INDOOR ANGLE OF ARRIVAL USING WIDE-BAND FREQUENCY DIVERSITY WITH EXPERIMENTAL RESULTS AND EM PROPAGATION MODELING

Mark Curry, Bertin Koala, Massimiliano Ciccotosto, and Yasuo Kuga

Department of Electrical Engineering
University of Washington, Box 352500
Seattle, WA 98195-2500

Abstract

In this work we have investigated the problem of angle of arrival (AOA) estimation in the indoor environment. Coherent, multi-path signals must be resolved. The approach is based upon measurement of the AOA using a band of frequencies, approximately 10%-20% of center, and utilizes order statistic filtering to estimate the true angle of arrival from the set of individual AOA's. A plane wave model is assumed for the propagating waves and a random arrangement of scatterers between the source and receiver array is assumed. We have constructed a four-element dipole array and associated receiver-acquisition system to test the approach. The results show good AOA estimates can be obtained in a building that would otherwise yield completely inconsistent estimates using narrowband methods. In addition we have simulated EM (electromagnetic) wave propagation characteristics inside buildings using 3-D computer simulation codes based on ray tracing. The model includes the physical and electrical description of the walls and the patterns of the antennae used. The EM modeling is used for evaluating the base level performance of indoor AOA algorithms.

I. INTRODUCTION AND APPROACH

Earlier studies on the propagation channel [2], have shown that in indoor environments the angle of arrival is random in the sense that the superposition of signals at the receiver appears to have been generated from many coherent sources. The AOA's tend to cluster, corresponding to the dominant propagation paths of the signal in that environment. We have found similar clustering in the environments we have examined. We make the assumption that the AOA along the LOS (Line Of Sight) to the source is statistically frequency independent. The secondary AOA's will be frequency dependent since the signals from source to receiver will be scattered from many objects in the environment. The basic approach is to determine an angular spectrum from each frequency using a Minimum Variance method that has been modified by applying sub-array averaging and forward-backward averaging to the data to accommodate the correlated signals. Once all of the angular spectra have been computed, a final angular spectrum is estimated from the median of the power at each AOA from the ensemble of frequencies. The median filter is a non-linear averaging method that can estimate the central tendency in the presence of strong outliers, or in our case non-Gaussian distributions. The median is that value M, such that $P(x<M) = P(x>M)$. The result is a single angular spectrum that has a peak at the true AOA as well as other weaker peaks from angles that are also frequency independent (if any). Our goal is to develop algorithms based on the underlying physics to the highest extent possible.

II. ANGULAR SPECTRUM ESTIMATION FOR A UNIFORM LINEAR ARRAY

This section briefly reviews the minimum variance spectral estimation method used to derive the angular spectrum. Consider a linear array of *N* sensors whose location and directional characteristics are known. Assume that there are multiple signal sources whose statistical characteristics are uncorrelated. For equally spaced sensors the steering vector is a replica of the l^{th} signal source,

$$\mathbf{a}(\psi_l) = \begin{bmatrix} 1 & e^{ja(\psi_l)} & e^{j2a(\psi_l)} & \dots & e^{j(N-1)a(\psi_l)} \end{bmatrix}^T, \tag{1}$$

where $a(\psi_l) = kd\sin\psi_l$ represents spatial frequency, and *d* denotes sensor spacing. The source signal *x*(*t*) and the noise n(t) are white Gaussian distributed, and statistically independent.

Consider an ideal, unit-amplitude signal, assumed to be propagating in the direction $\vec{\xi}$. The notation for this signal is $\mathbf{e}(\vec{\xi}) = \mathbf{a}(\psi_l)$. The idea is to apply the weight vector **w** to the sensor output. Any signal from the direction specified by **e** should have unit gain. Noise and signal propagating from other directions should be suppressed. In this case, the constrained optimization problem is:

$$\min_{w} E\left[\left|\mathbf{w}^H \mathbf{y}\right|^2\right] = \mathbf{w}^H \mathbf{R}\mathbf{w} \quad \text{subject to } \operatorname{Re}\left[\mathbf{e}^H \mathbf{w}\right] = 1 \tag{2}$$

where the constraint $\operatorname{Re}\left[\mathbf{e}^H \mathbf{w}\right] = 1$ ensures that the ideal signal has unit gain. The optimum weight vector is given by [3]:

$$\mathbf{w}_o = \frac{\mathbf{R}^{-1}\mathbf{e}}{\mathbf{e}^H \mathbf{R}^{-1}\mathbf{e}} \tag{3}$$

with output power in the steering vector direction:

$$\mathrm{P}^{MV}\left(\vec{\xi}\right) = \left[\mathbf{e}^H\left(\vec{\xi}\right)\mathbf{R}^{-1}\mathbf{e}\left(\vec{\xi}\right)\right]^{-1} \tag{4}$$

