can have a significant impact on broadband signals. The urban measurements [17] included multipath measurements with a 1-GHz bandwidth signal at 30.3 GHz. Transmitter and receiver beamwidths were 30° and 2.5°, respectively. Figures 7 and 8 are examples of results for receiver on-line pointing, and 3°-receiver off-line pointing. Multipath signals with delays exceeding 10 ns are clearly evident. As may be expected, the off-line pointing results in a relative amplitude increase for the multipath components.

Coherence bandwidth (which describes when frequency selective fading becomes important) is sometimes defined as the 3-dB down point of the autocorrelation function. Using the model proposed by Hufford [18], the coherence bandwidth is

$$\Delta f = \frac{1}{2\pi\tau}$$

where τ is the delay time. By this definition, a 15-ns delay yields a coherence bandwidth of roughly 10 MHz; thus, frequency selective fading is an issue for the proposed LMDS.

Results of measurements for narrow band 28.8-GHz radio wave propagation in residential areas are also given by Violette *et al*. [17]. The environments were classified as "dense" and "sparse" residential, consisting of single family one-story dwellings with mature vegetation. No particular trend based on the neighborhood classification is apparent. Path lengths varied from 100-1450 m. In most cases, the paths were blocked by obstacles (houses and/or trees). Resulting losses due to obstructions for most cases ranged from 33-60 dB, averaging at about 50 dB.

They determined that propagation by diffraction from roof edges and especially treetops accounted for most of the received signal. This was indicated by a test where the loss was reduced about 20 dB by elevating the antenna 10°, roughly toward the treetop level. In this case the treetops appeared in the common volume of the antenna beams of each terminal. A similar situation existed in another test where large fluctuations in signal levels corresponded with tree motion due to wind.

The measurements described above provide useful information regarding potential problems associated with the implementation of LMDS. For example, the results clearly indicate that multipath fading is a potential problem. The extent of the problem depends on many factors including transmitter and receiver locations (height is of particular importance) and path length and environment (suburban, urban, and rural). Most of the work cited

