ABSTRACT

In this paper, we detail a software channel simulator for UHF indoor radio channels in open-plan buildings. The simulator is based on wide band statistical models of individual multipath component amplitudes and delays developed in [1]. The simulator creates closely spaced channel impulse responses for both line-of-sight (LOS) and obstructed (OBS) topographies, with the same ensemble and local statistics as measurements reported in [2]. The effects of transmitter-receiver (T-R) distance, and the correlation of individual multipath component amplitudes over time and space are incorporated in simulation. The simulator has been extended to yield narrow band fading over small distances by synchronizing the phases of multipath components. Multipath power delay profiles, rms delay spread distributions, and narrow band fading distributions produced by the simulator accurately portray typical radio channels in a variety of open-plan building environments.

I. INTRODUCTION

Wireless communications will likely be used for reconfigurable voice, data, and video networks that link portable computers, vision systems, cash registers, and telephones in future stores, offices, and factories. Wireless links will be required for communication to large fleets of autonomous guided vehicles and automated portable databases likely to be used in future manufacturing [3].

Appropriate in-building radio system design requires knowledge of the different propagation environments likely to be encountered. With realistic models of channel behavior, it becomes possible to explore the impact of various communication system designs through analysis and computer simulation, as opposed to measurements which are expensive and time consuming.

Some propagation models have been used for preliminary design and analysis of indoor radio communications systems [4-6] which incorporate (large-scale) signal variations where responses from random, independent locations over a wide range of distances are used to estimate system performance. We believe small-scale channel models are also needed to explore handoff, timing recovery, and antenna diversity. Models in [7,8] indicate that individual multipath component amplitudes at constant excess delays are correlated over distances less than 3 wavelengths. Knowledge of the correlated small-scale fading of multipath components and hence how the impulse response changes for small portable movements has not been previously available. Over large-scale areas (greater than several wavelengths, where multipath component amplitudes become uncorrelated), macroscopic channel models which describe propagation in different environments have been used to provide first-order average bit error rates for different signaling and equalization techniques, and to determine preliminary system design [9-11]. With microscopic channel models, we can study handoff, timing jitter, diversity, and equalization based on small movements of portable location.

In this paper, we present techniques used to simulate statistical models from [1] based on empirical propagation data from [2]. The propagation simulator creates multipath channel power delay profiles with the same small-scale and large-scale statistics as measured data. With additional modeling of the phases of individual multipath components, the simulator generates narrow band fading over small-scale distances which could be useful in the analysis of antenna diversity, equalization, and co-channel interference in flat-fading channels.

II. IMPULSE RESPONSE CHANNEL MODEL

Wide band time domain multipath measurements were recorded at 19 discrete locations at 1/4 intervals along several 1-m tracks in five open-plan buildings [2]. CW fading measurements were made with a mobile receiver over the same tracks [12]. We introduce the following terminology to denote the factors that influence channel impulse response parameters. P represents the set of all 1-m local areas and X denotes the set of discrete small-scale locations separated by 1/4 along the 1-m track in each local area. A particular local area is denoted by \( P_n \in P \), where \( X \in X \) and \( l \) ranges on 1 to 19. Each \( P_n \) is classified by a particular topography \( S_n \in S = (S_1, S_2) \) where \( S_i \) is line-of-sight (LOS) topography, and \( S_2 \) is obstructed (OBS) topography, and has associated some large-scale transmitter receiver (T-R) separation \( D_n \in D \) which ranges between 15 m and 65 m. We assume that time variations in the impulse response are due to small-scale motion of portable radios. Each individual baseband impulse response is expressed as:

\[
|h(t, X_i, S_m, D_n, P_n)| = \sum_{k} A_k(T_k, X_i, S_m, D_n, P_n) \delta(t - T_k(X_i, S_m, D_n, P_n))
\]
III. SIMULATION TECHNIQUES

A. General Techniques

The multipath amplitudes $A_k$ in (1) are simulated in units of relative attenuation (dB) referenced to a 104 free space line-of-sight voltage level. The excess delays $T_k$ are integer multiples of 7.8 ns, the rms duration of the probing pulse in [2]. Based on measurements, the maximum simulated excess delay is 500 ns.