For correlated arrivals, **R** matrices are averaged from the correlation matrices of sub-array signals [4].

III. AOA FROM ELECTROMAGNETIC WAVE INDOOR PROPAGATION MODEL

We first describe some computer simulations of the indoor EM wave propagation model. The interactions considered in the program include the line of sight, diffraction from the walls, and the scattering fields. For each receiver location the total field $\vec{E}_{vi}$ is calculated by summing the vector field contributed by the line of sight, the reflected, transmitted and diffracted components of the transmitted field.

$$\vec{E}_{vi} = \vec{E}_l + \sum_{a=1}^{A} \frac{e^{-jkr_a}}{r_a} \prod_{m=1}^{M_R} R_{am} \prod_{n=1}^{N_T} T_{an} \tag{5}$$

where $\vec{E}_l$ *is* the line of sight electric vector contribution, $\frac{e^{-jkr_a}}{r_a}$ is the propagation loss along the a^{th} propagation path, with; a = ray index, A = number of rays that reach the receiver, k = wavenumber, r_a = propagation distance from the transmitter to the receiver, R_{am} = reflection coefficient for the m^{th} obstruction along the a^{th} ray path, *m,* = index for the number of obstruction that cause reflections, M_R = number of obstructions along the a^{th} ray path which cause reflections, T_{an} = transmission coefficient for the n^{th} obstruction, n = index for the obstruction through which transmission occurs, and finally, N_T = number of the obstructions along the a^{th} ray path through which transmission occurs.

Our test scenario is derived from a hallway area in the EE building; the same hallway that will be tested experimentally in the next section. In Figure 1 we show the received field strength at different receiver locations of the EE building with an antenna at position 34 on the ***y*** axis and 0.5 on the ***x*** axis and emitting 0dBm. The exact descriptions of the electrical properties of buildings' structures and objects are difficult to include in the EM wave simulation codes but we will assume simple dielectric walls to investigate the modeling. We used the fields estimated from this model as inputs to the method described earlier to investigate the AOA's of the dominant signal components. Figure 2 shows the angle of arrival spectrum, using our approach.

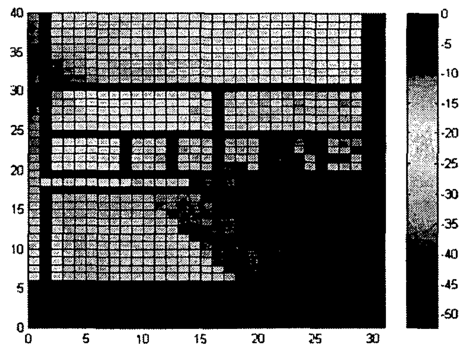

Figure 1. Simulation of EM wave propagation inside a building. One Transmitter is located at the top left. Black lines are dielectric walls.

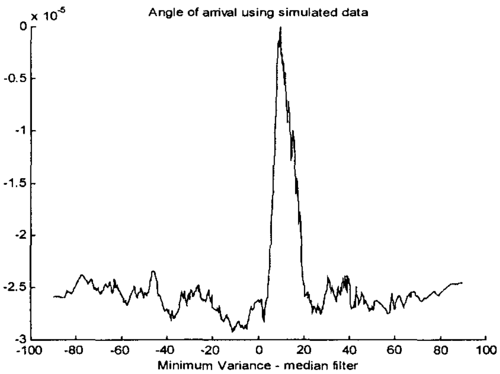

Figure 2: Using data obtained from the simulated EE building, we show the AOA estimation results. In this case there is no problem discerning the correct AOA at 18 degrees.

