900-MHz Multipath Propagation Measurements for U.S. Digital Cellular Radiotelephone

THEODORE S. RAPPAPORT, MEMBER, IEEE, SCOTT Y. SEIDEL, STUDENT MEMBER, IEEE, AND RAJENDRA SINGH

Abstract—**The results of multipath power delay profile measurements of 900-MHz mobile radio channels in Washington, DC, Greenbelt, MD, Oakland, CA, and San Francisco, CA, are presented. The measurements have focused on acquiring worst case profiles for typical operating locations. The data reveal that at over 98% of the measured locations, rms delay spreads are less than 12 μs. Urban areas typically have rms delay spreads on the order of 2–3 μs and continuous multipath power out to excess delays of 5 μs. In hilly residential areas and in open areas within a city, root mean square (rms) delay spreads are slightly larger, typically having values of 5–7 μs. In very rare instances, reflections from city skylines and mountains can cause rms delay spreads in excess of 20 μs. The worst case profiles show resolvable diffuse multipath components at excess delays of 100 μs and amplitudes 18 dB below that of the first arriving signal.**

I. INTRODUCTION

CELLULAR RADIOTELEPHONES are becoming increasingly popular. First available to the U.S. public in 1983, over 3 million car phones are in use in the United States today. It is predicted that by 1995, there will be over 20 million cellular telephones in operation [1]. To date, U.S. cellular radiotelephones have used strictly analog voice transmissions with 30-kHz RF channel spacings in the 800/900-MHz band. However, to accommodate the projected tenfold increase in users and the need for data as well as voice, it has been realized that a new U.S. cellular telephone standard must be developed that uses spectrally efficient digital modulation and speech coding techniques.

This paper presents the results of propagation measurements in four typical cellular radio markets throughout the United States [2]. The measurements reveal multipath characteristics for a variety of topographical surroundings and geographical regions, and provide large-scale statistics of the temporal extent of impulse responses in UHF cellular radiotelephone channels. These characterizations are required for determining suitable equalization requirements for next-generation time-division multiple-access (TDMA) U.S. cellular radiotelephone systems, which will gracefully begin to replace existing analog systems in 1991 [1].

Many researchers have already characterized UHF urban radio multipath channels worldwide [3]–[9]. These works have been valuable in assessing typical and worst case power delay profiles that describe the temporal extent of the multipath and the amplitude of multipath components from reflecting objects for various radio channels.

Wide-band multipath channels can be grossly quantified by their mean excess delay ($\bar{\tau}$) and root mean square (rms) delay spread (σ) [2]–[5], [9]–[14]. The mean excess delay is the first moment of the power delay profile and is defined to be

$$\bar{\tau} = \frac{\sum_k \alpha_k^2 \tau_k}{\sum_k \alpha_k^2}. \tag{1}$$

The rms delay spread is the square root of the second central moment of the power delay profile and is defined to be

$$\sigma = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \qquad \text{where } \overline{\tau^2} = \frac{\sum_k \alpha_k^2 \tau_k^2}{\sum_k \alpha_k^2} \tag{2}$$

and α_k^2 and τ_k are derived directly from the digitized oscilloscope values at the receiver. In (1) and (2), the delays of each profile are measured relative to a first detectable signal arriving at $\tau_0 = 0$. Excess delay spread (x dB) is defined as the maximum excess delay at which a multipath component is received with an amplitude within x dB of the maximum received signal level within a single power delay profile.

Multipath profiles measured between a base and mobile in many types of terrain are given in [3]. In hilly terrain, [3] indicates that signal components typically arrive 10–25 μs after the direct (line-of-sight (LOS)) signal and have amplitudes 10–20 dB weaker than the direct signal. Building facades induce multipath signals that have excess delays of less than 10 μs and amplitudes 10 dB below the direct signal. In mountainous regions, significant multipath can arrive with amplitudes within 10 dB of the direct signal at excess delays of 20 μs or more [3].

In [5], it was reported that urban radio channels provide more predictable path loss because of diffraction waves and waveguiding effects along city streets. In residential areas, shadowing losses are greater and cause wider variations in mean path loss. Data in [3], [5] indicate that measurements in residential areas also display larger delay spreads.

In [9], a simple radar cross-section model is proposed, and some measurements indicate a worst case rms delay spread of about 2 μs in suburban areas and 1 μs in rural and residential areas. Maximum excess delay spreads (23 dB) in suburban areas on the order of 8 μs are reported in [9].

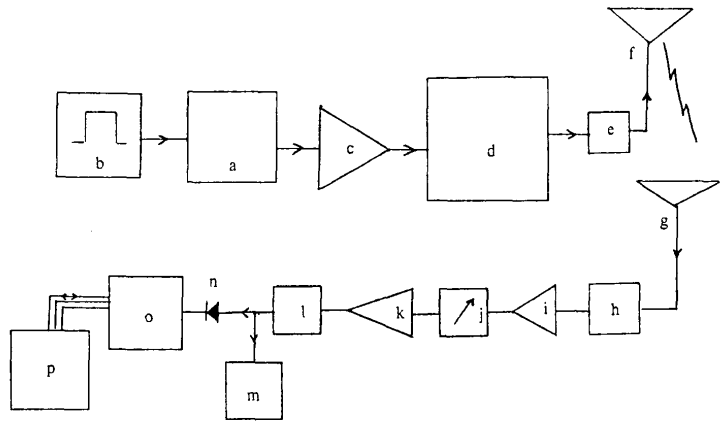
Manuscript received March 9, 1989. Parts of this paper were presented at the 1989 IEEE GLOBECOM, Dallas, TX, Nov. 27, 1989.

