Chapter 4
Signal Degradation for Line-of-Sight Communications
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Chapter 4
Signal Degradation for Line-of-Sight Communications

4.1 Background

This chapter broaches the question, “What is the LMSS signal degradation for a configuration in which line-of-sight communications are maintained with negligible shadowing in an environment where multipath is prevalent?” The multipath environment may consist of roadside trees, utility poles, hills and mountains, the ground, or a body of water. This question was, in part, addressed through the implementation of a series of experiments by the authors in central Maryland [Goldhirsh and Vogel, 1989], north-central Colorado [Vogel and Goldhirsh, 1988], western United States [Vogel and Goldhirsh, 1995], and Alaska [Vogel et al., 1994] at UHF (870 MHz), L-Band (1.5 GHz), and K-Band (20 GHz).

![Figure 4-1: Illustration of multipath scenario showing direct ray and reflected ray from nearby mountainside arriving at receiving antenna.](image)

A typical multipath scenario is one in which direct signals are received at the same time as indirect ones which arrive at the antenna via scattering from nearby trees, utility poles, other structures, the side of a mountain, or a nearby body of water. The sum total of...
received signals may add constructively or destructively resulting in signal enhancement or fade. An example scenario is illustrated in Figure 4-1. The received power is a manifestation of the phasor sum of the direct transmission and the combined indirect voltage levels. These depend upon the scattering cross sections of the multipath reflectors, their number, and their relative distances to the antenna, the received field polarizations, and the receiving antenna gain pattern, which may be influenced by a vehicle roof.

4.2 Multipath for a Canyon and Hilly Environments

4.2.1 Canyon Environment

The results described here were obtained by the authors from LMSS line-of-sight measurements in canyon passes in north central Colorado [Vogel and Goldhirsh, 1988]. The transmitter was on a helicopter which, for each run, flew behind a receiving mobile van and maintained a relatively fixed distance and path depression angle relative to the receiving antenna. The radiating antennas on the helicopter transmitted simultaneous L-Band (1.5 GHz) and UHF (870 MHz) CW signals. Simultaneous LMSS measurements were made at L-Band and UHF. The experimental parameters are summarized in Table 4-1. The receiving antennas were located on the roof of a van (2.4 m above the ground) where the pattern functions were nominally omni-directional in azimuth with a 3 dB beamwidth in elevation between 15° and 75°. Below 15°, the antenna gain function dropped off rapidly and any multipath arriving via scattering from surfaces near or below the horizontal were diminished by the pattern by at least 10 dB.

For each of the canyon roads driven, the wall facets were highly variable in height, orientation, foliage overlay, and distance from the roads. The mountain walls consisted of randomly oriented facets of rocks with protruding patches of trees. The roads through the canyons made many twists and turns, offering highly variable aspects to the multipath illumination scene. Such a scenario was considered as a worst case for multipath.
Table 4-1: Summary of experimental parameters for canyon measurements [Vogel and Goldhirsh, 1988].

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>L-Band</th>
<th>UHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Type</td>
<td>Spiral/Conical</td>
<td>Microstrip</td>
</tr>
<tr>
<td>Polarization</td>
<td>Right-hand Circular</td>
<td></td>
</tr>
<tr>
<td>Antenna Beamwidths</td>
<td>60°</td>
<td></td>
</tr>
<tr>
<td>Platform Type</td>
<td>Bell Jet Ranger Helicopter</td>
<td></td>
</tr>
<tr>
<td>Receiver Platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Type</td>
<td>Crossed Drooping Dipoles</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>Right-hand Circular</td>
<td></td>
</tr>
<tr>
<td>Height of Antenna (m)</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Beamwidth</td>
<td>60° (15° to 75°)</td>
<td></td>
</tr>
<tr>
<td>Detection Bandwidth (Hz)</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Sampling Rate (KHz)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Frequencies (GHz)</td>
<td>1.502</td>
<td>0.870</td>
</tr>
<tr>
<td>Signal Data Recorded</td>
<td>Quadrature Detected Outputs</td>
<td>Power</td>
</tr>
<tr>
<td>Other Data Recorded</td>
<td>Elapsed Time, Vehicle Speed</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-2 shows four cumulative fade distributions depicting “least square power curve fits” for the above described multipath scenarios at frequencies of 870 MHz and 1.5 GHz and path elevation angle 30° and 45°. Each curve was derived from a subset of four runs taken in two canyon passes (Boulder and Big Thompson Canyons); a run representing measurements where the vehicle traveled up or down a canyon pass at a particular path elevation angle to the transmitter. The resultant curves correspond to a combined driving distance of 87 km through canyon passes. Each of the best fit power curves agree with the measured cumulative distribution data points to within 0.1 dB rms. As mentioned, simultaneous measurements at L-Band and UHF were made for each run.
The distributions may be expressed by

