Time Delay Spread and Signal Level Measurements of 850 MHz Radio Waves in Building Environments

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Abstract—**Time delay spread and signal level measurements of 850 MHz radio signals were made over inside-to-outside radio paths at two residential locations and an office building. Root mean square time delay spreads of up to 420 ns were encountered in residential environments. However, when a direct path was present, this improved to less than 325 ns overall, and even to 100 ns at one residence. Received power levels were around −40 dB, with respect to levels received at 0.3 m antenna separation, under favorable conditions. In other cases, these relative levels varied from −40 to −80 dB. Median signal levels agreed well with continuous wave measurements made earlier at one site. No significant polarization dependence or floor level dependence were seen in these data.**

Introduction

THE PROPAGATION OF radio waves in and around buildings is characterized by strong multipath effects. The components of the signals reaching the receiver would usually have propagated through walls, floors or other buildings, undergone attenuation, reflection, and diffraction by structural and geographical features, and consequently arrive at slightly different times. The resulting time smear causes intersymbol interference, which limits the usable signaling rate of digital radio communications systems operating in building environments.

Time delay spreads of radio waves inside a large office building have been reported by Devasirvatham [1]. Measurements in a mobile radio setting have been made by Cox [2], [9]. Attenuation studies in houses have been reported by Cox, Murray and others [3]–[7], [10]. Time delay spread measurements in houses are not available, however.

This paper describes time delay spread and signal level measurements made at two residences and an office building, over inside-to-outside radio paths. The experiment is outlined, with examples of received signals, and the results of data analysis are presented. Some implications of the results for the design of communications systems serving buildings are discussed. More diverse measurements are needed before generalized conclusions can be attempted.

The Experiment

The experiment follows the method given in [2]. A block diagram is given in Fig. 1. Briefly, a 40 Mbit/s maximal length pseudonoise code generated by a 10 bit feedback shift register is broadcast by a biphase modulated 850 MHz transmitter. After multipath propagation, it is then correlated with the identical code (running 4 kbit/s slower) at the receiver. As the code generated at the receiver sweeps past the time smeared code in the received signal, the receiver output traces the power-delay profile of the received signal.

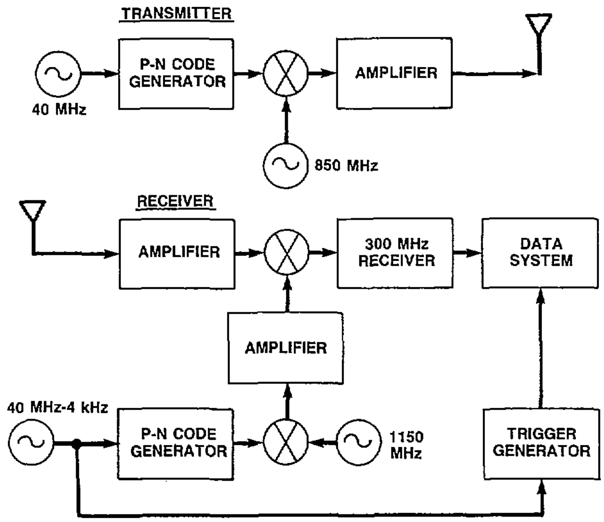

Fig. 1. Block diagram of time delay measuring system.

It can be shown [2] that the system is similar to a bistatic radar transmitting a set of single triangular pulses. Let n be the length of the shift register, f_c be the transmitted code rate, and d be the difference in the code rates generated at the transmitter and receiver. In the ideal case, without multipath propagation or receiver noise, the receiver output of the sliding correlation of the sequences is a triangular pulse. However, unlike a conventional radar system, the output also contains noise caused during the times that the codes were not correlated. If the average value of this noise is taken to be unity, the peak amplitude of the correlated pulse relative to the noise floor is

$$\text{pulse amplitude } p_a = 2^n - 1. \tag{1}$$

Further

$$\text{pulse base width } t_p = 2/f_c. \tag{2}$$

The ambiguity interval is determined by the time taken for the transmitted code to repeat itself, because a section of

