Fade Measurements Into Buildings From 500 To 3000 MHz

Wolfhard J. Vogel and Geoffrey W. Torrence
Electrical Engineering Research Laboratory
The University of Texas at Austin
Austin, Texas 78758, USA

Abstract - Slant-path fade measurements from 500 to 3000 MHz were made into six different buildings employing a vector network analyzer, a tower-mounlecl transmitting antenna and an automatically positioned receiving antenna. The objective of the measurements was to provide information for satellite audio broadcasting and personal communications satellite design on the correlation of fading inside buildings. Fades were measured with 5 cm spatial separation and every 0.2% of the frequency. Median fades ranged from 10 to 20 dB in woodframe houses with metal roofs and walls without and with an aluminum heat-shield, respectively. The median decorrelation distance was from 0.5 to 1.1 m and was independent of frequency. The attenuation into the buildings increased only moderately with frequency in most of the buildings with a median slope of' about 1 to 3 dB/GHz, but increased fastest in the least attenuating building with a slope of 5 dB/GHz. The median decorrelation bandwidth ranged from 1.2 to 3.8% of frequency in five of the buildings, and was largest in the least attenuating building, with 20.296 of frequency.

1. INTRODUCTION

Slant path indoor fade data arc nccdcd to support the design of satellite services such as audio broadcasting, messaging, paging, and telephony with information about the temporal, spatial and frequency structure of the satellite signal

Propagation measurements for slant-path into-building fading have previously been reported for (he frequency range fron 1700 to 1800 MHz. (swept) [1] and at 1.6 and 2.5 GHz (simultaneously) [2]. The latter measurements were made to provide guidance for the design of satellite telephony and paging systems using CDMA modulation and requiring power control, while the former were targeted towards the application of broadcasting from geostationary satellites. Each set of experiments used receiving antennas with reasonably realistic patterns, i.e., the dual frequency measurements employed azimuthally omni-directional antennas interacting more fully with the multipath environment inside buildings than the relatively directive receiving antenna of the broadcast reception measurements. This experiment used onc each wide-band transmit and receive antenna. Data were generated in the swept-cw mode, thus permitting a deterministic comparative assessment of the spatial and frequency structure of the received power levels over the frequency range from 500 to 3000 MHz.

After describing the experimental setup and data acquisition procedures and locations, wc present the results from our wideband swept into-building measurements in terms of the observed spatial and frequency characteristics and draw some conclusions.

Table 1: Building Names, Construction Details, and Elevation Angles.

Building Name	Approx. Year of Constr.	Wall Type	No. Of Stories	Roof Type	Avg. Elev. (°)	Avg. Dist. (m)
Commons Entry	1987	concrete tilt wall	1	tar	18	16
EERI, office	1944	block brick	1	tar	38	8.8
Farmhouse	1880	wood frame	2	metal	33	19,2
House Hallway + LR	1976	wood frame	2	metal	41	12
MER Lobby	1992	glass, concrete	2	tar	26	s
Motel Room	1980	brick	2	compos.	37	16

11. EXPERIMENTAL SETUP

The major components for this experiment were a 20 m crank-up transmitter tower mounted to the top of a van, a vector network analyzer (VNA), a personal computer (PC) and a linear positioner. The "Device Under Test" in this case consisted of a pair of wide-band antennas and the intervening path. The measurement determined the path loss as a function of' frequency and location. The PC controlled the VNA and linear positioner, and stored the data from the VNA.

The measurement strategy was to mount the transmitting antenna on the fully extended tower outside of the building to be tested. To establish a calibration, the receiving antenna first was positioned directly outside of the building, at a location without obstructions of the line-of-sight path, and both antennas were pointed at each other. Then one or more series of 16 sweeps were recorded, as the positioner was moving the receiving antenna in the direction of the transmitter in 5 cm steps between each sweep. This motion changed the multipath for each sweep. The smoothed average of the 16 unobstructed sweeps gives a very good estimate of the free space received power. For the. measurements, the receiving antenna was moved inside, both antennas were re-pointed, and another series of 16 sweeps was taken. The fully extended positioner was then retracted and moved to place the antenna 5 cm past the last sweep's position, and another series of 16 sweeps was taken. This was repeated as often as the size of the building under test allowed. Each set of 16 sweeps took about half an hour, with measurements in a large building taking many hours to complete. To make the measurements repeatable over a long duration, the tower was held rigid with guy wires.