for $P = 1$ to $10\%$

$$P = a A^{-b},$$

(4-1)

where $P$ is the percentage of distance the fade $A$ (in dB) is exceeded, and where the values of $a$, $b$ are tabulated in Table 4-2 at the two frequencies and elevation angles of $30^\circ$ and $45^\circ$. Equation (4-1) and the values in Table 4-2 have been adopted as a multipath model for mountainous terrain by the ITU-R [1994, 1997].
Table 4-2: Coefficients \(a, b\) in formulation (4-1) describing best fit cumulative fade distributions for multipath in mountainous terrain.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Elevation = 30°</th>
<th></th>
<th></th>
<th>Elevation = 45°</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>dB Range</td>
<td>(a)</td>
<td>(b)</td>
<td>dB Range</td>
</tr>
<tr>
<td>0.870</td>
<td>34.52</td>
<td>1.855</td>
<td>2-7</td>
<td>31.65</td>
<td>2.464</td>
<td>2-4</td>
</tr>
<tr>
<td>1.5</td>
<td>33.19</td>
<td>1.710</td>
<td>2-8</td>
<td>39.95</td>
<td>2.321</td>
<td>2-5</td>
</tr>
</tbody>
</table>

Figure 4-2 shows that over the percentage range of 1% to 10%, the fades due to multipath vary between 2 and 5 dB at 45° and 2 and 8 dB at 30° elevation. The higher frequency (L-Band) exhibits slightly larger fades that are generally within 1 dB or less relative to UHF. The slightly larger fades at L-Band might be attributed to the small amount of tree fading that may have been present. There may also have been a presence of more reflecting facets on the canyon walls with sizes comparable to 20 cm (L-Band) or larger than does exist for the UHF case (34 cm). Such facets (L-Band case) would offer larger cross sections (Mie scattering) than facets whose dimensions were small relative to a wavelength (UHF case) where Rayleigh scattering is applicable. Larger fades at the 30° elevation relative to 45° may be attributed to some tree shadowing. It also may be attributed to the fact that multipath is dominated by illuminated surfaces closer to the vehicle; this implies lower reflecting heights and more shallow elevation angles.

4.2.2 Hilly Terrain

Multipath fading at 1.5 GHz for low elevation angles and unshadowed line-of-sight propagation in hilly terrain was characterized by the authors [Vogel and Goldhirsh, 1995]. The receiving van employed a tracking helix antenna with beamwidths in the principal planes of approximately 36° (i.e., ±18° about the geometric axis). CW signals from INMARSAT’s geostationary satellite MARECS B-2 were received at elevation angles ranging from 7° to 14° for measurements made in Utah, Nevada, Washington and Oregon.

Distributions corresponding to measurements for several well-defined scenarios were executed and the results are given in Figure 4-3. Curve 1 (elevation = 14°) represents a nine-minute distribution for the case in which the vehicle was standing in an open area with minimal nearby terrain features. It therefore may be considered to represent a “benchmark” where minimal propagation effects are combined with the stability of the system dependent upon the receiver noise, and the transmitter and receiver gain changes. It is observed that the fade level is less than 1 dB at 1% probability. Curve 2 (elevation = 14°) represents a reference for the vehicle in motion (12 minute run) in a flat open terrain. In additions to effects described for the static case, signal fluctuations caused by antenna tracking errors may also have been introduced here. For the open field measurements, fades of less than 2 dB are experienced at the 1% probability. Curve 3 (labeled best aspect) corresponds to the scenario in which the line-of-sight was orthogonal to the driving direction. This distribution (17 minute run at 14° elevation) corresponds to the case in which the satellite and reflecting surfaces are on the same side of the vehicle (labeled “Best Aspect”). On the other hand, Curve 4 (10 minute run at elevation = 10°) corresponds to the case in which the satellite was (on average) ahead of
the vehicle and the straight four-lane divided highway approached chains of hills through a flat, wide valley. Because the road itself was rolling (e.g., sinusoidal), it may be reasoned that a greater likelihood exists for specular scattering from reflecting surfaces on the mountainous terrain in front of the vehicle than does exist for the case in which the satellite and scatterers are to the side of the vehicle. For the former case (labeled “worst aspect”), multipath levels approaching 7 dB were experienced for 1% of the driving distance.

