Millimeter-Wave Propagation at Street Level in an Urban Environment

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Abstract—**Measurements on point-to-point transmission at street level were performed in downtown Denver, CO, with RF probes that operated in the upper microwave and lower millimeter-wave bands. All probes were mounted on self-contained vehicles, thus permitting a variety of path scenarios. Information on performance of SHF/EHF channels when propagating in an urban environment on both line-of-sight and non-line-of-sight paths is presented.**

I. Introduction

A MEASUREMENT program was conducted on point-to-point transmission in an urban environment at frequencies in the upper microwave and lower millimeter-wave bands. The purpose of this program was to determine characteristics of signals propagated through, around, and reflected from buildings and other structures common to a city, with both terminals located at street level. Most of these measurements were made in downtown Denver, CO, over paths with a length of up to 1.5 km.

Three measurement efforts were conducted over a three-year period. Data were recorded for a variety of scenarios using two operating systems. The first system used narrow-band channels at 9.6, 28.8, and 57.6 GHz and the second used narrow-band channels at 11.4 and 28.8 GHz and a very wide-band channel at 30.3 GHz. Parameters measured in addition to received signal level (RSL) on all channels were the bit-error-rate (BER) at a 500-Mb/s transmission rate and the channel impulse response with a resolution of 1 ns or better. These parameters were generally recorded as a function of path length, antenna height, antenna polarization, and antenna bandwidth. For easy mobility, the measurement systems and their control instrumentation were housed in two small vans that also included positioners for the antenna sets.

Reflection loss and aspect sensitivity measurements were made on a roadway and on a variety of building surfaces. These measurements provided reference data for the assessment of street level interference between the reflected signals and the direct line-of-sight (LOS) signals. A series of non-LOS measurements using buildings as path obstructions provided data on propagation loss and the use of edge-diffraction as a means of enhancing a communications link. Measurement parameters included building height, depth, construction type and relative path length. A third set of measurements conducted along selected street segments in downtown Denver, CO, were taken to produce comparative data for the analysis and study of multipath effects. Each run produced either simultaneous RSL and BER data, or RSL and impulse response data.

Additional information and details about operating system #1 and measurements made with this system can be found in [1] and [2]. A complete description of operating system #2 (diagnostic probe) is contained in [3].

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II. Equipment and Experimental Configurations

The instrumentation, referred to as operating system #1 in this paper, was developed to measure RSL between terminals positioned on either LOS or non-LOS paths at three coherent frequencies: 9.6, 28.8, and 57.6 GHz. The beamwidths of the transmitting antennas are 10 degrees at all three frequencies. The receive antenna beamwidths are 4.8° at the 9.6-GHz channel and 1.2° at the 28.8- and 57.6-GHz channels. The receiver sensitivity and dynamic range (for early measurements) were −110 dBm and 60 dB. With system modifications these levels were later improved to −132 dBm and 80 dB.

Operating system #2 (referred to as a diagnostic probe) used at the transmit terminal a 28° antenna beamwidth at 11.4 GHz and a 30° antenna beamwidth at 28.8 and 30.3 GHz. The 28.8- and 30.3-GHz channels shared a common antenna by means of an orthomode transducer (linear polarization). Both narrow-beam and wide-beam antennas were used at the receiver terminal. In the narrow-beam mode, the antenna beamwidths were 10°, 2.4°, and 2.25°; respectively at 11.4, 28.8, and 30.3 GHz. In the wide-beam mode, the corresponding antenna beamwidths were 28°, 30°, and 30°. The receiver sensitivity was −132 dBm and the dynamic range was 80 dB for the 11.4- and 28.8-GHz channels and −80 dBm and 40 dB for the 30.3-GHz channel. Both the 11.4- and 28.8-GHz channels have IF bandwidths of approximately 5 kHz and the 30.3-GHz channel has a bandwidth of 1000 MHz.

One of the features of the diagnostic probe is the ability to measure the impulse response of the channel. This is accomplished by phase modulation of the 30.3-GHz carrier with a pseudorandom binary sequence at a rate of 500 Mb/s. The 30.3-GHz signal is transmitted through the channel to a receiver where the signal is demodulated to reproduce the 500 Mb/s pseudorandom sequence degraded by any distortion that may have occurred in the propagation between transmitter and receiver. At the receive terminal, a replica of the transmitted pseudorandom binary sequence is generated. A cross-correlation is performed between the received demodulated bit stream and the replica of the transmitted bit stream by allowing one bit stream to slide by the other in time as a result of a slight offset in the bit-clock frequencies. At the point in time when the bit sequences are perfectly aligned, an impulse is generated with a base duration equal to two bit times. The impulse response measurement repeats at a rate corresponding to the number of bits in the sequence (either 2^7 or 2^{15} is used) divided by the clock offset rate. Path losses and phase dispersion during propagation through the channel appear in the (cross correlated) output signal as changes in amplitude and impulse shape. A channel is completely described by the impulse response or its Fourier transform, the transfer function of the channel. Thus, the diagnostic probe is a means of acquiring data needed for the modeling of channel characteristics and predicting performance for specific applications.

In near real time, the received bit stream can be routed for processing by matched filters and decision-making circuitry to estimate the binary states of the received data stream. With knowledge of the transmitted word, a count of the occurrence of errors can be recorded. This provides a performance measure of a channel in terms of BER that can be compared to channel characteristics as seen by the impulse probe.

The impulse response cross-correlation and analog-to-digital converter had an effective dynamic range of 36 dB, a 1-dB amplitude resolution, and a 1-ns time delay resolution. The BER receiver had a minimum detectable error rate of 2×10^{-8} as a result of a 1-s interval error count gate needed to provide the necessary resolution.

To perform the along-the-street measurements, very fast sampling rates and remotely controlled RF and IF circuits were required because of the number of data channels used, the extremely high data rate of the wide-band channel, and the fact that one or both terminals were in motion. To accommodate this requirement, a high-speed multitasking real-time processor was carried on the receive terminal. This computer system allowed for the hardware control and all data handling to occur at a sufficient rate to resolve the channel characteristics even for the worst case when both terminals were in motion in an urban environment. For example, an impulse response can be processed and stored at 2-s intervals, and if the RSL of all channels were sampled at a 20 per-second-rate, impulse responses can be taken at 5-s intervals.

Antenna positioners at both terminals allowed for fixed antenna pointing or scanning in both the azimuth and elevation planes. For the measurements various link configurations were utilized to study the propagation factors of concern. The diagrams in Fig. 1 show three operating configurations. A description of these configurations and comments on the data obtained follows:

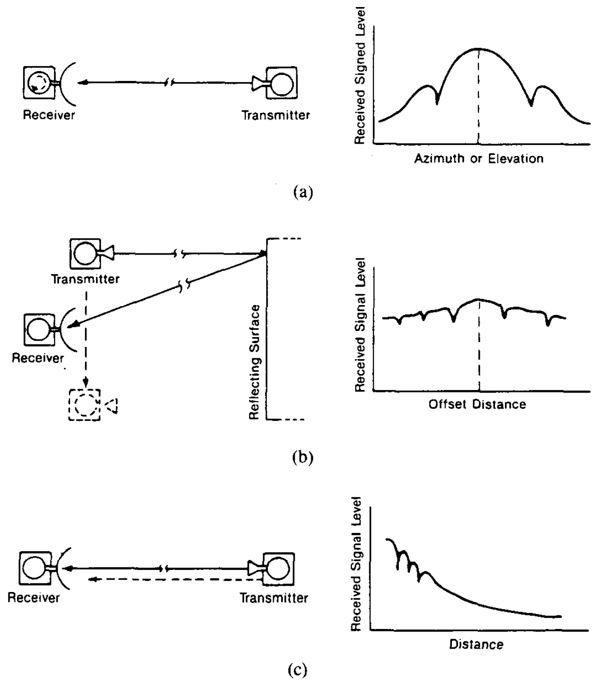


Fig. 1. Test link operating configurations. (a) Azimuthal or elevation scan. (b) Horizontal position scan. (c) Range scan.