Calibrations were repeatable to <1 dB inside the 700-2500 MHz range and <2 dB outside of it. In the absence of interference there was about 1 dB uncertainty due to thermal noise at 40 dB loss up to 2 GHz, falling to 30 dB at 2.5 GHz, and only about 20 dB at 3 GHz. In the city, when near cellular phone towers, interference added about 1 dB uncertainty at 30 dB loss and rapidly worsens below 900 MHz and above 2.5 GHz. However, this is for outdoors reception; for measurements inside buildings the interfering signals were attenuated as were the measurement signal, and therefore had only a small effect.

III. MEASUREMENT DETAILS

Measurements were made into six different buildings. Pertinent details are summarized in Table 1. All buildings were in the far-field of the transmitting antenna, A picture of the farmhouse, a sketch detailing the locations of walls, windows, and doors and the transmitter tower is shown in Figure 1. The measurement tracks are designated by dashed lines and the positioner locations for each series of 16 sweeps are numbered. Although the transmitting antenna has large beamwidth, it was re-pointed repeatedly (by remote control) to track the moving receiver direction to within $\pm 10^{\circ}$. The measurements were performed in dry weather.

IV. RESULTS

A. Time Variability

Previous experiments [1,2] have demonstrated conclusively that as long as the transmitting antenna and the receiving antenna are held stable, the time variability of transmissions into a building is very small, i.e., time variations are due to spatial variations converted to time. variations by motion. In this new measurement campaign, therefore, no new time variability data were obtained.

B. Space Variability

Average signal levels over the entire 500 to 3000 MHz band **were** calculated for each receiver position. The results are summarized in Figure 2 by a box anti whisker plot, which shows the mean, ± 1, and $\pm$ 1.96 standard deviation with respect to position in each of the six buildings. The building with the best radio frequency penetration was the Farmhouse (median = -5 dB), the worst was the House (median = -19.5 dB). Both have metal roofs, but the House aiso has an aluminum heat shield in all exterior walls. The other buildings fell into the range of -9 dB to -13 dB. Note that these data include some positions for which the receiving antenna was located in an open door or window in sight of the transmitter.

Examples of the signal level as a function of position at four frequencies (1 023, 1463, 2093, 2992 MHz) for the Motel have been plotted in Figure 3. At measurement sites where the receiving antenna was moved towards an open door or window, a dramatic increase of received power can be observed as the antenna comes within the view of the transmitter. In the Motel, for instance, the signal is 15 to 30 dB below the line-of-sight level while the direct path penetrates the wail. It increases

to near 0 dB as the antenna moves through the open door. The levels inside the House, with 25 to 45 dB below the line-of-sight, were the lowest of all the buildings measured, probably because its construction includes a metal roof and a tight energy-conserving aluminum heat shield under the cedar exterior.

To quantify the spatial variability of the signal level, autocorrelations were calculated at all 897 sample frequencies for lags from O to 3.2 m. Figure 4 is an example of the spatial autocorrelation vs. frequency for EERL at a lag of 50 cm, where the median value of the correlation has decreased to 1/e (37%). Contrary to intuition, the overall data do not exhibit a clear frequency dependence. One would expect that the spatial autocorrelation in a strong multipath environment decreases twice as fast at 3000 MHz than at 1500 MHz, because the wavelength at 1500 MHz is 20 cm compared to 10 cm at 3000 MHz. One reason for this may be the 15 cm diameter aperture size of (he antenna,

Table 2: Spatial Decorrelation Distance

Building Name	Median Decorrelation Distance (m)
Commons Entry	1.1
EERL Office	0.5
Farmhouse	0.85
House Hall + LR	0.55
MER Lobby	0.7
Motel Room	0.55

The decrease of the autocorrelation with distance at 1625 MHz has been plotted in Figure 5 for the House, MER, and the Motel. The slowest decrease was observed in the Commons, with a decorrelation distance of 1.1 m. The other buildings had more rapidly decreasing autocorrelation, with decorrelation distances from 0.85 to 0.5 m. l'able 2 summarizes these results.