![Figure 4-3: Comparison of multipath fading for several well defined low-elevation angle scenarios in western United States [Vogel and Goldhirsh, 1995].](image)

### 4.3 Multipath Due to Roadside Trees

Similar types of line-of-sight measurements were performed by the authors in central Maryland along tree lined roads [Goldhirsh and Vogel, 1989] as were described for the mountainous terrain case in Section 4.2. That is, repeated measurement runs at 30°, 45°, and 60° were implemented with the helicopter following the vehicle and cumulative distributions were derived at both UHF and L-Band. The distributions were observed to be relatively insensitive to path elevation. The three runs were combined into one
distribution at each frequency comprising 75 km of driving. The resultant distributions were found to follow an exponential form given by,

for \( P = 1 \) to 50%

\[
P = u \exp(-vA),
\]

where \( P \) is the percentage distance traveled in which the fade \( A \) is exceeded, and \( u, v \) are tabulated in Table 4-3. The corresponding distributions are plotted in Figure 4-4. Equation (4-2) and the corresponding values in Table 4-3 have been adopted by the ITU-R [1994, 1997] as a model for multipath caused by canopies from roadside trees.

**Table 4-3:** Coefficients \( u, v \) in formulation (4-2) describing best fit exponential cumulative fade distributions for multipath associated with tree-lined roads.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>( u )</th>
<th>( v )</th>
<th>Fade Range (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.870</td>
<td>125.6</td>
<td>1.116</td>
<td>1-4.5</td>
</tr>
<tr>
<td>1.5</td>
<td>127.7</td>
<td>0.8573</td>
<td>1-6</td>
</tr>
</tbody>
</table>

The fades at the two frequencies fit an exponential function from 1 dB (at an exceedance of 40% to 50%) to approximately 4.5 to 6.0 dB (at an exceedance of 1%). A slight dependence is exhibited due to frequency with L-Band giving approximately 1.5 dB greater fades at 1%. The indicated best-fit exponential curves were found to agree with each of the original measured cumulative distributions to within 0.2 dB. Fading due to multipath is presumed to emanate from scattering off tree canopies that reradiate, more or less, isotropically in elevation angle. Such an explanation is consistent with the fact that the distributions were relatively insensitive to path elevation angle in the angular interval between 30° and 60°.

Enhanced fading due to multipath effects are expected for antennas pointed at lower elevation angles (e.g., 5° to 20°) where scattering from tree canopies and trunks, other vehicles, and the road itself may be received with smaller antenna gain filtering.
4.4 Multipath at 20 GHz Near Body of Water - Low Elevation Angle Effects

As mentioned in Section 4-3, it is expected that the multi-path fading effects should be more pronounced at lower elevation angles where forward scattering from the ground is more likely. Low elevation angle (e.g., 8°) mobile satellite measurements were executed by the authors at 20 GHz in Alaska employing transmissions from the Advanced Communications Technology Satellite (ACTS) [Goldhirsh et al., 1994]. The extent to which ground reflections are important at low elevation angles depends on the location of the antenna on the vehicle’s roof relative to the satellite azimuth location, as well as the type of ground (e.g., dry versus wet ground). Cumulative fade distributions corresponding to various multipath (not shadowed) line-of-sight scenarios are given in Figure 4-5. These distributions were derived from measurements employing a tracking antenna located on the rear of the roof of a van, where the antenna beamwidth was 27°.
Figure 4-5: Multipath distributions for over-water and dry land scenarios at 20 GHz in vicinity of Fairbanks, Alaska. Elevation angle to satellite was 8°.

