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Initial Study of the Local Multipoint Distribution System Radio Channel

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INITIAL STUDY OF THE LOCAL MULTIPOINT DISTRIBUTION SYSTEM RADIO CHANNEL

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A broadband millimeter wave study was completed to characterize the radio channel for Local Multipoint Distribution Systems in Boulder, Colorado. The study determined characteristics for proposed 20-MHz channels centered at 30.3 GHz using two transmitter heights in a suburban environment. Distributions of delay spread, correlation bandwidth, frequency selective fading and scatter plots of signal loss are presented. The median signal loss for the 40-m transmitter height was 15 dB. Maximum delay spreads for this height were below 10 ns with a median value of less than 1 ns. Data was also collected to characterize a flat plate reflector proposed for use at 28.8 GHz. Cross cell interference and signal diffraction measurements were also made.

Key words: broadband, delay spread, local multipoint distribution system, radio channel

1. INTRODUCTION

A suite of measurements were made to characterize propagation representative of Local Multipoint Distribution System (LMDS) signals at 30.3 GHz. The study was designed to answer questions which could affect the economic viability of LMDS service. The primary emphasis was to complete a broadband area coverage study using two transmitter heights. This work characterized the delay spread and signal loss distributions for a random selection of single and multiple family dwellings. A second concern was the performance of passive repeaters, in particular their depolarization and loss characteristics at 28.8 GHz. Limited measurements were also made concerning signal diffraction over buildings and cross cell transmitter interference.

2. EQUIPMENT

The Institute for Telecommunication Sciences (ITS) used its 30.3-GHz wideband probe (WBP) for the experiments. Block diagrams of the transmitter and receiver as configured

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for the wideband LMDS measurements are given in Figures 1 and 2. The WBP uses a 28.8-GHz Gunn source mixed with a l.5-GHz signal which has been bi-phase shift key (BPSK) modulated by a 500-Mb/s pseudo-random bit sequence. The spectrum of this signal has a null-to-null bandwidth of 1 GHz. The 30.3-GHz output is amplified using a solid state amplifier and a traveling wave tube (TWT) to a level of 1 W. The TWT was operated below its saturation level, which is between 10 and 20 W. Transmitter output was monitored using a power meter. The passive repeater study used the 28.8 GHz continuous wave (CW) transmitter and receiver sections of the WBP, configured as shown in Figures 3 and 4. The 28.8-GHz CW signal was amplified to 17.2 dBm.

Both wideband and narrowband signals were transmitted using a vertically polarized standard gain horn antenna. The horn has a 26-degree beam width and 15.2-dB gain at 30.3 GHz. Two standard gain horns were fabricated to match the receive antennas of proposed LMDS systems. The horns have an E-plane beam width of 5.5 degrees and were coupled to the receiver using a waveguide. Vertically and horizontally polarized signals could be routed to the broadband or narrowband receiver input using manual waveguide switches.

The 30.3-GHz wideband signal was downconverted and demodulated using a correlation receiver. The resulting channel impulse measurement was stored using a digital audio tape recorder (DAT). This data was then processed by computer. The 28.8-GHz narrowband signal was downconverted to 12.63 MHz and the received signal power was measured using a spectrum analyzer.

The WBP system was calibrated using a line-of-sight (LOS) path on the Department of Commerce (DOC) Boulder campus. The transmitter was located on the mesa on the west edge of the campus and the receiver was in the DOC south field. The calibration path length was surveyed and is 1.051 km. The narrowband system was calibrated using a short LOS path on the DOC south field.

3. MEASUREMENTS

3.1 Area Coverage Survey

Forty-five receiver sites in Boulder were surveyed using Williams Village, a 13-story apartment building complex as the transmitter site. Transmitter heights of 16 m and 40 m were selected to study transmitter height dependence in the area coverage statistics. Transmitter and receiver locations are shown on Figures 5, 6, and 7. Typical receiver locations consisted of one- and two-story single family homes and one- to three-story townhomes. At these locations, the recording van was parked curbside and the mast was raised 1 m above the house roof height. A video camera with a telephoto lens aligned with the antenna bore sight was used to determine the roof height. The maximum antenna height was 8.5 m. Signal level was peaked by adjusting elevation and azimuth using a mast-mounted controller. A determination of line-of-sight [LOS versus obstructed line-of-sight (OLOS)] was then made using the video camera. Each station was recorded for 55 s using the short PN code (127 bits) and 120s using the long code (32767 bits). Since no delays beyond the 265-ns range of the short code were observed, only the short code data were processed.