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received code that is delayed beyond one code cycle would be indistinguishable from its copy in the current cycle of the code. Since

$$\text{code sequence length } N = 2^n - 1, \tag{3}$$

$$\text{ambiguitiy interval } t_a = N/f_c. \tag{4}$$

In a conventional bistatic radar system, to record this signal properly, the data acquisition rate would have to be higher than f_c. However, in this method, the effective information rate is only d, the rate at which the codes sweep past each other. This simplifies the data acquisition considerably. Thus, if the data are digitized at an interval of t_s by the data acquisition system, then for the equivalent pulse radar [2],

$$\text{effective sampling interval } t_e = t_s/k, \tag{5}$$

where

$$\text{scale factor } k = f_c/d. \tag{6}$$

The repetition time of the output trace is the time taken for the transmitter and receiver codes to slip past each other, and is given by

$$\text{trace repetition time } t_r = N/d \tag{7a}$$

$$= t_a k. \tag{7b}$$

For the system used in this study,

$$n = 10 \tag{8}$$

$$d = 4 \text{ kbit/s} \tag{9}$$

$$f_c = 40 \text{ Mbit/s}. \tag{10}$$

Hence

$$p_a = 1023 \tag{11}$$

$$t_p = 50 \text{ ns} \tag{12}$$

$$t_a = 25.6 \ \mu\text{s} \tag{13}$$

$$k = 10\,000 \tag{14}$$

$$t_r = 256 \text{ ms}. \tag{15}$$

The ambiguity distance is about 7.7 km. The root mean square (rms) width of the equivalent pulse is 10 ns, and is a measure of the resolution of the observations.

The bandwidth of the detection filter was 10 kHz. Since the data rate is 4 kHz, any distortion introduced by this filter is minimal.

The transmitter and receiver antennas were sleeve dipoles. The transmitter power was +26 dBm into the antenna. The highest output signal-peak/noise-floor ratio was determined by the correlation noise level of the pseudonoise code, and was better than 40 dB. Due to the presence of receiver front end noise, in a few cases the output signal-peak/noise-floor ratio dropped to about 8 dB in areas of heavy attenuation of the received signal.

A trigger pulse was generated once for each complete slip of the receiver's pseudonoise code sequence past the transmitted sequence, and was used to synchronize a digital data acquisition system. The position of this pulse relative to the code sequence could be changed in order to position the output trace suitably within a chosen recording time window.

All measurements reported in this paper were made with the transmitter located inside the buildings. Its antenna was located about 1.8 m above the floor. The receiver was in the Bellcore radio research van. This vehicle is described in [5]. It has an 8.2 m antenna mast which could be raised and plumbed to be vertical. The receiver sleeve dipole was located at the top of this mast.

The receiver van was parked at locations around the building being studied. The transmitter was designated as the "scanning unit" and was moved to various locations in the building. The receiver output was digitized at an interval t_s of 10 ms per point; i.e., an effective sampling interval t_e of 1 ns per point. Two thousand forty eight points representing a time interval of 2048 ns were digitized and stored for each measurement. Care was taken to verify that no returns were visible beyond this delay.

For a given sample, the scanning unit was moved through eight equally spaced points along the perimeter of a 1.2 m square and a measurement, as defined above, was made at each point. The eight measurements were then power averaged at each time point. These averaged power-delay profiles were obtained for several different transmitter-receiver locations.

Subsequently, averaged data up to 1800 ns after the first arrival of the signal were used for analysis after ascertaining that there was no output signal beyond this point. The rest of the 2048 ns of data were used to estimate the noise floor of the signal.

While most data were taken with both antennas vertically polarized, representative samples of the data at crossed relative antenna polarizations were also taken.

The Data

Brief descriptions of the experimental sites are given below.

A. Residence 1

Residence 1 is an apartment on level 2 of a two-floor condominium complex. The unit is in a longer arm of a group of three buildings built in a U-shape, around a courtyard 40 × 30 m in size. A similar plan is followed throughout the complex. The buildings are constructed of wood, with metal vapor barriers in the walls and aluminum siding. Windows are covered with nonmetallic screens.

