EXPERIMENTS IN MODELING THE SPACE-TIME INDOOR WIRELESS COMMUNICATION CHANNEL

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ABSTRACT

Most previously proposed statistical models for the indoor multipath channel include only time of arrival characteristics. However, in order to use statistical models in simulating or analyzing the performance of array processing or diversity combining, it is also necessary to know the statistics of the angle of arrival and its correlation with time of arrival. In this paper, a system is described which was used to collect simultaneous time and angle of arrival data at 7 GHz. Data processing methods are outlined, and results of data taken in two different buildings are presented. Based on the results, a model is proposed that employs a clustered "double Poisson" time of arrival model. The angular distribution is also clustered, with uniformly distributed clusters, and arrivals within clusters that have Laplacian distribution.

1. BACKGROUND

Wireless radio has recently become an increasingly viable option for indoor applications. The availability of new, higher frequency bands has made wireless an attractive option for high bandwidth digital applications such as local area networks. Wireless networks can be particularly advantageous for applications which require portability, or where installation of wiring is undesirable or impractical.

Multipath interference is known to be a significant problem in indoor channels, and the increasing use of wireless in indoor applications motivates the extensive study of the indoor multipath environment. Recently, other researchers have collected various types of data on indoor multipath propagation. The foundation for much of today's work was the paper by Turin, et al [1], which was a study of outdoor multipath propagation in an urban environment. This work motivated the research described by Saleh and Valenzuela in [2], an important early reference on indoor multipath propagation. Their work consisted of collecting indoor temporal data, from which they proposed a time domain model for indoor propagation. Their model is a basis for the model presented here. Other models have also been proposed more recently, such as that by Ganesh and Pahlavan [3].

In most of the research conducted to this point, the multipath angles of arrival have been addressed very little. The first to study it were Lo and Litva [4], who found that the multipath arrivals were present at varying angles in the indoor environment. However, they were not able to make any conclusive statements about the angles from their data. Recently, a few other researchers have begun to examine the area of angle of arrival in more detail. Guerin [5] collected narrowband angle of arrival data and wideband time of arrival data, but did not collect any data in which the two were measured simultaneously. Wang, et al [6], used a rectangular array to estimate both the elevation and azimuth angles of arrival for major multipaths, but also did not measure the corresponding time of arrival. Litva, et al [7], used a rectangular array to take simultaneous measurements of time and angle of arrival, and concluded that it is possible to make accurate measurements of both time and angle simultaneously, in order to better understand the indoor multipath channel.

This paper expands on some of this recent research. A data acquisition system is described which was able to collect simultaneous measurements of multipath arrivals in both time and angle over short transmission distances. This enables a joint temporal-spatial characterization of the indoor channel response. Using this data the statistical channel model proposed by Saleh and Valenzuela is extended to include angle of arrival. In addition, new parameters for the time and amplitude of arrival at a frequency of 7 GHz are shown for the existing model proposed by Saleh and Valenzuela. The data acquisition system and the model are discussed in greater detail in [8, 9].

2. THE SALEH-VALENZUELA MODEL

The model proposed by Saleh and Valenzuela is based on a clustering phenomenon observed in their experimental data. In their observations, the arrivals came in one or two large groups within a 200 ns observation window. It was observed that the second clusters were attenuated in amplitude, and that rays, or arrivals within a single cluster, also decayed on average with time. Their model proposes that both of these decaying patterns are exponential with time, and are controlled by two time constants: Γ, the cluster arrival decay time constant, and γ, the ray arrival decay time constant. Fig. 1 illustrates this, showing the mean envelope of a three cluster channel.

The impulse response of the channel is given by:

$$h(t) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty}\beta_{kl}\delta(t-T_l-\tau_{kl}), \qquad (1)$$

where the sum over l represents the clusters, and the sum over k represents the arrivals within each cluster. The amplitude of each arrival is given by β_{kl}, which is a Rayleigh

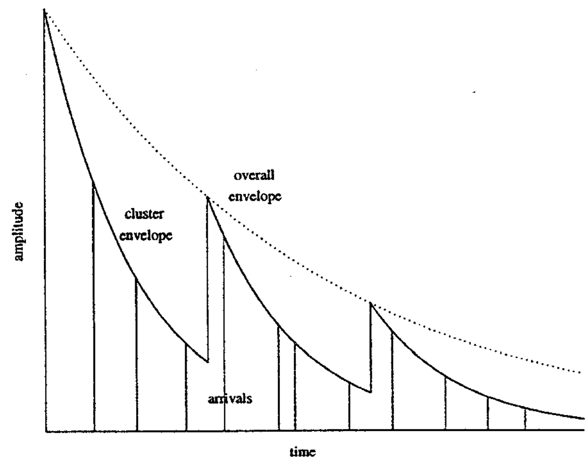

Figure 1. An illustration of exponential decay of mean cluster power and ray power within clusters.

distributed random variable, whose mean square value is given by

$$\overline{\beta_{kl}^2} = \overline{\beta^2(T_l, \tau_{kl})} \quad (2)$$
$$= \overline{\beta^2(0,0)} e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma}, \quad (3)$$

where $\overline{\beta^2(0,0)}$ is the average power of the first arrival of the first cluster. This average power principally is determined by the distance separating the transmitter and receiver.