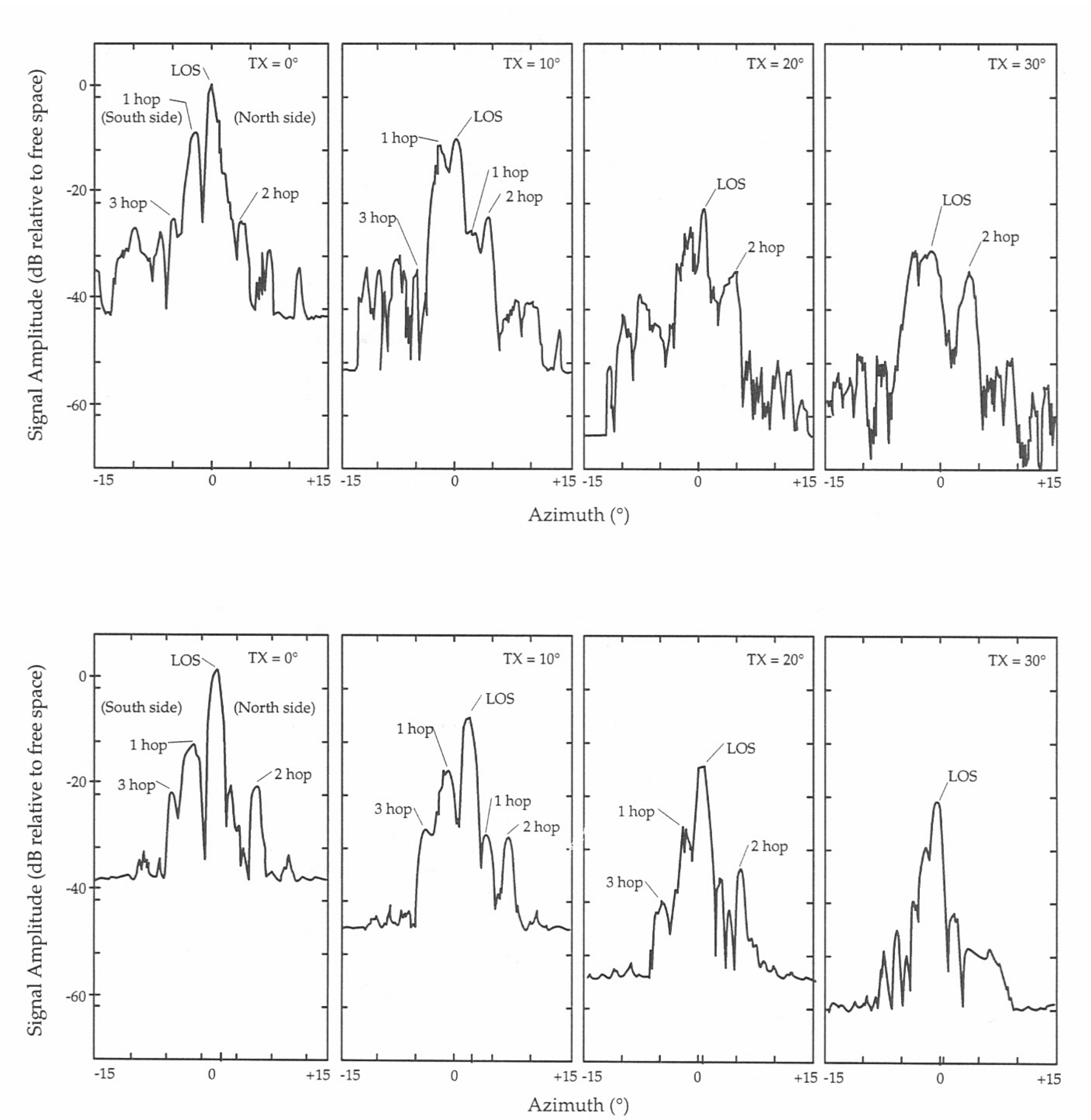

Figure 6. Measured signal levels near street level in downtown Denver, Colorado, with the transmitter antenna pointing away from the direct ray at angles of 0°, 10°, 20°, and 30°. In the top graph the antennas were vertically polarized, in the bottom horizontally. These plots are reproduced from [17].

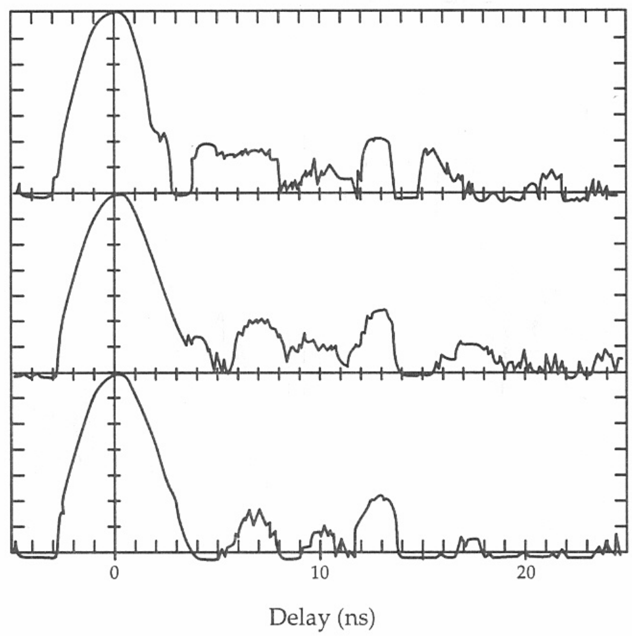

Figure 7. Impulse response records near street level in downtown Denver, Colorado. The vertical scale is 5 dB/div; the horizontal scale 1 ns/div. The graph is reproduced from [17].

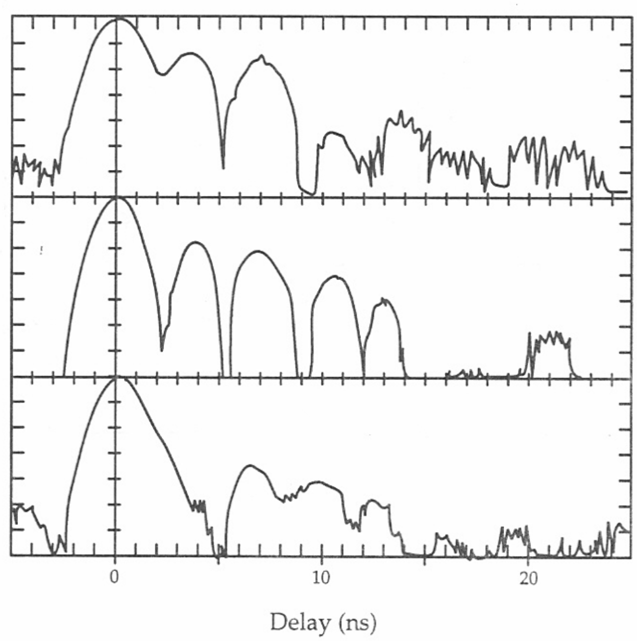

Figure 8. Impulse response records near street level in downtown Denver, Colorado, at roughly the same location as in Figure 7. The receiving antenna is pointed 3° off-path. The vertical scale is 5 dB/div; the horizontal scale 1 ns/div. The graph is reproduced from [17].

above involved transmitters and receivers that are close to the ground and have short paths (less than 1.5 km). Recently, ITS conducted experimental measurements that more closely resemble the transmitter/receiver geometry associated with LMDS for a suburban environment [19]. A brief summary of the pertinent results are given below.