The receiver van was positioned, in turn, in three locations. Two were in the courtyard, 8 and 31 m from the unit, with the receiver antenna slightly above roof level; i.e., at level 3. The third was in the courtyard of an adjacent group of buildings, 82 m away, again with the antenna at level 3. However, there was no line of sight to the apartment in this case, since it was obscured by buildings. Six transmitter positions were chosen inside the apartment for each receiver location.

Fig. 2 shows a typical power versus time delay profile,

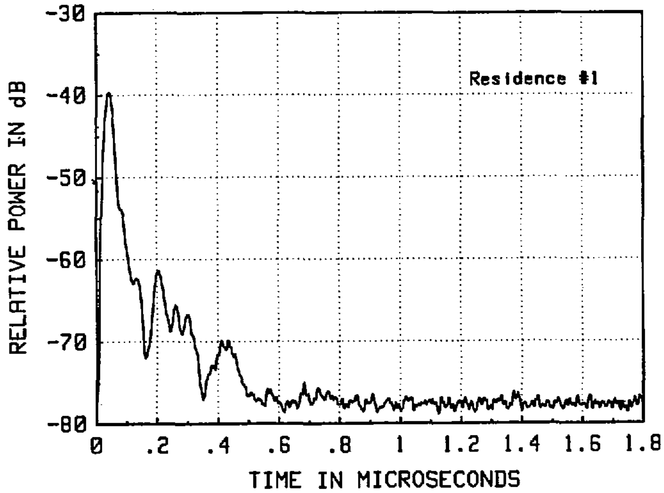

Fig. 2. Residence 1: an averaged power-delay profile with receiver in same courtyard.

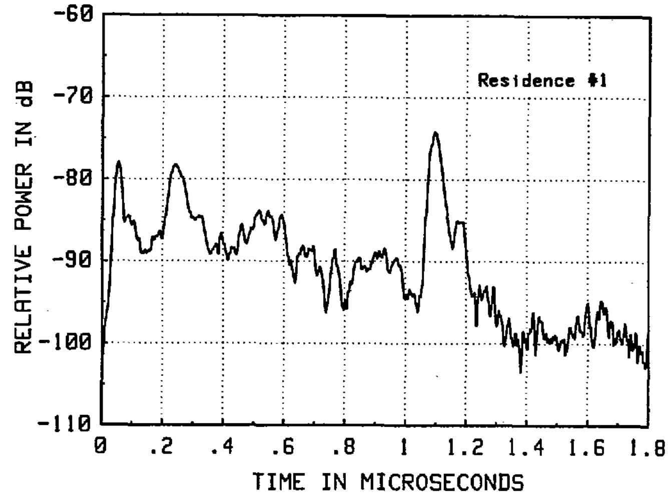

Fig. 3. Residence 1: worst-case averaged power-delay profile recorded with receiver in next courtyard. No line of sight.

where the power levels are normalized to the peak power received when the transmitter and receiver antennas were 0.3 m apart. In the case shown, the receiver was in the same courtyard as the residential unit. A well-defined pulse is seen with very little spread, due to the strong line-of-sight path. Fig. 3, on the other hand, shows a response when the receiver van was in the next courtyard. The absence of a good line-of-sight path together with a strong reflection from another building complex, indicated by a pulse arriving a microsecond later, contribute to a large spread in arrival time. The engineering implications of this will be discussed later.

B. Residence 2

Residence 2 is a two-story house at the edge of a one-acre zoned development. It is a wood-framed house with aluminum siding at the sides and back and a nonmetallic composition siding in front. There is full foil backed insulation in the walls and the windows are covered with nonmetallic screens. The inner walls are made of sheet rock.

The receiver van was positioned at three locations, two of which were on the road running parallel to the front of the house. The third position was on a road running past houses located behind this house. There was some obstruction by other houses in the last two locations. The distances from the house were approximately 46, 168, and 114 m, respectively.

