

Distributions of Multipath Delay Spread and Average Excess Delay for 910-MHz Urban Mobile Radio Paths

DONALD C. COX, SENIOR MEMBER, IEEE, AND ROBERT P. LECK

Abstract—Distributions of average excess delay and delay spread for Gaussian wide-sense stationary uncorrelated scattering channels associated with 100 small scale areas at different locations within a 2×2.5 -km region of New York City are presented. For delay spread the mean is $1.3 \mu\text{s}$, the standard deviation is $0.6 \mu\text{s}$, the maximum value observed is $3\frac{1}{2} \mu\text{s}$, and 10 percent of the areas exceeded $2\frac{1}{2} \mu\text{s}$; for average excess delay the mean is $1.1 \mu\text{s}$, the standard deviation is $0.9 \mu\text{s}$, the maximum is $4 \mu\text{s}$, and 10 percent of the areas exceeded $2 \mu\text{s}$. The region is representative of the heavily built-up areas of many large cities in the United States.

I. INTRODUCTION

RADIO propagation in the UHF urban mobile radio environment is dominated by highly dispersive multipath caused by reflection and scattering from buildings surrounding the mobile vehicles [1]–[8]. This multipath dispersion places an irreducible lower limit on the error rate at any specified bit rate for digital transmission, limits vehicle locating accuracy for radio ranging, and limits the minimum distortion at any specified modulation index for FM transmissions. Since future large scale mobile radio systems probably will use digital transmission and radio ranging for system control and either FM or digital modulation for voice transmission, descriptions of the multipath propagation are essential for determining the system configuration and performance.

The statistics of multipath propagation characteristics for this medium (i.e., the dispersive communication channel) are usually quasi-stationary for vehicle travel distances on the order of 5 to 30 m (small scale) but become grossly nonstationary for distances greater than 20 to 150 m [1], [2] (large scale). Some authors [5], [6] have combined the small scale medium fluctuations that are dominated by random phase additions of many signals that have nearly equal path delays with the large scale changes that are caused by the different reflecting structures (buildings, etc.) that contribute to the received power in different regions. Because of the gross nonstationarity of the medium throughout large regions it seems preferable to use a two-step statistical model. The first step, which has been emphasized in our previous papers [1]–[4], is to model the different small scale stationary channels and find channel parameters that are related to radio system performance. The Gaussian wide-

sense stationary uncorrelated scattering channel (GWSSUS) [9], [10] was shown to be a reasonable model [1], [2] for bandwidths up to 10 MHz since: 1) as a vehicle moves along streets over small scale distances the envelopes of the fluctuating signals at fixed time delays are usually Rayleigh distributed [1], [2] suggesting complex Gaussian processes; 2) the fluctuations at different delays separated greater than a resolution cell ($0.1 \mu\text{s}$) apart are usually uncorrelated since the RF power spectra at different delays are grossly different [1], [2], [4]; and 3) averages of received power at fixed delays are reasonably stationary for small scale distances [1], [2] (5–30 m). The GWSSUS channel is a model for a multipath channel made up of independent point scatterers. Therefore, it physically describes mobile radio propagation paths quite well too. Channel parameters that determine system performance are average excess delay d and delay spread s . These are defined in detail later.

This paper emphasizes the second step of the modeling process, that of presenting statistical distributions of average excess delay and delay spread for many small scale areas at different locations within a large region of a city. Using these distributions, specified system parameters and previous analytical results [9]–[13], upper bounds on system performance (such as bit error rates or FM distortion) can be determined. Since these statistics are nearly useless without a description of the characteristics (building heights, street widths, etc.) of the region to which they are applicable, the paper includes a description of the region. This part of New York City is representative of the heavily-built-up downtown areas of many large cities in the United States.

II. THE MEASUREMENTS

The measurements were made with a wideband measuring system that used the correlation properties of pseudo-random shift-register sequences [2]. The probing signal is not a pulse but the results are equivalent to measurements made using short RF pulses.

Briefly, a 910-MHz stable carrier with an aging rate of a few parts in 10^{10} per day is phase reversal modulated by a pseudo-random shift register sequence (9-bit register and 10-MHz clock). This signal was transmitted from a vertically polarized colinear antenna array, which is omnidirectional in azimuth and has an 18° beamwidth in elevation ($\pm 9^\circ$ from horizontal). The transmitting an-

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The authors are with Bell Telephone Laboratories, Inc., Holmdel, N. J. 07733.