Data at forty-five suburban receiver sites was collected and evaluated. Transmitters (with 26° beamwidth) were located at 16 and 40 m above grade with a median T-R path length of 4.5 km. Receiving antennas (5.5° beamwidth) were located at a height of 1 m above the roof level of nearby dwellings. The transmitted signal was broadband (1 GHz) at 30.3 GHz. Measured excess path losses varied from –6 dB to +32 dB. The median values for the 16-m transmitter height was 18 dB and 15 dB for the 40-m height. Multipath interference was found to be minimal. Measured delay spreads were between 0.7 and 10 ns with a median value of 1 ns.

4. SYSTEM REQUIREMENTS

For the proposed system, the received signal will need to be of high quality and high reliability, and therefore some amount of spectrum spreading (to trade wider bandwidths for higher signal-to-noise ratios) seems necessary. While digital television with the consequent availability of error-correcting codes seems highly desirable, it is an advanced technique that will probably have to await future development. For the present, available analogue techniques still allow us to use wide band frequency modulation to obtain useful improvements.

The so-called "FM improvement" is the ratio between the output SNR of the FM receiver, and the output SNR of an AM receiver in the same noise environment. It has the value (see [20], for example)

$$\rho_{FM} = 3\beta^2$$

where β is the "modulation index." Note that the required bandwidth for the FM transmission is, by Carson's rule, $B = 2f_m(\beta+1)$ where f_m is the one-sided bandwidth of the baseband modulating signal. For the NTSC video signal, f_m = 4.2 MHz. Note, too, that the improvement is not available unless the RF input "carrier-to-noise ratio" (CNR) exceeds an FM "threshold" of about 7 or 9 dB.

In standard audio FM transmissions, further improvements are possible by pre-emphasizing the higher frequencies of the signal at the transmitter and de-emphasizing them at the receiver. This works because most of the signal is concentrated at the lower frequencies, while most of the noise uses the de-emphasized higher frequencies. In the case of NTSC television, however, there are portions of the signal (particularly the chrominance signals) that use the upper frequencies, and the usual pre-emphasis/de-emphasis technique is no longer effective. We should note, however, that the microwave relay service and the satellite relay service both use FM modulation in their operations and they have developed their own pre-emphasis/de-emphasis procedure. This is mostly done to make television and FDM telephony appear to make similar demands upon the system. In the case of television, the lower frequencies are depressed relative to the higher frequencies. The result is a very slight improvement in SNR of about 2.9 dB (see [21], for example).

The important criterion for a system design is to ensure that the signal-to-noise ratio is amply large. In the present case this means that the final picture as viewed on the screen is of adequate quality. This, of course, is a subjective matter; the problem has been presented to "viewing panels" sponsored by the 1950's TASO group [22] that have produced results describing, for example, how "quality" varies with SNR. These TASO results are now widely used for design purposes and may be represented by the formula

$$G = 7.7 - 0.16 \times \text{SNR}$$

where G is the *picture grade* as seen by the "average" viewer. Qualitatively, this picture grade has values 1 = excellent, 2 = fine, 3 = passable, 4 = marginal, 5 = inferior, and 6 = unusable. In the context of the LMDS service it is proposed to require a grade 2 picture with a consequent required signal-to-noise ratio of 35.6 dB. Note that current television broadcasting systems are designed (see [23], for example) around a grade 3 picture, thus requiring only 29.4-dB SNR.

As it turns out, noise in the video signal becomes, to the human eye, less important as the frequency increases. Thus there is a difference between the noise power as measured by a wattmeter and as measured by the human eye. To allow for this difference the CCIR [24] has recommended a "unified weighting network" to be inserted in the probe of the wattmeter used to measure the thermal noise. The consequence is that the noise power to be used in estimating a signal-to-noise ratio is considerably smaller than that due to a flat thermal noise. For an NTSC signal that has been frequency modulated and then de-emphasized as described above, this subjective noise power is about 9.9 dB below the unaltered noise (see [21], for example).

