

Delay Doppler Characteristics of Multipath Propagation at 910 MHz in a Suburban Mobile Radio Environment

DONALD C. COX, SENIOR MEMBER, IEEE

Abstract—Statistical descriptions of the time delays and Doppler shifts associated with multipath propagation in a suburban mobile radio environment obtained from bandpass impulse response measurements are presented. The measuring equipment which has 0.1 μ s resolution in time delay and a data output bandwidth of less than 5 kHz is also described. For the first time small scale statistics of the multipath propagation for vehicle travel distances on the order of 30 m along streets are presented in the following forms: 1) average power-delay profiles made up of over 200 individual profiles, 2) cumulative distributions of signal amplitude at fixed delays, and 3) radio frequency Doppler spectra at fixed delays. Delay spreads for typical suburban streets are on the order of 0.25 μ s. Extreme cases have paths with significant amplitudes at excess delays of 5 to 7 μ s and the square root of the second central moment delay spreads up to about 2 μ s. Often the signal at fixed delays has a Rayleigh distributed amplitude but large departures from the Rayleigh distribution also occur. RF Doppler spectra at fixed delays indicate that some of the multipath is from one relatively discrete scattering center while at other delays several scattering centers distributed widely in angle are involved. The observed RF Doppler spectra are consistent with the cumulative amplitude distributions at the same delays.

I. INTRODUCTION

ONE of the predominant characteristics of UHF radio propagation in the urban and suburban mobile radio environment is the existence of multiple propagation paths (multipath) with different and varying time delays [1]–[3]. In this environment, transmission is between a fixed base station antenna, usually located on top of a building, and a mobile vehicle down on a street. The shortest path between the base and the mobile is usually blocked by intervening buildings so propagation by way of scatter or reflection from buildings around the mobile is significant. If the mobile is stopped, the radio link is relatively stable. Propagation to a moving vehicle produces a time-varying link. Different Doppler shifts are associated with scatter paths arriving at the vehicle from different angles [4].

A good description of the multipath characteristics can be obtained by measuring the complex bandpass impulse response of a mobile radio link as a function of distance along the direction of vehicle travel. After processing, these basic measurements yield delay Doppler power profiles (scattering functions), average power delay pro-

files (power impulse responses), complex correlation of transfer function fluctuations as a function of frequency separation, distributions of signal levels at various delays, and various other statistical descriptions of the link which result from the multipath delays. Virtually any statistical function which describes the link within the bandwidth of the measuring system can be obtained from these basic complex impulse-response measurements. Values for parameters such as delay spread and coherence bandwidth are readily obtained. These statistical descriptors and parameter values set bounds on many communications system performance parameters such as FM distortion in large index systems [12], adjacent channel interference levels, error rates in digital systems (both data and communications), combining effectiveness in some types of predetection combining diversity systems [18], and the effectiveness of phase-conjugate retransmission systems. Bounds on the accuracy of vehicle locating systems and synchronization problems in digital systems are also affected by these multipath parameters. Pulse envelope measurements have been made previously [1], [2] in urban areas at 500 MHz, 1.2 GHz, and 3 GHz. These previous measurements describe the gross structure of the propagation medium at these frequencies in urban areas.

The first part of this paper describes an instrumentation system for measuring the instantaneous complex impulse response (complex amplitude time-delay profile) of 910 MHz mobile radio links. Resolution of this system is 0.1 μ s. The second part of the paper presents data describing the "local" multipath statistics of a 910 MHz suburban mobile radio environment. These unique sets of detailed local statistics which cover vehicle travel distances of tens of meters have not been reported previously. The suburban delay characteristics are also important for comparison with urban measurements.

II. MEASURING SYSTEM

The obvious way to measure the complex impulse response or the time delay profile for a propagation medium is to transmit a short RF pulse through it and observe the received pulse or pulses. Collecting data from high resolution (1 μ s or less) pulsed measuring systems is difficult because of the large bandwidths required. Photographic recording, which leaves the data in a difficult

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The author is with Crawford Hill Laboratory, Bell Telephone Laboratories, Inc., Holmdel, N. J. 07733.

form for processing, is usually used [1], [2]. To simplify data recording and later processing, a system with a data output bandwidth compatible with analog tape recording systems (a few kHz to a few tens of kHz) is desirable. Measuring systems which make use of the correlation properties of pseudorandom shift register sequences [5] produce low data recording bandwidths for high resolution time-delay measurements. A measurement system which makes use of these sequences but operates in a different manner than those previously described [6]–[9] is described here.¹

Maximal length pseudorandom or pseudonoise shift-register sequences $s(t)$ consist of a series of +1 and -1 transitions. A short segment of such a sequence is illustrated in the top trace of Fig. 3(a). These sequences, which are produced by shift registers with internal feedback, are not random since their transition points are determined by logic circuits and clock pulses. A sequence $s(t)$ repeats itself exactly after a time interval $T = (2^N - 1)t_0$ where N is the number of bistable elements (bits) in the shift register and t_0 is the clock period. The minimum time interval between transitions is also t_0 . The sequences are called pseudorandom because their time autocorrelation functions,

$$R_s(\tau) = \frac{1}{T} \int_0^T s(t)s(t-\tau)dt,$$

illustrated by Fig. 3(b) are similar to the autocorrelation of band-limited noise. The triangle of the autocorrelation has a base width of $2t_0$ and is periodic with period T because of the repeating nature of $s(t)$. The nearly 0 portion of $R_s(\tau)$ has a residual or bias with a magnitude $1/(2^N - 1)$. The power spectrum [10] of this autocorrelation function is

$$S_s(f) = \int_{-\infty}^{\infty} R_s(\tau) \exp(-j2\pi f\tau) d\tau \\ = \left[\sum_{n=-\infty}^{\infty} 2^N \frac{\sin^2(\pi n/(2^N - 1))}{(\pi n)^2} \delta\left(f - \frac{n}{T}\right) \right] - \frac{\delta(f)}{2^N - 1}$$

whose envelope is proportional to $(\sin^2 \pi t_0 f)/(\pi t_0 f)^2$.