A normal probability plot of the autocorrelation at lag L, the median decorrelation distance for each building, has been plotted in Figure 6. A straight line in this graph would indicate a normal distribution. None of the curves represent a normal distribution, but the graph illustrates the variability of the decorrelation distance with frequency.

C. Frequency Variability

Figure 7 is an example of the signal level changes with frequency. The 8th sweep of the first series of 16 sweeps was plotted. Generally, variations with frequency arc quite rapid, as would be expected in a multipath environment, The slowest changes were observed in the Farmhouse, and it also exhibited the most decrease in level from the low to the high end of the band. A typical example of the frequency dependence of building penetration is depicted in Figure 8 for the Farmhouse, where the level decreased by 6 dB/GHz. The signal level slope, in dB/MHz, has been calculated for each sweep and the results arc summarized in Figure 9 by a box and whisker plot, which shows the mean, ± 1, and ±1 .96 standard deviation with respect to slope in each of the six buildings. The largest slopes were found in the Farmhouse. The least slope was measured at MER. This building has a glass curtain wall. The glass used for this building is energy-conserving, i.e., it reflects at RF. It is well known that the transmission through glass depends on the surface resistivity of its metallic coating and is not a function of frequency.

The autocorr elation of frequency variability reveals information about the utility of rake receivers to mitigate fading and the possibility of power control on the up-link (mobile to satellite) at onc frequency using knowledge of the fade on the down-link (satellite to mobile) at another frequency. An example of the autocorrelation at a given receiver location is plotted for each building in Figure 10. In five of six buildings the decorrelation bandwidth ranges from about 1% to 4% of the frequency. Noticeably slower decorrelation occurs in the Farmhouse with a decorrelation bandwidth of aboot 12%. Table 3 summarizes the frequency decorrelation results.

A normal probability plot of the autocorrelation at lag L, the median decorrelation bandwidth for each building, has been plotted in Figure 11. A straight 1 ıne in this graph would indicate a normal distribution. None of the curves represent a normal distribution, but the graph illustrates the variability of the decorrelation bandwidth with position.

V. CONCIXJS1ONS

We have observed the space and frequency

Table 3: Decorrelation Bandwidth

Building Name	Median Decorrelation Bandwidth (% frequency)
Commons Entry	2.0
EERL Office	3.6
Farmhouse	20.2
House Hallway + LR	1.6
MER Lobby	1.2
Motel Room	3.8

domain structures of simulated satellite signals from 500 to 3000 MHz propagated into six buildings on a slant path. Our findings are:

1. The attenuation 'of slant-path microwaves transmitted into buildings depends on the type of construction; the best (10 dB median) and worst (20 dB median) cases were woodframe houses with metal roofs and walls without and with an aluminum heat-shield, respectively (Fig. 2).
2. Attenuation was greater when the line-of-sight was obstructed by a concrete wall than by window glass, for instance.
3. The median decorrelation distance ranged from 0.5 to 1.1 m (Fig. 6) and was not dependent on frequency (Fig. 4).
4. The attenuation into the buildings increased only moderately with frequency in four of the buildings with 'a mean slope of about 1 to 3 dB/GHz, but increased fastest in the least attenuating building with a mean slope of 6 dB/GHz. The mean slope was near zero for the glass-walled MER building,
5. The median decorrelation bandwidth ranged from 1.2 to 3.8% of frequency in five of 'the buildings, and was largest in the Farmhouse, with 20.2% of frequency.

