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SIMULATION OF URBAN RADIO PROPAGATION AND OF URBAN RADIO COMMUNICATION SYSTEMS

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We survey here the results of eight years of research into the structure of radio propagation in urban/suburban areas, starting with wide-band propagation experiments and modeling at 500-3000 MHz [1], proceeding through preliminary simulation experiments [2], continuing with more elaborate modeling and simulation [3], [4], and currently in a high-rate data transmission simulation phase [5].

In the underlying experiments [1], pulse transmitters were placed at fixed, elevated sites in the San Francisco Bay Area. Once per second, these simultaneously sent out 100-ns-wide pulses at 488, 1280 and 2920 MHz. The pulses were received in a mobile van that moved through typical urban/suburban areas, labeled A (dense high-rise), B (sparse high-rise), C (low rise), and D (suburban/residential). The received pulses were displayed on a multitrace oscilloscope, which was triggered by a Rubidium frequency standard. (This standard was synchronized with a similar unit at the transmitters prior to each experimental run, so that absolute propagation delays were measurable.) One thousand such displays were recorded on film in each of the above-mentioned areas, with due regard for obtaining representative topographies in each area. See Figures 1 and 2.

The model upon which reduction of the data from this experiment has been based assumes that a transmission of the form $s(t) = \mathrm{Re}[\sigma(t)e^{j\omega_0 t}]$ is received as $r(t) = \mathrm{Re}[\rho(t)e^{j\omega_0 t}]$, where $\rho(t) = \sum_{k=0}^{K-1} \alpha_k \, \sigma(t-t_k)e^{j\phi_k}$. In this last expression, there is a random number, K, of paths. The kth of these has strength α_k, modulation delay t_k, and carrier phase shift ϕ_k. The purpose of the data reduction has been to determine as completely as possible the statistics of the random variables α_k, t_k, ϕ_k ($k = 0,\ldots,K-1$), and K.

Since the underlying experiment can resolve two paths only if they have a delay difference of more than 100 ns, the model above was first approximated by a discrete-time model. The delay axis was divided into 100-ns bins, centered at multiples 0,1,2,... of 100 ns, each bin being 100-ns wide. The center of the zeroth bin corresponds to line-of-sight (LOS) delay; a total of 71 bins was considered, corresponding to a maximum delay in excess of LOS of roughly 7 μs, a figure found experimentally to be satisfactory.

Data were then reduced as follows. The delay axis of each recorded multipath profile (Figure 1) was referenced to LOS delay. The delays of the paths in the profile were estimated by a technique explained in [1], it being recognized that multiple paths within a delay spread of 100 ns would be identified as a single path. The delays were quantized according to the bin

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numbers into which they fell, and probability-of-occupancy curves and path-number distributions were computed. (See Figures 3 and 4.) Strength distributions of paths in each bin were also found (Figure 5). Additionally, certain temporal and spatial correlations of variables — discussed later -- were estimated. On the other hand, carrier phase shifts were modeled _a priori_ as being uniformly distributed over $(0,2\pi]$. It should be noted here that neither the total delay spread nor the variance of the logarithmic strength were found to depend upon transmitter-receiver slant range, leading to the conjecture -- at least for the topographies tested — the multipath phenomenon largely occurs in the locality of the receiver.

Modeling of the urban multipath channel from the reduced data led to a modified Poisson-process description for path delay times, the modification being necessary to account for a tendency of paths not to occur independently, but rather to cluster [1], [3], [4]. The strength variables were shown to be Nakagami distributed for paths near LOS delay, and log-normally distributed for paths with larger delays [3]. The soundness of these models is shown in Figures 3-5, where the broken-line curves come from simulations, described below, based upon the models and using empirical parameters.

An elaborate multipath simulation program was written [4], based both on the reduced data and on physical reasoning when the data were insufficient or undecisive. The program incorporates the first-order statistics exemplified by Figure 3-5, but also the temporal and spatial correlations of the various strength/delay/phase random variables mentioned above.