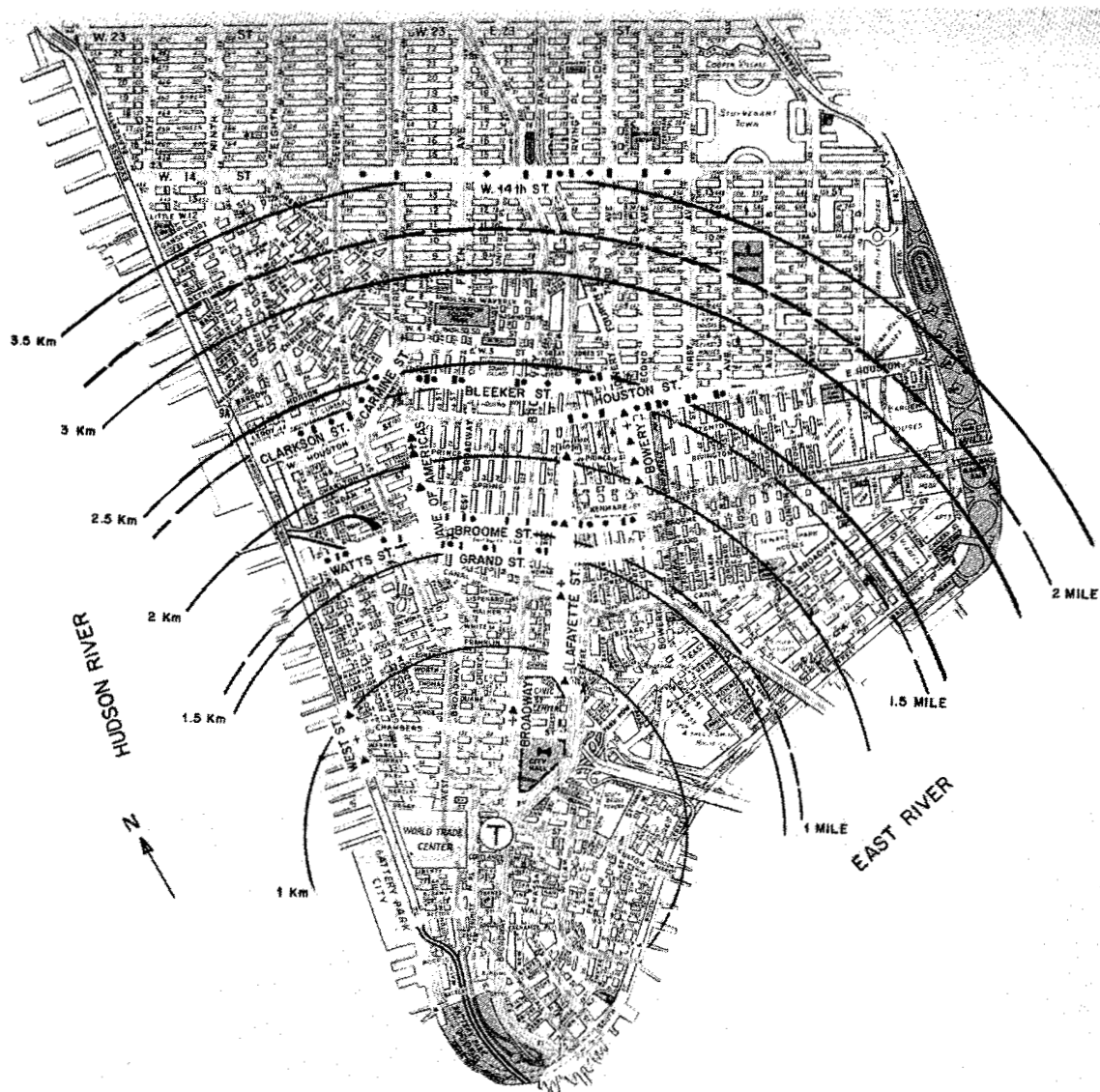


Fig. 1. Map of experimental area on Manhattan Island, New York City.

tenna was located 120 m above the street on top of the American Telephone and Telegraph building at 195 Broadway, New York City. This transmitting site is marked with a $\oplus$ on the map of lower Manhattan Island in Fig. 1.

The signal was received with an omnidirectional quarter wavelength vertical antenna on the roof of a $2\frac{1}{2}$ -m high mobile van driven along the city streets. In the RAKE-like receiver [2], [14] the received signal is correlated with a replica of the transmitted signal in two quadrature correlators whose amplitude outputs in time represent amplitude versus time delay for the low-pass quadrature components, $I(\tau)$ and $Q(\tau)$, of bandpass impulse responses of the propagation path [3]. Since transmitter and receiver logic are both driven from precision

frequency standards and small relative frequency drifts between the standards can be corrected manually whenever the mobile van is stopped, the absolute delay reference provided by a synchronizing pulse can be maintained to better than $0.05 \mu\text{s}$ for a few hours. The range of delays included in one impulse response (the delay window) is $15 \mu\text{s}$. This $15\text{-}\mu\text{s}$ window can be moved anywhere within an absolute delay range of 0 to $51.1 \mu\text{s}$ ($511 \text{ bits} \times 0.1 \mu\text{s/bit}$), which corresponds to path delays of 0 to about 15 km. The squared envelope of the complex impulse response, $p(\tau) = I^2(\tau) + Q^2(\tau)$ is the same power delay profile $p(\tau)$, which would be received if a triangular pulse with base width of $0.2 \mu\text{s}$ and a repetition rate of 20 KHz were transmitted through all equipment filters and the propagation medium and then detected with a square