The time of arrival is described by two Poisson processes which model the arrival times of clusters and the rays within the clusters. The time of arrival of each cluster is an exponentially distributed random variable conditioned on the time of arrival of the previous cluster. The case is the same for each ray, or arrival within a cluster. Following the terminology used by Saleh and Valenzuela, rays shall refer to arrivals within clusters, so that the cluster arrival rate implies the parameter for the intercluster arrival times and the ray arrival rate refers to the parameter for the intracluster arrival times. The probability densities of these arrival times are

$$p(T_l|T_{l-1}) = \Lambda e^{-\Lambda(T_l - T_{l-1})} \quad (4)$$
$$p(\tau_{kl}|\tau_{(k-1)l}) = \lambda e^{-\lambda(\tau_{kl} - \tau_{(k-1)l})}, \quad (5)$$

where Λ is the cluster arrival rate, and λ is the ray arrival rate.

3. EXPERIMENTAL SETUP

The system used to collect the data presented in this paper, illustrated in Fig. 2, used a network analyzer as a co-located transmitter and receiver, and sent the transmitted signal through coaxial cable to the remote transmit antenna. The network analyzer, designed to measure transmission and reflection coefficients at its two ports, was configured to measure the transmission coefficient from the transmit antenna to the receive antenna. The HP network analyzer that was used measures in the frequency domain by sweeping across a specified range of frequencies and has the capability of generating a time domain impulse response by calculating an inverse Fourier transform. Because the timing is all done internally to the network analyzer, this method of generating the impulse response provides a precise and consistent time reference when the antenna is pointed at different angles.

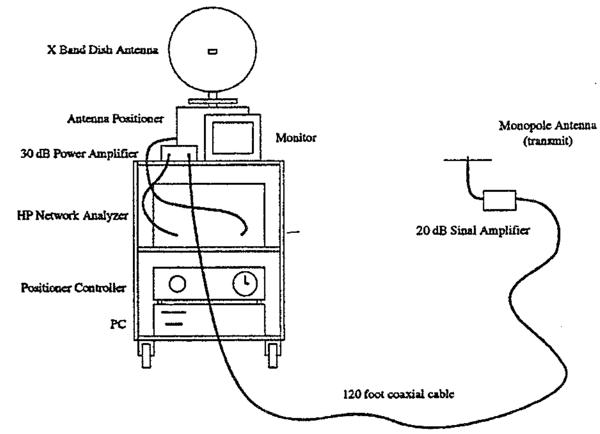

Figure 2. The Data Acquisition System

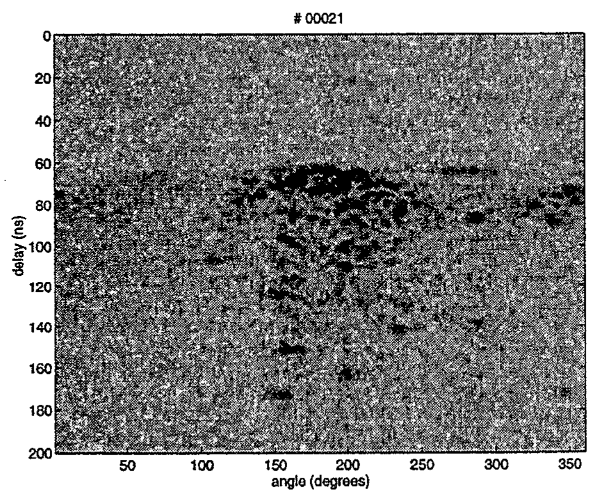

Figure 3. Raw Data Set

The frequency of 7 GHz chosen for the experiments was used primarily due to availability of equipment. Frequencies in this range have not been used in the past, but have become more relevant recently, with allocations in the United States of spectrum between 5 and 6 GHz specifically for use in wireless local area networks. The trend in indoor applications is toward higher frequencies, with some research being conducted at frequencies as high as 60 GHz [6].