A simple correlator for producing $R_s(t/k)$ consists of a multiplier (mixer) with input sequences $s(t)$ and $s'(t)$ followed by a low-pass integrator which integrates over the time interval 0 to T . The factor k scales the rate at which the autocorrelation function is produced in time. The sequences $s(t)$ and $s'(t)$ are produced by identical registers but $s(t)$ is clocked at a frequency f_c and $s'(t)$ is clocked at $f_c - \delta f_c$. The output of the integrating low-pass filter is $R_s(t/k)$ where $R_s(\tau)$ is the autocorrelation function of $s(t)$ and $k = (f_c/\delta f_c)$. That is, if $f_c = 10$ MHz then $t_0 = 0.1 \mu s$ and $R_s(\tau)$ has a base width of $0.2 \mu s$, but the $R_s(t/k)$ output triangle from the correlator has

a real time base width of $0.2 \times k \mu s$. If, for example, $\delta f_c = 2$ kHz then $k = 5 \times 10^3$ and $R_s(t/k)$ has a base width of 1 ms. This approach will work only if k is sufficiently large so that the difference between $s(t)$ and $s'(t)$ over 1 sequence period T is negligible. Empirically, $k = 5000$ produces a good correlation with only slight distortion (see Fig. 3(b)). Distortion is considerable at $k = 1000$, but the waveform still may be adequate for many probing applications. The time scaling of the correlation function also produces the desired frequency scaling of the power spectrum of the correlator output. The following sections describe a hardware implementation of a system using the principles just described.

Transmitter

Fig. 1 is a simplified block diagram of the time-delay measuring transmitter. All frequencies used in the transmitter are derived from a stable (a few parts in 10^{11} over an hour) 5 MHz frequency standard. A 10 MHz output from the frequency multiplier clocks a 9-bit shift register which produces a pseudorandom sequence $s(t)$ of + and - transitions. The sequence repeats every 511 clock periods or every 51.1 μs in time ($t_0 = 0.1 \mu s$, $N = 9$, $T = 51.1 \mu s$). This sequence then phase-reversal modulates a 70-MHz CW carrier from the frequency multiplier. This signal has a constant RF envelope with 180° phase transitions (i.e., +1 or -1) occurring at the transitions of the modulating waveform $s(t)$. This modulated signal is amplified and mixed with an 840 MHz CW carrier also from the frequency multiplier. The final amplifier produces about 10 W average power. The second mixer and following amplifiers have a half-power bandwidth of about 10 MHz. This bandwidth restriction which removes some of the sideband energy produces amplitude variations on the signal. This rounds off the sharp edges on the triangular correlation function produced in the receiver correlators described later. The radiated signal is of the form $[As(t) \cos 2\pi Ft] * a(t)$, where $s(t)$ is the sequence of +1 and -1 transitions, $F = 910$ MHz, A is an amplitude constant, $a(t)$ is the impulse response of the amplifiers and the asterisk denotes convolution. This signal is radiated from a vertical broadside collinear antenna array which has an omnidirectional pattern in azimuth, an 18° beamwidth in elevation and about 8-dB gain over an isotropic radiator.

Receiver

Fig. 2 is a simplified block diagram of the time-delay measuring receiver. As in the transmitter, all frequencies used in the receiver are synthesized from a stable 5 MHz frequency standard. A 10 MHz clock signal from the synthesizer drives a shift register to produce a reference pseudorandom sequence at the receiver which is identical both in character and in timing with the transmitter sequence.

Another identical shift register is driven at a 10 MHz - 2 kHz rate by a slow clock from the synthesizer. This produces a sequence $s'(t)$ identical with the transmitted

¹ The original design of this equipment was done by H. L. Schneider at Bell Telephone Laboratories, Holmdel, N. J. Similar equipment has been used on a tropospheric scatter propagation link [16], [17].

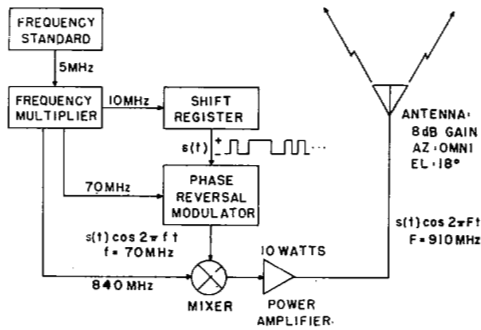


Fig. 1. Time-delay measuring transmitter.

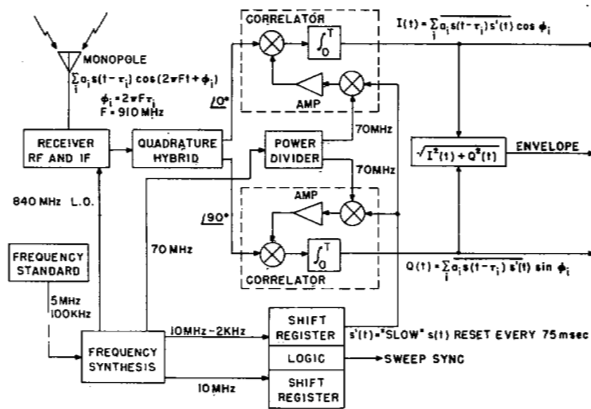


Fig. 2. Time-delay measuring receiver.

sequence, but drifting slowly by it in time. This slow clock sequence $s'(t)$ is compared with the reference sequence and reset every 75 ms. Resetting of $s'(t)$ provides a timing reference for measuring delay in the receiver correlators described later. The periodically reset slow sequence is applied to the two quadrature correlators.

At the upper left corner of Fig. 2, the receiver RF input signal is a sum of several transmitted waveforms delayed by different propagation path delays τ_i . It is of the form $\sum_i a_i s(t - \tau_i) \cos(2\pi F t - \Phi_i)$, where $\Phi_i = 2\pi F \tau_i$, $F = 910$ MHz, and the effects of the transmitter filter have been omitted. This signal is received on a quarter-wave-length monopole and applied to a conventional receiver consisting of a preselector filter, a low-noise preamplifier, a crystal mixer, and an IF amplifier. The 840 MHz local oscillator is derived from the frequency standard. The IF output is split in a quadrature hybrid and applied to the two correlators.

