A CHARACTERIZATION OF THE MULTIPATH IN THE HDTV CHANNEL

George Hufford
National Telecommunications and Information Administration
Institute for Telecommunication Sciences
325 Broadway, Boulder, CO 80303-3328

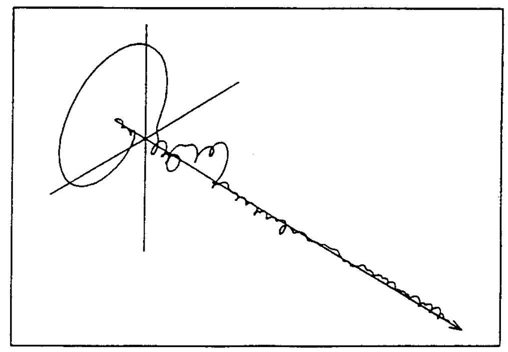
Abstract. The Institute for Telecommunication Sciences (ITS) has recently completed a program to measure the impulse responses of channels that would probably be used in over-the-air HDTV. To help in the analysis of these measurements, we have developed a simple statistical model which needs only two parameters together with a rough idea of the "archetypal" surroundings of the receiver. The two parameters—the "strength" and the "spread" of the "multipath tail"—then serve as a description of our data and we may tabulate the results versus changes in known system parameters. We may also propose the model as a fairly realistic simulation of "normally observed" multipath.

Introduction. High definition television (HDTV) is an example of a wideband communication system, and as such it suffers multiplicative noise whenever there is multipath in the propagation channel. For the design and testing of such systems it is helpful to know how much multipath they will find and what its characteristics are. This is particularly true of an over-the-air service in and around an urban area.

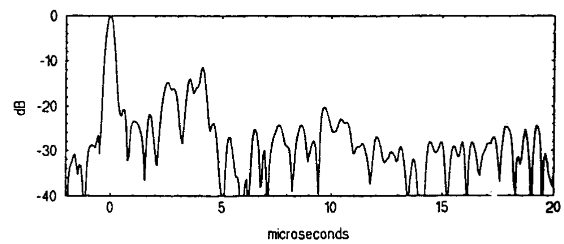
The Institute for Telecommunication Sciences (ITS) has recently been engaged in a program to measure the multipath environment in situations that correspond closely to current television channels and also to what might become the over-the-air HDTV channel. In these measurements the transmitter was an actual operating television station and the receiver, a mobile van equipped with 9-m high antennas.

The most direct measurement of multipath is the normalized impulse response, and this is what we tried to measure. To do this, a teletext-style sequence of zero and one bits was inserted into one of the frames of the vertical blanking interval of the transmitted signal from the cooperating television station. At the receiver the frame was isolated and the signal sampled, digitized, and recorded. Then the recorded data were transferred to a small personal computer and analyzed off-line. Details of the system, together with many sample measurements, may be found in [1] and [2].

An example of a measured impulse response is shown in Figure 1. It is a complex function of time since the carrier wave has been divided out. Its spectrum, as shown in Figure 2, displays mostly the effects of the vestigial sideband modulation and the shaping the signal must undergo to avoid interfering with the audio output.



(a)



(b)

Figure 1. A measured impulse response from a location in an urban area in Millbrae, Calif.: (a) A 3-D representation of the complex-valued voltages; (b) the amplitude of the same response function.

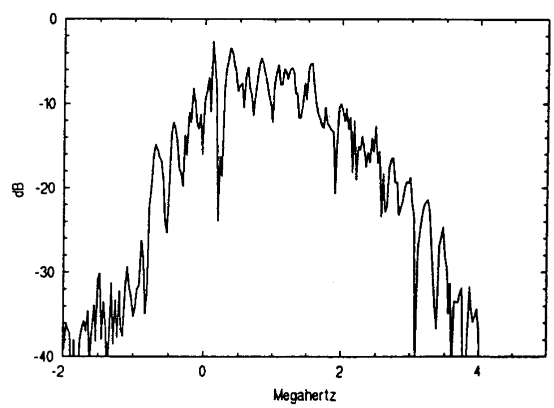


Figure 2. The spectrum of the impulse response in Figure 1.