B. Number of Multipath Components

The number of resolvable multipath components $N_p$ along a 1-m track (i.e., the distribution of $N_p(X_i, S_m, P_n)$) is not a strong function of $D_s$ and is Gaussian distributed with a mean of $N_p(S_m, P_n)$ and a standard deviation $\sigma_p(S_m, P_n)$ [1]. $N_p(S_m, P_n)$ itself is a random variable for each $P_n$ with the standard deviation $\sigma_p(S_m, P_n)$ linearly related to $N_p(S_m, P_n)$ as given in [1,8]. The number of multipath components at each location is determined independently from this Gaussian distribution.

C. Multipath Component Arrival Time

$M_k(T_k, X_i, S_m, P_n)$ is a boolean variable which is True when a multipath component arrives with excess delay $T_k$ at small-scale location $X_i$ within $P_n$ and False when no component arrives at $T_k$. The likelihood of a multipath component arriving at a particular $T_k$ was determined empirically [9] from all measured profiles. The probability of a multipath component existing at $T_k$ for a particular topography is given by $\Pr(M_k(T_k, S_m)) = 1 - \exp\left(-\frac{T_k}{P_n}\right)$ for $T_k < 500$ ns.

1.) Determine $N_p(X_i, S_m, P_n)$ at $X_i$, 4/1 away from $X_i$, from the Gaussian distribution on $N_p(X_i, S_m, P_n)$.
2.) $M_k(T_k, X_i, S_m)$=$M_k(T_k, X_{i-1}, S_m)$ for all $T_k$.
3.) If $N_p(X_i, S_m, P_n) = N_p(X_{i-1}, S_m, P_n)$, then all multipath components at $X_i$ arrive with the same excess delays as at $X_{i-1}$.
4.) If $N_p(X_i, S_m, P_n) > N_p(X_{i-1}, S_m, P_n)$, then the excess delays of additional multipath components must be determined. Components which arrived at $X_{i-1}$ arrive with the same excess delays as at $X_i$. Excess delays of additional multipath components not found at $X_{i-1}$ are found one at a time. For each new component not found at $X_{i-1}$, the likelihood of multipath (given by (2)-(3)) at each unoccupied excess delay interval is divided by the sum of the probabilities of all unoccupied excess delays so that the sum of all probabilities of arrival is equal to 1. The processing of finding the new excess delay can be represented by the probability of a transition of $M_k$ from False to True. The normalized False to True transition probability at each $T_k$ is

$$\Pr(M_k(T_k, X_{i-1}, S_m)|M_k(T_k, X_i, S_m) = \text{False}) = \frac{\Pr(M_k(T_k, X_{i-1}, S_m)|M_k(T_k, X_i, S_m) = \text{False})}{\sum_{s=0}^{\infty} \Pr(M_k(T_k, X_{i-1}, S_m)|M_k(T_k, X_i, S_m) = \text{False})}$$

(4)

The CDF of the transition probabilities is formed by summing (4) over all possible $\gamma$ (54 in our case) where we drop the $X_i$, $X_{i-1}$ dependence for ease of notation.

$$\gamma$$ is generated and compared with the CDF given in (5) to determine the $T_k$ of the additional multipath component.

5.) Repeat step 4.) to generate the remaining $T_k$'s until the $N_p(X_i, S_m, P_n) - N_p(X_{i-1}, S_m, P_n)$ additional excess delays are found. This relative probability approach preserves the higher probability of new components arriving at small excess delays, and components with larger excess delays arrive in proportion to the observed probability.