In each correlator $s'(t)$ is multiplied times (phase-reversal-modulated onto) a 70 MHz sinusoidal signal from the synthesizer producing a waveform $s'(t) \cos 2\pi f_{IF} t$. This signal is then amplified in a wide-band amplifier and applied to another multiplier (double-balanced mixer). The second input to this second mixer is the IF signal from the quadrature hybrid. These second mixers multiply the two signals producing for one quadrature correlator $\sum_i a_i s(t - \tau_i) s'(t) \cos(2\pi f_{IF} t - \Phi_i) \cos(2\pi f_{IF} t)$ and for

the other correlator $\sum_i a_i s(t - \tau_i) s'(t) \sin(2\pi f_{IF} t - \Phi_i) \cos(2\pi f_{IF} t)$ assuming that the phase reference at the transmitter is the same as that at the receiver. The outputs of the integrating filters are then

$$I(t) = \sum_i \frac{a_i}{T} \int_{t-T}^t s(t_1 - \tau_i) s'(t_1) dt_1 \cos \Phi_i$$

$$= \sum_i a_i R_s \left(\frac{t}{k} - \tau_i \right) \cos \Phi_i$$

for the one correlator and

$$Q(t) = \sum_i \frac{a_i}{T} \int_{t-T}^t s(t_1 - \tau_i) s'(t_1) dt_1 \sin \Phi_i$$

$$= \sum_i a_i R_s \left(\frac{t}{k} - \tau_i \right) \sin \Phi_i$$

for the other. Thus these correlation functions peak up, plus or minus depending on phase, at times proportional to the path delays τ_i . Resetting the slow register every 75 ms sets a new $t = 0$ reference for a new delay profile every 15 μ s in actual path delay. The reset instant $t = 0$ is indicated by a sync pulse from the logic. Thus in actual path delay, the observation window determined by the reset interval of the slow register is 15 μ s but the ambiguity window determined by the sequence length is 51.1 μ s (equivalent to a pulse-repetition frequency of about 20 000 pulses per second for a pulsed system). The observation window can be positioned manually anywhere within the ambiguity window.

Since the transmitter and receiver frequency standards drift slowly with respect to each other, the measured phase is not absolute. The drift is sufficiently slow (less than 360° in 10 s) so that the relative path phases are accurately known. Also, the drift is slow enough to permit measurement of the Doppler shift associated with various paths (rate of change of the Φ_i) to an accuracy of about 0.1 Hz as a measuring vehicle moves along a street. This is the first time that equipment which will measure both delay and Doppler shift simultaneously has been used to measure characteristics of the mobile radio propagation paths.

The function

$$E(t) = [I^2(t) + Q^2(t)]^{1/2} \text{ scaled by } k$$

is the same real envelope that would result from looking at the real envelope of a single pulse of RF transmitted over the same path if the complex envelope of the RF pulse after passing through the transmitter and receiver filters were the same as the correlation function $R_s(\tau)$ convolved with the complex envelope of the bandpass representation [10] of the same filters.

A plot of $E(t)$ properly scaled in time by the factor k is an envelope delay profile for a propagation path. The corresponding plot of $E^2(t)$ is a power delay profile which represents the power received as a function of path delay τ .

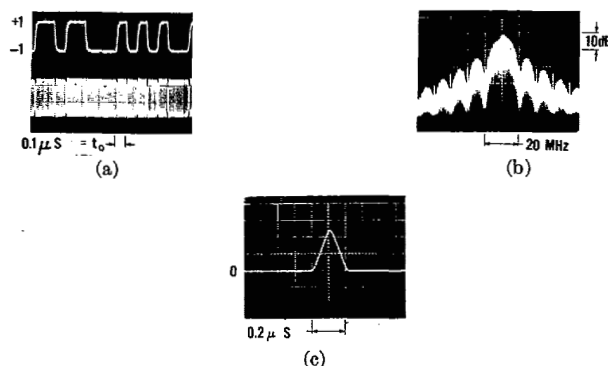


Fig. 3. Pseudorandom sequence characteristics (a) Top trace: actual segment of pseudorandom sequence $s(t)$. Bottom trace: segment of $s(t) \cos(2\pi 70 \times 10\%)$. (b) Correlation function $I(t)$ from receiver correlator. (c) Spectrum analyzer display of bottom trace of Fig. 3(a).

The two complex impulse-response data outputs have bandwidths of about 1 kHz ($\frac{1}{2}$ of the 10-MHz RF bandwidth divided by $k = 5000$). These data are recorded on a multichannel analog tape recorder and later digitized and processed in a computer.

Sample Waveforms

Fig. 3 shows actual waveforms generated in the transmitter and receiver. The upper trace in Fig. 3(a) is a short segment of an actual $s(t)$ generated by the transmitter shift register. The lower trace is the 70 MHz signal phase reversal modulated by the $s(t)$ in the upper trace.

Fig. 3(b) is a correlation function $I(t)$ from one of the receiver quadrature correlators with the transmitter 70 MHz signal fed directly into the quadrature hybrid (transmitter and IF amplifier filters omitted) and the RF phase adjusted to yield maximum output. The 0.2 μ s time scale indicated has been scaled by $k = 5000$ ($\delta f_c = 2$ kHz) so it represents the actual width of the probing signal. In the time scale of the correlator output it takes 1 ms to trace out the correlation function triangle (1 ms in actual correlator output time represents 0.2 μ s delay in the path between transmitter and receiver). A power delay profile for the transmitter and receiver running back to back at 910 MHz is shown later in Fig. 5(b) with an average profile taken along a suburban street. Fig. 3(c) is a spectrum analyzer display of the signal in the lower trace of Fig. 3(a).

III. SUBURBAN MEASUREMENTS

Complex impulse-response data were recorded in a vehicle moving along several business and residential streets in suburban New Jersey (Keyport, Hazlet, and Middletown). The transmitting antenna was located on a 20-m tower on top of 115-m high Crawford Hill, N.J., which is about 100 m above the suburban area. The transmitting antenna was a vertical collinear array with an omnidirectional pattern in azimuth. The quarter-wave-

length monopole used for receiving was mounted above the metal roof of the measuring vehicle. Measurements were made at a constant speed of 1.4 m/s. The data presented in this section are from two streets. These two data sets represent a typical set and an extreme set.

The characteristics of the data set from Annapolis Drive, Hazlet, N.J. is typical of the suburban data. This street is about 4 km from the transmitter and runs nearly perpendicular to a line drawn from the transmitter to the street. Annapolis Drive is about 9-m wide and runs through a housing development. Houses are about 12 m back from the street and are separated from each other along the street by small (6- to 10-m wide) sideyards. The houses are mostly wood construction with some brick trim. About half of them are two stories and half are one story high. There are no large vacant areas along the street or along adjacent streets. It is about 60 m from Annapolis Drive to the backs of houses facing adjacent streets. All houses within several blocks are similar. The ground is relatively flat throughout the development. The direct path between transmitter and measuring vehicle is generally obstructed by intervening houses.