T. S. Rappaport and S. Y. Seidel are with the Mobile and Portable Radio Research Group, Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

R. Singh is with Lunayach Communications Consultants, Washington, DC 20005.

IEEE Log Number 9035683.

0018-9545/90/0500-0132$01.00



a) Fluke 6062 Signal Generator
b) HP 8082 Pulse Generator
c) ZHL 1042J Amplifier
d) Linear Amplifier (60 W or 7 Wout)
e) Bird Wattmeter
f) 3 dB 3/8λ whip
g) 9 dB omni
h) 892 MHz Cavity Filter
i) ZHL 4240 Amp
j) HP 0-110 dB Attenuator
k) ZHL 42 Amplifier
l) 892 MHz Cavity Filter
m) Tektronix 2710 Spectrum Analyzer
n) Triangle PT-22 Detector
o) Tektronix 11401 Digital Oscilloscope
p) Compaq Portable Computer

Fig. 1. Measurement system block diagram and equipment list.

Measurements in [6] have shown that individual multipath components fade according to a Rayleigh distribution, although significant variations from the Rayleigh distribution do occur. This is also reported in [7]. Root mean square delay spreads in New York City of about 2 μs were reported in [6].

Except for [5], the above-mentioned works have been confined to one particular city or geographical setting. In this paper, we provide results of a measurement campaign conducted for the Cellular Telecommunications Industry Association during the latter part of December 1988. The work involved the measurement of UHF mobile radio channels in four cities currently served by cellular radio: Washington, DC, Greenbelt, MD, Oakland, CA, and San Francisco, CA. These measurements were performed in a ten-day period to provide a reasonable sample of local worst case multipath profiles from many typical operating cellular markets. These cities were selected because they provided a wide range of usual topographies and were locations where local cellular operators had committed to providing us unrestricted access to cell sites. First, we describe the measurement apparatus, and then give descriptions of the four measurement locations. Statistics of important channel parameters are then presented, and the resulting propagation characteristics of each of these four cities are analyzed from the data. The relative frequency approach to probability is used to present statistical models for typical next-generation U.S. digital cellular radio channels.

II. The Measurement Apparatus

Fig. 1 shows a block diagram of the apparatus used for the measurements, including an equipment list. The mobile transmitter is capable of generating both pulsed and CW transmissions, and is similar to time-domain multipath measurement systems used to measure the power delay profiles in indoor radio channels [10], [13]. To operate close to the cellular radiotelephone band while preventing interference to and from adjacent cellular radio channels, a 4-MHz RF spectrum centered at 892 MHz was used to transmit a 500-ns half-power duration RF pulse, which was repeated at 100-μs intervals. This provided a multipath resolution of about 500 ft. The transmitter used a linear amplifier with 60-W output, which was fed to a 3-dB gain, 3/8 λ vertical whip antenna. Inverters were used to provide ac power to equipment in the mobile. Measurements in Washington, DC, and Greenbelt, MD, used a 7-W (output) class-C amplifier. By carefully limiting the drive power, it is possible to provide linear pulse amplification with the class-C amplifier.

The base receiver front-end used specially designed eight-stage cavity filters, which provided less than 4-dB passband loss with 25-dB attenuation at ± 2 MHz from center frequency. These filters were needed to avoid receiver overload during operation near cellular base station transmitters. A spectrum analyzer was used at the receiver to identify the strengths and frequency of adjacent signals. A 70-dB low-noise amplifier chain with a decade attenuator was required to adjust the received signal power to within the dynamic range of the square-law pulse detector. A digital oscilloscope and IEEE-488 interface recorded the measured impulse responses and stored them in a personal computer. The average noise floor after the front-end cavity filter (with the antenna connected) was consistently measured to be between -94 and -106 dBm over a 4-MHz 3-dB RF bandwidth at all receiver locations (with the decade attenuator set to 0 dB). The system measurement range was 129–148 dB, depending on the base station receiver location and transmitter power.

Receive antennas at all four measurement locations were 9-dB omnidirectional vertically polarized antennas typically

used at cellular radio sites. The antenna patterns maximize power on the horizon, which is desirable for mobile radio operation except in regions where illuminated mountains may induce severe time dispersion.

III. Measurement Locations

One of the goals of this measurement program was to provide data that could be used to determine the viability of unequalized 30-kHz-spaced TDMA. Because multipath channel characteristics will impact directly the quality of service for next-generation digital cellular systems, it was vital that these measurements focused on revealing local worst case power delay profiles where car phone usage is high. Major thoroughfares, business districts, interstate highways, bridges, and residential areas were selected for measurements. However, within each of these sensible measurement areas, the receiver operator recorded data only when the channel appeared more time dispersive than in the previous several minutes. To produce realistic data for actual cellular telephone systems, the receiving antenna system was mounted at existing cell sites when possible.

In Washington, DC, the base station receiver antenna was located downtown on the roof of a nine-story office building (35 m tall) at 19th and K Streets, NW, and was not obstructed by immediate surroundings. The mobile traversed downtown Washington on a circular route that included DuPont Circle, Washington Circle, George Washington University, and the Key Bridge. Some measurements were made with the mobile in neighboring Arlington, VA.