It should be noted that at 28 GHz there is no appreciable external noise—either natural or manmade. The sky temperature horizontally will equal the ambient temperature so that the resulting received noise will be the same as simple thermal noise. The only real possibility for additional external noise might be from the sun. If the receiving antenna points directly at the sun (something that might very well happen at sunrise or sunset) it will observe an increase of approximately 13 dB. Otherwise, the only additional noise will arise internally from the receiver itself. For this we shall assume here a receiver noise figure of 6 dB, although much quieter receivers do exist.

Part of the present proposal for LMDS involves a *network* of transmitters each serving a circular area of perhaps 5 or 10 km. The arrangement is thus reminiscent of cellular telephones, and just as in the cellular environment it is now important to consider interference between neighboring cells.

The plan is to divide the 2-GHz band between 27.5 and 29.5 GHz into two 1-GHz blocks and furthermore to use variously, vertical and horizontal polarization from separate transmitters. Thus, in some sense there are four distinct "orthogonal" circuits that can be used to separate the cells. The two polarizations, however, provide a rather inexact orthogonalization, and it is problematical whether the concept would actually work sufficiently well.

There are a large number of places where a cross-polarized wave can be generated: reflections and scattering from walls, roofs, and trees—even the antennas are usually imperfectly polarized. The addition of oblate rain drops is only one more impairment.

On the other hand, there is an argument by which such a cellular network might perform adequately: that the narrow beam antennas proposed will already provide the necessary discrimination. They should pick up only the transmitter they point to and ignore all others. If this is a valid notion one might even ask why the system needs two channels or two polarizations. If we assume many identically modulated transmitters using approximately the same frequencies and the same polarizations, then simply turning to the best available signal (normally the nearest) might be an effective strategy. Of course, those who live directly on the line connecting two of these transmitters might still have trouble. For example, if someone is at the edge of a cell and sees a second transmitter directly behind the assigned transmitter, then that second will be about three times further away than the first. On a clear, dry day, the second signal will be only about 9.5 dB below the first, and that is just about at the "FM capture" threshold. In such a case it might be useful to have even a slight addition to the desired-to-undesired signal ratio as could be obtained, for example, by the use of orthogonal polarizations.

5. LINK BUDGETS

Of primary interest in this link budget analysis is the effect of the over-the-air transmission channel. As discussed in Section 2, free space loss and rain are perhaps the most important factors for line-of-sight (LOS) paths, both of which are a function of path length. The ratio of the power available at the receiver-to-reference noise power is plotted as a function of path length (cell radius) in Figures 9 and 10. In addition to free space loss and rain/water vapor attenuation, these curves include the following factors:

- transmitter power per channel (0.0 dBW);
- transmitting antenna gain (10 dBi);
- receiver antenna gain (7.5″ dish: 32 dBi); and
- noise power (NTSC) kT_0B, B = 8.4 MHz (–134.7 dBW).

In this list, receiving and transmitting antenna gains are representative of presently available equipment. The noise power is referenced to 290 K for the NTSC bandwidth of 8.4 MHz. If there are additional factors or if there should be changes to the factors above, one can simply add to or subtract from the CNR for a specified path length.

The link budget curves show the estimated CNR for a cell radius of up to 15 km using the given transmitter power, antenna gain, and rain or water vapor attenuation (99.9% availability) in San Francisco and Los Angeles. The CNR required at the receiver for FM is a function of the modulation index (β), receiver noise figure, and minimum SNR that will provide the desired picture quality. The receiver noise figure is effectively fixed by the available technology. For the purposes of this analysis, the SNR is set at 36 dB based on the TASO specifications for a "fine" picture. The modulation index can be adjusted by changing the FM bandwidth. The minimum CNR required for 18- and 36-MHz bandwidths are plotted in Figures 9 and 10 as horizontal lines (thresholds) using the following factors:

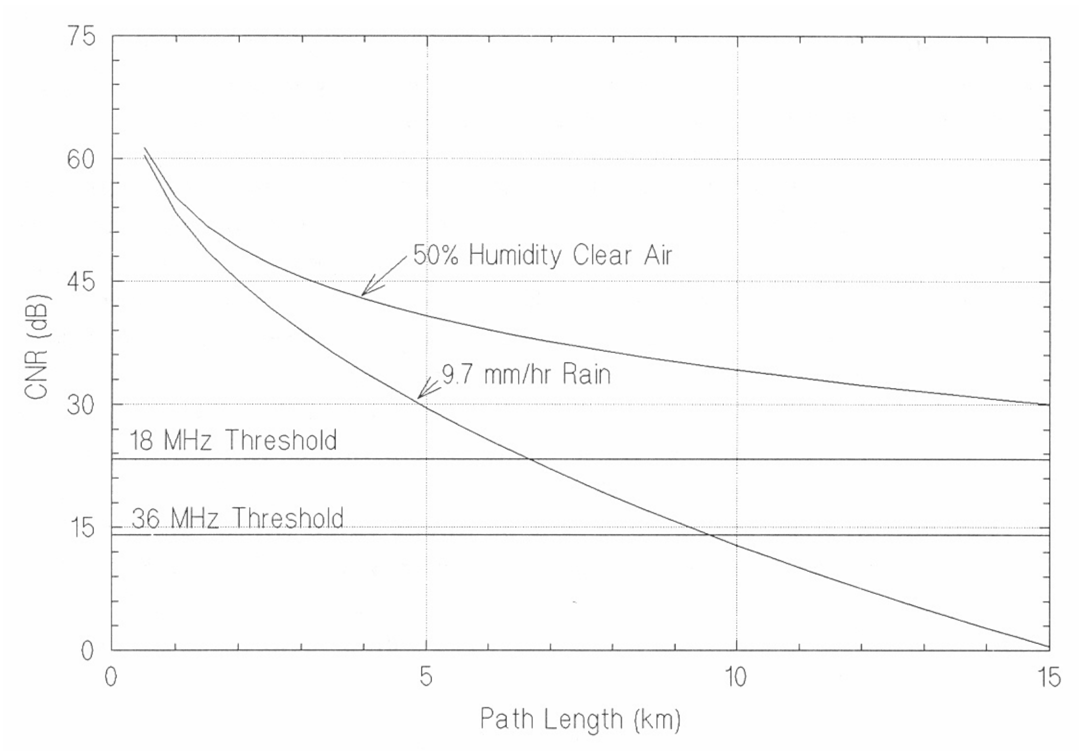

Figure 9. San Francisco: Link budget as a function of path length.

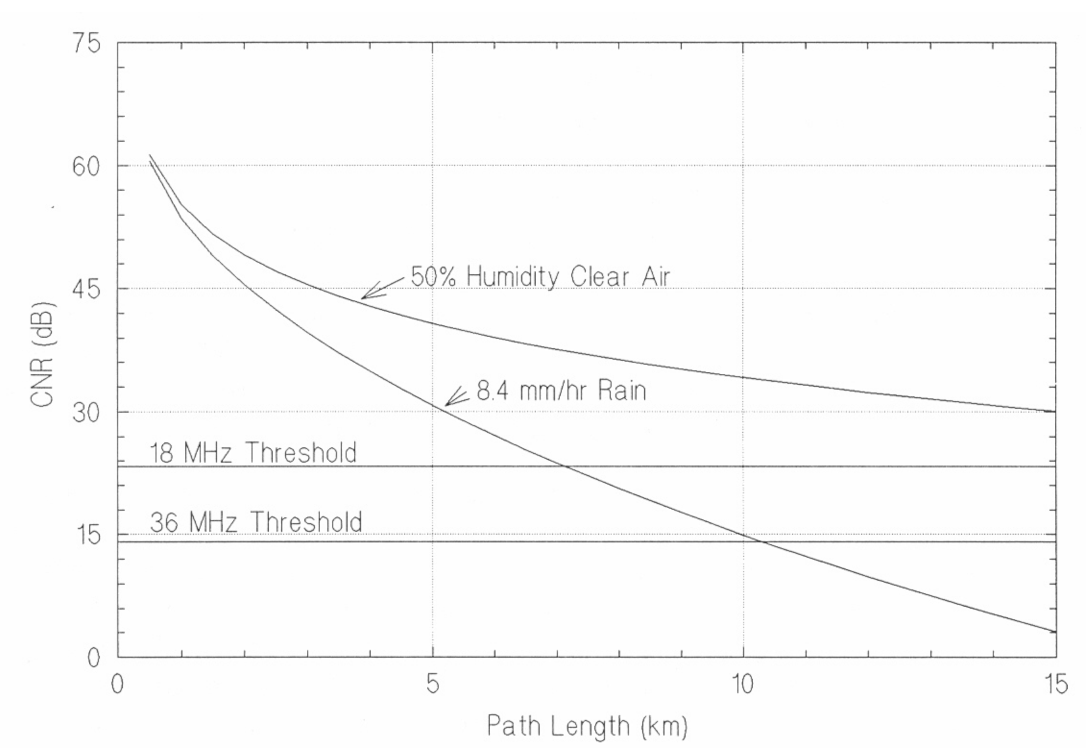

Figure 10. Los Angeles: Link budget as a function of path length.