The transmitter was moved through six locations on the first level and four locations on level 2 of the house. Approximately half the locations were toward the front of the house and the other half were toward the back.

Fig. 4 shows the worst-case delay profile recorded. This was obtained at the third location, 114 m from the house and facing the rear of the house. Reflections from other houses in the area are seen to be significant.

C. Office Building

The office building studied was the AT&T Bell Laboratories Crawford Hill Laboratory, also designated HOH. It is a medium-sized rectangular two-level structure, built against the side of a small hill behind it, in the form of an H with unequal arms. The main portion is 118 × 14 m in plan, with a 20 × 23 m perpendicular projection about 33 m from one side, extending behind it toward the hill. This connects with a 44 × 14 m section on level 2 which is parallel to the main portion. The building is served by a driveway which rises from below its level, and also winds around behind it.

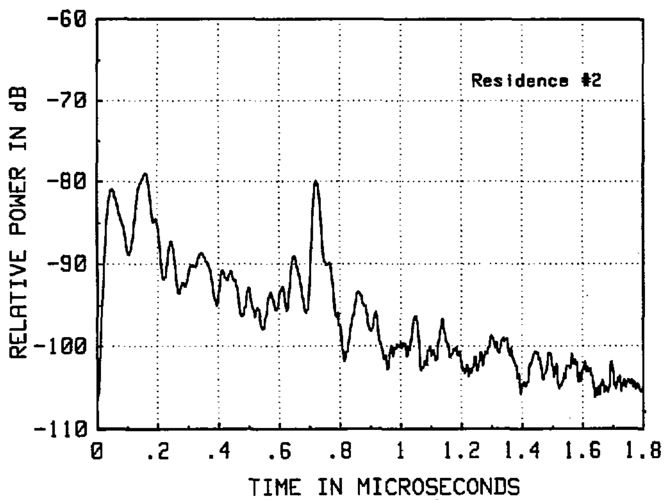

Fig. 4. Residence 2: worst-case averaged power-delay profile recorded.

The building has a steel frame and glass outer walls with metal venetian blinds on the windows. Inside, partitions are constructed from sheet rock and wooden cupboards. There is a significant amount of laboratory equipment in the rooms.

The receiver van was positioned in the driveway, both in front of the building and behind it. Due to the change of the level of the road, in the first case the receiver antenna was approximately at level 1 of the building, 69 m away. At the second position, the antenna was at about level 3; i.e., above the roof of the building and 15 m away from the rear section.

Fig. 5 shows the worst averaged power-delay profile seen during these measurements. The second of the two sets of reflections seen in Fig. 5 is delayed 0.6 μs and is believed to be due to reflections from the hill behind the building.

Analysis and Results

The root mean square time delay spread (i.e., the square root of the second central moment) of each of the averaged

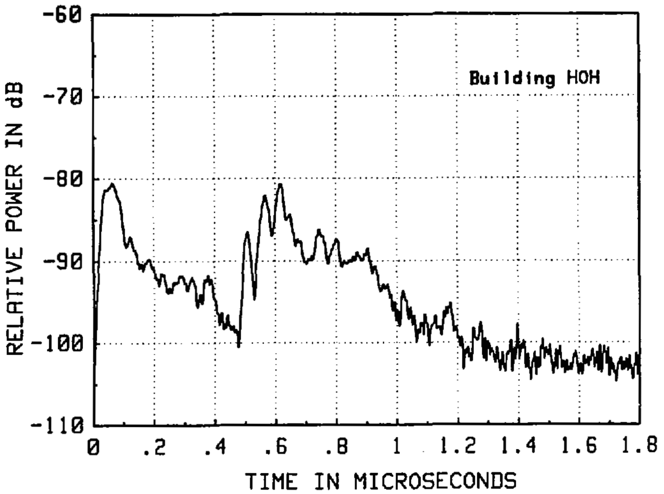

Fig. 5. Office building HOH: worst-case averaged power-delay profile recorded.

time delay profiles was calculated. Since the inverse of the rms delay spread can be defined as the correlation bandwidth of the medium, the results may be easily interpreted in the frequency domain as well [9].