In Greenbelt, MD, measurements were made in a residential area with small hills, apartment buildings, and multistory office buildings. The mobile traversed the I-295 Baltimore–Washington Parkway and the I-95 Beltway, as well as several city streets in Greenbelt. The antenna height was 21 m above ground on the roof of a mobile telephone switching office (MTSO) for a cellular radiotelephone company. The mobile was unable to cover an area that exceeded 4 km in a radial direction due to limited transmitter power (7 W) and the hilly terrain. It is interesting to note that the measurement apparatus had a coverage range almost identical to that provided by the commercial cellular-radiotelephone carrier.

In downtown Oakland, CA, the receiving base station was located on the corner of 14th and Clay Streets, at an operational MTSO. The receiving antenna was 43 m above ground, was not obstructed in most directions, and had a good view to the San Francisco Bay and surrounding hills/mountains. Maximum transmitter-receiver (T-R) separation was 12 km. Measurements were made primarily when the mobile was traveling along major highways, urban areas, and the Bay Bridge. Specifically, the mobile traveled along I-580, I-880, I-980, Lakeshore Avenue, the Nimitz Highway, and Broadway. It should be noted that the Bay Bridge is an elevated point in the Oakland–San Francisco area, and is one location where time dispersion is likely to be severe. A mobile is able to illuminate simultaneously the large building facades of downtown San Francisco and surrounding mountains from the Bay Bridge.

Measurements were made in the mountainous terrain region of the residential south side of San Francisco, near Candelstick Park. The receiver antenna was located 10 m above the ground at a commercial cell site on top of a small two-story restaurant. Maximum T-R separation was 5 km. In relation to the receiver, the San Bruno Mountains are located 5 km Southwest, Mt. Davidson is 6.8 km Northwest, and the San Francisco skyline is 8 km Northeast. Nearly 10 percent of the San Francisco data were collected on Mansell Street, which overlooks San Francisco, Oakland, and surrounding mountains. The LOS path between Mansell Street and the cell site was obstructed by a small hill (McLaren Park).

A total of about 6000 multipath delay profiles from the four cities were recorded over a wide range of vehicle speeds (0–100 km/h) as constrained by local traffic patterns to provide large-scale statistics over all possible operating conditions. Since statistics are presented over large-scale areas, vehicle speed is not considered and all profiles are weighted equally within a particular city.

IV. Channel Model and Noise Threshold

A. Channel Model

The low-pass output of an RF carrier modulated with a 500-ns sounding pulse closely approximates the impulse response $h_b(t)$. As in [10] and [13], instead of measuring the output $r(t)$, $|r(t)|^2$ is measured. Let θ_k represent the phase of each multipath signal, α_k the voltage amplitude of each resolved multipath signal, and $p(t)$ the probing pulse.

$$|r|(t)|^2 = r(t)r^*(t) = \mathrm{Re}\left[\sum_j \sum_k \alpha_j \alpha_k p(t-\tau_j)p(t-\tau_k)e^{-j(\theta_j-\theta_k)}\right]. \tag{3}$$

Note that if $|\tau_j - \tau_k| > 500$ ns for all $j \neq k$, then

$$|r(t)|^2 = \sum_k \alpha_k^2 p^2(t-\tau_k) \tag{4}$$

and the power profile measurement has a path resolution of 500 ns. For $|\tau_j - \tau_k| < 500$ ns, there is pulse overlap, and it is assumed there are unresolvable subpaths that combine to form one observable path. However, even with pulse overlap, we assume that θ_j and θ_k are statistically independent random variables over $[0, 2\pi)$. Thus, the expected value of $|r(t)|^2$ is

$$E_\theta\{|r(t)|^2\} = \sum_k \alpha_k^2 p^2(t-\tau_k) \tag{5}$$

which accounts for pulse overlap. The delays within each profile are measured with respect to a first detectable signal arriving at $\tau_0 = 0$. Absolute power measurements were made by referencing the oscilloscope voltage of received profiles to the peak oscilloscope display voltage for calibration runs that used a known peak input signal power. Since a square-law detector was used, the oscilloscope voltage display corresponds to received power.

Back-to-back power and input signal-to-noise (SNR) calibrations are made using both CW and pulsed signals to verify

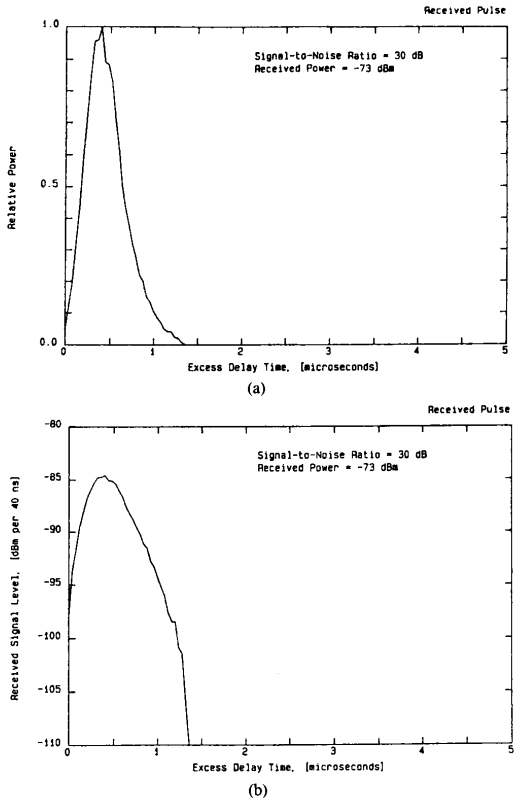


Fig. 2. Probing pulse. (a) Received pulse with transmitter and receiver connected back to back, −73.5-dBm pulse power into receiver, 30-dB input signal-to-noise ratio. (b) Absolute received power (in dBm) for back-to-back calibration shown in (a).