6.) If $N_p(X_i, S_m, P_n) < N_p(X_{i-1}, S_m, P_n)$, the excess delays which no longer exist are determined once at a time in a manner similar to 4.) and 5.). The likelihood of no multipath (1-$\Pr(M_k(T_k, S_m))$) at each occupied excess delay interval is divided by the sum of the probabilities of no multipath over all occupied excess delays so that the sum of all probabilities of no multipath is equal to 1. The process of finding the removed excess delay can be represented by the probability of a transition of $M_k$ from True to False. The normalized True to False transition probability at each $T_k$ is

$$\Pr(M_k(T_k, X_{i-1}, S_m) = \text{True}|M_k(T_k, X_i, S_m) = \text{False}) =$$

$$\sum_{\gamma=0}^{\infty} \Pr(M_k(T_k, X_{i-1}, S_m) = \text{False}|M_k(T_k, X_i, S_m) = \text{False})$$

(6)

and the CDF of True to False transition probabilities is the sum of (6) over all $\gamma$. 598
D. Average Multipath Component Amplitudes

The amplitude of individual multipath components $A_K$ depends on $T_K, X_i, S_m, D_n, P_n$. The $A_K$ were converted to dB referenced to a free space line-of-sight power level $A_0$ (voltage level $A_0$) measured at 10$\lambda$ T-R separation [2]. We work in dB since $A_K$ (dB) are independently generated from a Gaussian distribution with conditional mean $\mu$ and standard deviation $\sigma$. The $A_K$ amplitude with $T_K$ at each $X_i$ and ranges between 0.25 and 4.0 dB [7,8]. Before imposing correlation models, the distribution in dB of the multipath component amplitude at $(T_K, X_i)$ is Gaussian with mean $\bar{A_K}$ (dB) and standard deviation $\sigma_{\text{small-scale}}$. Components at fixed excess delay $T_K$ are uncorrelated.

E. Small-Scale Multipath Component Amplitudes

The distribution of individual multipath components $A_K$ is log-normal around (8) with a standard deviation $\sigma_{\text{small-scale}}$ of 4 dB for LOS and 5 dB for OBS [7,8]. The $\bar{A_K}$ (dB) is independently generated from this normal distribution for each excess delay.

F. Correlation Coefficient Functions

$A_K(T_K, X_i, S_m, D_n, P_n)$ in dB is generated from a Gaussian distribution as detailed in $E$. For successive multipath components $A_K(T_K, X_i, S_m, D_n, P_n)$, the Gaussian distribution becomes the conditional Gaussian distribution with mean and standard deviation modified by $A_K(T_K, X_i, S_m, D_n, P_n)$. The amplitude of the multipath component with the next smallest excess delay denoted by $A_{K'}(T_{K'}, X_i, S_m, D_n, P_n)$, and the correlation coefficient between $A_K$ and $A_{K'}$ is shown in [1,7]. Temporal correlation models given in [7] are implemented in $X_i$. For $X_i$ through $A_{K'}$, spatial correlation on components generated at fixed excess delay values over $X_i$ since temporal correlation coefficients are not large, and simultaneous implementation of temporal and spatial correlation coefficients would require excessive computation times.

We consider the amplitudes in dB of multipath components at fixed excess delays to form a multivariate Gaussian (jointly normal) distribution as a receiver is moved along a 1-m track. The $A_K(T_K, X_i, S_m, D_n, P_n)$ in dB form a vector $\bar{A_K}$, where each element in $\bar{A_K}$ is the amplitude of a multipath component at a constant excess delay $T_K$ at a discrete receiver location $X_i$. $\bar{A_K}$ can be partitioned as [13],

$$\bar{A_K} = \begin{bmatrix} A_{K_1} \\ \vdots \\ A_{K_p} \end{bmatrix}$$

where $A_{K_i}$ is comprised of all previously generated multipath component amplitudes at fixed excess delay $T_K$ and small-scale locations $X_i$, $i < l$. $A_{K_i}$ is the multipath component amplitude to be determined at $X_i$. We drop the dependence on $S_m, D_n, P_n$ for ease of notation.