- receiver noise figure (6 dB);
- SNR as specified by TASO (36 dB = "fine" picture quality);
- FM advantage $3\beta^2$,
  $\beta = 1.14$ at 18 MHz, $\beta = 3.28$ at 36 MHz; and
- emphasis and unified noise weighting 12.8 dB.

Other important considerations include the effects of propagation through vegetation, obstructions, and multipath fading. These effects are not included in the link budget curves shown. As indicated in previous sections, attenuation per tree can be as high as 20 dB. Diffraction at even small depths (see Figure 4) easily results in more than 10 dB of attenuation. Based on the measurements described in Section 3 it is expected that attenuation due to vegetation and/or obstructions (*e.g.,* diffraction) will be likely at many locations in a suburban environment. Here one may loosely predict 20-30 dB additional attenuation for partially obstructed paths. Also, measurements indicate that if reflections from buildings are used as the primary path, additional reflection losses will likely exceed 20 dB.

The link budget for a passive repeater can be included using formulas from Section 2.6. For example, assuming a 0.36-m^2 repeater, the gain is roughly 70 dB. If the repeater is 3 km from the transmitter, and the receiver is 0.25 km from the repeater, the CNR at the receiver is

CNR at repeater (Figure 8 for San Francisco) (clear air 50% humidity)	45 dB
Repeater gain	70 dB
Free Space Loss (repeater to receiver)	109 dB
CNR at receiver	6 dB

A sample link budget for a cell radius of 5.6 km in San Francisco using a 1 W per channel transmitter is calculated as follows:

Transmitter power/channel	P_t	=	0.0	dBW
Transmitter antenna gain	G_t	=	10.	dBi
Receiver antenna gain, 7.5″ dish	G_r	=	32.	dBi
Free space loss	L_{bf}	=	136.2	dB
Rain attenuation	A_r	=	12.	dB
Water vapor attenuation at 100% humidity	A_w	=	1.4	dB
Clear air attenuation at 50% humidity	A_0	=	.7	dB
Noise power (NTSC) kT_0B, $B = 8.4$ MHz	N_r	=	–134.7	dBW
Receiver Noise Figure	N_f	=	6.	dB
FM improvement, $3\beta^2$ at 18 MHz	M_{FM}	=	5.9	dB
De-emphasis and the unified noise weighting	E	=	12.8	dB

Thus, for the rain-faded (99.9% availability) 18-MHz FM bandwidth,

$$\text{SNR} = P_t + G_t + G_r - L_{bf} - A_r - A_w - N_r - N_f + M_{FM} + E = 39.8 \text{ dB}$$

and with a clear atmosphere,

$$\text{SNR} = P_t + G_t + G_r - L_{bf} - A_0 - N_r - N_f + M_{FM} + E = 52.5 \text{ dB}$$

We should recall that the *required* SNR (for a grade 2 picture) is 36 dB.

Another way to look at these results is to assume that this required SNR corresponds to a "normal" situation. Then the proposed design can be said to provide a *fade margin* of 52.5 – 36.0 = 16.5 dB, so that adequate service is provided as long as fades from rain or trees or other obstructions do not exceed this value. In Figure 11 we have plotted cumulative distributions of basic transmission loss assuming extra absorption due only to rainfall. Note that 16.5 dB below the normal level at 6 km, service should be available except for approximately 0.04% of the time.

Although this analysis seems adequate for rainfall fading, there are field measurements that indicate there will likely be a significant number of homes in the suburban environment that suffer another 20 dB or more of attenuation due to vegetation or obstructions (see Section 3). If the above fade margin is then not sufficient, received SNR will need to be increased using one of a variety of techniques. One might increase the transmitter power or the modulation index. For example, if the bandwidth is increased to 36 MHz, M_{FM} increases to 15 dB.

As proposed, LMDS will be designed for two-way communications. In this case the link budget factors (L_{bf}, A_r, A_w, A_0, and antenna gains) for the over-the-air channel will