square-law detection, receiver linearity, and proper dynamic range. Measurements presented here are given in peak power terms, since they are most meaningful for pulsed systems [15]. Fig. 2 shows the shape of the probing pulse from a calibration measurement with a 30-dB input SNR. The probe and all measured multipath profiles are recorded as discrete displays on the digital oscilloscope and have nonzero values only at discrete time intervals that are integer multiples of 40 ns. To determine the peak power over a particular time interval, one merely sums up the power contribution over the necessary number of discrete points. In Fig. 2(b), it can be seen that the input signal has a peak power of −85 dBm over a 40-ns interval. By integrating over the duration of the probe (approximately 500 ns), the total transmitter power is −73 dBm.

B. Noise Threshold

Receiver sensitivity and noise threshold are critical in the interpretation of measured channel parameters. Generally, a noise threshold is applied to raw profiles to distinguish between actual multipath components and receiver noise. The time-domain measurement system used in this measurement campaign is identical to a pulse position indicator radar [15].

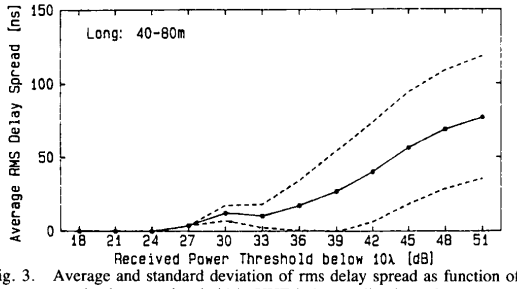


Fig. 3. Average and standard deviation of rms delay spread as function of received power threshold in UHF indoor radio channels.

As is well known from radar theory, for a given SNR, a lower noise threshold induces more false alarms and will yield results that portray channels with worse time dispersive characteristics than would a receiver using a higher threshold (less sensitivity). Similarly, a more sensitive measurement apparatus (i.e., one with a larger measurement range—larger transmitter power or lower noise figure) will be capable of detecting weaker multipath components that would be thresholded away as noise in less sensitive instrumentation. Depending on receiver threshold, measured rms delay spreads can differ by almost an order of magnitude. Work in [11] shows how a 9-dB change in receiver power threshold can affect perceived rms delay spread values by nearly a factor of two. Fig. 3 shows that for measurements in [10], the rms delay spread values are closely tied to receiver sensitivity. Fig. 3 represents the rms delay spread values as a function of receiver threshold for LOS indoor radio channels and shows how a more sensitive receiver will portray large delay spread values. The fact that channel measurements are subject to fair interpretation only after careful consideration has been given to the equipment and the thresholding scheme used leads us to believe that a standardized technique is needed for interpretation and presentation of measured channel impulse response data. This has not been addressed in any of the previous literature pertaining to mobile radio communications and may provide a partial explanation for the wide range of delay spread values reported [3]–[7]. In short, it is important to use a measurement system with sensitivity comparable to commercial radiotelephones if data are to be meaningful.

Commercial cellular telephones have a noise floor on the order of −125 dBm over a 30-kHz bandwidth. This corresponds to a noise floor of −104 dBm over a 4-MHz bandwidth, which yields a threshold of −94 dBm for a 10-dB input SNR over 4 MHz. As is shown subsequently, our threshold is typically between −90 and −100 dBm.

For the data, an empirical/analytical technique has been used to determine threshold. This technique has been used to interpret multipath propagation inside buildings and assumes an average SNR of at least 10 dB across the measured profile [12]. The thresholding technique is as follows:

1) The assumption is made that the output (display) SNR for all data profiles exceeds 10 dB. Thus, we stipulate the *a posteriori* condition that the received multipath components in all of our measurements have sufficient SNR to be detected (i.e., 10 dB). This is certainly valid for the first observable

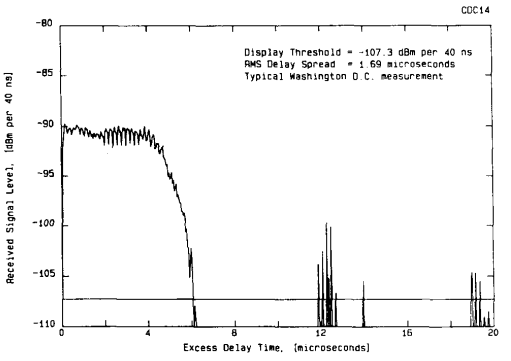


Fig. 4. Multipath power delay profile measured in Washington, DC, with mobile on DuPont Circle. Note the almost uniform distribution of multipath power out to 5 μs. This is common for channels confined to urban areas.