A simple model. To help in the analysis of our data, we have devised a very simple model into which we shall try to fit our measured responses. The model derives inspiration from Cox [3] and assumes the impulse responses form what Bello [4] calls a GWSSUS (Gaussian Wide Sense Stationary Uncorrelated Scatterers) process. Our notion is that it is possible to choose *archetypal* regions within which the statistics of observed impulse responses will be homogeneous. These would be regions of moderate size that can be characterized by the kind of structures and the amount of vegetation present. For example, we might talk of an "urban high rise" region or a "wooded residential" region. At locations in such a region we would expect multipath components to have about the same mixture of amplitudes and the same time delays, and therefore the impulse responses to

0018-9316/92$03.00 © 1992 IEEE

have the same sort of appearance. As a statistical ensemble they should be describable with only a few parameters.

Given an archetypal region, we then assume that measured impulse responses form a Gaussian process with multipath components (scatterers) infinitely dense and all pairwise independent. Replacing the infinitely dense components with a more tractable sequence spaced by the small interval τ and assuming a simple exponential behavior to the overall shape, we suppose the impulse response can be written in the form

$$h(t) = \delta(t) + \sqrt{\frac{r\tau}{T}} \sum_{j=1}^{\infty} e^{-j\tau/2T} z_j \delta(t - j\tau), \qquad (1)$$

where r and T are parameters and where the z_j are complex-valued random variables. All the z_j are pairwise independent and their real and imaginary parts are independent Gaussian variables with zero means and standard deviations equal to $\sqrt{1/2}$. In consequence, the amplitudes are Rayleigh distributed and the phases uniformly distributed. The first term here is the direct wave which has been normalized to an in-phase unit impulse. The subsequent summation is then a "tail" of randomly sized multipath components. As we have implied, (1) is an approximation which improves as τ becomes smaller.

This equation is supposed to represent the impulse response of the propagation channel as it exists between the transmitting and receiving antennas. What we measure will also include transmitter and receiver distortion and especially the characteristics of a band limited transmitted pulse shape. Let $s(t)$ be the system pulse—the transmitted pulse as altered by the equipment involved. Then what we measure takes the form

$$x(t) = s(t) + \sqrt{\frac{r\tau}{T}} \sum_{j=1}^{\infty} e^{-j\tau/2T} z_j s(t - j\tau). \qquad (2)$$

In particular, the expected total energy in this received signal is

$$\mathcal{E}\left\{ \int |x(t)|^2 \, dt \right\} = S_0 + \frac{r}{T} \sum_{j=1}^{\infty} e^{-j\tau/T} S_0 \, \tau \approx (1 + r) S_0, \qquad (3)$$

where S_0 is the total energy in the system pulse. From this equation we see that r measures the *strength* of the multipath tail and is, indeed, the ratio of the energy in the tail to that in the direct signal. We also note that T is a measure of the *delay spread* of the tail—after a time T, the expected power will have dropped by a factor $1/e$. In Figure 3 we have plotted the amplitude of a simulated pulse, using the formula in (2) with parameters r and T that fit the curve in Figure 1. The curves in Figures 1 and 3 seem fairly similar, at least for the first few microseconds. Admittedly, after about 5 μs the measured curve in Figure 1 becomes buried in noise, and the similarity stops.

The Fourier transform of (1) is also a random process. It is a random function of the frequency ν which is Gaussian and stationary and has, because of the direct wave, mean 1. Its autocorrelation function is given by

$$\mathcal{E}\left\{ (H(\nu) - 1)(H(\mu) - 1)^* \right\} = \frac{r}{1 - 2\pi i(\nu - \mu)T}, \qquad (4)$$

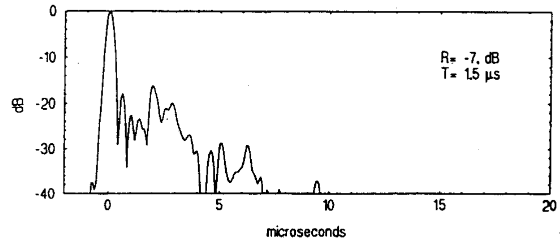


Figure 3. A simulated response function using parameters that might describe the function in Figure 1.

which is a function only of the difference $\nu - \mu$, as it should be. The Fourier transform of (2) is, of course, just the transform of (1) except that it is multiplied by the spectrum $S(\nu)$ of the system pulse.

Summarizing the Data. To fit our measured data to this proposed model we need only estimate values for r and T. This means, however, that we must somehow remove the effects of the system pulse. There are several ways one might suggest to do this, but most of them require a fairly accurate knowledge of this pulse, and unfortunately that is not available to us. We even suspect the system pulse we used changed from day to day. The approach we have finally taken is the following.