TABLE I
STREET CHARACTERISTICS

STREET	CANYON WIDTH METERS	BUILDING HEIGHT STORIES	BUILDING CONCENTRATION	STREET ORIENTATION	DISTANCE Km
Grand	11	5-10	Solid	Circumf.	1.5
Watt	15	2-10	70% Solid	Circumf.	1.5
Broome	17	5-10	Solid	Circumf.	1.5
Lafayette				Radial	1.5-2.5
Houston	32	2-10	70% Solid	Oblique	2.5
Clarkson	15	5-10	50% Solid	Circumf.	2.5
Carmin	17	2-5	Solid	Oblique	2.5
Bleeker	13	3-10	Solid	Circumf.	2.5
Bowery	30	2-5	90% Solid	Oblique	2.6-2.5
W 14th	25	5-20	Solid	Circumf.	3.5
Ave. Americas	23	5	80% Solid	Radial	2.0

law detector [2]. The delay resolution of the equipment is about $0.1 \mu\text{s}$ (10-MHz bandwidth RF signal).

Data including complex impulse response components, synchronizing pulses, vehicle speed, etc., were recorded on an analog tape recorder in the mobile vehicle while it was driven at 1.4 m/s along the streets marked in bold letters in Fig. 1. These data were then sampled and stored on digital tape for computer processing. Data shown later are from the approximately $2 \times 2\frac{1}{2}$ -km region, which ranges from 1.5 to 3.5 km from the transmitter. (Data taken at the southern end of the island were described in [1].) Table I summarizes the significant characteristics of the streets. Street widths are from building front to building front (the "canyon" width) and orientations are with respect to a radial from the street to the transmitter (circumf. is circumferential). Even the streets that did not have solid building fronts were generally shielded from the transmitter by buildings along adjacent streets. Data sets were taken from small areas that were either in street intersections (the solid rectangles along oblique and circumferential streets and the solid triangles along radial streets in Fig. 1) or in regions between intersections (midblocks indicated by solid circles and plus marks in Fig. 1). About 60 percent of the data are from midblock areas and 40 percent from intersections. Except for the buildings the ground is essentially level throughout the measuring area.

Fig. 2 is a photo looking into the measuring area from near the transmitting antenna. The measuring region is generally the region of the relatively low buildings beyond the tall buildings in the foreground of the picture.

Individual complex impulse responses were taken every 10 cm along the streets (for examples see [1] or [2]). For the areas chosen for analysis individual power delay profiles $p_i(\tau_k)$ were computed from the samples of the low-pass quadrature impulse response components $I_i(\tau_k)$ and $Q_i(\tau_k)$ by

$$p_i(\tau_k) = I_i^2(\tau_k) + Q_i^2(\tau_k)$$

where i orders the set of profiles along the street, and k orders the delay samples of each profile. A specified delay τ_k is the same propagation delay from transmitter to



Fig. 2. Photo looking toward experimental region from transmitting site.

receiver for all profiles from a given area because the delay references for both transmitter and receiver were derived from stable clocks.

Average power delay profiles $P_m(\tau_k)$ were computed for 50 consecutive individual profiles from each of the areas m . A 50 profile average is a time domain description of the GWSSUS communications channel that exists between the base station and the 5-m long street area. The average power delay profile is a bandlimited estimate of Bello's $g^*(t, \tau)g(t, \tau)$ for the time varying medium [9], [10] that occurs when a car moves down the street [3]. Specifically

$$P_m(\tau_k) = \frac{1}{50} \sum_{i=1}^{50} p_i(\tau_k) = \langle |h_m(\tau_k)|^2 \rangle_i$$

where $h_m(\tau_k)$ is the bandpass impulse response discussed in [3] and, m distinguishes the different small areas (5-m long street segments) within the $2 \times 2\frac{1}{2}$ -km region.

Fig. 3 is an average power delay profile from Bleeker Street between 6th Avenue and McDougal Street. This profile is typical of profiles with moderate values of average excess delay and delay spread as defined later. The first intersection in the foreground of Fig. 4 is McDougal; 6th Avenue was behind the photographer; the transmitter was to the right. This photo shows the part of Bleeker Street over which the data were analyzed. This street is typical of the 10- to 20-m wide streets with up to 10 story buildings listed in Table I. The 0.9- μs average delay and 1.2- μs delay spread for this profile are about average for the entire region as will be illustrated later. The 0 excess delay is at the first arrival delay for all profiles. For Fig. 3, 0 excess delay is 7.1 μs absolute delay from the transmitter to the receiver.¹ The dotted curve that is nearly the same as the solid average profile curve is the standard deviation of the power fluctuations at each fixed delay

¹ The range marks in Fig. 1 are there to show approximate relationships in the measuring region. The map distances are only approximate.