The simulation envisages a receiver traveling through an urban area and measuring a multipath profile at a sequence of geographical points separated by distance d. At the first point, a string of 71 0's and 1's is generated from the clustered-path-delay model, a 0 indicating "no path in this bin," a 1 indicating the presence of a path; e.g., the string 10011010....010000 indicates the presence of paths in bins 0,3,4,6,...,66, corresponding to paths at LOS and at delays of 300, 400, 600,...,6600 ns beyond LOS. (Typically there are about 20-25 1's in the string for areas A and B, and about 10 for areas C and D.) For each 1 in the string, a strength and a phase variable is generated. The phase variables are drawn independently from a uniform distribution. The strength variables are drawn from log-normal distributions, a deviation from the empirically determined Nakagami distributions for near-LOS bins. The parameters of these distributions vary as a function of bin number; additionally, correlations of the strengths in bins that are close to one another are included, the magnitudes of the correlations being determined from the underlying empirical data.

At the second and subsequent geographical points in the simulated vehicle's route, a new string of 0's and 1's is first generated, using the clustered-delay model, as modified to reflect spatial correlations with the path delays at the previous geographical point. Again, for each 1 in the string, a phase and a strength variable are generated, with spatial correlations relating them to phase/strength variables at the previous geographical point. The spatial correlation distances run from a fraction of a wavelength for the phases, through tens of wavelengths for the strengths and delays, to hundreds of wavelengths for global variations of the means and variances of the strength distributions, which are also considered to be random variables.

The simulation program just described has been exhaustively tested [4] for all geographical areas and all frequencies of the original experiment and for a large range of values of d. The results have uniformly shown a good match to experiment, as exemplified by Figures 3-5.

Current work [5] is related to simulation of high-rate (100 Kbps-1 Mbps) data transmission systems operating in the urban environment. We are presently evaluating error statistics for a number of candidate demodulators of a differentially phase-shift-keyed system whose basic signal is a 127-chip PN code. Of interest in the present report is the envelope of the response of a filter matched to such a signal after the signal has passed through the multipath medium. Figure 6 shows a typical response, which can be compared to Figure 2.

[1] G. L. Turin, et al., "A statistical modelfor urban multipath propagation," Trans. IEEE, VT-21, pp. 1-9, Feb. 1972.

[2] G. L. Turin, et al., "Simulation of urban vehicle monitoring systems," Trans. IEEE, VT-21, pp. 9-16, Feb. 1972.

[3] H. Suzuki, "A statistical model for urban radio propagation," Ph.D. Thesis, Dept. of EECS, Univ. of Calif., Berkeley, 1975. See also Trans. IEEE, COM-25, pp. 673-680, July 1977.

[4] H. Hashemi, "Simulation of the urban ratio propagation channel," Ph.D. Thesis, Dept. of EECS, Univ. of Calif., Berkeley, 1977. See also Proc. 1977 Nat'l. Telecomm. Conf., paper 38-1.

[5] G. L. Turin and M. Kamil, work in progress, sponsored by SRI International, under contract with the Advanced Research Projects Agency.

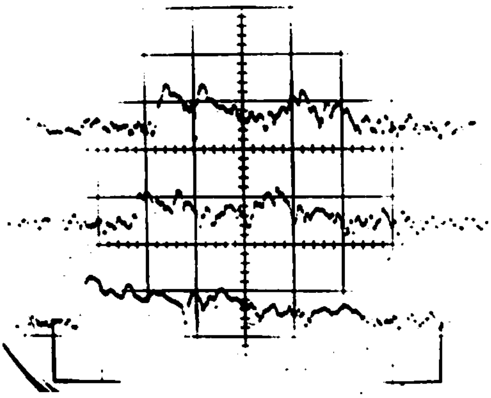

Figure 1. Example of multipath profiles: dense high rise. Top to bottom: 2920, 1280, 488 MHz. Vertical scale: 35 dB/cm. Horizontal scale: 1μs/cm. Different apparent LOS delays are due to differences in equipment delays. From [1].