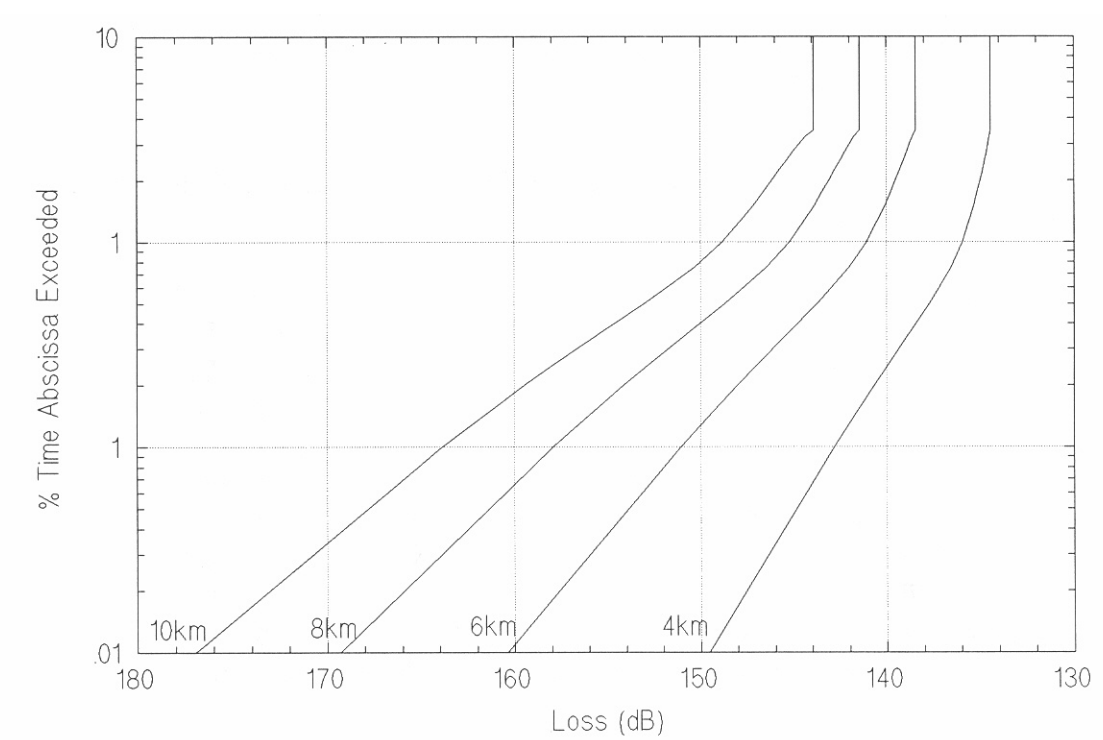

Figure 11. The cumulative distribution for the basic transmission loss on line-of-sight paths of various lengths. Rain statistics used are those for San Francisco.

remain the same. For customer to base transmissions, it is expected that transmitter power will be much less and the signal will be narrow band (perhaps digital); in this case the SNR improvements as described above are not applicable. Other factors (such as losses due to obstructions or reflections) that affect the primary signal must again be taken into account. Additional information regarding the system (transmitter power, type of modulation, receiver specifications) are required to determine the feasibility of two-way communications.

6. CONCLUDING REMARKS

The successful implementation of LMDS depends to a large extent on factors affecting the over-the-air channel. Several of these factors, including rain, clear air attenuation, vegetation, obstructions, and multipath, have been reviewed in this report. A summary of the results and recommended measurements needed to address uncertainties are discussed below.

Losses due to rain and humidity are reasonably well understood. Empirical and semi-empirical models for rain have effectively been used in satellite and ground based communications design. Cell size is dictated primarily by system parameters (*e.g.,* transmitter power, modulation, and antenna gain) and the desired availability based on rain attenuation models. Predicting the number of homes that can be served based on rain attenuation is a straight-forward process. Figures 1, 2, 9, and 10 of this report can be used to estimate system requirements for a desired cell coverage area in San Francisco or Los Angeles.

Uncertainties in predicting rain propagation losses are primarily due to difficulties in predicting drop size and shape distribution and the fact that rain is usually not homogeneous over a given path. In this report we have used the commonly accepted drop size distribution for low rain rates and the commonly accepted model for point-to-path rain attenuation. Note, however, that the latter is a function of prevailing meteorological conditions, and the resolution of uncertainties in the Crane global model [9] for a given region will require a series of measurements during rainy weather.

Propagation losses resulting from vegetation and other obstructions are much more difficult to quantify and will likely vary depending on the "man made" geography. In addition, simply increasing transmitter power or altering cell size may not solve the problem. Experimental work cited in this report shows that such losses for a suburban area result in a further 20-30 dB excess path loss for a significant number of homes. In this investigation it appeared that attenuation was most likely caused by vegetation and possibly by diffraction around building edges. These paths were said to be "obstructed LOS" since the type of obstruction was not obvious to the investigators. The results are highly specific since they represent a particular type of geography with respect to buildings, vegetation, and terrain. At the present time these results can only be used as a very rough guide to estimate the severity of losses that may be encountered.