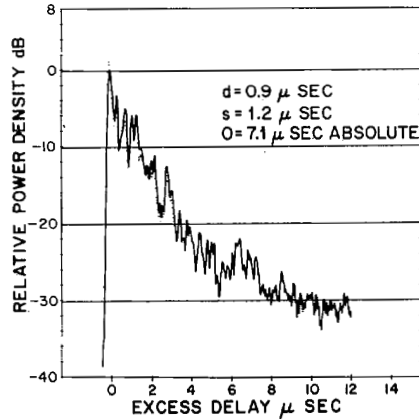


Fig. 3. Average power delay profile for Bleeker Street between 6th Avenue and McDougall Street.



Fig. 4. Bleeker Street looking east toward intersection with McDougall Street.

relative to the peak of the average profile. For a Rayleigh distribution of the fluctuations, the mean and standard deviation curves should coincide. The closeness of the two curves for most of the experimental plots indicates that the complex Gaussian (Rayleigh envelope) process is a good model for these channels.

A measure of the average excess delay d_m of an average power delay profile is the center of gravity or first moment of the profile with respect to the first arrival delay τ_A

$$d_m \triangleq \left[\frac{\sum_{k=1}^{725} \tau_k P_m(\tau_k)}{\sum_{k=1}^{725} P_m(\tau_k)} \right] - \tau_A$$

where k ranges over 14.5 μ s of the 15- μ s measuring window and $\tau_{k+1} - \tau_k = 0.02 \mu$ s.

The noise level of the average profiles is always more than 30 dB below the peak level of the profiles. Thus to insure that noise did not contribute in the calculation of d_m , $P_m(\tau_k)$ was set to 0 for all

$$P_m(\tau_k) < [\max(P_m(\tau_k))]/1000.$$

That is, $P_m(\tau_k)$ was truncated 30 dB below the maximum profile value, $\max(P_m(\tau_k))$. Of course, in the calculation,

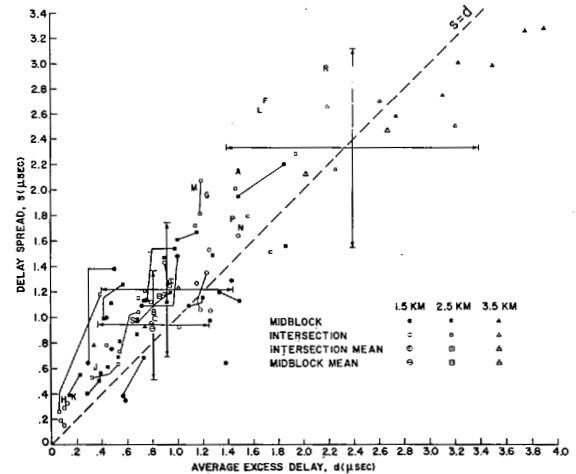


Fig. 5. Scatter plot of average excess delay versus delay spread.

the values of $P_m(\tau_k)$ are relative power levels, not levels expressed in dB relative to some reference.

The average excess delay is the average delay measuring error that would occur in a narrowband CW ranging system operating over the channel represented by the average power delay profile [12]. This average delay error is of course related to the ranging error r_e by $r_e = d_m C$, where C is the velocity of light. For example, for the profile in Fig. 3, $d_m = 0.9 \mu$ s and $r_e = 270$ m (900 ft).

A measure of the width of an average power delay profile is necessary to assess the impact of the delay spread on communication system performance. A good measure of the delay spread [9]–[11], [13] is the square root of the second central moment (i.e., the rms width) of a profile m given by

$$s_m \triangleq \left(\frac{\sum_{k=1}^{725} (\tau_k - d_m - \tau_A)^2 P_m(\tau_k)}{\sum_{k=1}^{725} P_m(\tau_k)} \right)^{1/2}.$$

Again $P_m(\tau_k)$ was truncated 30 dB below the maximum.

Communication system performance limitations caused by multipath propagation are not very sensitive to the shape of the power delay profiles but are quite sensitive to the delay spread s_m [11], [13]. For example, irreducible digital error rates and FM distortion can be calculated directly from the values of s_m as discussed later [11].

III. THE DATA

The data presented are taken from average power delay profiles for 100 different small areas (5-m street segments), that is, 100 different GWSSUS channels, within the $2 \times 2\frac{1}{2}$ -km region in Fig. 1. They represent 5000 individual complex impulse responses or 7 250 000 individual data samples.