Curve 1 was obtained from measurements obtained in an open dry field in Fairbanks, Alaska where the vehicle was moving slowly. This distribution shows a maximum fade level due to multipath of approximately 3 dB at 1% probability. For this situation, the small contribution due to multipath is from diffuse scattering from a ground having a low reflection coefficient. On the other hand, the other four curves were obtained when the vehicle was parked near a body of water (Tanana River), and the earth-satellite path was directed over the water in front of the vehicle. Each curve corresponds to a different vehicle orientation vis-à-vis the earth satellite path. Curve 2 labeled as “Parallel A” represents the scenario in which the front of the vehicle was facing the satellite. On other hand, Curve 4 labeled as “Parallel B” corresponds to the configuration in which the rear of the vehicle was facing the satellite. Curve 3 labeled as “Perpendicular A” represents the case in which one side of the vehicle was facing the satellite, and Curve 5 denoted as “Perpendicular B” corresponds to the scenario in which the other side of the vehicle was facing the satellite. Although the vehicle was stationary for each orientation, the tracking antenna was in slight motion as it was continuously tracking the satellite position. Hence, the multipath scene was in a constant state of change simulating vehicle motion. These measurement runs individually ranged from 2 to 5 minutes, and the antenna pointing varied within ± 5° of true line of sight (well within the antenna beamwidth of ±13.5°)
during this time. The most benign of the near-water multipath distributions is given by Curve 2, which shows a maximum fade of 5 dB at 1%. As mentioned, this orientation (Parallel A) was such that vehicle was facing the satellite and the antenna was located at the rear of the vehicle. Hence, the vehicle shielded reflections from the body of water mitigating multipath effects. On the other hand, when the vehicle’s rear was facing the satellite (Curve 4 and Parallel B), relatively large multipath fading is observed. For this case, minimal shielding by the vehicle occurred. For this case, fading as high a 13 dB existed at 1% probability. Perpendicular orientation also offers an aspect with minimal roof shielding. Perpendicular B case shows the largest multipath fading of 14 dB at 1%. It is conjectured that the distributions for the two perpendicular cases are not similar because the vehicle was located at different relative positions relative to the surrounding scene for these cases.

### 4.5 Multipath Versus Driving Directions

Figure 4-6 shows eight distributions derived from measurements corresponding to different driving scenarios for three roads in central-Maryland during the 20 GHz ACTS mobile-propagation campaign [Goldhirsh et al., 1994]. The measurements associated with these distributions were performed in March (1994) during which time the deciduous trees were devoid of leaves. For the Route 295 driving measurements, the earth-satellite path was slightly to the right of the driver traveling south and to the left of the driver traveling north as shown in the sketch of Figure 4-7. Hence, for the condition in which the vehicle is driven south, less shadowing should be expected in the left lane (as shown) vis-à-vis the right lane. The low fades associated with the distributions of Curves 1 and 2 correspond to the above cases (left lane traveling south and right lane traveling north). Signal degradation for these cases is caused by multipath as is evident from the relative low fade values associated with the distributions. Curves 3 and 4 in Figure 4-6 correspond to the geometry in which the vehicle is closer to the line of roadside trees where the likelihood for shadowing and tree attenuation is more pronounced. Curves 5 to 8 represent distributions for other directions and other roads in which the shadowing aspect is more pronounced. It is apparent from the highly variable fade levels in Figure 4-6, for the same geographic location, the driving direction relative to the vehicle-satellite bearing plays a significant role in establishing the level of fading.
Figure 4-6: Fade distributions due to multipath and shadowing in central Maryland at 20 GHz. Curves 1 and 2 represent primarily multipath, other curves correspond to varying degrees of tree shadowing from canopies devoid of foliage.

Figure 4-7: Relative azimuths of mobile-satellite path and driving direction for Route 295 (four-lane highway with two lanes in each direction).
Another example showing multipath fade levels at K-Band (18.7 GHz) in a roadside tree environment, when the satellite was directly in front of or behind the moving vehicle, is shown in Figure 4-8 as the curve labeled 0° orientation. The other curves in this figure show distributions for tree lined scenarios in which the orientation of the earth-satellite path relative to the vehicle direction was 45° and 90°. These curves, also alluded to in Chapter 7, were derived from measurements in Germany employing a tracking antenna on a mobile van. This effort was commissioned by the European Space Agency employing Italsat F1 as the radiating source platform [Joanneum Research, 1995; Paraboni and Giannone, 1991]. It is clear that the fading for the 0°-orientation case was primarily due to multipath although some tree shadowing effects may have existed near the 1% fade level.