4. DELAY AND ANGLE MEASUREMENT

The data collected by the data acquisition system consists of a series of time domain impulse responses of the channel for each angle. This data in matrix form represents a complete "image" of the channel. An example of one data set is shown in image form in Fig. 3.

It is assumed that the indoor multipath channel is dominated by specular multipath, which is supported by the data. As a result, the image plots such as the one shown in Fig. 3 can be modeled as a collection of point sources blurred by a point spread function. This assumption re-

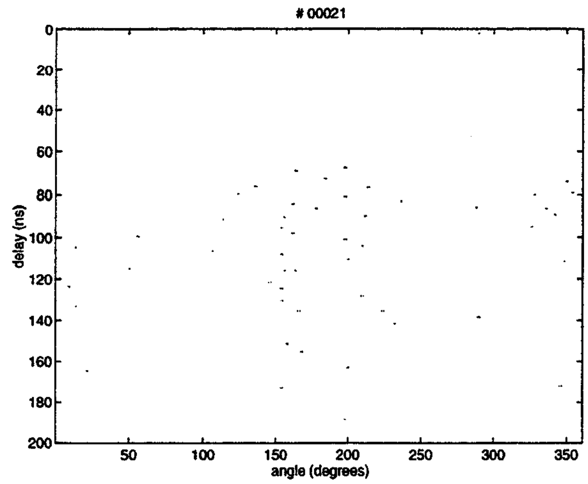

Figure 4. Raw Data Set After Processing

duces the problem of identifying exact time and angle of arrival to a simplified deconvolution, which lends itself very well to the CLEAN algorithm [10]. The CLEAN algorithm was originally used for processing of astronomical images, which are also often modeled as groups of point sources convolved with a blurring function. Essentially the algorithm is a recursive subtraction of the point spread function from the maximum value of the image. The highest peak is found, the amplitude, time, and angle stored, and the impulse response is subtracted from the image. This process is repeated until some threshold is reached. Fig. 4 shows the processed version of the data set in Fig. 3.

5. EXPERIMENTAL DATA

A total of 65 data sets were collected with the data acquisition system in two buildings on the Brigham Young University campus. In the Clyde building, a reinforced concrete and cinder block structure, 55 data sets were collected. For comparison, ten additional data sets were collected in the Crabtree Building, constructed mostly of steel and gypsum board. After processing the data, the time, angle, and amplitude of all major multipath arrivals were measured for each transmit and receive location.

Visual observation of the data showed that clustering like that observed by Saleh and Valenzuela was present in the data. The nature of the clustering tended to follow the model of Saleh and Valenzuela quite well. In general, the strength of clusters tended to decay with increasing delay times, and arrivals within each cluster showed a similar pattern of decay. Unlike the Saleh-Valenzuela data, however, a higher average number of clusters per data set were observed.

In order to analyze the statistical properties of the clustering structure, each data set was organized into clusters. This process was done by hand, since the number of data sets was not large enough to make this task prohibitive, and the computerized algorithms that were experimented with were not reliable enough.

In order to determine the angular distribution of arrivals within clusters, a histogram was generated of all angles of arrival with respect to the mean angle of arrival of the respective cluster. This is shown in Fig. 5. The distribution appears to be Laplacian, and this is confirmed by the superimposed curve for a Laplacian distribution. This was the case with the data in both buildings, and the variance in both cases was similar.

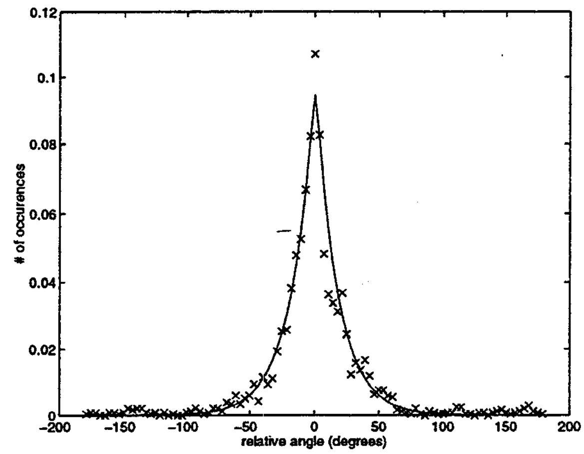

Figure 5. Histogram of arrival angles with respect to cluster means. The best fit Laplacian distribution is superimposed.