Let $p(t) = \mathcal{E}\{|x(t)|^2\}$ be the expected power at each delay time t so that if $x(t)$ is derived from (2) we have

$$p(t) = |s(t)|^2 + \frac{r}{T} \int_0^{\infty} e^{-u/T} |s(t - u)|^2 \, du. \qquad (5)$$

Now let us suppose that $s(t)$ is of finite duration and that after the fairly short time span t_0 we may assume it vanishes. Then we set $q(t) = \int_t^{\infty} p(t)\, dt$ and we find, after some reduction, that whenever $t \geq t_0$

$$q(t) = r B(T) e^{-t/T}, \qquad (6)$$

where

$$B(T) = \int_{-\infty}^{\infty} e^{t/T} |s(t)|^2 \, dt.$$

To estimate r and T what we have done is to evaluate $q(t_0)$ and to find a t_1 so that $q(t_1)$ is approximately half of $q(t_0)$. We then solve, finding

$$T = \frac{t_1 - t_0}{\ln\left(q(t_0)/q(t_1)\right)}, \qquad r = \frac{q(t_0) e^{t_0/T}}{B(T)}. \qquad (7)$$

To estimate $p(t)$, we simply take the measured impulse responses for a single archetypal region—a region that we believe is homogeneous—and average together the corresponding functions $|x(t)|^2$.

The resulting process seems to be fairly robust. It depends on the system pulse only in the choice of the time t_0 and in the function $B(T)$, both of which are rather insensitive to small system changes. A measure of this would be to find how variable these statistical estimations are. To do this, we have subjected some of our archetypal sets to the so-called "jackknife" approach (see, *e.g.*, [5]), and we have found standard deviations for estimations for r of the order 0.5 dB and for T of the order 1 μs.

Table 1. Multipath characteristics for a variety of archetypal regions as measured with omnidirectional antennas. The columns describe the region, the number of measured sites, the multipath strength R, and the delay spread T.

	VHF			UHF		
	no.	R (dB)	T (μs)	no.	R (dB)	T (μs)
Rural flat						
East of Denver, 60 km	11	−13.3	5.55	14	−13.6	6.06
Rural rough						
Lyons, 50 km	8	−14.4	3.54	6	−12.2	1.23
Santa Cruz Mtns, 40 km	5	−6.6	2.97	6	−8.1	.82
Open residential						
Boulder, 30 km	10	−13.8	5.97	10	−11.8	7.58
Thornton, 30 km	11	−15.3	1.53	9	−15.2	5.65
Piedmont, 19 km	6	−8.5	1.32	9	−11.5	1.66
Berkeley, 22 km	11	−11.4	4.45	13	−11.5	1.13
Pinole, 30 km	8	−12.4	5.98	8	−10.9	1.54
Palo Alto, 45 km	13	−14.7	4.46	14	−10.7	1.01
Fremont, 48 km	4	−11.9	2.95	14	−6.5	6.39
Wooded residential						
Denver, 25 km	8	−14.8	3.43	8	−10.0	.93
Longmont, 54 km	9	−14.6	.91	9	−11.2	3.44
Piedmont,19 km	3	−9.0	2.69	5	−10.8	1.13
Berkeley, 21 km	3	−7.4	.64	4	−12.8	2.08
Palo Alto, 41 km	5	−11.4	7.84	9	−10.4	6.07
Suburban activity center						
Boulder, 32 km	3	−4.5	1.11	3	−3.1	.84
Stanford, 42 km	8	−7.0	1.31	13	−5.7	.48
Santa Clara, 60 km	14	−6.7	4.65	12	−7.1	2.04
Urban, 3 to 5 story buildings						
Denver, 24 km	8	−2.5	2.39	6	−4.6	1.23
Cow Hollow, 4 km	3	−12.2	10.20	4	−4.7	.69
Millbrae, 17 km	7	−9.6	8.44	10	−7.4	1.62
Berkeley, 20 km	12	−8.2	3.02	18	−9.4	1.21
San Jose, 63 km	9	−3.8	.88	9	−8.5	1.74
Urban, near a high rise region						
Denver, west, 22 km	8	−13.0	2.25	7	−12.8	2.56
Denver, east, 23 km	8	−2.6	1.63	14	3.6	1.94
Denver, north, 24 km	7	−9.2	14.88	9	−12.0	7.25
San Francisco, 6 km	1	−2.0	3.67	3	−4.9	11.84
Oakland, 15 km	5	−5.9	.44	8	−2.4	.63

Table 2. Multipath characteristics for two wooded residential areas, measured in both Summer and Winter.