1) Azimuth and Elevation Scans (Fig. 1(a)): In this configuration, the transmitter and receiver were set at a fixed distance and the receiving antenna was scanned either in azimuth or elevation. The measurements to determine building and material losses on non-LOS paths were usually conducted in this mode. The transmit terminal was also equipped for azimuth and elevation adjustments.

2) Horizontal Position Scan (Fig. 1(b)): The receiver was set on a line perpendicular to a reflecting surface and the transmitter was moved on a line parallel to the reflecting surface. This mode of operation was used to determine aspect sensitivity of the reflected signal in a folded path mode.

3) Range Scan (Fig. 1(c)): The receiver was stationary, the transmit and receive antennas usually were pointed at each other, and the transmitter was moved along a line toward the receiver. The recorded signal represented a measure of signal amplitude as a function of distance for a LOS path with multipath components. This was also the most frequently used mode for measuring BER and impulse response.

III. Measurements

A. Reflection Properties

To establish a reference with which to compare and evaluate subsequent measurements, a 3-ft (92-cm) square

TABLE I
RECORDED AMPLITUDES FROM SEVERAL SURFACES
ZERO ANGLE OF INCIDENCE

Test	Surface	9.6 GHz	28.8 GHz	57.6 GHz	[one-way]	Path Length
		SIGNAL AMPLITUDE (dB relative to free space)				
2-0-18	Metal	0	-1	-1	50 Meters	(Paint Shop)
2-1-28	"	+2	-5	-7	41 "	(N. American)
2-1-0	"	-2	-3	-1	50 "	(Paint Shop)
3-0-14	"	+1	-8	-7	80 "	(Gen. Cable)
3-0-22	"	-6	+1	-9	109 "	(Gen. Cable)
		-1	-3	-5	(Average)	
3-0-44	Brick (Solid)	-2	-7	-7	95 Meters	(Joslins)
3-1-0	"	-6	-14	-8	47 "	(")
2-0-22	Concrete (ribbed)	-6	-11	-19	64 "	(Neodata)
2-1-42	"	-5	-7	-18	65 "	(")
2-0-42	Brick (Windows, doorway)	-9	-14	-18	93 "	(RB3)
2-1-22	"	-12	-15	-15	135 "	(")
2-0-10	Concrete Aggregate	-6	-12	-17	75 "	(Cryogenics)
3-0-10	"	-12	-10	-20	75 "	(")
		-8.5	-11.25	-15.25	(Average)	

aluminum flat plate was stationed 58 m from the co-located transmitter and receiver. The test site was chosen to be free of reflecting surfaces behind and to the sides of the plate. Measurements with this configuration using a receive antenna azimuth scan (Fig. 1(a)) showed an identical pattern to those measured with the transmit and receive terminals separated on LOS paths. Also, the compared amplitudes indicate a reflection coefficient for the flat plate of -1 for all three frequencies, 9.6, 28.8, and 57.6 GHz. Three horizontal position scans (Fig. 1(b)) were taken with the transmitter moved by 6 m to either side of the receiver with the flat plate oriented at azimuth angles of 0°, 1°, and 2° and for each case a single peak occurred and each showed a reflection coefficient of -1. This reference measurement verified the proper performance of the instrumentation and confirmed the fact that if a highly conductive reflecting surface is flat relative to the probe wavelength, a high degree of aspect sensitivity will result.

Measurements of reflected and/or scattered signals were made for a variety of surfaces at normal incidence for terminal to reflector path lengths of 41 to 135 m. The exterior building surfaces used as reflectors were metal, brick, concrete, and concrete aggregate. Both the transmitting and receiving terminals were co-located on a line perpendicular to the building, with both sets of antennas pointing at the building.

The results for the zero angle of incidence measurements are presented in Table I. Test numbers, building surface, signal amplitude, path length, and location are given in the table. Reradiated or reflected signal levels were significantly higher for metal than for brick and concrete walls. Values were averaged as shown in the table to indicate an order of magnitude for the reflectivity of the respective surfaces. Note an apparent reduction in signal level with increasing frequency. Most of the variability in the results is believed to be due to variations in surface roughness and because of the wide beamwidth, some ground multipath may appear in the 9.6-GHz data.

The data in Table I show a large variation of effective reflection coefficients for identical surfaces when a different path length or spatial position was used in the measurements. Large scale variations were also evident in subsequent horizontal position scan measurements showing received level fades of 30 dB as a function of short transmitter off-set distances (1 to 2 m). These measurements indicate that most building surfaces, being relatively rough and uneven (at millimeter wavelengths) will exhibit neither the high reflection coefficients nor the high degree of aspect sensitivity observed from the reference "smooth plate" measurements at normal incidence.

In an urban environment, one of the principle reflecting surfaces is the street itself. In order to isolate the characteristics of these reflections from other urban reflecting surfaces, several measurements were made on rural roadways free of reflecting surfaces at the sides. Several range scan measurements (Fig. 1(c)) were made; one example is shown in Fig. 2. The RSL is shown as a function of terminal separation distance for 9.6, 28.8, and 57.6 GHz. The height of the antennas above ground was about 2 m and any reflections on the road surface occurred under very low angles. The gradual decrease in level as the transmitter-receiver distance increases is due to the distance squared free-space factor. An additional signal loss

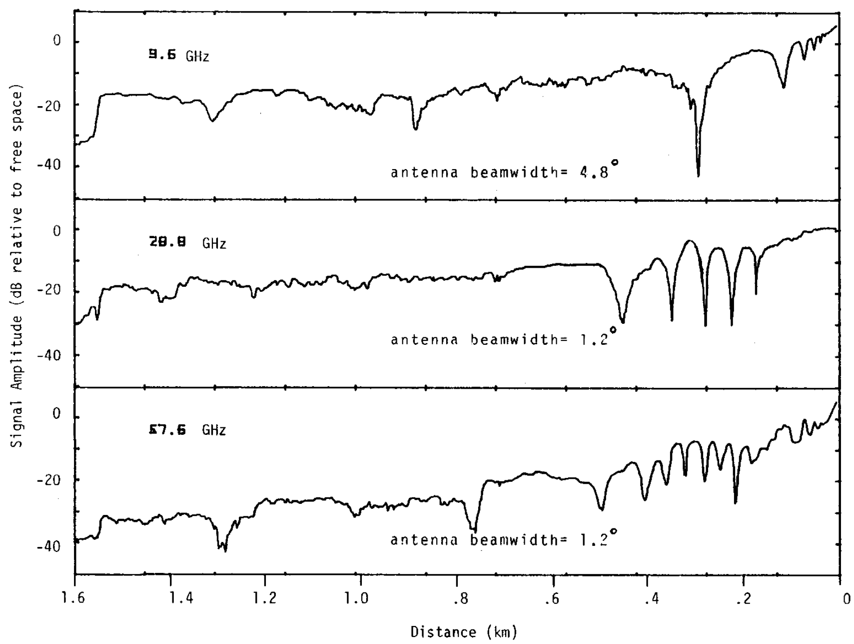


Fig. 2. Signal amplitude as a function of range measured along an asphalt road in a rural area. The transmitter is moved at a nearly constant velocity toward the receiver. Vertical antenna polarization. Transmitter height = 2.15 m. Receiver height = 1.8 m.

at 57.6 GHz as a function of terminal separation is the attenuation due to gaseous absorption of oxygen. At the Denver area elevation (approximately 1525 m), the rate of attenuation is approximately 10 dB/km. Between 0.2 and 0.6 km, a strong interference pattern was recorded. These alternate levels of fade and enhancement are due to the destructive and constructive combination of the direct LOS signal and the ground-reflected components. These patterns are typical of those observed and are subject to variation as a function of frequency, antenna height, antenna beamwidth, antenna pointing, and street surface roughness and curvature.