Another important issue is the role of reflected signals in the implementation of LMDS. Two important questions are: "Can reflections from environmental surfaces be used as a primary signal when an LOS path is not available?" and "Is interference due to reflections a problem for LOS paths?" As indicated in Section 3, measurements have been made that show in an urban environment reflected signals are clearly detectable (both at 28.8 GHz cw and 30.3 GHz broadband). Propagation losses due to reflections ranged from 10 to more than 30 dB. In this case, the transmitter and receiver were near ground level and the paths were short (less than 2 km). An important remaining question is whether or not sufficient reflected signal strength would be available in "shadowed" areas (with respect to LMDS transmitters) to provide adequate coverage for residents.

As proposed, LMDS would use orthogonal polarization for isolation purposes. As shown in Section 2, rain-induced depolarization is not a major problem. Measurements performed by ITS, however, show that cross-polarization levels are significant (less than 10 dB down) for clear air non-LOS paths involving microwaves. Also, the experimental results described in Section 3 show high cross-polarization levels when vegetation is in the path. These results indicate that polarization isolation may not be effective in general.

In summary, obstructions (such as vegetation and man-made structures) provide the most difficult challenge in predicting the number of homes that a base station can serve. Such predictions are also compounded by other issues such as the amount of effort a customer will (or is allowed to) go to in order to receive the LMDS signal. For example, problems with vegetation may be eliminated if customers can (and will) place antennas above tree levels. It might be possible to place a common receiving antenna on the roof of an apartment complex so that potential customers in a shadow zone can receive the signal. Assuming that such measures will not be undertaken, the impact of vegetation, shadowing, and multipath on the number of residences that can be reached is quite uncertain at this point and will require further investigation.

Future studies of the viability of proposed LMDS should include a well thought out measurement campaign. Ideally, the goal would be to gather enough data to create realistic statistical models for the prediction of received signal levels in a variety of urban, suburban, and rural environments. The development of such models requires one to confront difficult issues such as "What constitutes an archetypal urban or suburban environment?" or "How should the data be acquired and how much is enough?".

Clearly, a massive effort would be required to achieve all of the desired goal. But a more modest study can be started, first by identifying obvious areas where radio propagation problems are expected. In addition to providing information regarding the influence of these environments on LMDS, they will provide input needed to develop more general models. Future measurement efforts should include the environments and general considerations described below.

The proposed LMDS system relies heavily on polarization to prevent interference. ITS has found that cross-polarization amplitudes can be significant for non-LOS paths. Further measurements are required to determine if the use of polarization diversity will be effective. Cross-polarization measurements should be performed in all of the environments described below.

1. Urban (multistory buildings) shadow zones:

The presence of multistory buildings in urban areas is expected to create shadow zones. In such cases, a large number of customers (*e.g.,* adjacent residential neighborhoods and high-rise apartments) may not have LOS access to the transmitters. Potential problem areas in large cities that might support LMDS should be identified. Measurements (which might involve azimuthal scanning) to determine available signal levels should be performed. Several different locations should be used to obtain statistics on signal levels available in such urban shadow zones.

2. Urban multipath fading:

Recent measurements performed by ITS show that multipath interference was not a severe problem in a suburban environment consisting mainly of single story residences (see the last paragraph of Section 3). These results are not likely to be applicable to an urban environment with a high density of large structures. It is recommended that broadband measurements simulating LMDS transmitter/receiver geometry be performed in an urban environment and adjacent residential areas in order to determine the extent of multipath fading problems.

3. Suburban (single-story dwellings) environments with mature vegetation:

ITS has found that signal levels are strongly affected by vegetation. It is expected that the presence of tall mature trees will have a significant impact on signal levels for a number of homes. Neighborhoods with relatively high, moderate, and low densities of mature trees should be identified. Measurements should be made to determine estimates of the spatial distribution of signal levels in each case.

4. Inclement weather:

Measurements of signal levels for the maximum expected LOS path lengths during rain storms should be made to provide verification of the Crane model for the Los Angeles and San Francisco regions.

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14. SUPPLEMENTARY NOTES

15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A local miltipoint distribution system will essentially broadcast television signals (and perhaps more) to subscribers in small cells. It has been proposed to put such systems in the frequency band from 27.5 to 29.5 GHZ where the wave length is only about 1 cm, and where equipment is not well established and propagation effects are not entirely known. In this report, we discuss what is known about the expected behavior of the radio waves and we suggest areas that need more study.

16. Key Words *(Alphabetical order, separated by semicolons)*

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