The total power in each averaged profile, normalized to the power obtained when the separation between the antennas was 0.3 m, was also calculated. Since this is an average, not only over eight physical locations, but also over an 80 MHz frequency bandwidth which corresponds to many correlation bandwidths, it gives the equivalent average continuous power which would be received from a narrow-band continuous wave (CW) source when moved through the same measurement area.

The solid curve (curve 1) in Fig. 6 shows the distribution of rms delay spread at residence 1 when the receiver was in its courtyard. The maximum rms delay spread is under 100 ns. The dotted curve (curve 2) shows the rms delay spread distribution obtained when the receiver was in the next courtyard. The difference between this and the results of the solid curve is significant. The maximum rms delay spread is now 422 ns. Even the minimum rms value of 220 ns is greater than the maximum of the previous case. The absence of a line of sight, clearly, has a major impact in this location.

Fig. 7 is a scatter plot of average received power against rms time delay spread for these locations. The two sets of data are in clearly defined clusters. An additional 20–30 dB of attenuation is present at the second location.

Results from residence 2 are shown in the next three plots. Fig. 8 shows the rms delay spread distribution for all the receiver locations with the physical level of the transmitter location as a parameter. The maximum rms delay spread is 312 ns and is not significantly affected by the level on which the transmitter was located. No significant received power dependence with transmitter location level was found either. Fig. 9 shows delay spread distributions obtained when both antennas were vertical (co-pol, curve 1), the receiver antenna was horizontal and at right angles to the direction to the house (cross-pol broadside, curve 2), and finally, horizontal and pointing along the direction to the house (cross-pol end-on, curve 3), respectively. It is seen that the delay spread

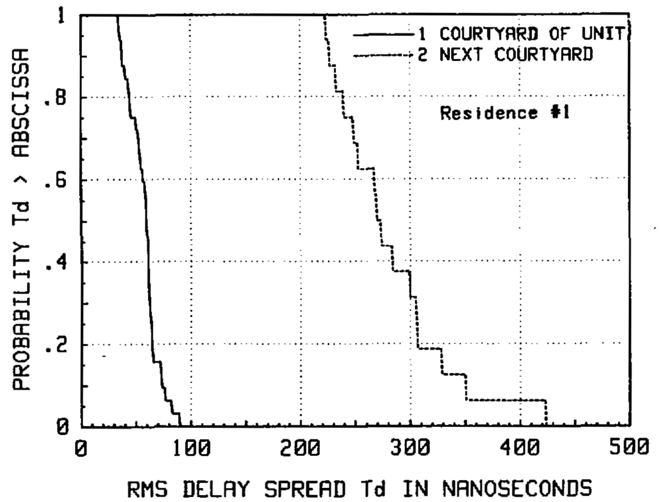

Fig. 6. Residence 1: cumulative distributions of root mean square time delay spreads at the two courtyards.

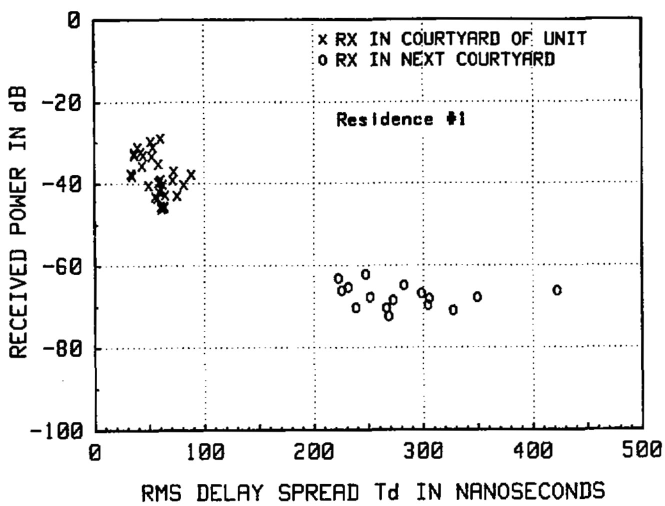

Fig. 7. Residence 1: scatter plot of average received power against root mean square time delay spread.