The data from American Legion Drive, Keyport, N.J., contain multipath with the largest excess delays (greatest delay spread) of all the suburban data taken. This street is about $5\frac{1}{4}$ km from the transmitter. The data presented later were taken at a place where the street makes an oblique angle with a line drawn to the transmitter. American Legion Drive is about 60 to 90 m behind a business district; there are no buildings facing American Legion Drive itself. The side of the street away from the transmitter runs along a waterfront. The street is level but is situated in a depression in the surrounding land area. The direct path from the transmitter to American Legion Drive is obstructed by an intervening business district (Keyport) which consists mostly of three story commercial buildings of various types of construction. The buildings are on land about 4 to 6 m above the street.

For the delay data presented, zero delay has been shifted to an arbitrary absolute delay reference point but all delay profiles of a given data set have their zero at the same absolute delay. That is, zero delay is arbitrary for each data set but it is set at a fixed absolute delay value for an entire data set. This is possible because synchronism between transmitter and receiver is maintained by stable frequency sources and not by an arbitrary trigger level on the received impulse response.

Individual Envelope Delay

An individual envelope delay profile is a plot of received "pulse" amplitude as a function of path delay referred to a fixed absolute delay reference, that is, it is the envelope of a bandpass impulse response of the propagation medium. Examples of some envelope delay profiles are shown in Fig. 4. The horizontal scale is actual propagation time delay from an arbitrary fixed delay reference. The individual delay sweeps occur at a rate of about 10 per meter of travel along the street (about 10 cm of street

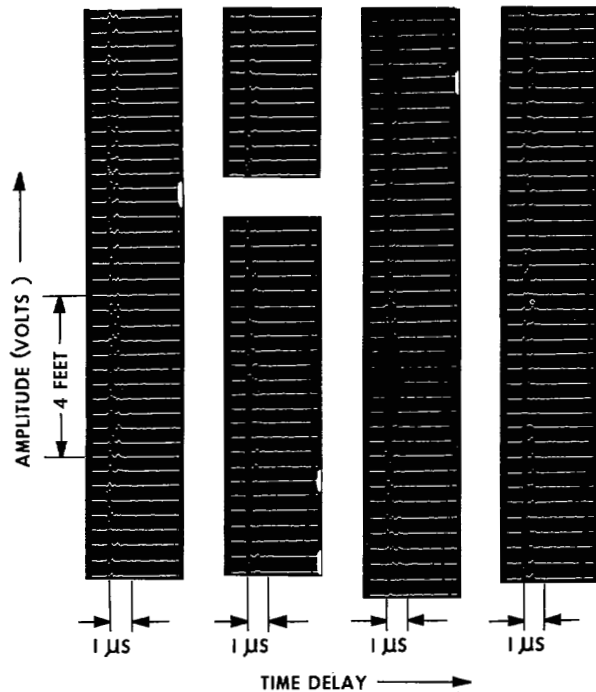


Fig. 4. Individual envelope delay profiles from Annapolis Drive.

between sweeps). The sequences start at the upper left corner of a set and progress down and to the right along the strips.

The individual envelope delay profiles in Fig. 4 are from Annapolis Drive. For this street most of the significant multipath occurs within the first microsecond after the minimum delay path (attenuated direct or diffraction path). For any specified fixed delay, the envelope fades rapidly as a function of distance along the street. This deep fading even occurs at the time delay for the minimum delay path. Fading of the signal at one delay does not appear to be correlated with fading at other delays. Sometimes the minimum delay path signal is weaker than the multipath (for example 3rd, 10th, 15th, and 20th traces up from bottom of third strip over from left) and sometimes the entire signal fades as illustrated by the 12th trace up from the bottom of the strip on the right side. These total fades indicate loss of signal over the entire 10-MHz bandwidth of the probe signal. This rapid (over a few cm of travel) and deep fading in addition to the other evidence presented later suggests the existence of multiple path interference *within* the $0.1 \mu\text{s}$ (30 m) resolution of the probe signal and suggests that several paths exist with path length differences within 30 m of each other.

Average Power Delay Profiles

The individual outputs $I(t)$ and $Q(t)$ of the receiver were sampled with an 8-bit analog-to-digital converter and stored on a disc for further processing. Simultaneous sampling of both $I(t)$ and $Q(t)$ from a multichannel

analog tape was done at a scaled rate equivalent to $0.02 \mu\text{s}$ of propagation delay between samples. Time synchronism was maintained with the sweep sync which was also recorded on an analog channel. Sampled individual power delay profiles $p_i(\tau_k)$ were then computed by

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

where the subscript i orders the set of profiles (sweeps) 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 receiver for all profiles of a given set. Note that

$$p_i(\tau_k) = E_i^2(\tau_k)$$

where the $E_i(\tau)$ are envelope profiles as illustrated in the preceding section. An average power delay profile $P(\tau_k)$ for a set of N consecutive individual profiles is then computed as

$$P(\tau_k) = \frac{1}{N} \sum_{i=1}^N p_i(\tau_k) = \langle |h(\tau_k)|^2 \rangle_i$$

where $h(\tau_k)$ is the bandpass impulse response [10]–[12].

These profiles can be described by several parameters. The center of gravity or first moment of the profile with respect to the first arrival delay is a measure of the average delay D . Average delay is calculated by

$$D \triangleq \frac{\sum_{k=1}^M \tau_k P(\tau_k)}{\sum_{k=1}^M P(\tau_k)} - \tau_A$$

where M is the index of the last sample along the delay axis which has a significant amplitude and $k=1$ is an arbitrary point before the minimum arrival delay τ_A chosen so that the profile amplitude is insignificant. The locations of $k=1$ and M are chosen so that moving the $k=1$ point to smaller delay values or moving the last sample to larger delay values does not affect the value of D . Average delay is related to the ranging error which would occur in narrow-band CW phase ranging systems.

The square root of the second central moment is one possible measure of the delay spread S or width of a power delay profile. It is calculated as

$$S \triangleq \left[\frac{\sum_{k=1}^M (\tau_k - D)^2 P(\tau_k)}{\sum_{k=1}^M P(\tau_k)} \right]^{1/2}$$

where the parameters are as defined previously. Other measures of width such as delay between outer -3-dB or -10-dB points are also useful for some profiles. Delay

spread sets limits on many communication system performance parameters as indicated in the introduction.

The average power transmission factor L can be found by summing the average received power at all delays τ_k which receive significant power. That is

$$L \triangleq L_0 \sum_{k=1}^M P(\tau_k).$$

The constant L_0 must be determined by absolute calibration of received power through the data recording and digitizing system. For the purpose of comparing average profiles with the same L_0 , the absolute value of L_0 is not required so it has not been determined for the data presented; only relative values of L are given.