3.2 Passive Repeater Study

Narrowband measurements were made on a short path using a 1.2 m^2 aluminum reflector. Geometry of the test is given in Figure 8. Both vertically and horizontally polarized signals were received using the 5.5-degree horn antennas. Signal strength was measured using a spectrum analyzer to monitor the 12.63-MHz IF of the 28.8-GHz receiver. The repeater loss was calculated using the following link equation [1]

$$L_{pr}(dB) = P_r - (P_t + G_t - G_r + G_{pr} - L_{fs}(r_1) - L_{fs}(r_2)) \tag{1}$$

where:
L_{pt} = passive repeater loss
P_r = received power
P_t = transmit power
L_{fs} = free space loss
G_t = gain of transmit antenna
G_r = gain of receive antenna
G_{pr} = passive repeater gain = $20 \log 4\pi A/\lambda^2$
A = area of repeater.

3.3 Diffraction Study

Four stations were recorded in the shadow zone of the 3100 Marine Street National Oceanographic and Atmospheric Administration (NOAA) site, a five story office building. Using transmitter and receiver heights, the NOAA building height and ground elevations from topographic maps, the diffraction angle was determined. Wideband excess path loss was then tabulated as a function of the diffraction angle. This diffraction angle is a deviation from the line-of-sight path that the signal must make to reach the receiver by bending over the top of the obstruction (Figure 9).

3.4 Interference Study

Wideband interference was studied by moving the transmitter to Table Mountain, 14.4 km north of Williams Village (Figure 5). A vertically polarized signal was transmitted directly south towards Williams Village. The receiver was positioned at several locations used in the Area Coverage Survey and scanned to determine received signal strength using both vertical and horizontal receive antennas.

4. DATA PROCESSING

The two channels of wideband data were digitally recorded and transferred to a micro computer for processing. Data were stored as a time series representing the cophase and quadphase baseband signals. At each of the 45 stations, which were occupied for both transmitter heights and sometimes several receiver mast heights, approximately 520 complex short code-word channel responses were recorded. This data was edited and a total of 103 recordings were selected for final processing. Several algorithms were used to reduce the channel response data to time and frequency domain parameters for each station. This produced a set of parameters for each of the 500-plus channel responses for each recording. These parameters are:

1. Excess Path Loss,
2. Delay Spread,
3. Correlation Bandwidth,
4. Frequency Selective Fading.

The average values of these parameters for each recording were then used to calculate distributions or scatter plots for each transmitter height. The algorithms for parameters 2 and 3 can be found in [2]. Only additional data processing and calibration methods will be discussed here.

5. CALIBRATION AND PROCESSING ALGORITHMS

Excess path loss was determined by comparing the received signal energy to the average received signal energy over the calibration path on the DOC campus. This path was line-of-sight with the transmitter located on the mesa to the west of campus and the receiver van stationed in the south field. The system was configured identically to the LMDS survey system. The transmit power was set to 1 W and monitored using a power meter. This meter was connected to the transmitter using a 20-dB coupler on the output waveguide before the antenna mounting flange. The only variable elements in the system were at the receiver. Here a variable gain IF amplifier and a variable attenuator were used. The settings of these components were recorded at each site and used to obtain differences in the system gain relative to the calibration path. Received energy was calculated as in [1], as it is the integral of the power delay profile, and is referred to in the following as ΣP.

Using this convention, the excess path loss is calculated by

$$A = \Delta G - 20\log(r/r_0) - 10\log(\Sigma P/\Sigma P_0) \tag{2}$$

where: A = excess path loss
ΔG = $G - G_0$
G_0 = system gain for calibration path
G = system gain
r_0 = calibration path length
r = path length.