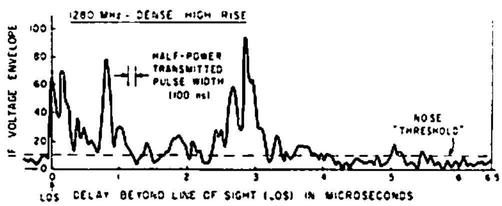

Figure 2. Middle trace of Figure 1 on a linear scale. Notice the clustering of paths.

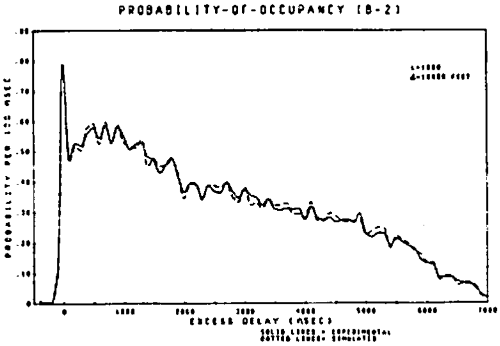

Figure 3. Probability-of-occupancy curves for sparse high rise, 1280 MHz. Ordinate is probability that a path will occur within ±50 ns of abscissa value (abscissa origin = LOS delay). Solid curve: experimental. Broken curve: simulated, from samples that are sufficiently spatially separated to be independent. From [4].

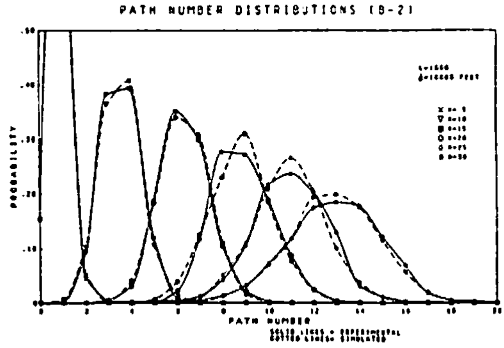

Figure 4. Path-number distributions for sparse high rise, 1280 MHz. Ordinate is probability that there will be the number of paths given by the abcissa within the first N bins, starting with the LOS bin. Solid curve: experimental. Broken curve: simulated using spatially independent samples. From [4].

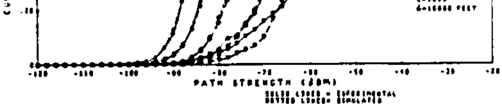

Figure 5. Path-strength distributions for sparse high rise, 1280 MHz. Ordinate is probability that the strength of a path in the indicated delay interval will be less than abscissa value. Solid curve: experimental. Broken curve: simulated, using spatially independent samples. From [4].

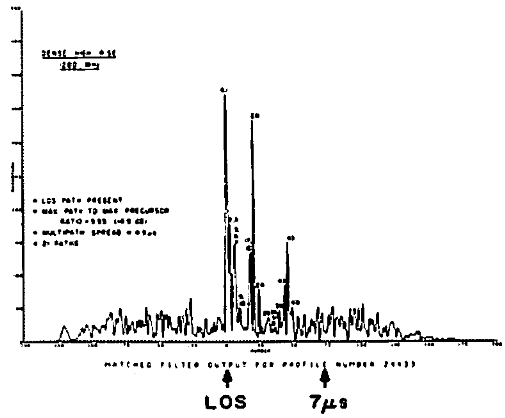

Figure 6: Example of simulated output envelope of filter matched to 127-chip, 10 Mchip/s, PN/PSK sequence. Input to filter is result of passage of chip sequence through multipath channel. Low-level "clutter" is result of multipath addition of sidelobes of sequence's autocorrelation function. Note clustering of paths, as in Figure 2. From [5].