Fig. 5(a) is a series of average power delay profiles from Annapolis Drive. The horizontal axis is excess propagation delay with the zero set at approximately the minimum possible propagation path delay from transmitter to receiver τ_A . Each profile is the average of 30 consecutive individual profiles covering about 3 m of travel along the street. The vertical scales for the different profiles are displaced vertically along Fig. 5(a) but the relative magnitudes of the profiles with respect to their scales have been preserved. That is, the maximum of profile number 1 is 505 compared to a maximum value of profile 2 of 1000. The vertical scales are logarithmic in power. The average profiles are ordered in the same way that the sets of individual profiles were taken along the street. That is, average profile 1 contains individual profiles 1 through 30, average profile 2 contains individual profiles 31 through 60, etc., where individual profiles 1 through 210 occur consecutively along the street. The 7 average profiles in Fig. 5(a) are very similar. This indicates that the 210 individual profiles for the 21 m of street are samples of a random process with good stationary properties in the wide sense (stationary means). The overall average profile for the 21 m of street should be a good description of the process. It is interesting to note that, over the 3-m section of street represented by profile 7, the reflection or scatter path at $0.2 \mu\text{s}$ is slightly stronger on the average than the minimum delay path at 0 (the direct or diffraction path obstructed by houses, etc.).

The average power delay profile in Fig. 5(b) is the overall average of the 7 average profiles (210 individual profiles along 21 meters of street) of Fig. 5(a). The vertical scale on the left is logarithmic in power and on the right linear in dB. The dashed curve is the power delay profile for the transmitter and receiver running back to back (the characteristic "pulse" of the probe) including all filters, the tape recorder and data processing equipment but not including any propagation anomalies. The multipath profile is significantly wider than the probe. The power concentration from the minimum path delay, 0 to about $0.15 \mu\text{s}$, is probably due to the obstructed direct path, reflection or backscatter from the fronts of houses on the opposite side of the street from the transmitter and oblique reflection or scatter from the sides of houses

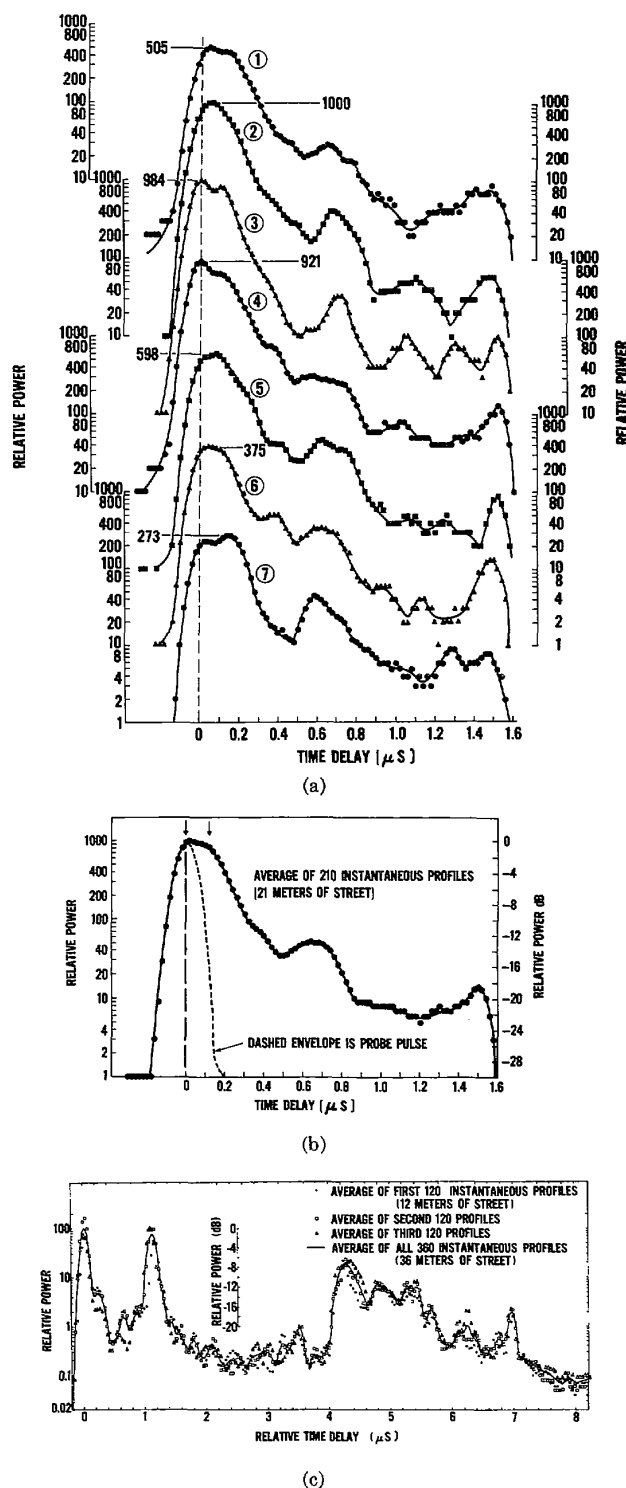


Fig. 5. (a) Average power delay profiles from Annapolis Drive. Each profile is an average of 30 consecutive instantaneous profiles (3 m of street). Profiles 1 through 7 are consecutive sets of 30 instantaneous profiles. (b) Overall average of power delay profiles in Fig. 5(a). (c) Average power delay profiles from American Legion Drive.

TABLE I
AVERAGE POWER DELAY PROFILE CHARACTERISTICS—ANNAPOLIS DRIVE

Average Profile	Average Delay D (μ s)	Delay to Maximum (μ s)	Delay Spread S (μ s)	Profile Width -3 dB (μ s)	Profile Width -10 dB (μ s)	Relative Transmission Factor L (dB)	Relative Magnitude of Maximum (dB)
1	0.17	0.04	0.25	0.22	0.42	-2.0	-3.0
2	0.13	0.06	0.20	0.18	0.36	≈ 0	0
3	0.11	0	0.22	0.20	0.36	0	-0.1
4	0.12	0	0.23	0.20	0.40	≈ 0	-0.4
5	0.17	0.08	0.24	0.18	0.38	-1.5	-2.2
6	0.19	0.04	0.29	0.20	0.50	-3.4	-4.2
7	0.23	0.14	0.31	0.24	0.74	-4.2	-5.6
Average	0.15	0.02	0.24	0.22	0.38	-1.4	-2.1