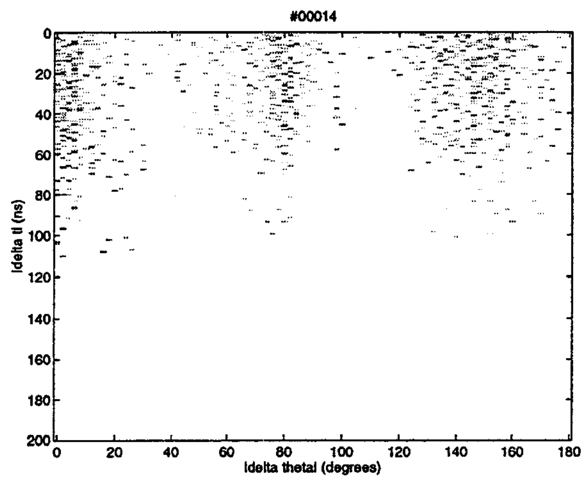

Figure 6. Example of a correlation histogram

6. A PROPOSED TIME/ANGLE MODEL FOR INDOOR MULTIPATH PROPAGATION

One of the most important reasons for collecting data with simultaneous information about time and angle of arrival is to learn something about the correlation of the two. In order to examine this property, correlation histograms were created. Fig. 6 is an example. The picture contains a point for every Δt and $\Delta\theta$ with respect to the first arrival. In this case, there is an obvious clustering effect in angle, and less obvious clusters in time. In most of the data collected, there was little indication of a strong correlation between time delays and angular separation. While this issue should be further explored, we believe that there is sufficient evidence to support the assumption that time and angle are distributed independently.

parameter	Clyde Building	Crabtree Building	Saleh-Valenzuela
Γ	33.6 ns	78.0 ns	60 ns
γ	28.6 ns	82.2 ns	20 ns
$1/\Lambda$	16.8 ns	17.3 ns	300 ns
$1/\lambda$	5.1 ns	6.6 ns	5 ns
σ	25.5°	21.5°	—

Table 1. A comparison of model parameters for the two buildings and from the Saleh-Valenzuela paper.

Assuming that time and angle are statistically independent, we propose an independent angular impulse response for the indoor channel:

$$h(\theta) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty} \beta_{kl}\delta(\theta - \Theta_l - \omega_{kl}), \qquad (6)$$

where β_{kl} is the ray amplitude for the kth arrival in the lth cluster, Θ_l is the mean angle of each cluster, assumed to be distributed uniformly on the interval $[0, 2\pi)$. The ray angle within the cluster, ω_{kl}, is modeled using a zero mean Laplacian distribution with standard deviation σ:

$$p(\theta) = \frac{\sigma}{\sqrt{2}} e^{-|\sqrt{2}\theta/\sigma|}. \qquad (7)$$

7. MODEL PARAMETERS

From the data, model parameters were derived for the Saleh-Valenzuela time of arrival model, and the values of σ were derived for the extended model, as illustrated in Fig. 5. The parameters for the two buildings that were studied are compared to the parameters found by Saleh and Valenzuela in Table 1.

In both buildings, Γ and γ are very close together, but the numbers are considerably higher in the Crabtree Building. This is logical, since the presence of more metal in the Crabtree building gives stronger reflections, and the thin walls have less attenuation, so both decay parameters are much slower than their counterparts in the Clyde Building. It is unexpected that γ is larger than Γ, but there are no physical reasons that would suggest this to be impossible.

The noticeably faster arrival rate ($1/\Lambda$) in both buildings, as compared to the Saleh-Valenzuela data, is due to the fact that our data acquisition system was capable of detecting clusters that arrive parallel in time, but separate in angle, which would be otherwise considered a single cluster. The higher RF frequency used in our experiments may have also been a factor.

8. CONCLUSIONS

From the data gathered for this paper, conclusions can be made about the clustering structure of the multipath signals, the angular distribution of multipaths, the behavior of multipath signals in buildings of varying structure.

There is a definite clustering pattern of the multipath signals in indoor channels. The temporal clustering observed by Saleh and Valenzuela is supported by the data presented here, and a clustering pattern in angle was also observed. The mean angles of each cluster were found to be distributed uniformly over all angles. The distribution of arrivals within clusters was approximately Laplacian, with standard deviations ranging from 20° to 25°. The model proposed in this paper was very accurate in modeling the angle of arrival for the data.

Useful areas for continued research include both verification and application of the model presented here. More data is needed in other types of buildings and at other frequency bands, The angle-of-arrival model presented here is a useful alternative to the only previous option for simulation: random assignment of angles or guessing at the angular properties of the channel. The most important area for continued research is applying the model for its intended purpose–comparison of array processing algorithms. This can be done either by mathematical analysis or Monte Carlo simulation. A mathematical analysis is difficult due to the large number of variables in the model, but the model can be a very useful tool for the generation of random multipath channels for simulation.

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