Frequency selective fading levels in proposed 20-MHz channels were calculated using the magnitude of the complex impulse spectrum. The primary concern was to normalize the received power spectrum by the spectrum of our system. This was done in order to obtain a flat power spectrum over the desired bandwidth. A development of the frequency selective fading algorithm follows.

We can express the received signal as

$$x(t) = \frac{\gamma}{2kr} h * p(t) \tag{3}$$

where $2kr$ (k the wave number, r the path length) provides the general "free space path loss", γ is a "receiver gain" which includes the receiving antenna and a factor to convert from "field strength" to A/D values, p is the (emulated) transmitted pulse and includes the transmitter power and antenna effects as well as the triangular shape, and finally, h is the impulse response of the radio channel except that the free space propagation effects have been removed. We assume that all the signals have been reduced to base band and, therefore, that x, h, and p are *complex* signals with real (cophase) and imaginary (quadphase) components.

In the frequency domain, we can write

$$X(f) = \frac{\gamma}{2kr} H(f)\, P(f) \tag{4}$$

where we use the convention that Fourier transforms are represented by their corresponding capital letters. What we really want to display is the function $H(f)$.

Calibration data from the DOC south field provides a propagation path that seemed very clean and free of obstructions or scatterers. Using the subscript 0 for this path, we can assume that the impulse response $h_0(t)$ is just the delta function, so that $H_0(f) = 1$ and

$$X_0(f) = \frac{\gamma_0}{2kr} P(f) . \tag{5}$$

This is nearly our final result, but we need to know more about the function $X_0(f)$.

We can suppose that the measured signal in the calibration run had the form

$$x_0(t) = x_1(1 - |t|/\tau) \quad for\ |t| < \tau \tag{6}$$

and, therefore,

$$X_0(f) = x_1 \tau\, sinc^2(\pi f \tau). \tag{7}$$

We know that τ is 2 ns. All that remains is to estimate the amplitude x_1. One could look at the calibration run and measure an average peak value. But another way is to use an average "energy," which is also available from the calibration run, because then we would have

$$\|x(t)\|^2 = \int |x(t)|^2 dt = x_1^2 \frac{2}{3} \tau . \tag{8}$$

Such a computation shows an "energy" equal to 10.7 ns, therefore $x_1 = 2.83$.

To express these results in decibels, we would write

$$10 \log |H(f)|^2 = (G_0 - G) + 20 \log(r/r_0) - 20 \log x_1 \tau + 10 \log \frac{|X(f)|^2}{\sin c^4(\pi f \tau)} \tag{9}$$

and we would plot the negative of this as excess path loss. If we express τ in seconds, we find

$$20 \log x_1 \tau = 164.9\ dB$$

and we can include this as a constant to simplify the path loss expression.

In practice, it is not possible to extract the power spectrum over the entire 1-GHz bandwidth. As the power spectrum approaches its nulls, the available signal power drops below the noise spectrum. This effect is further complicated by the variable signal-to-noise ratio of the data set. Since these effects cannot be avoided, we decided to use the spectrum between -100 and 100 11Hz. Over this bandwidth, the spectrum was always above the noise floor and it was possible to normalize by $sinc^4$ ($\pi f\tau$). The normalized spectrum was then divided into ten 20-MHz channels and the average excess path loss and the *max-min* excess path loss or Δ excess path loss for each channel was calculated. For a typical station with 520 recorded impulses, 5200 average excess path loss, and Δ excess path loss numbers were calculated. This data is referred to as excess path loss per channel and Δ excess path loss per channel. Also tabulated were the average and median values of these data for each station. The averaged results are labeled average excess path loss per channel and average Δ excess path loss per channel and plotted as distributions for each transmitter height.

Because the transmitter was located behind glass in Williams Village and no glass was present on the calibration path, an additional calibration constant was needed for excess path loss data. Measurements showed that the 0.125-in tinted glass in the Towers added 3 dB of attenuation at 30.3 GHz. This constant was subtracted from excess path loss results.