between the transmitter and the street. Recall that houses are 12-m back from a 9-m wide street so the vehicle was about 18 m in front of the houses. This would result in 36 m or 0.12 μ s excess delay for back scatter or reflection from the house on the opposite side of the street from the transmitter. The bulge on the profile at 0.4 μ s appears to be backscatter from the backs of houses which face towards Colby Lane, the street which runs parallel and adjacent to Annapolis Drive and was opposite the transmitter. The backs of these houses which faced away from the measuring vehicle were about 60 m from the measuring vehicle. The power minimum at 0.5 μ s is the open street, Colby Lane, whose centerline was about 75 m from the measuring vehicle. The secondary power concentration at 0.65 μ s is probably backscatter from the fronts of the houses facing Colby Lane on the other side of the street (distance ≈ 90 meters from measuring vehicle). The cause of the slight peak at 1.5 μ s is not known but the rapid decrease of power after 1.5 μ s is probably due to the fact that the ground begins to slope downhill at about 240 m from Annapolis Drive and scattering objects were no longer of sufficient height to reflect energy back. These conjectures on the cause of the features seen in Fig. 5(b) assume that single scattering predominates. Multiple scattering would make feature interpretation impossible. Multiple scattering is probably insignificant for the first 0.25 μ s or so, but it may become significant at longer delays.

Several of the parameters which describe the 7 average profiles in Fig. 5(a) and the overall average profile in Fig. 5(b) are tabulated in Table I. In this table average delay and delay to the profile maximum are relative to the 0 on the delay axes of the figures (the minimum propagation path delay). The profile widths are given between the -3-dB and -10-dB points of the profiles. The relative transmission factors are relative to the profile with the largest transmission (lowest path "loss") and the relative magnitudes of the maxima are given relative to the profile with the greatest maximum. The delay spread and width parameters have all been calculated without removing the convolutional effects of the finite width probe (dashed curve). The calculations [13] indicate that if the measured delay spread including

probe effects is greater than 0.2 μ s, the actual delay spread of the medium without probe effects is within 0.02 μ s of the measured value. This fact has been further substantiated and will be reported later in a paper which compares the probe and the measurement in the frequency domain. The error decreases with increasing delay spread. Since the delay spread varies more than 0.02 μ s from street to street and from location to location on the same street, correction for this small discrepancy is not warranted.

Fig. 5(c) is a set of average power delay profiles from American Legion Drive. These profiles are extreme among the suburban data but are not unique in their characteristics. The three different sets of data points indicate three profiles each of which is the average of 120 consecutive individual profiles covering about 12 m of street. In order along the street the profile indicated by the $\circ$ was first, immediately followed by the $\square$, and then the $\triangle$. Again, these three profiles are quite similar indicating that they are averages of samples from a relatively stationary random process. The solid curve is the overall average of the three profiles indicated by the data points. This profile is an average of 360 instantaneous profiles covering 36 m of the street. The power concentration at the minimum propagation path delay (0 on the relative delay scale) is almost as narrow as the unspread probe "pulse." The concentration at 1.1 μ s is also quite narrow. The paths associated with these maxima appear discrete within the 0.1 μ s resolution of the equipment. The multipath from 4 μ s to almost 7 μ s appears to be associated with a multitude of unresolvable reflecting surfaces. An interesting feature, however, is that the maximum at 4.3 μ s and the one at 5.4 μ s are separated by the same 1.1 μ s delay as the first two maxima at 0 and 1.1 μ s. Table II summarizes the characteristics of the profiles in Fig. 5(c).

Cumulative Distributions of Signal Level at Fixed Delays

The series of individual envelope delay profiles in Fig. 4 show considerable amplitude fluctuation or fading at all delays. Fading of successive power delay profiles taken at 450 MHz with a 0.5 μ s resolution pulse probe was also observed by Young and Lacy [1]. They deduced that the fades were caused by RF phase cancellation among

TABLE II
AVERAGE POWER DELAY PROFILE CHARACTERISTICS—AMERICAN LEGION DRIVE

Average Profile	Average Delay D (μ s)	Delay to Maximum (μ s)	Delay Spread S (μ s)	Profile Width -3 dB (μ s)	Profile Width -10 dB (μ s)	Relative Transmission Factor L (dB)	Relative Magnitude of Maximum (dB)
○	2.10	0.01	2.11	1.22	4.96	-2.6	-4.1
□	1.55	0.01	1.96	1.18	4.38	0	0
△	2.18	1.08	2.06	1.16	4.58	-1.1	-2.2
Average	1.90	0.01	2.05	1.20	4.50	-1.1	-2.3

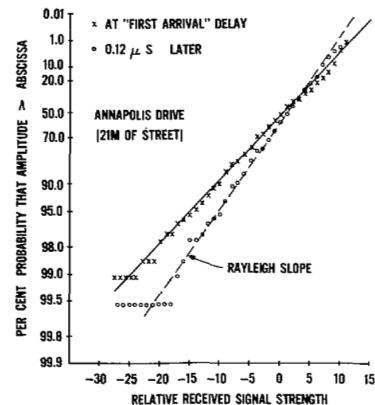
signals propagating along unresolved paths. Fig. 4 illustrate that the fading still exists with the factor of 5 better delay resolution (0.1μ s) used in this experiment.

To the author's knowledge, the distribution of signal amplitude at fixed delays for such high resolution time delay data taken in a mobile radio environment has not been presented previously. Cumulative distributions of signal amplitude have been obtained at many fixed delays for this collection of suburban data.

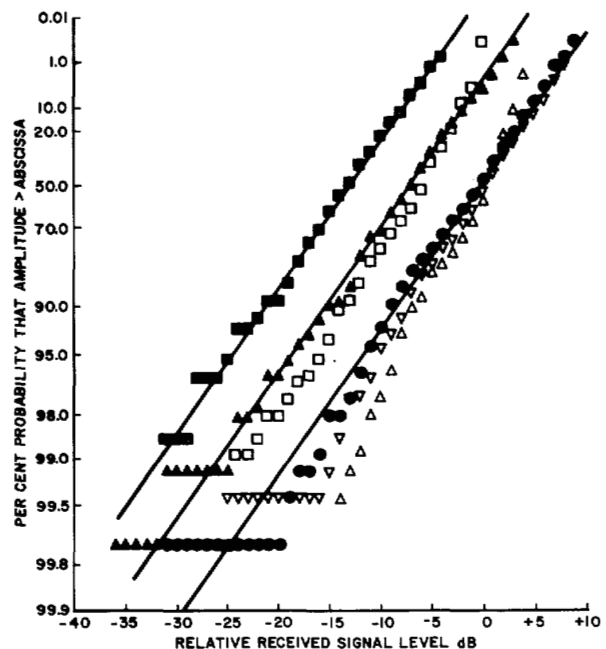
Fig. 6(a) shows examples of such amplitude distributions for the same Annapolis Drive data used to produce Fig. 5(b). The distributions are plotted on Rayleigh coordinates. A Rayleigh distribution appears as a straight line with the specific slope of the dashed line on these coordinates. The X on Fig. 6(a) are the distribution of the 210 signal amplitude samples at the minimum propagation path delay marked by the left arrow at 0 relative delay on Fig. 5(b). This signal spent more time at lower signal levels than a Rayleigh distributed signal would.