Fig. 5 is a scatter plot of average excess delay versus delay spread for the 100 different average profiles. If all profiles had the same shape the data points would lie along a straight line through the origin. The scatter in the points and the different trend at low delay (usually $s > d$) and the high delay (often $s < d$) show the phe-

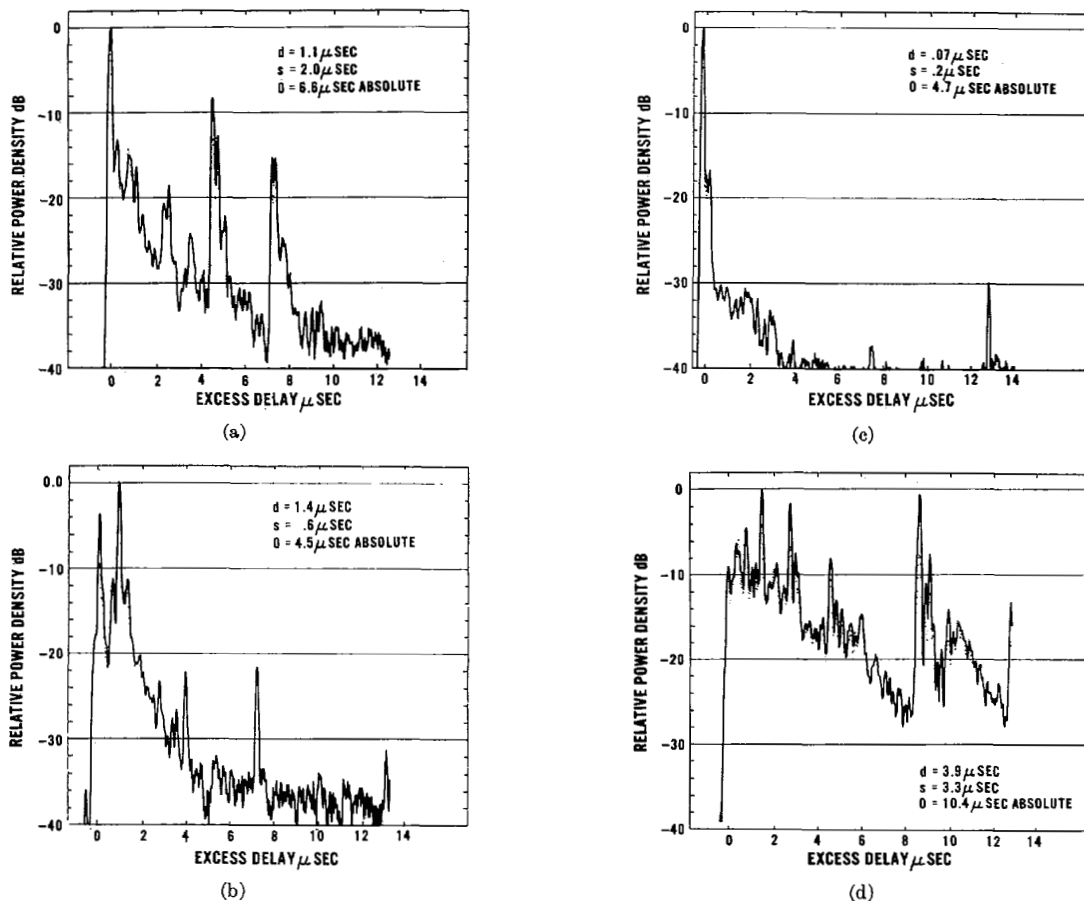


Fig. 6 Average power delay profiles. (a) Intersection of Bowery and Houston. (b) Broome Street between Thompson and Sullivan. (c) Intersection of Watt and Varick. (d) West 14th Street between 6th and 7th Avenues.

nomena observed in the different average profiles. Some profiles, Fig. 3 for example, exhibit a relatively smooth decrease in scattered power with increasing excess delay while others, Figs. 6(a) and 6(d), for example, are quite "spikey." Also, low to moderate d and s are more often associated with smooth profiles, while large values of d and s are usually produced by one or more intense reflections (spikes in the profile) at large excess delays (see Fig. 6(d)). The points on the scatter plot have been separated as to location as indicated in the key. The letters indicate points with locations indicated in Table II. Intersection and midblock means for the circumferential streets 1.5, 2.5, and 3.5 km from the transmitter are indicated on the plot. The large dimension arrows indicate the overall means and standard deviations for both intersection and midblock samples at 1.5, 2.5, and 3.5 km. One is immediately tempted to claim a significant distance dependence for both the delay and delay spread but we believe that the observed differences in these means are caused predominantly by differences in the street characteristics rather than by distance from the

TABLE II
LETTERED POINT LOCATIONS

Lettered Points	Location
A	Intersection of Lafayette & Prince
B	Intersection of Lafayette & Broome
F	Intersection of Bowery & Prince
G	Bowery Between Houston & Prince
H	Intersection of Sixth Avenue & Charlton
J	Intersection of Sixth Avenue & King
K	Sixth Avenue Between Charlton & King
L	Intersection of Bowery & Stanton
M	Intersection of Bowery & Houston
N	Broadway Between Reade & Chambers
P	Broadway Between Reade & Chambers
R	Intersection of Bowery & Spring
S	Intersection of Sixth Avenue & Spring