At distances greater than 0.6 km, the projection of the antenna beam (at this very shallow angle) on the reflecting surface is large (i.e., exceeds in dimension the axis of the Fresnel ellipsoid). The result is that the reflected signal reaching the receiving antenna does not contain a well-defined phase front and, therefore, combines with the direct signal without major interference. At distances less than 0.2 km, the main beam of the 1.2° receiving antennas, at the upper two frequencies, no longer intercepts the roadway. This becomes true at a closer distance for the 9.6-GHz channel because the receiver beamwidth is 4.8°.

B. Non-Line-of-Sight Measurements

Four buildings were used as path obstructions in these measurements. Each building was different in terms of construction materials, architectural design, and size. Measurements were performed as a function of the distance of the transmit and receive terminals from the building and as a function of the pointing angles of the transmitting and receiving antennas. Photographs of the four buildings are shown in Fig. 3. For each measurement, the transmit and receive terminals were placed on opposite sides of the building and were set on a line perpendicular to the building walls. In Table II the measured RSL values (in decibels referred to one milliwatt) are given as a function of frequency, construction type, width of building at path intersection, and total path length.

The results for Building #1, Test A, show no detectable signal above the noise threshold (−132 dBm) on the 28.8- and 57.6-GHz channels. The antennas in this case were pointed perpendicular to the front and back wall of the building and were separated by a distance of 42 m (through the building). If this 42-m path were a LOS path, the RSL would be −23, −20, and −38 dBm for the 9.6-, 28.8-, and 57.6-GHz channels, respectively, thus the loss through the cement-block structure was about 84 dB at 9.6 GHz and greater than 100 dB at 28.8 and 57.6 GHz. Tests B and C also measured RSL with the antennas still pointed perpendicular to the building walls, but placed at greater distances away from these walls. These three tests indicated that this flat-roofed structure supported a diffraction mode of signal propagation with a lower path loss than the direct-path mode (propagating through the building), because the RSL increased as the spacing of the antennas from the building was increased and the illumination of the exterior edges of the building was enhanced. The conclusion was clearly confirmed by performing an elevation scan with the receiving and transmitting antennas which showed that a signal maximum occurred when both antennas pointed directly to the roof edges as in Test D. It appears that the maximum contribution to the received signal is transported by a double-

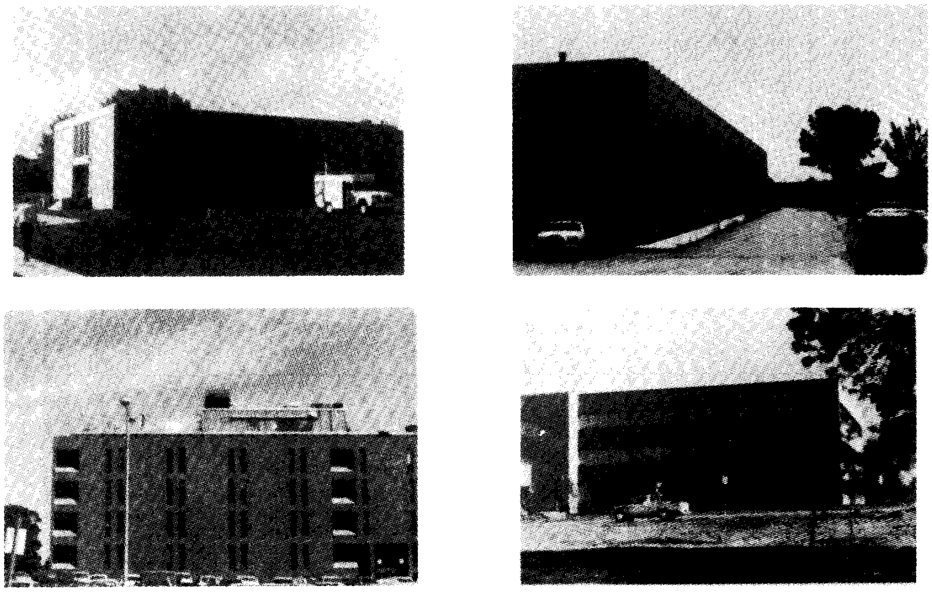


Fig. 3. Photographs of four test buildings.

TABLE II
RECEIVED SIGNAL LEVELS WITH BUILDINGS AS PATH OBSTRUCTORS

Building #/ Test #	Construction Type	Antenna Pointing	Building Width/Height (Meters)	Path Length (Meters)	Received Signal (Level of dBm) Frequency (GHz) 9.6	28.8	57.6
1 A	Solid Cement-Block Walls	Direct	17/6	42	-107	<-132	<-132
1 B	"	"	"	• 53	- 87	-130	<-132
1 C	"	"	"	→ 90	- 92	- 98	-113
1 D	"	Toward Roof Edge	"	→ 53	- 80	- 80	- 93
2 A	Solid Pre-Cast Concrete	Direct	100/7	200	<-132	<-132	<-132
2 B	"	Toward Roof Edge	"	"	-113	-117	-132
2 C	"	"	"	→ 260	-104	-104	-130
3 A	Brick w/ Windows	Direct	40/16	120	-113	-130	<-132
3 B	"	Toward Roof Edge	"	"	-104	-114	-127
4A	Chromatic Glass	Direct	53/9	72	- 88	- 90	-107

*

edge diffraction mode. Tests 2B, 2C, and 3B also show the higher values of RSL when both the transmitting and receiving antennas were pointed directly at the roof edges.

In Test 4A, an office building with predominantly glass walls was the path obstruction. These walls (windows) are a chromatic coated glass and appear as mirrors (in the visible spectrum) from outside but are transparent from the inside. With only the front and back walls in the path (the building was empty), surprisingly high losses of 60, 65, and 64 dB for the 9.6-, 28.8-, and 57.6-GHz channels, respectively, were observed when compared to an equivalent 72-m LOS path. Apparently the chromatic glass coating has a high conductivity in the millimeter region.

Additional measurements were made on non-LOS paths (125 to 425 m) in the dense high-rise sector of downtown Denver. These measurements were conducted in a much less rigorous fashion (regarding exact terminal position), than for the measurements described above. A general observation from these data was that significant signal enhancement could be achieved by choosing the antenna pointing in the horizontal plane very carefully, presumably taking advantage of multipath signals due to reflections at the building walls and/or diffraction at the vertical edges. Even though several blocks of multistory structures separated the terminals, signals above the receiver noise thresholds could be achieved by careful pointing of both antennas.

C. *Line-of-Sight Measurements*

A series of LOS measurements were made on several streets in downtown Denver, CO. These were range scan measurements according to Fig. 1(c) with a maximum path length of approximately 1 km. The pictures in Fig. 4 were taken on the 17th Street path used in these experiments. The data collected during these runs included RSL's at all frequencies, impulse response curves, and BER. The RSL's and the impulse response curves provide information about the fade characteristics (multipath signal amplitudes and delay times), and the BER data indicate channel performance. The experimental variables were street geometry, terminal location, and antenna beamwidths and pointing.