ACKNOWLEDGMENT

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REFERENCES

[1] Vogel, W. J. and G.W. Torrence, "Propagation Measurements for Satellite Radio Reception Inside Buildings," *IEEE Transactions on Antennas and Propagation*, Vol. 41, No. 7, pp. 954-961, July 1993

[2] Vogel, w'. J., G. W. Torrence, and H.-P. Lin, "Slant-Path Building Penetration Measurements at L- and S-Band," *Electrical Engineering Research Laboratory Report*, EERL-95-301, 23 March 1995

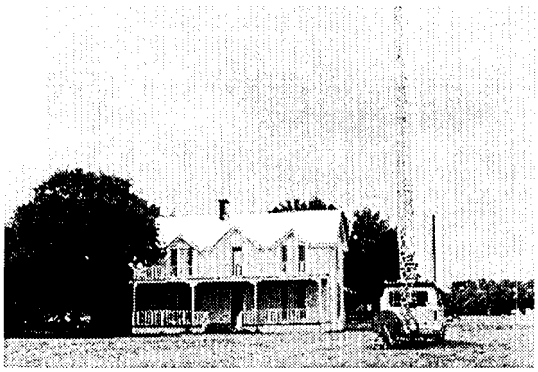

Fig. 1a: The Farmhouse, now with a sheet-metal roof.

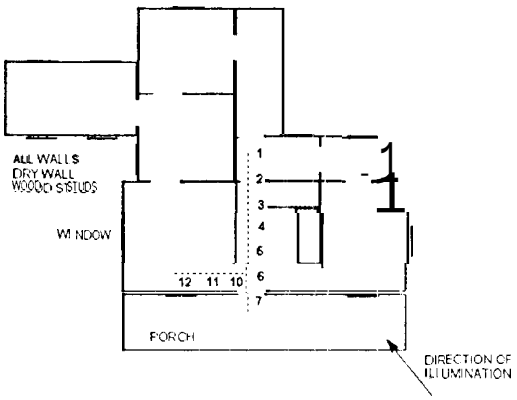

Fig. lb: Floor-plan of the measurement locations in the Farmhouse.

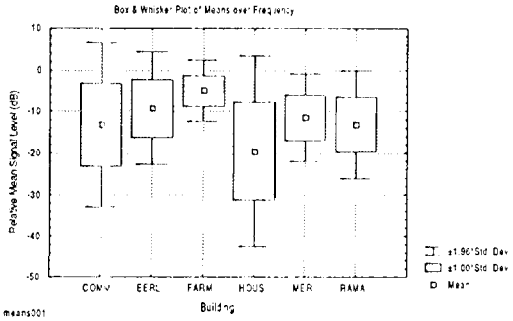

Fig. 2: Box and whisker plot for the distribution of the mean signal levels with respect to frequency.

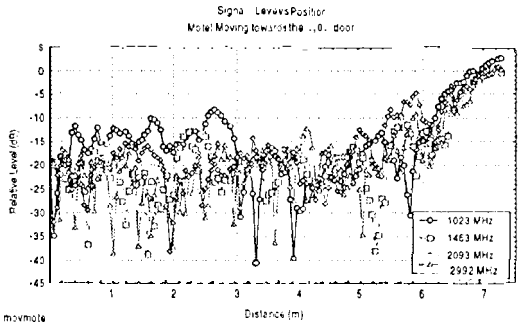

Fig. 3: The relative signal level vs. position at four frequencies in the Motel.

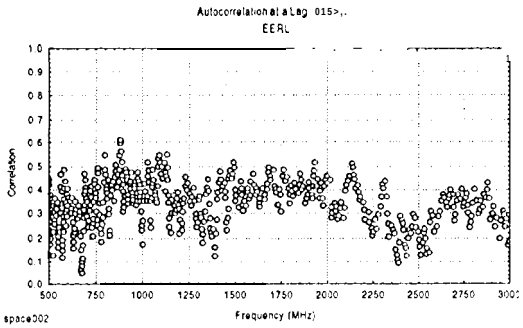

Fig. 4: Spatial autocorrelation at a lag of 50 cm in EERL.

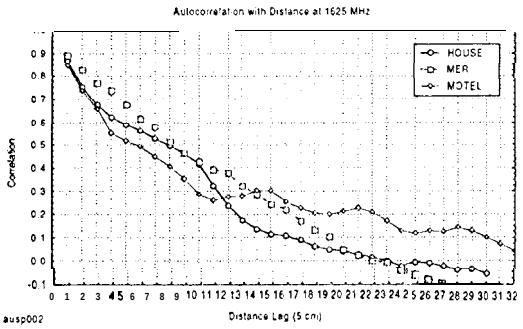

Fig. 5: The spatial autocorrelation vs. distance lag in the House, MER, and the Motel.