![Figure 4-8: Cumulative fade distributions from measurements made in Germany at 18.7 GHz in a tree-shadowed environment at elevation angles 30°-35°. The curve labeled 0° orientation is representative primarily of line-of-sight multipath. The other indicated orientation angles are the driving azimuths relative to the satellite [Murr et al., 1995].](image-url)
4.6 Empirical Multipath Model

We have observed that a large variability of multipath fading occurred for different road scenarios, frequencies, and elevation angles. Nevertheless, the range of attenuation values at the different percentages is sufficiently small to enable development of a single empirical model. The model proposed here, called Empirical Multipath Model (EMM), represents the median of 12 multipath distributions previously considered here at frequencies from 870 MHz to 20 GHz and elevation angles from 8° to 60°. This model encompasses the following measurement scenarios: (1) Canyons at 870 MHz and 1.5 GHz for 30° and 45° elevations, (2) rolling hills and mountains at 1.5 GHz for 10° and 14° elevations, (3) roadside tree measurements at 870 MHz and 1.5 GHz for 30° to 60° elevations, (4) roadside tree measurements at 20 GHz for 38° elevation, (5) open fields and near-water (with vehicle shielding) at 20 GHz for elevation of 8°. The resultant model is given by, for $A$ between 1 and 4.6 dB

$$P = u \exp(-vA),$$

where

$$u = 94.37, \quad v = 0.9863,$$

and where $P$ is the percentage of distance driven over which the attenuation $A$ (dB) is exceeded assuming only multipath conditions. The range of $P$ covered by the above interval of $A$ is between 1% to 50%. A comparison of the EMM model distribution with the above mentioned 12 distributions is given in Figure 4-9 (solid line with no data points). For probabilities of 2% and greater, the model distribution is approximately within ±1.5 dB of the measured distributions and at 1%, it is within ±3 dB. The distributions having high fade values at the lower percentages (e.g., 1%) might also include some shadowing effects. In employing (4-3) at the lower elevation angles (e.g., 8°), the model does not include multipath for over-water scenarios unless the vehicle roof shields the multipath ray. At the higher elevation angles (e.g., above 20°), it is assumed the antenna pattern rejects reflections from the ground.
Figure 4-9: Comparison of line-of-sight multipath distributions for different scenarios and frequencies with single empirical multipath model (EMM) distribution (thick curve without data points).

4.7 Summary and Recommendations

Several models have been described giving the relationship between percentage of distance traveled and attenuation. The different models pertain to various multipath scenarios where the mechanism of fading is caused by the direct signal and an interfering multipath signal being received at the antenna as shown in Figure 4-1. The models considered here are: (1) Mountainous terrain at 870 MHz and 1.5 GHz for 30° and 45° elevation angles (see Equation (4-1)) and Table 4-2) [ITU-R, 1994; 1997]. (2) Roadside tree measurements at 870 MHz and 1.5 GHz for elevation angles between 30° and 60° (see Equation (4-2)) and Table 4-3). Models pertaining to (1) and (2) are ITU-R recommendations [ITU-R, 1994; 1997]. (3) The Empirical Multipath Model (EMM) is given by (4-3) and (4-4) and shown in Figure 4-9. Unlike the previous models described, the new empirical relationship covers elevation angles between 8° and 60° and frequencies between 870 MHz and 20 GHz and is representative of all terrain. The one exception corresponds to the scenario where the vehicle is in proximity to a body of
water and the elevation angle and antenna beamwidths are such that rays within the main beam may reflect from the water and are not obstructed by the vehicle. This scenario at the 1% probability level gave fades at 20 GHz which ranged from 8 dB to 14 dB (Figure 4-5).

The EMM is representative of the median of 12 measured distributions encompassing the above described scenarios and falls within ±1.5 dB of the measured distributions at 2% probability and greater. At 10% and greater, the model values fall within ±1 dB. The engineer may conveniently employ this single exponential expression with the caveat that it is in agreement with the measured distributions to within the stated dB variations.

4.8 References


D-12350, December 1994, California, Institute of Technology, Pasadena, California.)