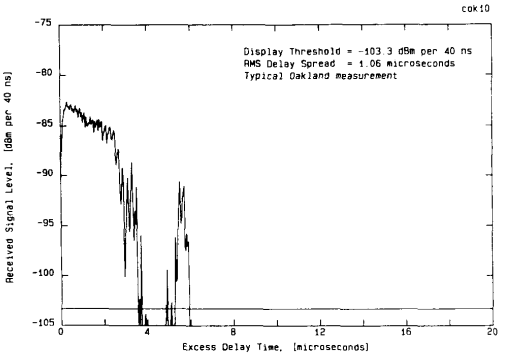


Fig. 5. Multipath power delay profile measured in Oakland, CA, with mobile on 8th and Western (urban commercial district). The profile displays nearly continuous power out to 4 μs. Distinct reflection at 6 μs.

multipath component since the scope relies on internal triggering to detect the leading edge of any received profile. In low SNR conditions, the scope will not acquire trigger, and the displayed profile will appear jittery. The operator was trained not to record data during this condition and to operate the oscilloscope so that the smallest time span is used to capture all apparent multipath components. This required that the operator continuously look for multipath components beyond the current temporal oscilloscope setting. The temporal resolution of the received profile is better when a smaller time span is used.

2) Each recorded profile is checked during data processing to have at least 10 dB of dynamic display range. Based on item 1, this must occur for all valid profiles. The dynamic range noise floor in each snapshot is found by first sorting the lowest 25% of the oscilloscope points, and then removing the highest and lowest 25% of these low points (median filtering). The remaining low points are averaged, to yield a power level that is the dynamic range noise floor. If a profile does not have at least 10 dB of the dynamic display range, the profile is discarded and not considered in computation of the channel statistics. This step is necessary to avoid the inclusion of profiles that do not portray the channel because of signal fading or impulsive noise reception during measurements. For example, a display that contains only noise would otherwise result in the computation of an unusually high delay spread. Visual inspection was used to ensure the validity of this threshold procedure for all profiles.

V. The Data

A. Overview

Fig. 4 shows a typical power delay profile measured in Washington, DC. The solid line shows the noise threshold used based on the technique given in Section IV. The noise threshold is -107.3 dBm per 40 ns (about -96 dBm per 500 ns), and the rms delay spread is 1.69 μs. It can be seen that the 500-ns probe is spread nearly uniformly out to 5 μs. In urban areas, when the LOS path is obstructed, strong multipath components are often observed out to several microseconds. These multipath signals may arrive over waveguidelike paths

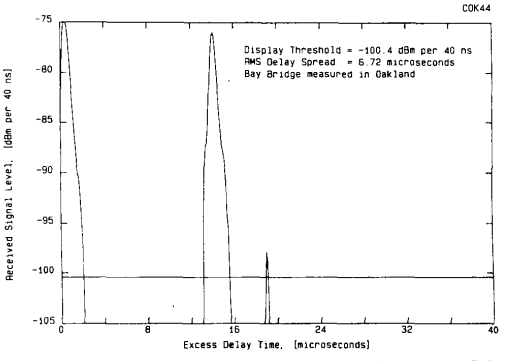


Fig. 6. Measurement in Oakland, CA. Mobile transmitter on Bay Bridge, San Francisco side. Root mean square delay spread of 6.7 μs is typical for elevated areas in urban areas.

provided by streets that run radially between the transmitter and receiver. It can be seen that multipath signals arriving as late as 20 μs can occur in urban areas, although at delays greater than about 5 μs, the multipath appears to be from discrete reflectors rather than from a continuous scattering source.

In an urban core, the shadowing provided by large buildings actually can serve to inhibit severe multipath effects. Fig. 5, which shows a measurement with the transmitter in a high-rise section of Oakland, indicates that multipath spreads can be as small as 6 μs and that rms delay spreads can be as small as 1 μs. Note the nearly uniform power out to 4 μs, which is similar to Fig. 4. Our data indicate that rms delay spreads in urban areas are generally less than 2 or 3 μs, with larger values arising when the mobile traverses bridges and overpasses (shown subsequently in Fig. 6). This agrees with previous results [3], [6], [9]. This result is intuitive, as large buildings serve to confine RF energy along city blocks while shadowing potential multipath signals from outlying reflecting objects, such as bridges and overpasses, which tend to be less confined than downtown.

Fig. 6 shows a power delay profile measured with the receiver in Oakland and the transmitter on the Bay Bridge near

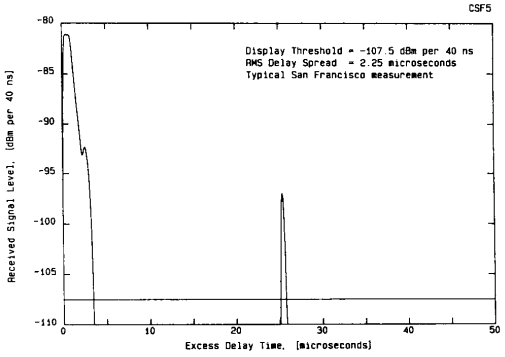


Fig. 7. Multipath power delay profile measured in South San Francisco, CA, with mobile at Bayshore Drive and US-101, near San Francisco International Airport.

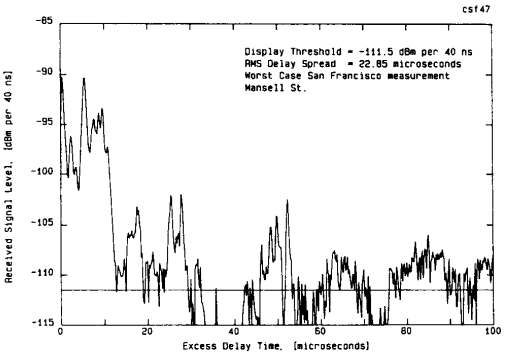


Fig. 8. One of the worst case multipath power delay profiles measured during campaign. Mansell Street in San Francisco.