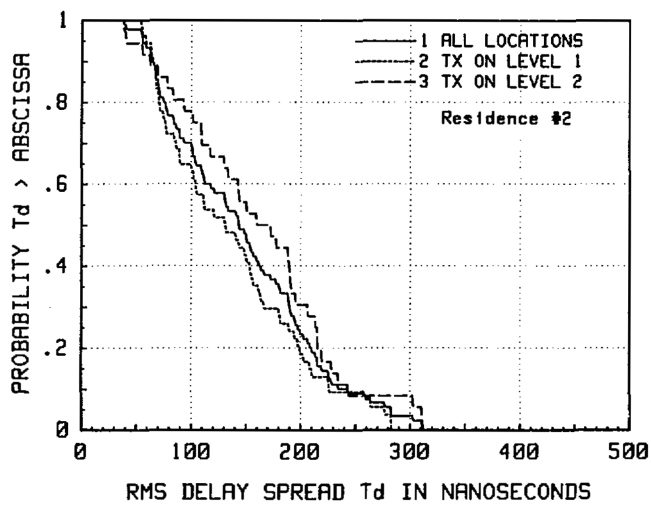

Fig. 8. Residence 2: cumulative distributions of root mean square time delay spread for the two floors of the building.

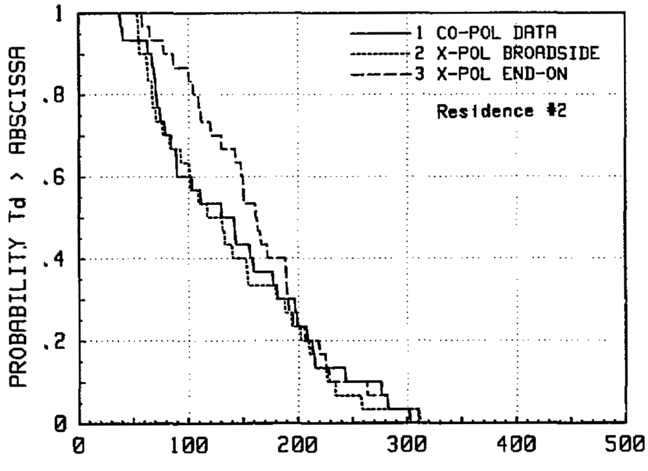

Fig. 9. Residence 2: cumulative distributions of root mean square time delay spread for the three principal relative antenna polarizations.

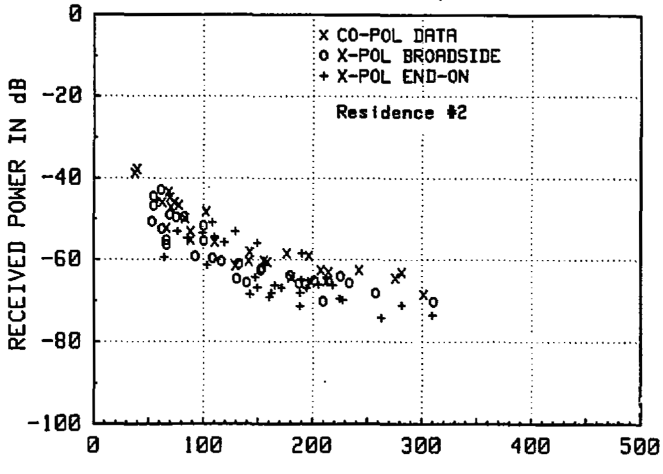

Fig. 10. Residence 2: scatter plots of average received power against root mean square time delay spread for the three principal relative antenna polarizations.

distributions are also independent of these relative antenna polarizations. The power versus delay spread scatter plots for the three polarizations, shown in Fig. 10, confirm that the data are well mixed, both in power levels and in delay spread. This agrees with the results for average power levels in CW measurements [10].