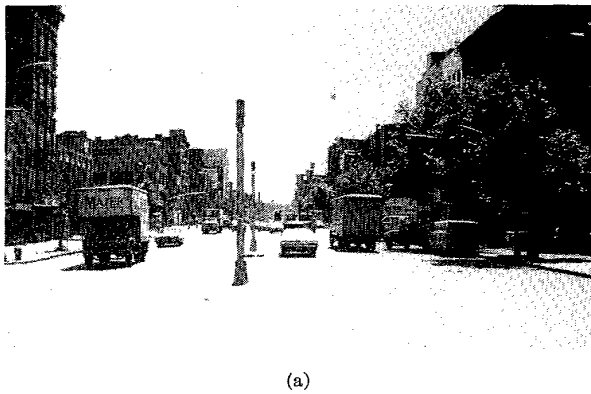


Fig. 7. (a) Looking south on Bowery near Houston. (b) Looking east on 14th Street toward intersection with 6th Avenue.

transmitter. For example, 14th Street at 3.5 km radius has the tallest buildings and is a wide street whereas, in contrast, all the streets at 1.5 km radius are narrow and have 5–10 story buildings (see Table I). The data points on Fig. 5 connected by light lines (either straight or with kinks) indicate data from small areas that are either within the same midblock or within the same intersection; the small areas are separated between 10 and 30 m apart. The light lines connecting the data points were drawn to avoid other unrelated data points so the line positions are not significant.

It is instructive to look at examples of average power delay profiles at the extremes of the data set as illustrated in Fig. 5. The “spiky” profile in Fig. 6(a) is the point *M* for which $s > d$. In contrast, Fig. 6(b) is at the other extreme with $s < d$ and with more scattered power reaching the receiver at an excess delay of $1 \mu\text{s}$ than at the minimum delay. Fig. 6(c), with minimum s and d , is relatively free from multipath propagation whereas Fig.

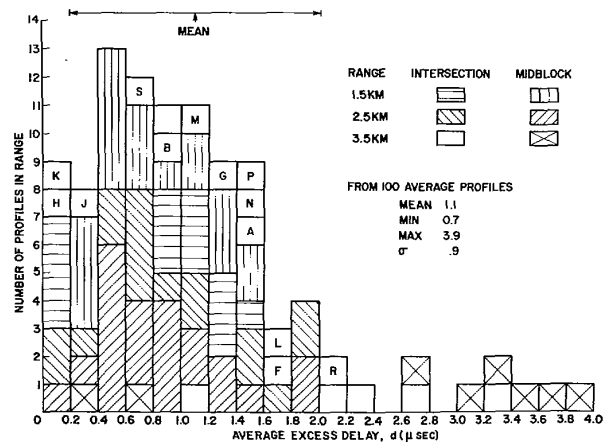


Fig. 8. Average excess delay histogram.

6(d) has the maximum s and d observed. In fact, the values calculated for Fig. 6(d) may be low because it appears that significant power may be present at excess delays outside the measuring window (i.e., $> 14 \mu\text{s}$). The standard deviation of the fluctuations in scattered power at $9\text{-}\mu\text{s}$ excess delay is much less than a Rayleigh distribution as indicated by the dotted curve about 7 dB below the solid average power curve. This is typical of the intense relatively stable scattering regions with large excess delays [1], [4].

Fig. 7(a) is a photo looking south on Bowery in the vicinity of the Fig. 6(a) street segment. The transmitter was ahead and to the right (see Fig. 1). The view looking along Houston at the same intersection is quite similar (street widths and building heights and distributions are similar). The characteristics of Broome Street in the vicinity of the Fig. 6(b) segment are very similar to those of Bleeker as displayed in Fig. 4. Fig. 7(b) is looking east on 14th Street near the street segment for Fig. 6(d). The transmitter was to the right. Note the taller buildings that are characteristic of most city centers.

Fig. 8 is the average excess delay histogram for the 100 areas. Again, the midblock and intersection data for the circumferential streets at 1.5, 2.5, and 3.5 km from the transmitter and the lettered points (Table II) have been tagged as indicated in the key. Fig. 9 is a similar histogram for delay spread. From these histograms it is evident that the largest values of d and s are contributed by areas along Bowery and at 3.5 km radius along 14th Street. These large value “tails” of the distributions, that fluctuate because of the small number of samples, are quite sensitive to the number of samples from these areas. These large values are also the ones that significantly limit system performance. The restrictions placed on system design by the “tails” of these distributions definitely must be considered but fine design lines should not be drawn because of the small-sample-size fluctuations. For example, a reasonable conclusion from Fig. 8 is that about 10 percent of the areas have an average excess delay of $> 2 \mu\text{s}$ (600-m average measuring error) and that about 5 percent

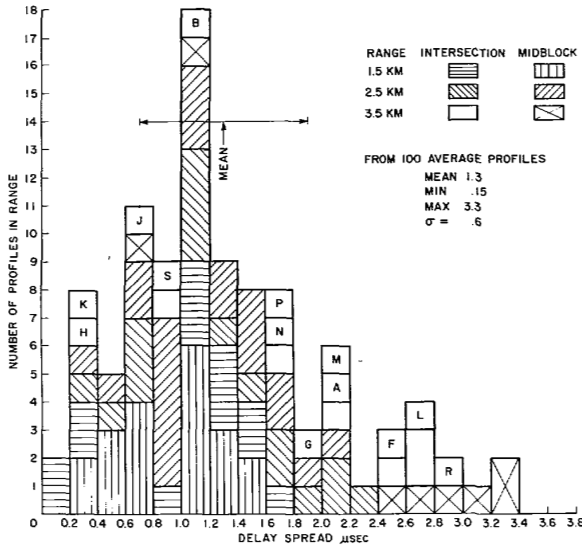


Fig. 9. Delay spread histogram.