San Francisco. Transmitter-receiver separation was 8.5 km. It is clear from the figure that there are several multipath components arriving early in Fig. 6, which is typical of measurements made along open areas, such as a bridge or overpass, within a city. Scatterers appear specular and are easy to identify from topographical maps. It is well known that an ellipse is the locus of points that have equal time delays between the two foci. By replacing the transmitter and receiver at the foci, it is possible to distinguish the probable location of reflecting objects, assuming a single-hop path. The strong multipath component at 14.5-μs excess delay (which corresponds to 4.35-km excess travel distance) is deduced to be from the San Francisco skyline. This component undergoes deep fades as the mobile passes through suspension pillars that shadow the vehicle from the city. Using radar cross-section techniques and the model in [9], it is easy to show that a double-hop path, which goes from the mobile and travels twice between the San Francisco skyline and the Bay Bridge before going to Oakland, could produce a delayed signal within 15 dB of the LOS path. The component at 19 μs, which is 22 dB down from the LOS path, is probably due to a multiple-hop path between large buildings in San Francisco. It is also possible that the multipath component is induced by reflections from hills and mountains in the vicinity of the Oakland receiver, although mountain reflections usually disperse over several microseconds.

Figs. 7 and 8 result from measurements made in South San Francisco. Fig. 7 is an example of a measured profile that shows the existence of three multipath components within the first few microseconds and a specular component 15 dB down at 25 μs. Fig. 8 illustrates that in mountainous/hilly regions, multipath components can have excess delays greater than 100 μs. This is a staggering result when one considers that this implies a 30-km excess round-trip travel distance. The case of 100-μs excess delays appears to be quite rare, as it has not been reported before in the literature. Because the multipath components at 100 μs do not appear specular but dispersed, they are most likely due to mountains or a city skyline, which appear as rough scatterers from large distances. The Mansell Street hill is an unusual location since it has LOS to the San Francisco skyline, the Oakland skyline, the San Bruno

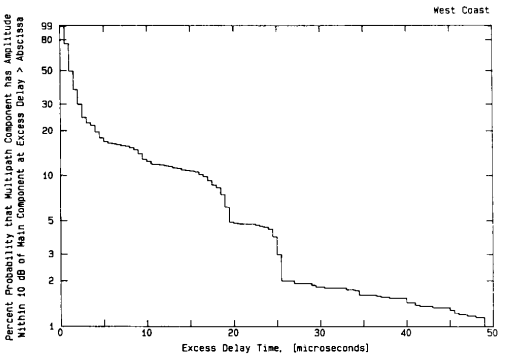


Fig. 9. Probability that a multipath component has amplitude within 10 dB of maximum for excess delay greater than or equal to abscissa (West Coast measurements).

Mountains, Mount Davidson, and the Bay Bridge. These potential reflectors induce excess delays of approximately 50 μs, 100 μs, 35 μs, 20 μs, and 90 μs, respectively. The LOS path between base and mobile is partially obstructed by McLaren Park. Looking at Fig. 8, it appears that all of these scatterers are represented in the received profile. Worst case rms delay spreads are typically 10–25 μs at this location.

B. Statistical Results

Root mean square delay spread and excess delay statistics have been compiled based on the experimental data. After threshold screening, we have a data pool of 5706 measured profiles. Cumulative distribution functions (CDF's) have been plotted to show percentiles for particular values of rms delay spread and excess delay spread (10 dB). It must be remembered that the following results are based on measurements that have emphasized worst case characteristics along typical roadways in representative U.S. markets.

Figs. 9 and 10 show CDF's of the largest excess delay in a profile at which a multipath component has an amplitude within 10 dB of the main component for both West Coast measurements and the entire data pool, respectively. West Coast measurements give data that are probably representative for near-worst-case markets, whereas the entire ensemble

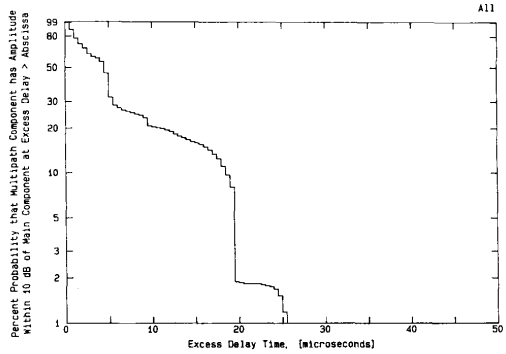


Fig. 10. Probability that a multipath component has amplitude within 10 dB of maximum for excess delay greater than or equal to abscissa (equal weighting for each city.)

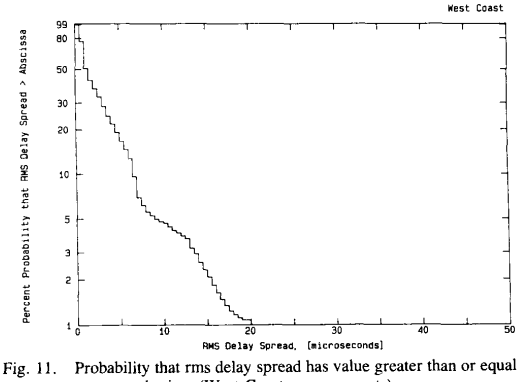


Fig. 11. Probability that rms delay spread has value greater than or equal to abscissa (West Coast measurements).

gives typical channel statistics. If we assume the empirical data from each city form a data pool representative for all of the locations in U.S. markets, Fig. 10 indicates that a channel will have a multipath within 10 dB of the main signal component at excess delays greater than 25.5 μs for 1% of the time. Half the time, there will be a multipath within 10 dB of the main signal component at excess delays greater than 4.5 μs.