Attenuation studies made at residence 2 at 815 MHz have been reported earlier by Cox *et al.* [5, p. 937, fig. 14]. These studies were made in April 1982, using a continuous wave source. Relative signal levels obtained from the present work were compared with those of the earlier study. The median signal level relative to the level at 0.3 m antenna separation over all transmitter locations at each receiver location was found. These are shown in Table I, together with the distances from the house. The corresponding levels from the earlier study [5, p. 937, fig. 14] for the first floor and the second floor, respectively, corrected to 0.3 m reference distance, are also given. Considering the large uncertainties involved in such measurements, the results from these two different techniques are in good agreement.

The distributions of rms delay spread obtained for the inside-to-outside measurements at the office building are shown in Fig. 11. The maximum rms delay spread is now 321 ns. Both levels of the building give comparable values of delay spread. The power versus delay spread scatter plots for the data at this location, shown in Fig. 12, confirm that the relative received power levels are not significantly different at the two physical building levels.

TABLE I
COMPARISON OF WIDE-BAND AND NARROW-BAND SIGNAL LEVELS RELATIVE TO LEVEL AT 0.3 m ANTENNA SEPARATION

DISTANCE (meters)	RELATIVE SIGNAL LEVEL (dB) WIDEBAND	CW 1ST FLOOR	CW 2ND FLOOR
46	-52	-49	-54
114	-64	-62	-64
168	-68	-69	-69

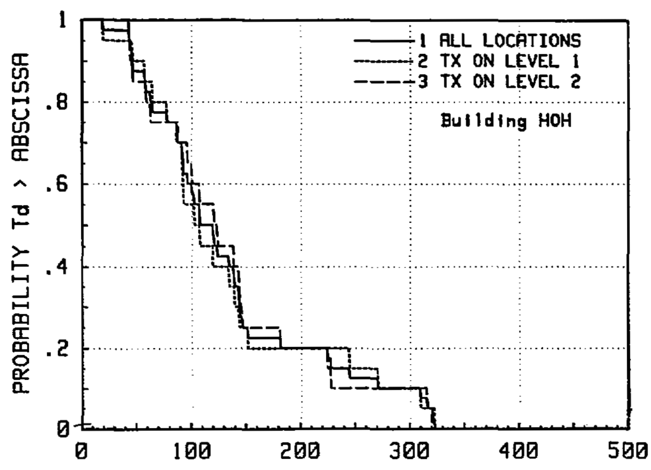

Fig. 11. Office building HOH: cumulative distributions of root mean square time delay spread for the two floors of the building.

Discussion

Some broad generalizations may be drawn from the results given above. If substantiated by further measurements, they could have useful implications for the design of universal personal communications systems [11].

The importance of base station antenna location is well illustrated by the results of residence 1. If the units around a courtyard are served by an antenna placed in that courtyard, then, using a worst-case rms delay spread of 100 ns, it is indicated in [8] that a data rate of 800 kbit/s could be supported at an irreducible error rate of 0.001. This assumes binary DPSK modulation with raised cosine pulses over such a nonequalized channel.

Rms delay spreads of up to 312 ns could support a maximum data rate of 250 kbit/s for 0.001 error probability in residence 2 for the same type of signaling [8].

It is interesting to note that the worst-case rms delay spread obtained at the office building is of the same order as the result from residence 2. It is also greater than the delay spread observed within another, much larger office building [1]. This result would not have been expected from an inspection of the

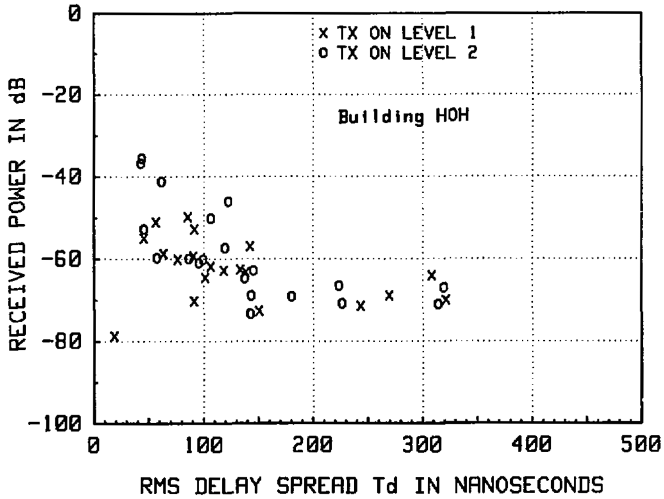

Fig. 12. Office building HOH: scatter plots of average received power against root mean square time delay spread for the two floors of the building.