	Summer			Winter		
	no.	R (dB)	T (μs)	no.	R (dB)	T (μs)
Denver (25 km)						
VHF/Omni	8	−14.8	3.43	8	−12.0	1.11
VHF/LPA	8	−18.0	8.37	9	−16.6	4.37
UHF/Omni	8	−10.0	.93	9	−15.4	3.63
UHF/LPA	8	−13.5	6.92	9	−16.5	6.24
Longmont (54 km)						
VHF/Omni	9	−14.6	.91	11	−12.1	.66
VHF/LPA	9	−17.8	2.68	11	−17.4	3.15
UHF/Omni	9	−11.2	3.44	10	−12.1	3.43
UHF/LPA	9	−14.5	7.03	11	−12.0	7.38

We now have made measurements in and around the two cities of Denver and San Francisco. At each measurement site we used two frequencies—one VHF (channel 7 at both places) and one UHF (channels 31 in Denver and 44 in San Francisco). And then for each frequency there were two antennas—one omnidirectional turnstile antenna and one directional log-periodic antenna.

In Table 1 are displayed the summarized data for essentially all our measurements using omnidirectional antennas. Note that we have measured the strength r in decibels, and to remind us of this fact we have used the capital letter R. In each archetypal set the Denver measurements are first, followed immediately by the San Francisco measurements. Although there are some sore thumbs apparent, the estimated parameters seem fairly consistent. For example, the wooded residential areas in the Denver area seem to observe multipath tails of about −15 dB at VHF and −10 dB at UHF. The delay spreads seem to be in the 1- to 3-μs range. Generally, multipath appears to be from 2 to 4 dB stronger at UHF than at VHF, while delay spreads are variable and show little or no dependence on any environmental factor that we can see. In particular, note that the distance between transmitter and the measurement area (as indicated in the left column of Table 1) seems to have no influence on the delay spread or, indeed, on the multipath strength. This should be compared with other results [3] where on very short paths the multipath is of much shorter duration.

There were also a few measurements taken under winter conditions. These were made in the Denver area with snow on the ground and after the deciduous trees had lost their leaves. Results for two wooded residential areas (where one might expect the greatest effects) are shown in Table 2. In these two areas both summer and winter data were taken at almost the same points, allowing us a direct comparison. We note that the two sets are very nearly equal with perhaps the stronger multipath tails appearing in the winter. Presumably the trees in full leaf will attenuate off-path waves to produce this effect. As an aside, Table 2 also shows a comparison between the two sets of antennas. The omnidirectional antennas saw perhaps 1 to 5 dB stronger tails than did the directional antennas. This is to be expected. Table 2 also shows, however, a consistently longer tail on the directional antennas. This may be just an artifact arising from the smaller signals where such measurements are less reliable.

Conclusions. Measurements made on propagation paths approximating those to be expected in the over-the-air HDTV service show that multipath is nearly always present. Under most conditions, however, the total strength in the extra signals is small and a good digital system might well be blind to them. To test whether this is so for a given system, we would suggest using channel simulations that follow our proposed model. A reasonable signal on the "bad" side might have parameters $R = -3$ dB and $T = 5$ μs.

REFERENCES

[1] G. A. Hufford, J. R. Godwin, R. J. Matheson, V. S. Lawrence, and L. E. Pratt, "Characterization of the HDTV channel in the Denver area," NTIA Report 90-271 (NTIS Order No. PB 91-176388), 1990.

[2] G. A. Hufford, J. R. Godwin, and V. S. Lawrence, "Characterization of the HDTV channel in the San Francisco area," NTIA Report 91-278 (NTIS Order No. PB 92-108331/AS), 1991.

[3] D. C. Cox, "910 MHz urban mobile radio propagation: Multipath characteristics in New York City," *IEEE Trans. Communications*, COM-21, pp. 1188–1194, 1973.

[4] P. A. Bello, "Characterization of randomly time-variant linear channels," *IEEE Trans. Communications*, CS-11, pp. 360–393, 1963.

[5] B. Efron, *The Jackknife, the Bootstrap, and Other Resampling Plans*, Society for Industrial and Applied Math., Philadelphia, 1982.