Figs. 11 and 12 show CDF's that indicate the likelihood that a particular value of rms delay spread will be exceeded for the West Coast and the entire ensemble, respectively. Under the assumption that our data base in each city is representative of U.S. markets, Fig. 12 indicates that channels will have an rms delay spread greater than 15.5 μs for 1% of the time. The rms delay spread (σ) will be greater than 6.0 μs 10% of the time and 2.0 μs half the time. Recent work has shown that the ratio of rms delay spread to symbol duration in a digital radio channel must be kept below 0.2 or 0.3 [16]–[20]. Assuming a 40-kb/s data rate with DQPSK modulation and a critical (σ/T) value of 0.25, the maximum tolerable σ value is 12.5 μs. At rms delay spreads larger than this, equalization may be required. (If this ratio is relaxed to 0.3, the critical rms delay spread is 15.0 μs.) From Fig. 12, the critical rms delay spread is exceeded by 1.9% (or 1.1%) of the locations.

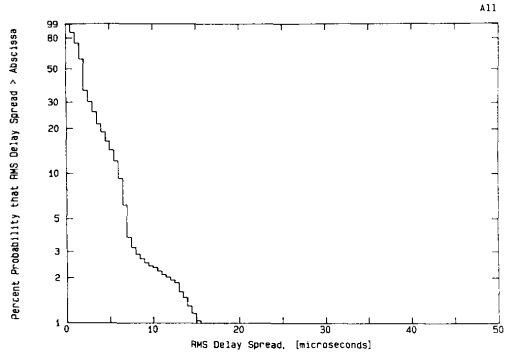


Fig. 12. Probability that rms delay spread has value greater than or equal to abscissa (equal weighting for each city).

Figs. 9 and 11 may be applied to predict channel parameters in near-worst-case markets. Root mean square delay spreads greater than 12.5 μs occur 4 percent of the time based on worst case West Coast measurements. The probability that rms delay spread exceeds 15 μs is slightly greater than 2%. Since all measurements represented in the CDF's have concentrated on local worst case situations, it stands to reason that next-generation digital cellular systems will most often encounter tamer channels than are portrayed here. Our data show that in many cities where terrain is flat (such as Washington or Greenbelt), rms delay spreads do not exceed 7 or 8 μs and no outages due to time dispersion will occur. In areas with large rolling hills, such as Oakland, rms delay spreads do not exceed 13.5 μs, so this city also appears immune to frequency-selective fading outages for a critical σ/T of 0.25 or higher. These conclusions are confirmed by the vast amount of literature, which indicates rms delay spreads larger than 7 or 8 μs are usually not seen, except in mountainous regions [3]–[6], [9].

Only at locations like Mansell Street in San Francisco where unusually large scatterers are illuminated (mountains and bridges) and LOS paths are shadowed, do rms delay spreads exceed 15 μs. It can be argued that in these rare locations, special precautions will be required to mitigate cochannel interference. Useful techniques to mitigate multipath and cochannel interference at such sites will include base station and mobile power control, directional antennas, and electrically steered antennas (including direction and elevation angle steering). It is likely that a microcellular approach will have to be taken for these locations, where low power cells with directional antennas are distributed to accommodate users in locations with severe time dispersion.

VI. Conclusion

This paper has presented 900-MHz multipath propagation measurements in four U.S. cities currently served by cellular radio. The measurements were made to determine the time dispersive characteristics of typical channels that will be used for digital cellular radio systems beginning in 1991. About 6000 power delay profile measurements were made in four

cities over a wide range of geographies and topographical areas. These data were obtained at local worst case locations and have formed the basis for statistical models that can be used to predict the percentage of locations that will experience particular values of rms delay spread and excess delay spread (10 dB). It has been shown that depending on the precise symbol duration, unequalized 40-kb/s TDMA channels will be harmed by multipath at less than 1% to 4% of the vehicle locations. It must be stressed that these figures were arrived at by propagation measurements that searched for local worst case profiles over hundreds of kilometers of typical operating routes, such as highways, bridges, and city streets. There is near certainty that typical time dispersion will be less severe in most U.S. markets, although some locations that have an unobstructed view to the mountains could experience more severe multipath.

Acknowledgment

Technical support provided by the staff of Lunayach Communications Consultants, Washington, DC, and Cellular One, Inc., of Greenbelt, MD, and Oakland, CA, is greatly appreciated. The authors wish to thank the Cellular Telecommunications Industry Association for supporting this work. We acknowledge the helpful comments of the reviewers.

References

[1] *Users' Performance Requirements*, Issue 1, June 1988, Cellular Telecommunications Industry Association, report issued by Advanced Radio Technologies Subcommittee.

[2] T. S. Rappaport and S. Y. Seidel, "900 MHz multipath propagation measurements in four United States cities," *Electron. Lett.*, vol. 25, no. 15, pp. 956–958, July 20, 1989.

[3] A. Zogg, "Multipath delay spread in a hill region at 210 MHz," *IEEE Trans. Veh. Technol.*, vol. VT-36, no. 4, pp. 184–191, Nov. 1987.

[4] B. Davis and R. Bogner, "Propagation at 500 MHz for mobile radio," *IEE Proc.*, vol. 132, pt. F, no. 5, p. 307, Aug. 1985.