The ○ on Fig. 6(a) are for the signal at 0.12μ s (right arrow) on Fig. 5(b). At this delay the effects of signal at 0 delay are about 16 dB down on the probe "pulse." The ○ closely follow the Rayleigh slope straight line. This suggests that quite a few scatter paths with independent RF phases contribute to the overall signal received at this delay. Note that even though the mean signal levels at 0μ s and 0.12μ s are nearly equal, the distribution of levels is quite different. This situation does not always exist and for some sections of suburban streets the signal at the minimum propagation path delay is also Rayleigh distributed.

Fig. 6(b) is a similar set of signal level distributions for the data shown in Fig. 5(c). The ▽ and ● are distributions from delays near the power concentration at 0 on the average power delay profile. These two distributions generally follow the Rayleigh distribution (solid lines) but departures up to 3 dB occur at low signal levels. The solid triangles ▲ representing the distribution of signal level at 0.12μ s and the solid squares ■ for the 0.24μ s signal level fit the Rayleigh lines very well. The power concentration at 1.14μ s did not appear to fluctuate as much as the others in the series of individual envelope delay profiles. This qualitative impression is substantiated by the distribution represented by the open triangles which indicates a total fluctuation range of only 18 dB. This type of distribution could be produced by a pre-dominant path interfered with by one or more randomly



(a)



(b)

Fig. 6. (a) Cumulative signal amplitude distributions from Annapolis Drive. (b) Cumulative signal amplitude distributions from American Legion Drive. (Distributions from 360 individual profiles from 56 m of street.) ● at delay = 0 or first arrival, ▽ at delay = 0.94μ s, ▲ at delay = 0.12μ s, ■ at delay = 0.24μ s, △ at delay = 1.14μ s, □ at delay = 4.26μ s, and solid lines are Rayleigh distributions.

phased weaker paths or by one predominant path experiencing an amplitude change due to change in scattering angle as the vehicle moved down the street. The distribution at $4.26 \mu\text{s}$ is within 3 dB of the Rayleigh line over a large portion of the distribution.

Each distribution in Fig. 6(b) is made up of 360 samples. The bands of data points at high probabilities in both Figs. 6(a) and (b) are due to the finite number of samples. For example, 1 sample out of 360 is 99.72 percent.

Doppler Spectra at Fixed Delays

Scattered signals arriving at the measuring vehicle will be Doppler shifted by different amounts depending on the angle that the arrival path makes with the direction of vehicle travel. When the Doppler shift is expressed in units of cycles per meter of vehicle travel, it is not dependent on actual vehicle velocity. (Conversion to units of Hz requires only multiplication by vehicle velocity in m/s.) Signals arriving from scatters directly ahead of the vehicle will be shifted higher in frequency (positive) by the maximum amount $1/\lambda$ where λ is the wavelength of the signal; those directly behind will be shifted negatively by the same amount.

Since the equipment used in this experiment uses quadrature coherent detection and stable frequency references, the Doppler shifts associated with various scatter paths can be measured. This Doppler shift information is useful in communication system analysis and for further resolving the multipath structure of the media since paths having nearly the same time delay can be separated if they arrive from different angles.

Fig. 7(a) is the RF Doppler spectrum of the signal at the fixed delay of $0.04 \mu\text{s}$ for the 36 m of street represented in Fig. 5(c). It was obtained by complex Fourier transforming the measured $I_i(\tau)$ and $Q_i(\tau)$ samples at $0.04 \mu\text{s}$ delay for $i = 1$ to 360 after they had been multiplied by a Hamming window to reduce spectrum sidelobes [14]. The horizontal axis is frequency offset from center frequency (910 MHz) in cycle per meter of travel. The approximate maximum possible plus and minus shifts are indicated by the vertical dashed lines. The left vertical scale is a logarithmic power scale; the right vertical scale is linear in dB relative to the spectral maximum. Noise and spurious responses are about 30 dB below the spectral maximum. Hamming window sidelobes are about 40 dB below the maximum. Vehicle velocity could not be held constant within the spectrum resolution of the sample and the equipment frequency stability. The general "double peaked" nature of the overall spectral peaks is probably due to a discontinuity in measuring vehicle velocity. Independent rough checks on vehicle velocity, recorded simultaneously with the data, indicate that changes of velocity on the order of that required to produce the peaks at $+1.3$ and $+1.2$ did occur. Nevertheless, the velocity was held sufficiently constant to ensure that the overall power concentration from $+1.2$ to $+1.3$ was produced by a different scattering center than that from $+0.8$ to $+1.0$. These two (possibly more) scattering

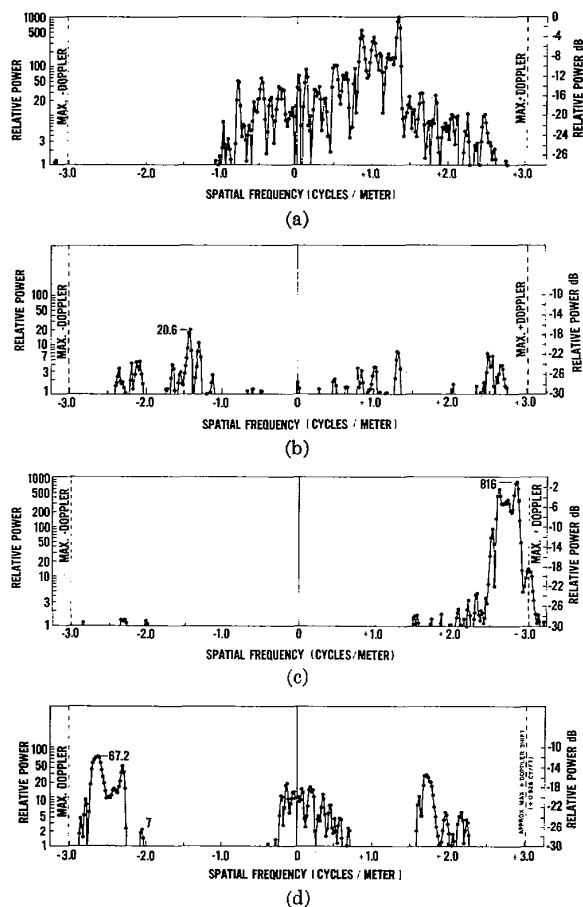


Fig. 7. RF Doppler spectra from American Legion Drive. (a) At $0.04 \mu\text{s}$ relative delay (maximum of average power delay profile). (b) At $0.24 \mu\text{s}$ relative delay. (c) At $1.14 \mu\text{s}$ relative delay. (d) At $4.26 \mu\text{s}$ relative delay.