6. RESULTS

6.1 Area Coverage Survey

A list of processed data grouped by transmitter height is given in Table 1. The list associates station number with data file name and lists the input parameters needed for data processing. It also gives the LOS and OLOS determinations for each station and receiver height. From this table, the station path length distribution can be determined. This distribution (Figure 10) has a median value of 4.5 km.

The data processing sequence is illustrated by a series of plots. First, a set of time series parameters for each station is calculated. Figures 11 through 13 show typical results for Station 26. Figure 11 shows the received power and excess path loss for the 514 impulse recordings with the transmitter on the 13th floor of Williams Village. Figure 12 is a similar plot for delay spread calculated using different threshold values. Figure 13 shows the received impulse dynamic range (DYR) and correlation bandwidth (CBW) results for this station. The DYR plot is the ratio of the peak of the impulse to the peak of the last 10 percent of its tail. These data are then used to calculate an average and standard deviation for each parameter.

Figure 14 shows some of the raw data for Station 26. Here the channel impulses with the minimum and maximum delay spreads are displayed. Figure 15 shows two real FFT's used for correlation bandwidth calculations. The frequency where magnitude drops below 0.5 was plotted as a time series in Figure 12.

The next set of graphs show typical results from frequency selective fading calculations. Figure 16 gives the magnitude of the complex power spectrum for the minimum delay spread impulse and also the normalized excess path loss for this impulse (Station 26, file u3p28). These frequency domain data are then separated into ten 20-MHz channels between -100 and 100 MHz. The average excess path loss and the Δ excess path loss are calculated for each channel. Figure 17 shows similar spectrum plots for Station 1 (u3p37). Distributions of these data for the ten channels are given in Figures 18, 19, 20, and 21. In order to make distributions for the two station groupings (13th floor transmitter versus 5th floor transmitter), averages, standard deviations, and median values were calculated for each distribution and tabulated by station; these results are listed in Tables 2 and 3. The delay spread calculations used 10 dB, 15 dB and noise plus 3 dB thresholds. Where the noise level is set to the peak signal for the last 10 percent of each impulse record. If the range between peak signal and the noise is less than the threshold plus 3 dB, that impulse is thrown out from the delay spread calculation.

Scatter plots of wideband excess path loss versus distance for the two transmitter heights are given in Figures 22 and 23. We see some higher losses, especially close in, for the lower transmitter height. Also, we see more stations with near zero excess path loss, at longer path lengths, for data collected using the 13th-floor transmitter site. Distributions for these two data sets are given in Figures 24, 25, 26, and 27. Here we see a median excess path loss of 18 dB and 15 dB, respectively, for the lower versus higher transmitter location. Distributions of average excess path loss per channel for the two cases show similar median values as compared to their wideband counterparts, but show slightly larger variance in the data sets. This is probably due to the averaging which was done over a smaller bandwidth (20 MHz) when the data was reduced to ten channels. These results are given in Figures 28, 29, 30, and 31.

The distributions of average Δ excess path loss per channel for the two transmitter heights are similar, with median values between 2 and 3 dB but with more outliers for the lower transmitter site. These data are shown in Figures 32, 33, 34, and 35. Distributions for average delay spread, Figures 36 through 39, indicate median values of less than 1 ns at both transmitter heights. This is at the resolving limit of our system and is partially due to the choice of a 10-dB threshold. For a 30-dB threshold, this limit is 0.8 ns; a 10-dB threshold raises this limit by truncating the base of the received pulse. The correlation BW results are also given using distributions. These distributions show a median value of 225 MHz for the lower transmitter and 250 MHz for the sites surveyed using the higher transmitter. These results are given in Figures 40 through 43.

6.2 Passive Repeater Study

Table 4 gives a summary of the measured passive repeater loss versus angle. We measured losses between 4 and 6 dB. These losses can be attributed to scattering off the tripod and surrounding buildings as well as the surface of the reflector which was not perfectly flat. The 3-dB antenna pattern of the plate was measured at 0.2-degrees. This is consistent for a 1.2-m^2 reflector operating at 28.8 GHz [1]. This made aiming the reflector difficult. Antenna patterns for the repeater are shown in Figures 44 and 45. Cross polarization was measured by transmitting a vertical signal and measuring both vertical and horizontal polarizations at the receiver. Cross polarization varied between 16 and 24 dB and is shown versus angle in Figure 46.