[5] J. P. de Weck, P. Merki, and R. Lorenz, "Power delay profiles measured in mountainous terrain," in *38th IEEE Veh. Technol. Conf. Proc.*, 1988, p. 105.

[6] D. C. Cox, "910 MHz urban mobile radio propagation: Multipath characteristics in New York City," *IEEE Trans. Commun.*, vol. COM-21, p. 1187, Nov. 1973.

[7] A. Bajwa and J. Parsons, "Small area characterisation of UHF urban and surburban mobile radio propagation," *IEE Proc.*, pt. F, vol. 129, p. 102, Apr. 1982.

[8] G. Turin, "A statistical model of urban multipath propagation," *IEEE Trans. Veh. Technol.*, vol. VT-21, no. 1, p. 1, Feb. 1972.

[9] J. van Rees, "Measurements of impulse response of a wideband radio channel at 910 MHz from a moving vehicle," *IEEE Trans. Veh. Technol.*, vol. VT-36, pp. 1-6, Feb. 1987.

[10] T. S. Rappaport, "Characterization of UHF multipath radio propagation inside factory buildings," *IEEE Trans. Antennas Propagat.*, vol. 37, pp. 1058–1069, Aug. 1989.

[11] K. Takamizawa, S. Y. Seidel, and T. S. Rappaport, "Indoor radio channel models for manufacturing environments," in *IEEE 1989 Southeastcon Proc.*, 1989.

[12] T. S. Rappaport, "Radio channel modeling in manufacturing environments (part 1)," *Intermediate Report of Research*, Bradley Department of Electrical Engineering, Virginia Tech, Blacksburg, VA. Prepared for Computer Integrated Design, Manufacturing, and Automation Center of Purdue University.

[13] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 138-145, Feb. 1987.

[14] D. M. J. Devasirvatham, "Multipath time delay spread in the digital portable radio environment," *IEEE Commun. Mag.*, vol. 25, pp. 13-21, June 1987.

[15] M. Skolnik, *Introduction to Radar Systems*. New York: McGraw-Hill, c. 1980.

[16] S. Yoshida and F. Ikegami, "A comparison of multipath distortion characteristics among digital modulation techniques," *IEEE Trans. Veh. Technol.*, vol. VT-34, no. 3, p. 128, Aug. 1985.

[17] K. Metzger and R. Valentin, "An analysis of the sensitivity of digital modulation techniques to frequency-selective fading," *IEEE Trans. Commun.*, vol. COM-33, p. 986, Sept. 1985.

[18] S. Ariyavisitakul *et al.*, "Fractional-bit differential detection of MSK: A scheme to avoid outages due to frequency-selective fading," *IEEE Trans. Veh. Technol.*, vol. VT-36, no. 1, pp. 36–42, Feb. 1987.

[19] B. Glance and L. Greenstein, "Frequency-selective fading effects in digital mobile radio with diversity combining," *IEEE Trans. Commun.*, vol. COM-31, p. 1086, Sept. 1983.

[20] J. C-I Chuang, "The effects of time delay spread on portable radio communications channels with digital modulation," *IEEE J. Select. Areas Commun.*, vol. SAC-5, no. 5, pp. 879–889, June 1987.

Theodore S. Rappaport (S'83-M'84-S'85-M'87) was born in Brooklyn, NY, on November 26, 1960. He received the B.S.E.E., M.S.E.E., and Ph.D. degrees from Purdue University, West Lafayette, IN, in 1982, 1984, and 1987, respectively.

In 1983 and 1986 he was employed with the Harris Corporation, Melbourne, FL. From 1984 to 1988 he was with the NSF Engineering Research Center for Intelligent Manufacturing Systems at Purdue University. In 1988, he joined the Electrical Engineering faculty of Virginia Tech where he is an Assistant Professor and Director of the Mobile and Portable Radio Research Group. He conducts research in RF propagation prediction through modeling, and mobile radio communication system design, and consults often in these areas.

Dr. Rappaport received the Marconi Young Scientist Award in 1990 for his contributions in indoor radio communications. He is an active member of the IEEE Communications and Vehicular Technology Societies, and is a member of ASEE, Eta Kappa Nu, Tau Beta Pi, Sigma Xi, and a life member of the ARRL.

Scott Y. Seidel (SM'89) was born in Falls Church, VA, in 1966. He received the B.S. degree in 1988, and the M.S. degree in 1989 in electrical engineering both from Virginia Polytechnic Institute and State University, Blacksburg. He is pursuing the Ph.D. degree in Electrical Engineering at Virginia Polytechnic Institute and State University.

He has had industrial experience as a co-op working summers at Bendix Field Engineering, Columbia, MD, throughout his undergraduate career. He has been involved in the development of channel models for both indoor and urban micro-cellular radio channels. Mr. Seidel is currently supported by a National Science Foundation Graduate Research Fellowship, and is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi.

Rajendra Singh is President and founder of LCC Incorporated, a telecommunications consulting firm based in Washington, DC, which provides cellular engineering design services, predictive coverage software and field measurement collection equipment to over 200 cellular systems in the US and abroad. He founded APPEX Inc., a cellular roaming clearinghouse, and presently serves as Chairman of the Board. He published his Ph.D. dissertation on "spectrum efficient schemes for mobile radio communications" and has published numerous technical articles on cellular engineering applications. He has been on the faculty of two major universities, and taught graduate level courses in cellular system design, mobile radio propagation theory and statistical communications.