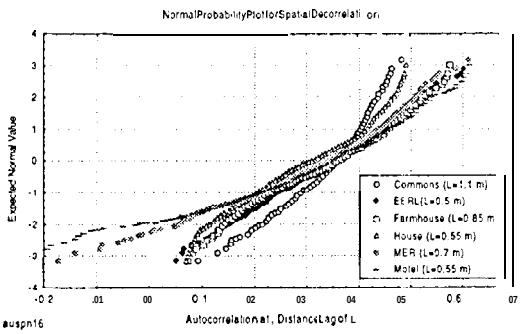

Fig. 6: A normal probability plot for the spatial autocorrelation at the decorrelation distance in the six buildings.

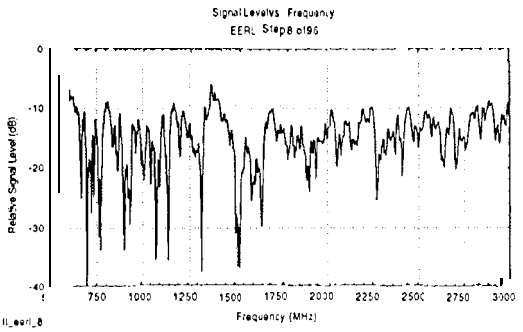

Fig. 7: Signal level vs. frequency in EERL.

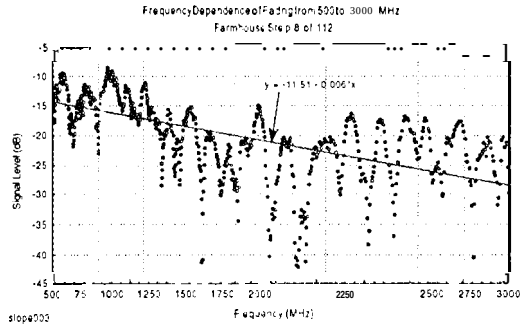

Fig. 8: Frequency dependence of fading from 500 to 3000 MHz in the Farmhouse.

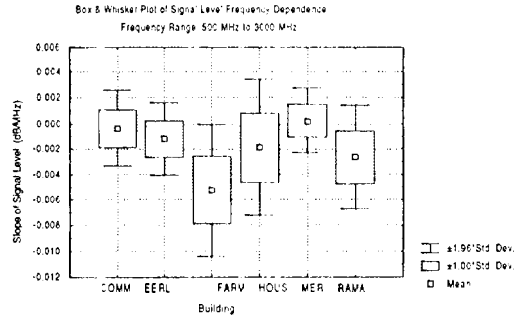

Fig. 9: Box and whisker plot of the signal level slope with frequency in the six buildings.

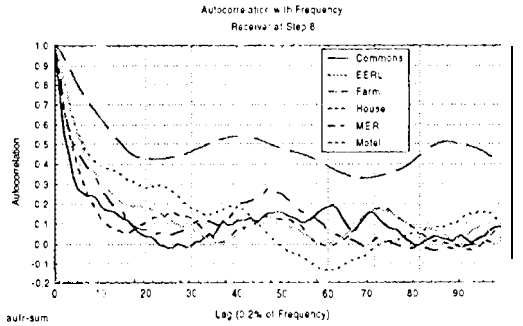

Fig. 10: The frequency autocorrelation in each building at Step 8 for lags from O to 20% of the frequency.

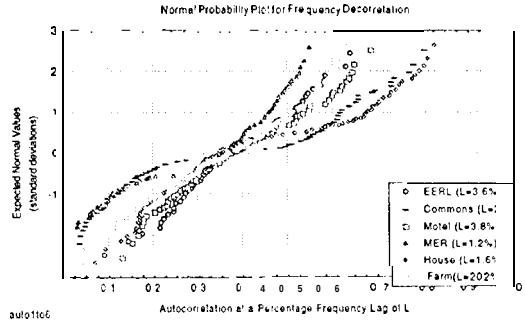

Fig. 11: Frequency autocorrelation at the decorrelation bandwidth in the six buildings.