6.3 Diffraction Study Results

The diffraction data are reported in Table 5. The stations selected were blocked from direct line of sight by the 3100 Marine Street NOAA building (Figure 6). By using the heights of the transmitter and receiver antennas, a diffraction angle was calculated. This angle is the deviation from LOS (from the transmitter to the top of the obstruction) that the transmitted signal must make to reach the receiver. Results indicate excess path losses of 35 dB to 9 dB for a range of angles from 5 to -0.46 degrees. A small negative angle indicates that there was a geometrical line of sight but that the radio signal was partially blocked. These results are compared to knife-edge diffractions calculated for the same angles [3]. The measured results do not have the smooth variation of the calculated ones. This may be due to additional obstructions on path, the non-ideal roof of the NOAA building, and uncertainty of elevations. In addition, there was an instrumentation shed on the NOAA roof which could have effected the signal diffraction.

6.4 Interference Study

A vertically polarized transmitter was pointed at Williams Village from a distance of 14.4 km. A direct signal was recorded at some locations but no reflected signals from Williams Village were measurable at the surveyed sites for either polarization. The surveyed sites are listed in Table 1.

7. CONCLUSIONS

7.1 Area Coverage Survey

Randomly selected single and multiple family dwellings in Boulder, CO, were surveyed to determine area coverage parameters for proposed LMDS channels. Signals were transmitted from two heights in Williams Village, 16 and 40 m, and received at an instrumentation van equipped with mast-mounted horn antennas. Radio path lengths for the survey varied between 1981 and 6927 m with a median value of 4.5 km. For each location, a time series of wideband 30.3-GHz signals was analyzed for excess path loss, delay spread, correlation bandwidth, and frequency selective fading.

The measured excess path losses were consistent with signals propagating over the tops of or through one to four trees without leaves [4]. The range of excess path losses varied from -6 dB to +32 dB. The median value for the 16-m transmitter height was 18 dB and for the 40-m height was 15 dB.

Multipath interference was minimal for the survey due to the directional receive antenna which had a beam width of 5.5 degrees. Using a 10-dB threshold, measured delay spreads were between 0.7 and 10 ns with a median value of less than 1 ns for both transmitter heights. Correlation bandwidth for these stations ranged between 11 and 471 MHz and 2 and 491 MHz for the upper and lower transmit heights, respectively. Median values for the two transmit heights were 250 and 225 MHz, respectively.

The complex spectrum of the signal was also analyzed to determine frequency selective fading for ten 20-MHz channels. The average excess path loss per channel for these data correlated with the wideband excess path loss results. However, the variance of this data set was 1 to 2 dB larger. This probably was due to the greater bandwidth over which the signals were averaged in the wideband case. The max-min (Δ) excess path loss per channel for all stations had a median value between 2 and 4 dB for both transmitter heights. This is consistent with the small delay spreads measured. The maximum average Δ excess path loss per channel for any station was 10 and 22 dB for the high and low transmitter sites, respectively.

7.2 Passive Repeater Study

Measurements of received power and cross-polarization effects were made for a range of angles between 3 and 109 degrees. Results indicate 16 to 24 dB cross polarization and 4 to 6 dB losses due to the non-ideal repeater and interference. The measured antenna pattern for the repeater was 0.2 degrees and this is consistent with theoretical results for a flat plate operating at 28.8 GHz. This made aiming the repeater difficult and would require surveying equipment and a skilled technician. It also makes it difficult to serve more than one or two households from each repeater location.

7.3 Diffraction Study Results

Four stations were measured in the shadow of the NOAA Marine Street facility. The diffraction angle for these sites varied between -0.03 and 3 degrees and excess path loss ranged between 9 and 35 dB.

7.4 Interference Study

An adjacent cell transmitter was set up to study possible cell-to-cell interference. No such effects were measurable using both vertically and horizontally polarized receive antennas aimed at Williams Village.

8. REFERENCES

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