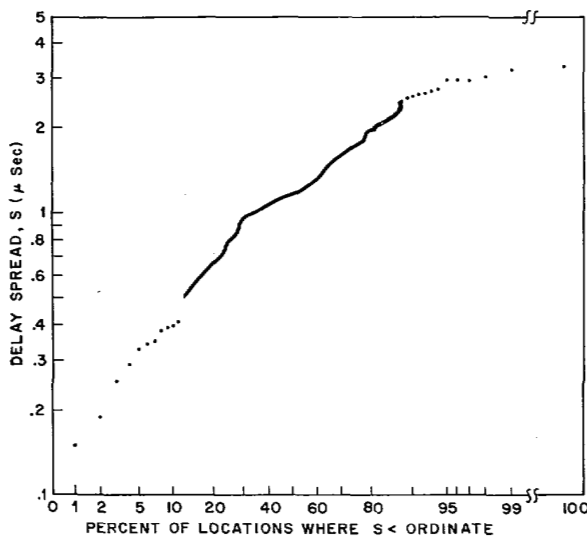


Fig. 10. Delay spread distribution.

have $d > 3 \mu\text{s}$. To try to determine the percentage or average excess delay to any more precision is unreasonable. It should be noted that large values of d and s are not unique to these areas. Values observed in the Wall Street area [1] (south of the transmitter) were up to $2.5 \mu\text{s}$ and in suburban areas [2], [3] were up to $2 \mu\text{s}$. Scatter plots of the spatial distributions of d and s along the circumferential streets at 1.5 and 2.5 km show that d and s are randomly distributed along these streets. The spatial distribution for 14th Street has a trend with the largest values occurring between 4th and 7th Avenues. The data sample along 14th Street is not large enough, however, to make this trend significant.

TABLE III

Delay Spread Exceeded %	Delay Spread usec	Allowable Bit Rate for Error Rate of	
		10^{-3}	10^{-4}
5	3	25K	8K
10	2.5	30K	10K
50	1.2	60K	20K

Fig. 10 is the cumulative distribution for the delay spread data in Fig. 9. A log-normal distribution on these coordinates is a straight line. At this time there is no theoretical basis for predicting the shape of the delay spread distribution but a log-normal law often is followed over long intervals over which nonstationarity exists in the small area statistics [15], [16]. (Also, the small area mean signal attenuation for CW transmission is log-normally distributed.) The delay spread range is $0 \leq s \leq \infty$, which also is compatible with this distribution. (The set of data points actually fit a square root-normal distribution very closely but there is no reason to think this is anything but fortuitous.) There is some suggestion of saturation of the distribution for large delay spreads ($s > 3 \mu\text{s}$). This may be a result of insufficient measuring window width for the large delay spread profiles as is suggested also in Fig. 6(d). If this were the case, the extreme tails (< 5 percent of the data) of the distribution may have even larger s than indicated. Delay spread has a significant impact on communications systems performance [10], [11], [13] as mentioned in the introduction. For example, in the case of digital transmission, the irreducible error rate for a nonequalized channel and a given bit rate is determined by s (but is relatively independent of the actual shape of the average power delay profile). Thus for a specified maximum error rate over a specified fraction of a region, a maximum useable bit rate can be determined using Fig. 10 and analytical results from [11]. Table III contains an example of maximum useable bit rates for error rates of 10^{-3} and 10^{-4} not to be exceeded over 5, 10, and 50 percent of a large region. Binary biphasic ($0, \pi$) modulation with raised cosine pulses and differential phase shift keying (DPSK) detection are assumed in determining the bit rate limitations for the table.

IV. CONCLUSIONS

For 100 small areas in a 2×2.5 -km region in New York City, the statistics of the 910-MHz Gaussian wide-sense stationary uncorrelated scattering channels range up to $4 \mu\text{s}$ with a mean of $1.1 \mu\text{s}$ and a standard deviation of $0.9 \mu\text{s}$ for average excess delay d and range up to $3\frac{1}{2} \mu\text{s}$ with a mean of $1.3 \mu\text{s}$ and a standard deviation of $0.6 \mu\text{s}$ for delay spread s . Of more concern are the extremes of the distributions where over 10 percent of the areas (GWSSUS channels) exhibit $d > 2 \mu\text{s}$ and $s > 2\frac{1}{2} \mu\text{s}$.