1) Received Signal Levels: The RSL traces recorded in Fig. 5 come from a range scan along 17th Street in Denver, CO. The total path length was 0.9 km and the street intersections occurred at 0.1-km intervals.

Note that the urban street range scan (Fig. 5) shows fewer deep fades than the rural road scan (Fig. 2). The reason for this is the presence of many more multipath components due to reflections from the building walls along the street; and these additional reflected signals reduce the probability of deep fades in received signals. The condition for the deepest fade to occur on a LOS path is that the sum of all the multipath signals is exactly equal in amplitude to the direct signal and 180° out of phase with this signal. Since the reflection coefficient of the street surface is nearly unity at small grazing angles, the presence of street reflection alone produces this deep fade condition. Additional multipath components occurring simultaneously with the street reflected signal make the required amplitude and phase balance far less likely. Also note in Fig. 5 that at distances greater than about 0.1 km for the 9.6-GHz plot and 0.3 km for the 28.8- and 57.6-GHz plots, more numerous and deeper fades appear because the main lobe of the receiving antenna begins to illuminate the building surfaces. At these distances the most severe fades due to buildings would likely be caused by a single reflection from a wall surface, but two and three hop reflections can also provide a significant signal at the receiver, as can be seen in the impulse data shown later in this paper.

An inspection of the exterior surfaces of the buildings along 17th Street revealed that the majority consisted of brick, stone, or concrete with many glass windows at street level. An earlier section of this paper showed that these types of surfaces had a poor reflection coefficient at normal incidence, due largely to surface roughness and irregularities that were sizeable relative to the RF wavelength. At grazing incidence, of course, the surface appears smooth and its reflection coefficient approaches -1. A test to determine if a surface is considered smooth is the Rayleigh criterion [4]

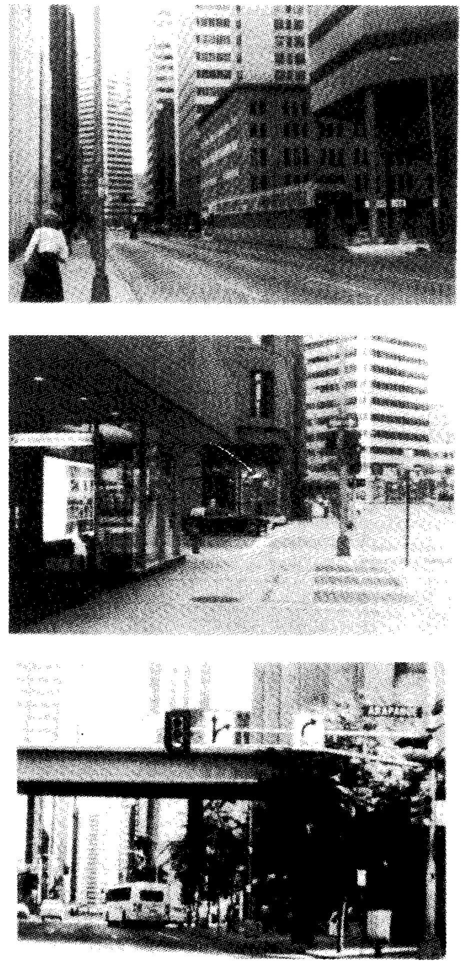


Fig. 4. Photographs of street fronts along 17th Street in Denver, CO.

$$H \leqq \lambda/8 \cos \theta$$

where θ is the angle of incidence, λ is the RF wavelength, and H is the height of the surface irregularity. The criterion requires that the phase shift of the wave reflected from the top and the bottom of the irregularity not exceed $\lambda/4$. Using 30 GHz as an example, at zero angle of incidence, H cannot exceed about 0.13 cm but at an angle of incidence of 8°, which is a realistic angle for an along-the-street reflection, H cannot exceed about 6.37 cm. This ratio of almost 50 to 1 demonstrates the reason some of the wall reflection levels have been observed to approach the level of the direct signal [1], [2]. For signals propagated between two terminals along a street, another influence on the number of wall reflected components that will reach a receiver is the fact that the street intersection width

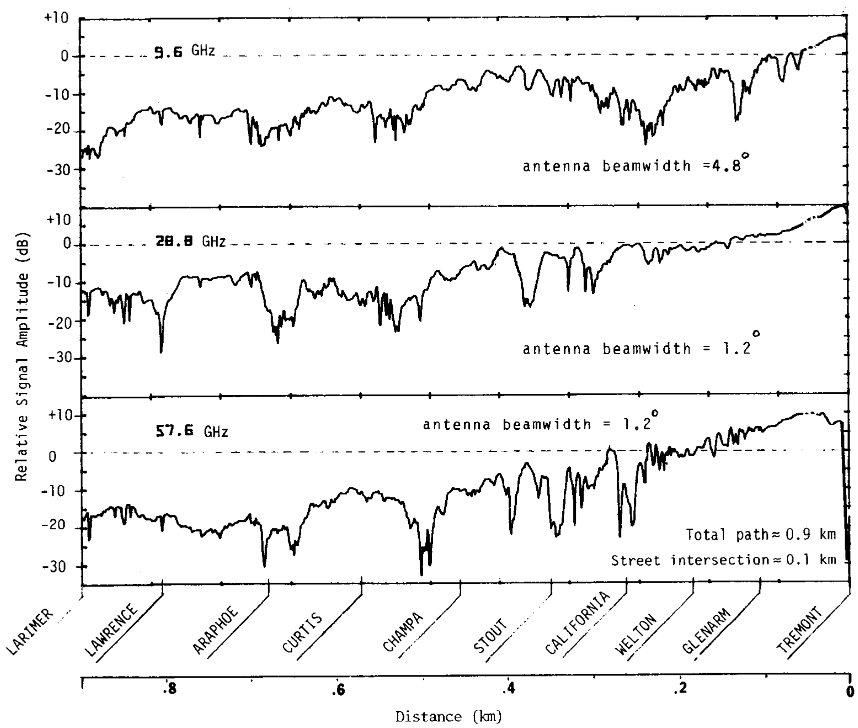


Fig. 5. Signal amplitude as a function of range measured along 17th Street in downtown Denver, CO. The transmitter is moved at a nearly constant velocity toward the receiver. Vertical antenna polarization. The heights of the transmit and receiver antennas were 2.15 and 1.8 m, respectively.

(24 m for 17th Street) is a large fraction of the block length (100 m for 17th Street), and consequently, some potential reflections are diverted at the intersections. A computer model used to predict link performance in an urban environment (not yet published) has been developed. The program takes the open spaces of street interaction into account, and a comparison of numerical and measured data has shown that the amplitude values found for first and higher order multipath components fit the measured data with good agreement.

In an urban situation where one or both terminals are in motion, it may be difficult to maintain good coupling if the antenna beamwidths are too narrow. In order to examine the effect of misalignment of a narrow-beam receiving antenna three range scan measurements were conducted on 17th Street using the same equipment with which the data of Fig. 5 were taken. The results are shown in Fig. 6. Wide-beam transmitting antennas were used to fully illuminate the sides of the street and narrow-beam receiving antennas were pointed off the LOS by 0°, 2°, and 4° in azimuth. The top traces (0°) closely resemble the data in Fig. 5 because they were recorded under similar conditions. The lower two traces clearly show the presence of strong building reflected multipath signals when the receiving antennas were pointed off the LOS. The resulting very significant effect on channel performance can be seen from the impulse response curves and the BER data that follow in the next section.