$$\bar{A}_{K_1} = \begin{bmatrix} A_{K_1}(T_K, X_1) \\ \vdots \\ A_{K_i}(T_K, X_i) \end{bmatrix}$$

and covariance matrices

$$\Sigma = \begin{bmatrix} \sigma^{2} & \rho_1 \sigma^2 & \rho_2 \sigma^2 & \ldots & \rho_{l-1} \sigma^2 \\ \rho_1 \sigma^2 & \sigma^2 & \sigma^2 & \ldots & \sigma^2 \\ \rho_2 \sigma^2 & \sigma^2 & \sigma^2 & \ldots & \sigma^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{l-1} \sigma^2 & \sigma^2 & \sigma^2 & \ldots & \sigma^2 \end{bmatrix}$$

where $\sigma^2 = \sigma_{\text{small-scale}}(T_K, S_m, P_n)$ and $\rho_t$ represents the spatial correlation coefficient between two multipath components at discrete locations along a 1-m track separated by $q_t/4$. The conditional distribution of $A_{K_i}(T_K, X_i)$ given $A_{K_i}$ is a univariate Gaussian distribution with conditional mean [13]

$$\bar{A}_{K_i}(T_K, X_i) = \bar{A}_{K_i}(T_K, X_i) + \Sigma_{12}[\Sigma_{12}]^{-1}(\bar{A}_{K_j} - \bar{A}_{K_i})$$

and conditional variance

$$\Sigma = \Sigma_{22} - \Sigma_{21}[\Sigma_{11}]^{-1}\Sigma_{12}. \tag{13}$$

The covariance matrices (11) and the vectors $\bar{A}_{K_1}$ and $\bar{A}_{K_i}$ are updated for successive multipath components at $(T_K, X_i)$ as $l$ ranges from 2 to 19. The $A_{K_i}(T_K, X_i, S_m, D_n, P_n)$ in dB are determined from a Gaussian distribution with conditional mean and conditional variance found from equations (9)-(13).

G. Phase of Multipath Components

Although information about the phase of individual multipath components was not measured in [2], it is desirable to simulate the phase of multipath components to compare wide band and narrow band (CW)
measurements with simulated channels. The simulated phase includes phase shift due to propagation and additional phase shifts induced by reflection coefficients of random scatterers. The phase of an individual multipath component at a given location can be assumed to be uniformly distributed over \([0-2\pi]\) since multipath components travel distances of several hundreds of wavelengths and are likely to arrive with arbitrary phases [2]. As the portable moves over small distances, however, we assume the phase change of individual multipath components is not random, but deterministic based on the local scattering geometry. The following procedure is used to simulate individual multipath component phases at each excess delay \(T_k\). The phases of components which first exist at \(X_0\) are assumed to be uniformly distributed over \([0-2\pi]\). The phase difference between components at a fixed excess delay as a portable moves a short distance is assumed to be deterministic caused by the path length difference travelled by the multipath component from a randomly generated fixed scatterer. Multipath components are assumed to be from a single scatterer (i.e. one hop paths in a 10 m wide building aisle).

H. CW Fading

Once the phase of each individual multipath component is known, the CW signal over small-scale areas may be simulated. The CW signal given in (14) is the phasor sum of all multipath components at \(X_i\).

\[
CW(X_i,S_m,D_n,P_n) = \sum_k A_k e^{j\phi_k}
\]  

(14)

In order to simulate measurements in [12], additional power delay profiles are simulated by linear interpolation of multipath component amplitudes between each \(X_i\) and \(X_{i+1}\). The phases of components in additional profiles are computed as before.

IV. SIMULATION RESULTS

A. Power Delay Profile Impulse Response

An important consideration in the utility of statistical models is their likeness to physical measurements. Simulated profiles must possess similar time dispersion and path loss statistics over an ensemble of simulated measurements and must look like actual measured data. Figures 1 and 2 give examples of simulated LOS and OBS topography multipath power delay profiles at discrete locations along 1-m tracks. These profiles represent realistic multipath channel impulse responses for factory radio channels.