IV. EXPERIMENTAL RESULTS

A four-element dipole antenna is used at the receiver, operating in a frequency range of 900 - 1000 MHz. The number of frequency steps varies from 10 to 50. Baseband data is collected using our custom four-channel receiver and data acquisition system based on the TI TMS320C25 DSP. Data processing is done in MATLAB. The system was set up in the hallway of the EE building as shown in Figure 3. This case was chosen specifically because it is a difficult one. Tests in simpler environments yield correspondingly better AOA estimation. The spectrum contains components along the LOS angle from transmitter to receiver (even in the presence of walls), as well as two other components that correspond to dominant signals. Dominant signals are ones that are relatively strong and have planar wave fronts. The estimate of the LOS angle is close to the true LOS angle (±10 degrees). Figure 4 shows the behavior of the individual frequencies. Figure 5 shows the final, median filtered spectrum. Even with the strong hallway component we are able to produce a reasonable AOA estimate. The additional width of the peak can be attributed to the many additional random scatterers in the environment. In general we have found that as the number of frequencies increases, the ability to resolve the true AOA improves. In general, as the number of scatterers increases for a fixed distance from source to receiver, the number of frequency steps to resolve the true AOA must also increase.

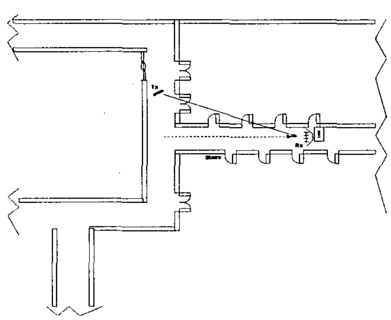

Figure 3: Plan view of the area of the EE building used for the tests. The transmitter is positioned at about 18° the antenna boresight. The distance from Tx to Rx is 21 m.

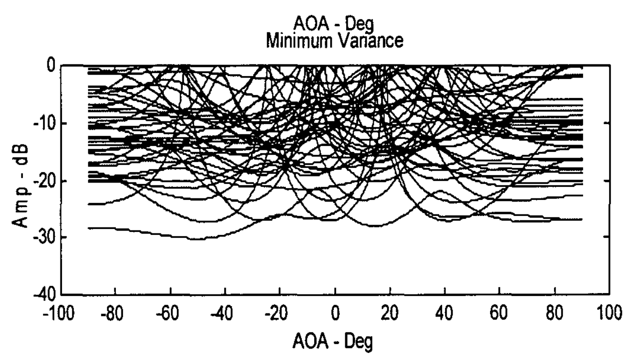

Figure 4: Superposed angular spectra for each individual frequency in the hallway experiment. Note the apparently random AOA for each incident temporal frequency. Each spectrum is obtained using 40 points in the frequency range 0.9-1 GHz. The plot is meant to show the difficulty in obtaining an AOA estimate from individual estimates alone.

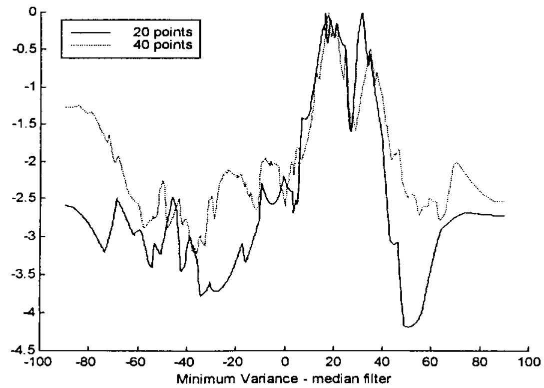

Figure 5: The median filter is applied to the Minimum Variance angular spectra presented in Figure 6. It is evident the correct angle can be estimated. Estimates from more frequencies may result in even better results.

V. CONCLUSION

While the indoor multipath environment is a difficult one for angle of arrival estimation, by utilizing wide band frequency diversity and order statistic filtering a reasonably good estimate can be obtained. The median filter has been found to be a robust estimator for multipath AOA work. We demonstrated consistent results when applying the technique to a ray traced, electromagnetic propagation model. The model was validated by comparing measured fields to the simulated fields for the problem of estimating the angle of arrival. Our results have shown that studying difficult (multipath) problems with EM models, provides insight to extending high resolution signal processing methods that typically are used in non multipath environments. These types of situations typically occur in wireless communications applications.

VI. REFERENCES

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