In an operational scenario, antenna pointing may not be practical because of complexity or the added size of a positioner pedestal. Also, the location of terminals may not be known or multiple terminal coverage may be required. For these cases very wide beam antennas at both terminals may be the solution. With this situation in mind, the second operating system (diagnostic probe) mentioned in Section II was used to determine the propagation effects with widebeam antennas.

Fig. 7 compares a set of range scan curves obtained with wide-beam antennas (approximately 30° at both terminals) to a similar set obtained under identical test conditions, except that narrow-beam receiving antennas were used. An increase in fading for the first two channels that have a narrow bandwidth (5 kHz) is apparent when the narrow-beam antennas (right side) are replaced by wide-beam antenna (left side). The third channel at 30.3 GHz has a very wide bandwidth (1000 MHz) and the RSL plot for the range scan shows far less fading with the wide-beam antenna than with the narrow-beam antenna. This reversal of conditions can be explained by noting that the spacing in frequency (F) of fade nulls is expressed by $F = 1/(t_2 - t_1)$, where $t_2 - t_1$ is the difference in path delay time between the direct signal and the multipath signal. As an example, with the wide-beam antenna some multipath signals may travel 1.5 m or about 5 ft further than the direct signals and, therefore, are delayed by roughly 5 ns. Fade nulls will then occur at a 200-MHz

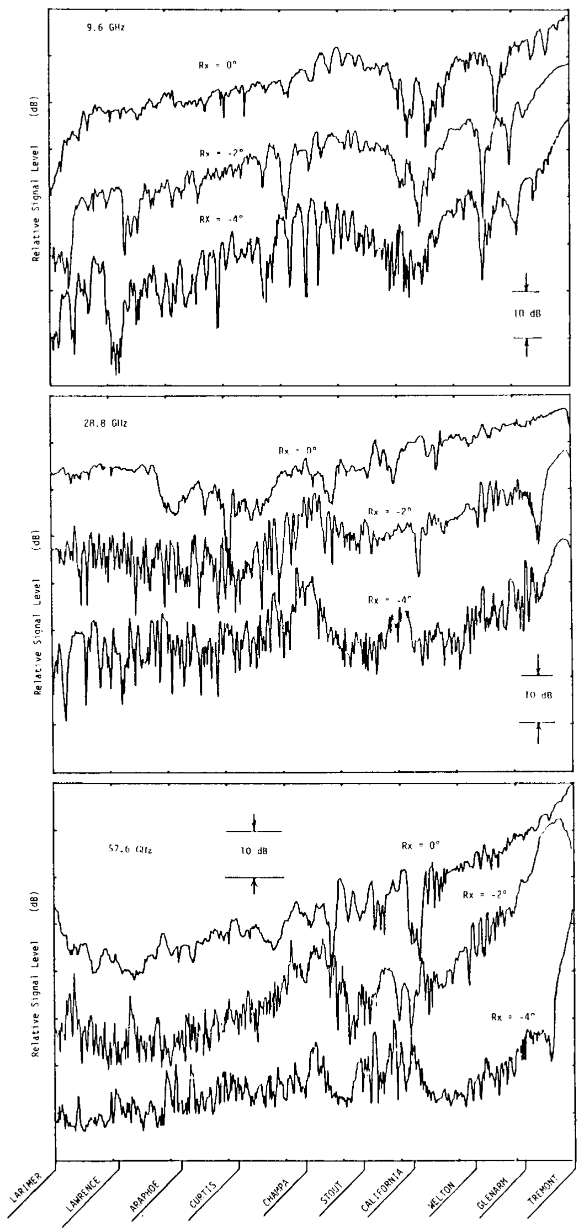


Fig. 6. Signal amplitude at 9.6, 28.8, and 57.6 GHz as a function of range measured along 17th Street in downtown Denver, CO. The transmitter is moved at a nearly constant velocity toward the receiver. Vertical antenna polarization. The receiving antenna is pointed as indicated for each run, with each successive curve offset 10 dB for clarity. The total path length is 0.9 km.

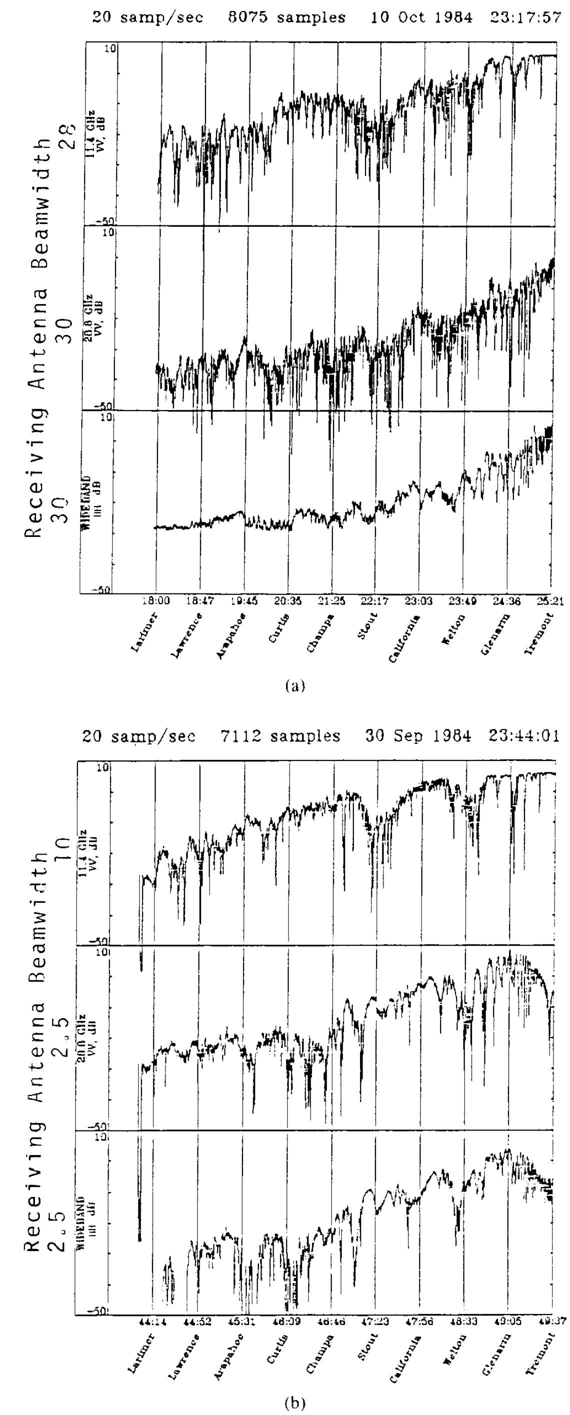
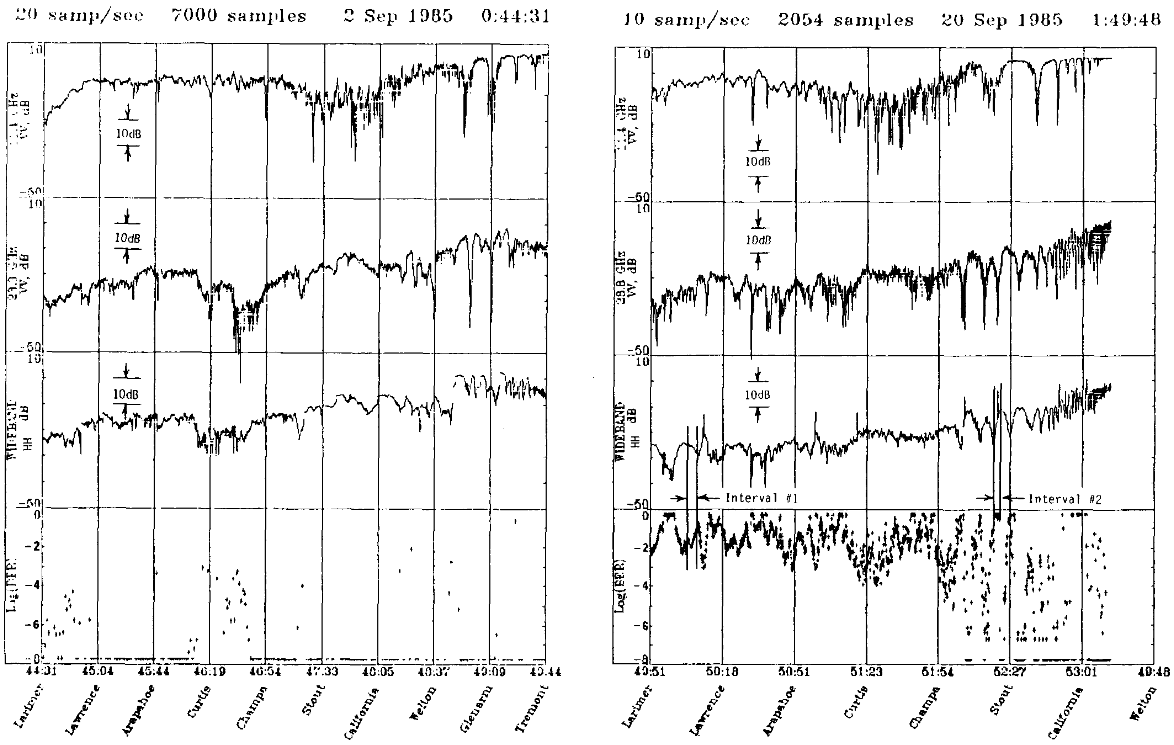