B. Number of Multipath Components

Accurate simulation requires reproduction of the empirical distributions of \(N_p(X_i,S_m,P_n)\), \(N_p(S_m,P_n)\), and \(\sigma_p(S_m,P_n)\). The distribution of \(N_p(X_i,S_m,P_n)\) in a simulated local area is Gaussian, just as measurements were shown to be in [8]. The distributions of \(N_p(S_m,P_n)\) and \(\sigma_p(S_m,P_n)\) have also been accurately simulated [1].

C. Probability of Multipath Component Arrival

\(Pr(M_k(T_k,X_i,S_i))\) for simulated LOS topographies at a received power threshold of 46 dB below a 10 dB free space reference is shown in Figure 3 for a given set \(P\). This curve closely approximates observed probabilities in [8].

D. Average Multipath Component Amplitudes

Figure 4 shows how the large-scale mean power law exponent \(n(T_k,S_i)\) changes for both measured and simulated LOS topographies. In addition to the mean path loss for a local area, the simulated distribution of \(A_k(T_k,S_m,D_n,P_n)\) about (8) is indeed log-normal as was measured in [2,13].
E. Small-Scale Multipath Component Amplitudes

A small-scale fading distribution is shown in Figure 5, and illustrates accurate simulation of the log-normal distribution of $A_w(T_K, X_1, S_m, D_n, P_n)$. The distribution of $\sigma_{small-scale}(T_K, S_m, P_s)$ for measured and simulated local areas classified by topography is within about 0.5 dB [1].

F. Correlation

Recreation of spatial correlation coefficients is necessary for the simulator to be useful in small-scale simulation of such improvement techniques as handset diversity. The spatial correlation coefficient function for simulated LOS topography is shown in Figure 6. The shape of the correlation coefficient function is similar to the LOS spatial correlation coefficient function of measured data where multipath components at small separations and small excess delays are correlated and are slightly anti-correlated for separations of about $2A$ [7]. Since temporal correlation is imposed only in $X_1$, temporal correlation is not reproduced over a large ensemble of simulated results.

G. RMS Delay Spread

The Cumulative Distribution Functions (CDFs) of the rms delay spread for measured and simulated LOS radio channels using the models in [1] are shown in Figure 7a. The CDFs of the rms delay spread in measured and simulated OBS topographies is given in Figure 7b.

Figure 4. Variation of $n(T_K, S_m)$ with excess delay for measured and simulated LOS topography locations.

Figure 5. Distribution of 19 simulated multipath component amplitudes along a 1-m track in LOS topography at a constant excess delay of $T_K = 7.8$ ns.

Figure 6. Average spatial correlation coefficient function for simulated LOS topography locations.

Figure 7. CDF of rms delay spread [ns] of a.) Measured and Simulated LOS and b.) Measured and Simulated OBS open-plan building radio channels measured in [2].
H. CW Fading

CW fading statistics of simulated local areas have been computed. An example of CW fading along a 1-m track is shown in Figure 8 for a simulated LOS topography location. The periodic spacing of the nulls similar to measured narrow band fading [12] suggests that the method used to incorporate phase is valid as a first approximation. The fading CDF of Figure 8 closely approximates the Rayleigh CDF. The simulator accurately reproduces common fading distributions which were shown to be mostly Rayleigh, Log-normal, or Rician in open-plan environments [12].

Figure 8. Typical simulated CW fading based on wide band models for a mobile receiver moving along a 1-m track in LOS topography.

V. CONCLUSION

We have incorporated statistical indoor radio channel impulse response models into a computer simulation that recreates the statistics of measured wide band impulse responses of UHF radio channels in various topographies. The addition of randomly generated phase components having a pseudo-deterministic phase change with motion yields simulated CW fading distributions identical to measured open-plan building radio channels. The simulator accurately recreates both the large-scale and small-scale channel statistics of measured data and can be used to design and analyze the performance of future indoor radio networks. Complete simulation results may be found in [1].

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REFERENCES