This region contains wide and narrow streets with low and high buildings and is representative of the heavily built-up downtown areas of many large cities in the United States.

The distribution of d indicates that the average error experienced by a CW ranging system would be >600 m over 10 percent of the region. As an example of communications system limitations implied by the distribution of s , the bit rate for digital transmission cannot exceed 30K bits/s if the irreducible error rate is to remain below 10^{-3} over 90 percent of the region.

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REFERENCES

- [1] D. C. Cox, "910 MHz urban mobile radio propagation: multipath characteristics in New York City," *IEEE Trans. Commun.*, vol. COM-21, pp. 1188-1194, Nov. 1973.
- [2] —, "Delay Doppler characteristics of multipath propagation at 910 MHz in a suburban mobile radio environment," *IEEE Trans. Antennas Propagat.*, vol. AP-20, pp. 625-635, Sept. 1972.
- [3] —, "Time and frequency domain characterizations of multipath propagation at 910 MHz in a suburban mobile radio environment," *Radio Sci.*, pp. 1069-1077, Dec. 1972.
- [4] —, "A measured delay-Doppler scattering function for multipath propagation at 910 MHz in an urban mobile radio environment," *Proc. IEEE*, vol. 61, pp. 479-480, Apr. 1973.
- [5] G. L. Turin, F. D. Clapp, T. L. Johnston, S. B. Fine, and D. Lavry, "A statistical model of urban multipath propagation," *IEEE Trans. Veh. Technol.*, vol. VT-21, pp. 1-9, Feb. 1972.
- [6] W. R. Young, Jr., and L. Y. Lacy, "Echoes in transmission at 450 megacycles from land-to car radio units," *Proc. IRE*, vol. 38, pp. 255-258, Mar. 1950.
- [7] D. C. Cox and R. P. Leck, "Comparison of time domain and frequency domain statistics for 910 MHz mobile radio propagation paths in New York City," USNC/URSI Meeting, Boulder, Colo., Aug. 22, 1973.
- [8] D. C. Cox, "Distributions of average delay and delay spread for 910 MHz multipath propagation in New York City," in *IEEE Microwave Mobile Radio Symp.*, Boulder, Colo., March 7, 1973.
- [9] P. Bello, "Characterization of randomly time-variant linear channels," *IEEE Trans. Commun. Syst.*, vol. CS-11, pp. 360-393, Dec. 1963.
- [10] P. A. Bello and B. D. Nelin, "The effect of frequency selective fading on intermodulation distortion and subcarrier phase stability in frequency modulation systems," *IEEE Trans. Commun. Systems*, vol. CS-12, pp. 87-101, Mar. 1964.
- [11] W. C. Jakes, Ed., *Microwave Mobile Communications*. New York: Wiley.
- [12] J. S. Engel, "Effects of multipath transmission on the measured propagation delay of an FM signal," *IEEE Trans. Veh. Technol.*, vol. VT-18, pp. 44-52, May 1969.
- [13] M. J. Gans, "A power-spectral theory of propagation in the mobile radio environment," *IEEE Trans. Veh. Technol.*, pp. 27-38, Feb. 1972.
- [14] B. B. Barrow, L. G. Abraham, W. M. Cowan, Jr., and R. M. Gallant, "Indirect atmospheric measurements utilizing rake tropospheric scatter techniques—Part I: the rake tropospheric scatter technique," *Proc. IEEE*, vol. 57, pp. 539-551, Apr. 1969.
- [15] M. Schwartz, W. R. Bennett, and S. Stein, *Communication Systems and Techniques*. New York: McGraw-Hill, 1966, p. 384.
- [16] S. H. Lin, "Statistical behavior of rain attenuation," *Bell Syst. Tech. J.*, vol. 52, pp. 571-572, Apr. 1973.

Rain Attenuation of Millimeter Waves at $\lambda = 5.77, 3.3$, and 2 mm

JOERG SANDER

Abstract—Measurements of rainfall attenuation of millimeter waves at $\lambda = 5.77, 3.3$, and 2 mm were conducted during the years 1969-1970. Simultaneously recorded meteorological quantities were the rainfall rate and a part of the drop-size spectrum. Attenuation coefficients as a function of rainfall rate were thus determined. These attenuation coefficients were related to parameters that, under certain assumptions, describe the drop-size distribution in rain.

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The author was with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Mass. He is now with the Heinrich-Hertz-Institut, Berlin-Charlottenburg, Germany.

I. INTRODUCTION

THIS PAPER presents results of rain attenuation of electromagnetic waves at $\lambda = 5.77, 3.3$, and 2 mm ($f = 52, 90.8$, and 150 GHz). The investigations were carried out in the years 1969-1970. Since the propagation path was the same for all three wavelengths, the results are directly comparable. Along this propagation path the rainfall rate R and a substantial part of the drop-size spectrum were recorded simultaneously. First, the measured attenuation coefficients and R were correlated. In addition, the attenuation coefficients were compared with parameters that partially describe the drop-size distribution of the rain.