Fig. 7. Received signal levels from 17th Street runs using a wide-beam receiving antenna (a) and a narrow-beam antenna (b).

spacing, producing as many as 5 fades and enhancements within the bandpass of the wide-band channel, but a single fade or enhancement can span an entire narrow-band channel.

All the plots for the narrow-beam receiving antennas (right side of Fig. 7) show similar fading characteristics, even the wide-band channel. With the narrow-beam antennas the arrivals of reflected multipath signals are restricted to shallow angles and thus delay time differences are less. Delay differences of 1 ns or less are typical and result in null spacings of 1000 MHz or more, which explains why the narrow- and wide-band channels per-



(a) (b)

Fig. 8. Received signal levels and BER from 17th Street runs using a narrow-beam receiving antenna (a) and a wide-beam receiving antenna (b).

formed similarly when using the narrow-beam receiving antennas.

Note that the fade depths for the narrow-band channels reached or exceeded 30 dB quite frequently in Fig. 7. Many such plots were recorded over the course of the measurements with both operating systems. System #2 consistently recorded greater fade depths than System #1 (Fig. 5). The reason was determined to be the better time resolution using the larger processor where sampling rates for all channels of 20 per second (compared to 2 per second) was possible and allowed the recording of the rapid transition period at the bottom of the fade. There was an average of about 10-dB increase in recorded fade depths with System #2 for range scans where terminals approached each other at a velocity of about 5 MPH (8.1 KmPH).

2) Bit-error-rate Measurements: Using the diagnostic probe (operating System #2), RSL data from all channels and BER data from the wide-band 30.3-GHz channel are simultaneously recorded, as shown in Fig. 8. The BER is the output of a BER receiver that compares the received data stream to a locally generated (correct) data stream. In the absence of noise and multipath signals, the receiver output indicates a very low BER (2×10^{-8} for this probe).

The data in Fig. 8 are from two runs along 17th Street. In the run on the left, a narrow-beam antenna (high antenna gain) was used. The BER output shows mostly very low error rates of 2×10^{-8}. This is a situation of high signal-to-noise ratio; however, there are a few higher BER values that resulted from intersymbol interference caused by delayed multipath signals. In the run on the right, a wide-beam antenna (low antenna gain) was used. This reduced the system gain by about 25 dB, resulting in a much lower signal-to-noise ratio and an increased reception of the multipath signal reflected from the buildings along the street. These two conditions have a pronounced effect on the recorded BER. In the early part of the run (from Larimer to Champa), there is an almost direct inverse correlation between the wide-band (30.3 GHz) RSL and the BER. This would indicate that the bit-errors are determined primarily by the signal-to-noise ratio. As the path is shortened (in the region from Champa to California), the received signal has increased 15 to 20 dB above the level at the start of the run (compare interval #2 to interval #1). Even with this significant increase in signal-to-noise ratio, some periods of maximum bit-errors 5×10^{-1} are recorded in the region of major fade activity (Champa to California). These high BER's are primarily the product of intersymbol interference.

3) Impulse Response Measurements: In the second mode of operation of the diagnostic probe, both RSL's for all channels and impulse response curves were recorded. The impulse response curves produce a record of the pres-