sites alone. Thus, it would be useful to determine if a worst-case rms delay spread of around 450 ns is a reasonable upper bound for outside coverage of buildings in general. Measurements in the 300 to 500 m range are also needed [11].

Summary

Time delay spreads and signal level measurements were made at two residences and a medium sized office building. In all cases, the propagation paths were from within the building to a simulated base station outside the building. Worst-case rms delay spreads of less than 325 ns were obtained for both the office building and the one-acre zoned house. This could support digital data rates of up to 250 kbit/s for 0.001 error probability, using binary differential phase shift keying (DPSK) modulation. Received signal levels were between 40 and 80 dB below the levels received at 0.3 m antenna separation.

The residence located in a medium-density complex showed a worst-case rms delay spread of under 100 ns when the base station was located to serve its neighborhood with a line-of-sight path to the residence. Received power levels were then 30 to 50 dB below the level at 0.3 m separation. This delay spread could support data rates of 800 kbit/s for 0.001 error probability using binary DPSK. The rms delay spread increased up to 422 ns when there was no line of sight. These measurements demonstrated the importance of an unobstructed path from the base station antenna to the building being served.

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References

[1] D. M. J. Devasirvatham, "Time delay spread measurements of wideband radio signals within a building," *Electron. Lett.*, vol. 20, no. 238, pp. 950–951, Nov. 1984.
[2] D. C. Cox, "Delay doppler characteristics of multipath propagation at 910 MHz in a suburban mobile radio environment," *IEEE Trans. Antennas Propagat.*, vol. AP-20, no. 5, pp. 625–635, Sept. 1972.
[3] H. H. Hoffman and D. C. Cox, "Attenuation of 900 MHz radio waves propagating into a metal building," *IEEE Trans. Antennas Propagat.*, vol. AP-30, no. 4, pp. 808–811, July 1982.
[4] D. C. Cox, R. R. Murray, and A. W. Norris, "Measurements of 800 MHz radio transmission into buildings with metallic walls," *Bell Syst. Tech. J.*, vol. 62, no. 9, pp. 2695–2717, Nov. 1983.
[5] D. C. Cox, R. R. Murray, and A. W. Norris, "800 MHz attenuations measured in and around suburban houses," *AT&T Bell Lab. Tech. J.*, vol. 63, no. 6, pp. 921–954, July 1984.
[6] S. E. Alexander, "Characterizing buildings for propagation at 900 MHz," *Electron. Lett.*, vol. 18, no. 21, pp. 913–914, Oct. 1982.
[7] ——, "Radio propagation within buildings at 900 MHz," *Electron. Lett.*, vol. 19, no. 20, p. 860, Sept. 1983.
[8] W. C. Jakes, *Microwave Mobile Communications.* New York: Wiley, 1974, pp. 236–240.
[9] D. C. Cox and R. P. Leck, "Correlation bandwidth and delay spread in multipath propagation statistics for 910 MHz urban mobile radio channels," *IEEE Trans. Commun.*, vol. COM-23, no. 11, pp. 1271–1280, Nov. 1975.
[10] D. C. Cox, R. R. Murray, H. W. Arnold, A. W. Norris, and M. F. Wazowicz, "Cross polarization coupling measured for 800 MHz transmission in and around houses and large buildings," *IEEE Trans. Antennas Propagat.*, vol. AP-34, pp. 83–87, Jan. 1986.
[11] D. C. Cox, "Universal portable radio communications," *IEEE Trans. Veh. Technol.*, vol. VT-34, pp. 117–121, Aug. 1985.

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