centers are within 3 dB of each other. Other less intense centers are indicated at $+0.5$ to $+0.6$ and from there on down to about -1.0 c/m. In the positive direction $+2.6$ is about the end of this scattered power spectrum. The received power at $0.04 \mu\text{s}$ delay is quite concentrated between $+0.8$ and $+1.3$ c/m which corresponds generally to the angle between the vehicle line of travel and the transmitter. As the vehicle moves along a street, signals from scattering centers may become more or less intense as the angle to the vehicle changes. Some spectral broadening due to this amplitude modulation may occur but it is thought to be small. (The spectral broadening due to the 36 m sample window with the Hamming window is on the order of 0.05 c/m wide; a signal going from 0 to max to 0 in 3 m of travel would be broadened to about 0.3 c/m width and its amplitude would be reduced at least 7 dB below the value it would have if it were present over the entire 36 m.) Spectral broadening due to amplitude modulation is difficult to distinguish from other broadening in this measurement.

Fig. 7(b) is the equivalent RF Doppler spectrum at $0.24\text{-}\mu\text{s}$ delay. The relative power and dB scales are re-

ferred to the same level as Figure 7(a). At $0.24 \mu\text{s}$ the average received power is about 13.5 dB below the average received power at $0.04 \mu\text{s}$ (see Fig. 5(c)). This is reflected in the overall lower power levels seen in the Doppler spectrum of Fig. 7(b). The major spectral components are still about 10 dB above noise and spurious. This situation with several concentrations of power distributed throughout the spectrum is consistent with the Rayleigh amplitude distribution for the signal at $0.24 \mu\text{s}$ in Fig. 6(b).

The spectral plot in Fig. 7(c) is from the major power concentration at $1.14 \mu\text{s}$ in Fig. 5(c). Only one major Doppler shifted spectral peak is evident at almost the maximum possible positive Doppler shift. This indicates a strong reflector ahead of the vehicle and is consistent with the amplitude distribution in Fig. 6(b). The shallow fading is probably due to changes in amplitude of the reflected wave with angle from the reflecting surface and may be caused by either surface irregularities or the finite size of the reflector.

Fig. 7(d) is a similar RF Doppler spectrum for $4.26 \mu\text{s}$ delay on Fig. 5(c). Three major clusterings of scattered power are evident. The irregular structure and width of these clusters indicate that they are associated with groups of scattering centers (very rough surfaces or groups of buildings or maybe even sides of small hills) and not with individual smooth reflectors. The scattering center at about 0 Doppler shift must be almost at right angles to the path of vehicle travel. The positive shifted center must lie ahead of the vehicle at an angle of about 55° to the path of the vehicle and the negative shifted one behind it at an angle of about 35° .

The Doppler spectra in Figs. 7(a)–(d) are cross sections of a total delay Doppler scattering function [7], [15]. These sections along with Fig. 5(c) illustrate the dominant features which would be seen in such a function. Specifically, the total spread in frequency and delay are illustrated.

IV. SUMMARY

The bandpass impulse response measuring equipment described has been very useful for measuring multipath delay and Doppler characteristics at 910 MHz in a suburban mobile radio environment. The $0.1 \mu\text{s}$ resolution in delay and resolution in Doppler frequency shift have provided quantitative descriptions of the propagation medium which are useful in communications system analysis and have provided additional insight into the physical nature of the multipath. The low (kHz) bandwidth of the data output has made data recording and interfacing with digital data processing equipment relatively easy. This ease in data processing has permitted much more detailed analysis of the data than has been possible in previous mobile radio time delay experiments.

For the first time small scale statistics of the multipath for vehicle travel distances on the order of 30 m along streets are available in the following forms: 1) average power-delay profiles made up of over 200 individual pro-

files, 2) cumulative distributions of signal amplitude at fixed delays, and 3) radio frequency Doppler spectra at fixed delays.

Data from Annapolis Drive, Hazlet, N.J., is typical of the suburban data. Second central moment delay spreads are on the order of $0.25 \mu\text{s}$. Average power delay profiles tend to have power concentrations on the order of $0.25\text{-}\mu\text{s}$ wide just after the minimum propagation path delay between transmitter and receiver. The most intense scattering appears to be from buildings along the street in the immediate vicinity of the vehicle. Signal still arrives at a reduced level for delays of over $1 \mu\text{s}$. Because of the relatively large delay associated with these low-level signal components they contribute significantly to the delay spread parameter. Cumulative signal level distributions at fixed delays are often Rayleigh but significant departures from the Rayleigh are not unusual.

Data from American Legion Drive, Keyport, N.J., is a sample of an extreme but not unique set of suburban data. It is more nearly like data from urban areas. Scattering seems to be from discrete objects farther away from the vehicle since significant power concentrations are seen in the power delay profile out to excess delays of 6 or $7 \mu\text{s}$. The second moment delay spread along this section of street is about $2 \mu\text{s}$ and the average delay is also about $2 \mu\text{s}$ after the minimum propagation path delay. Cumulative signal level distributions at fixed delays are often Rayleigh but some discrete paths exhibit distributions with a much smaller fading range than the Rayleigh distribution. Statistics for this section of street are relatively stationary for longer travel distances than for the more typical suburban situations. This is consistent with the fact that in the more typical case the dominant scatterers are in close to the vehicle and large changes in angle to the scatters occur for short vehicle travel distances. For the more extreme case, the dominant scatters are hundreds of meters away so angular changes are much smaller for an equivalent vehicle travel distance. For the extreme case the vehicle is more nearly in the "far field" of the scatters. The RF Doppler spectra resolve the angles from the vehicle (within a two-fold ambiguity) to scatterers having nearly the same delay. Some of the power concentrations appear to be discrete both in the delay and the Doppler coordinates. This indicates that only one scatterer or scattering center is involved. Other significant power concentrations at relatively long delays have several discrete Doppler components shifted both positive and negative. These multiple paths at nearly the same delay produce rapid fading of the high resolution "pulse" envelopes as the vehicle moves along the street.

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