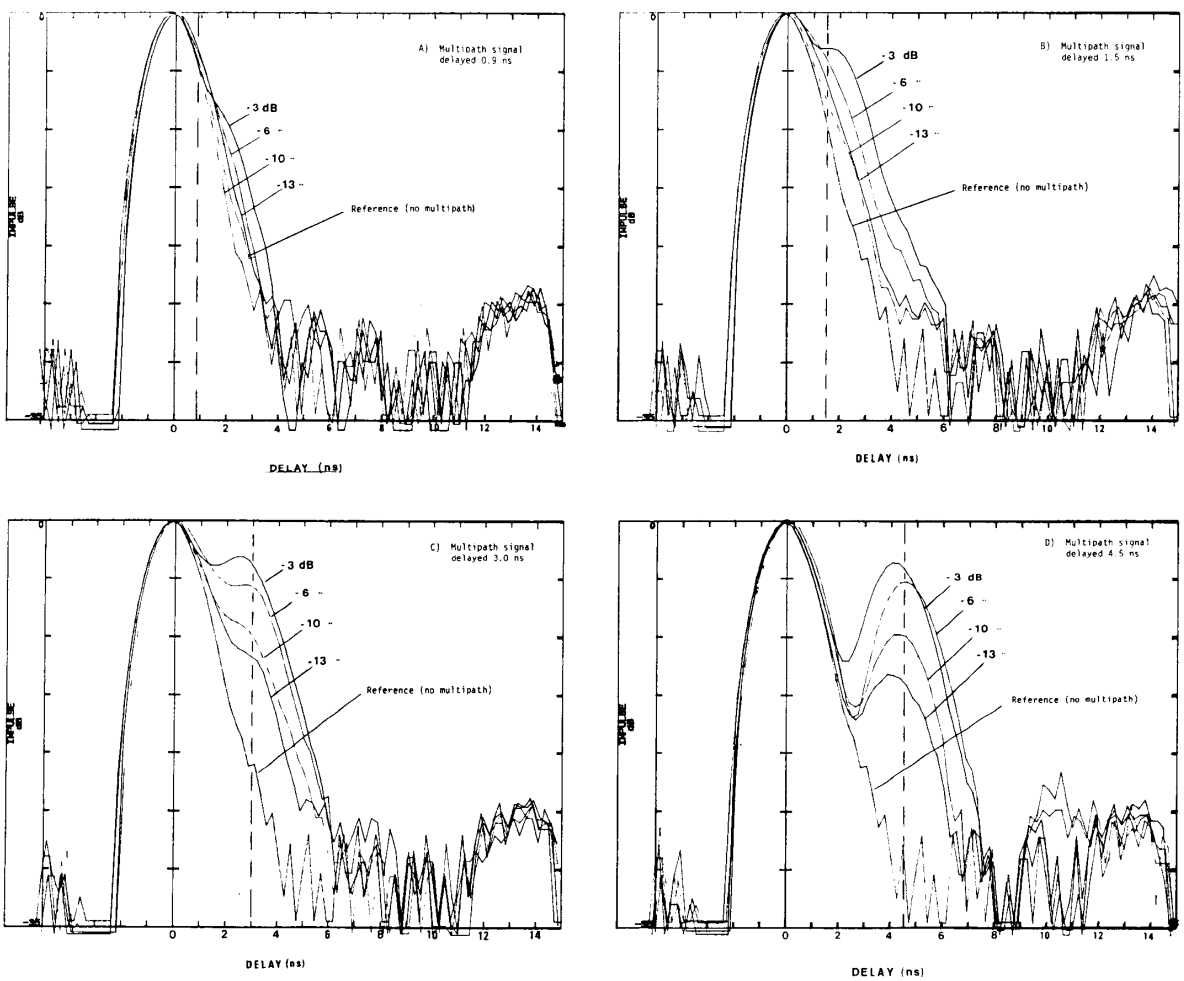


Fig. 9. Sets of reference impulses plus (controlled) multipath signals.

ence of multipath (reflected) signal to the direct path signal. The examples shown in Fig. 9 are outputs of controlled calibration runs.

The figure shows four sets of reference impulses plus multipath signals with electrically delayed paths of approximately 0.9, 1.5, 3.0, and 4.5 ns as indicated in the figure. The reference impulse curve of each set is for a no multipath condition. In each set the multipath signal was delayed by a fixed amount and then the combined amplitude levels were recorded for multipath-signal to direct signal ratios of −3, −6, −10, and −13 dB. For short delays (Fig. 9(a)), the presence of a multipath signal is manifest in the broadening of the trailing edge of the impulse response. If the delay and amplitude of the multipath signal were not known, one could conclude only that such signals were present, but could not predict the delay and amplitude values with any confidence. However, when the multipath delays reach 3 ns and more, as shown in Fig. 9(c) and (d), the multipath components become clearly separated from the reference impulse, and both delay and amplitude value can be assessed within the measurement accuracy.

Several sets of impulse response measurements were made along the same 17th Street path used for the RSL measurements in the previous section. In some cases, both amplitude and impulse measurements were recorded on the same run, with the amplitude recorded continuously and the impulse curves sampled at 6- to 10-s intervals.

The impulse response traces in Figs. 10–12 were taken during the last half of runs from Larimer to Tremont along 17th Street. They all cover the same segment of 17th Street (Stout to Tremont). The system configurations were the same on all three runs except for antenna beamwidth and antenna pointing. The sample of curves shown in each figure has been limited to those taken over a distance of five blocks because of the number of curves generated. Even at 10-s intervals, nearly 50 curves were recorded in the 1-km run. The transmit antenna beamwidth was 30°. The beamwidth and pointing direction of the receiving antenna were as follows:

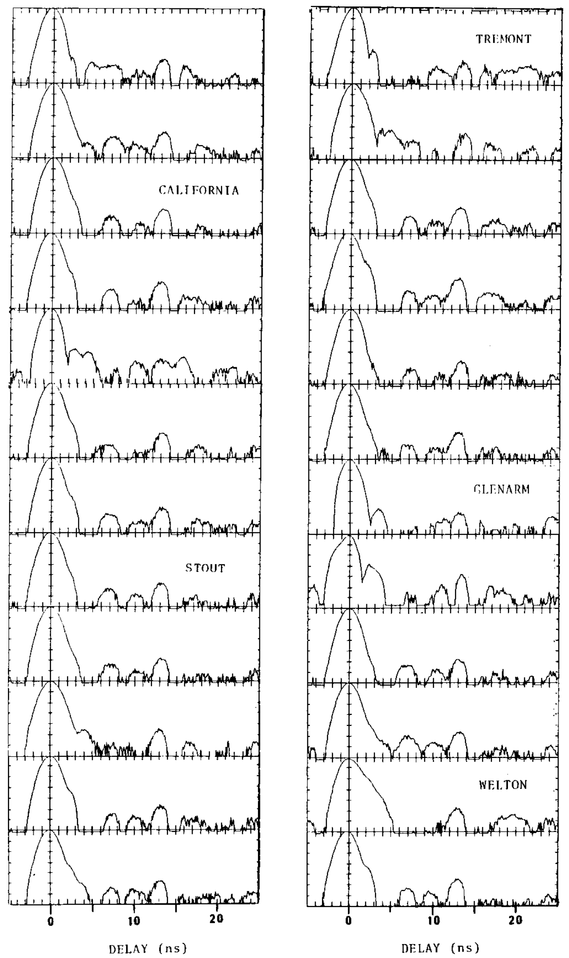


Fig. 10. Impulse response curves recorded along 17th Street. A narrow-beam antenna was used with the receiving antenna adjusted for on-line pointing. The amplitude scale is 5 dB per tick mark (35 dB total).

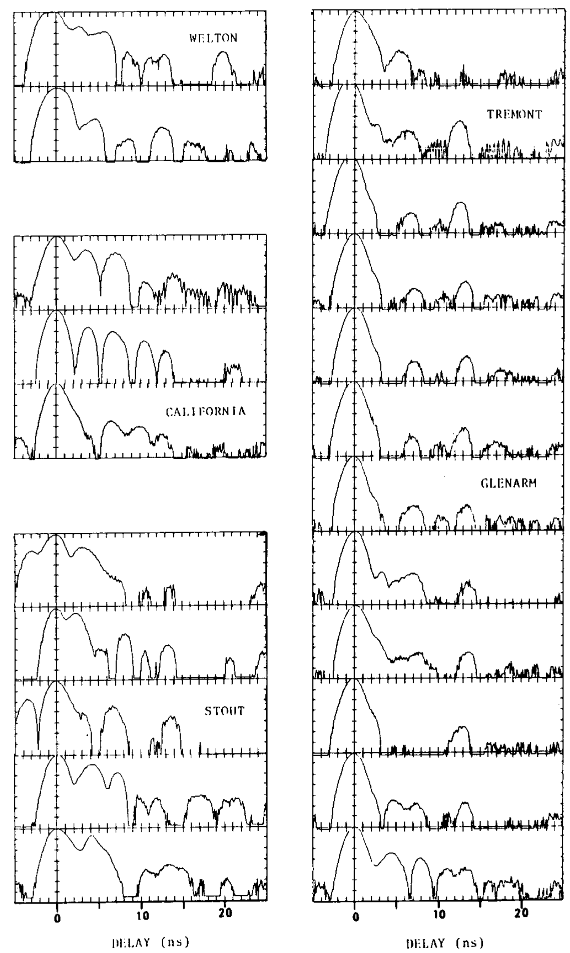


Fig. 11. Impulse response curves recorded along 17th Street. A narrow-beam receiving antenna was used with the antenna pointed off the LOS by 3°. The amplitude scale is a 5 dB per tick mark (35 dB total).

Figure	Beamwidth	Pointing
10	Narrow (2.3°)	on-line
11	Narrow (2.3°)	3° (off-line in azimuth)
12	Wide (30°)	on-line

The curves in Fig. 10 show the presence of some multipath signals. These are evident in the broadening and reshaping of the trailing edge of the main envelope. It is difficult to determine the delay and amplitude values of individual multipath signals with accuracy, but they can be estimated to fall in the 1- and 4-ns delay range and at −15 to −25 dB below the amplitude of the direct signal.

Pointing the narrow-beam antenna off the LOS by 3° produced a dramatic change in the received multipath signals as may be seen by comparing Fig. 11 to Fig. 10. There are many multipath signals with delays in the 3- to 10-ns range and amplitude ratios of +6 to −10 dB relative to the direct signal. With the receiving antenna off-pointed, there were occasions when a multipath signal was stronger in amplitude than the direct component. An example is the impulse curve measured at the Stout Street intersection. The computer is programmed to position the signal with the greatest amplitude at 0 delay, and for this case a multipath signal was strongest and the direct signal, always the first to arrive, occurred at −3.3 ns (in the response curve display).

The curves in Fig. 12 were produced using a wide-beam antenna and on-line pointing. Many multipath signals are present in this data also. This is not unexpected because the wide-beam antenna would illuminate both sides of the street. The delay values of the individual multipath signals fall in the 1- to 10-ns range and the amplitude levels relative to the direct signal are in the range from −2 to −15 dB.

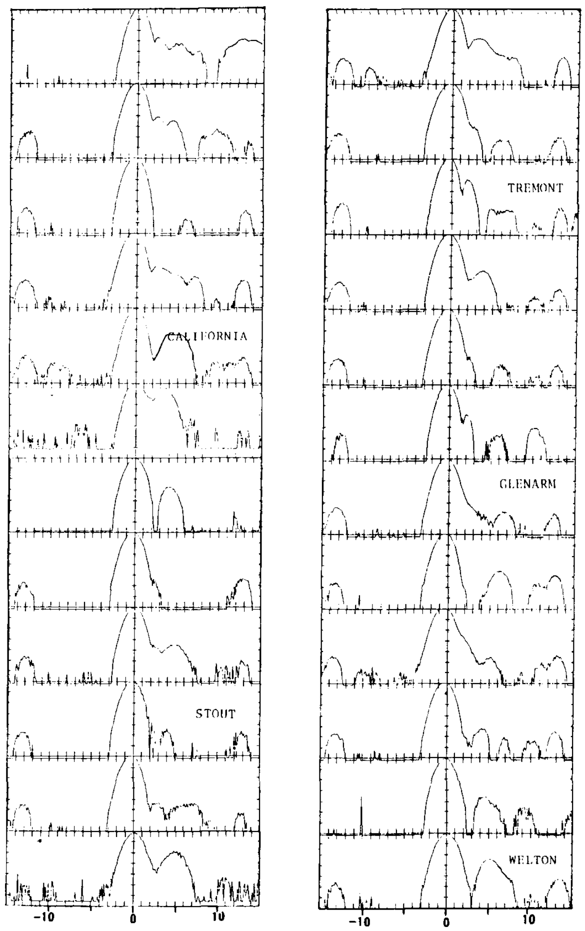


Fig. 12. Impulse response curves recorded along 17th Street. A wide-beam receiving antenna was used with the antenna adjusted for online pointing. The amplitude scale is 5 dB per tick mark (35 dB total).

IV. SUMMARY

A. Non-Line-of-Sight Paths

Continuous wave signal probes were used to measure signal loss, at 9.6, 28.8, and 57.6 GHz on paths obstructed by buildings of several common materials, with results that showed signal attenuations in excess of 100 dB. When the LOS followed a path directly through clear glass walls, the attenuation was small at all probe frequencies. However, when the glass wall had a metalized coating to reduce ultraviolet and infrared radiation, the attenuation increased by 25 to 50 dB for each metalized layer. In most cases no signals could be detected through steel reinforced concrete or brick buildings, but if an edge diffraction mode from a roof or even a double edge diffraction mode was used, detectable signal levels could be achieved. A coherent bandwidth for a diffraction channel of this type would be on the order of tens of megahertz based on the magnitude of the time delay spread in the received signal. Both coherent bandwidth and system gain improve as antenna beamwidths are narrowed; however, illuminating a common volume becomes increasingly difficult.

B. Line-of-Sight Paths

Because of the confined surroundings in an urban environment and the existence of many obstructions and scatter objects with flat surfaces such as buildings, roadways, signs, cars, trucks, etc., reflected signals play a major part in defining the propagation characteristics of a line-of-sight channel at street level.

Data were recorded to determine the reflection coefficient of building walls at normal incidence. As would be expected, the reflection coefficients were a direct function of the conductivity and smoothness of the reflecting surface. All of the buildings examined in downtown Denver, CO, produce a reflection coefficient at normal incidence of -0.2 or less at frequencies of 28.8 and 57.6 GHz. For a point-to-point transmission link operating along a street lined with buildings, the angle of incidence (θ) on the reflecting surfaces approaches 90° (near grazing angles). The criterion for surface smoothness includes the function $1/\cos\theta$ and, therefore, as the angle of incidence becomes larger, the surface as seen by the radio wave appears smoother and the reflection coefficient become larger. This fact was supported by the measured data, for which it is evident that reflection from street and building surfaces at very shallow angles produced reflection coefficients near -1.

Even with relatively narrow-beam antennas (2.3 degrees) that were positioned at heights above the street of 2 to 3 m, multipath signals from the street surface produced fades in excess of 30 dB. Because of the small angle between the direct path and the street reflected path, the delay time difference was always less than 1 ns. With these small delay times for multipath signals from the street, the channel distortion is low, or conversely, the available bandwidth is large, greater than 500 MHz. Multipath reflections from building walls and other reflecting surfaces along the street, with narrow-beam antennas in the system, generally had amplitudes that were 15 dB or more below the direct signal at delay time not greater than 10 ns. These low-level multipath signals will cause some channel degradation at a bandwidth above 200 MHz. Note, however, that the worse case distortion will occur when the interference between the direct signal and the street-reflected signal produces a deep fade allowing the much weaker, longer-delay multipath signal to approach the amplitude of the combined direct and street-reflected signal. For near optimum channel performance of a communications link operating with narrow-beam antennas along an urban street, the data taken in Denver suggests, as a rule of thumb, that the antenna beamwidth (3 dB) be twice the expected antenna pointing error.

Measurements using antennas with wide beamwidths of 30 degrees were performed on the along-the-street path, and multipath signals equal to amplitude to the composite direct plus street-reflected signal occurred often with delay times up to 10 ns relative to the direct signal. Therefore, a link using 30-degree beamwidth antennas could support bandwidths of about 10 MHz if a 30-dB fade margin were provided.

Linear antenna polarizations (VV and HH) were compared to determine if millimeter-wave propagation in an urban environment shows any dependence on polarization. In particular, the "Brewster's" angle effect for shallow angle reflections was examined to determine if reflected signal levels could be reduced by selecting an appropriate polarization. Hundreds of impulse response curves were recorded for each polarization under nearly identical conditions and it was not possible to detect any difference in reflected signal power as a function of antenna polarization at grazing angles as small as 8 degrees.

All information on channel performance was obtained from the diagnostic probe operating at 30.3 GHz with a PSK modulation of 500 Mb/s. The probe measures the impulse response of a channel that allows multipath amplitude and delay times to be determined along with the corresponding BER.

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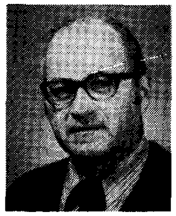

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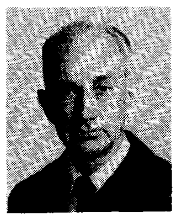

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Dr. Schwering is a member of SIGMA XI and a Visiting Professor at Rutgers University and at New Jersey Institute of Technology. He is a member of URSI, Commission B, and recipient of the 1961 and 1982 Best Paper Awards of the IEEE Antennas and Propagation Society (jointly with G. Goubau). During the year 1984/85, he worked with the US Army Research Office, Research Triangle Park, NC, under the Visiting Laboratory Associates Program.