Angles-of-Arrival of Multipath Signals in Indoor Environments

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1. Introduction

Recent innovations in indoor wireless communications have led to increased interest in radiowave propagation mechanisms. Due to limited spectrum resources adaptive antenna techniques are being implemented to increase channel capacities. Analysis of Angles-of-Arrival (AOA) for each individual multipath signal in different indoor environments provides useful information for the design of adaptive antennas and communication systems.

Conventionally AOA have been estimated using a beamforming technique. This method, however, has certain limitations, such as the inability to distinguish the arrival of two signals within an array beamwidth and to resolve AOA for weak signals from side lobes. MUltiple SIgnal Classification (MUSIC) [1] is a well known technique for estimating AOA of multiple signals which overcomes the limitations of the conventional beamforming method. In indoor environments the multipath signals are usually correlated. For MUSIC to be applicable in such a scenario the signals have to be decorrelated [2]. Further, in the application of MUSIC, it is necessary to know the number of multipath signals. This can be determined using the Minimum Descriptive Length (MDL) criterion [3].

In this paper, we estimate the AOA of multipath signals inside a multistorey building. We apply the MDL criterion to determine the number of significant multipath components from measurement data, and then use MUSIC with a forward/backward spatial smoothing technique to obtain the AOA of the signals in both azimuth and elevation. The measurements were made in a small classroom as well as a large convention hall (Great Hall) which are located in the Tower Building of the University of Technology at Broadway, Sydney. All measurements have been carried out by using a vector network analyser (VNA) coupled to an automatic scanning system that moves a receiver antenna around a rectangular planar grid forming a synthetic rectangular array. Computer simulations have also been carried out for comparison with the results obtained from measurement data.

2. Formulation

Consider a rectangular planar array composed of $M \times N$ identical passive sensors with K narrow-band plane waves impinging on the array from multipath sources of directions $[\phi_1\theta_1, \phi_2\theta_2, \cdots \phi_K\theta_K]$ where ϕ_K and θ_K are azimuth and elevation AOA respectively. If the AOA of the kth source are denoted by (ϕ_k, θ_k), the complex envelope of the total received signal at an array element located at the intersection of the mth row and nth column, can be written as

$$z_{m,n}(t) = \sum_{k=1}^{K} s_k(t)\exp\{j\beta[d_x(m-1)u_k + d_y(n-1)v_k]\} + n_{m,n}(t) \tag{1}$$

where d_x and d_y denote the elements spacing along the X and Y axes respectively, $\beta = \frac{2\pi}{\lambda}$, $u_k = \cos\phi_k \sin\theta_k$ and $v_k = \sin\phi_k \sin\theta_k$. Hence the multipath signals received by all sensors are given using the following vector notation

$$\mathbf{Z}(t) = \mathbf{A}\,\mathbf{S}(t) + \mathbf{n}(t)\,. \tag{2}$$

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$\mathbf{Z}(t)$ is an $MN \times 1$ vector containing the complex elements of total received signals for an $M \times N$ rectangular array arranged as

$$\mathbf{Z}(t) = [Z_{0,0}(t), Z_{1,0}(t), \cdots Z_{M-1,0}(t), \\ Z_{0,1}(t), \cdots Z_{M-1,N-1}(t)]^T . \quad (3)$$

A, the angle steering matrix ($MN \times K$), contains the AOA of signals

$$\mathbf{A} = [\mathbf{a}(\phi_1, \theta_1), \cdots \mathbf{a}(\phi_k, \theta_k), \cdots \mathbf{a}(\phi_K, \theta_K)] \quad (4)$$

where **a** is the direction vector ($MN \times 1$), that is

$$\mathbf{a}(\theta_k, \phi_k) = [1, e^{-j\beta(d_x u_k)}, \cdots, e^{-j\beta(d_x(M-1)u_k)}, \\ e^{-j\beta(d_y v_k)}, \cdots, e^{-j\beta(d_x(M-1)u_k + d_y(N-1)v_k)}]^T . \quad (5)$$

$\mathbf{S}(t)$ represents the source vector ($K \times 1$)

$$\mathbf{S}(t) = [S_1(t), \cdots S_k(t), \cdots S_K(t)]^T . \quad (6)$$

$\mathbf{n}(t)$ is a noise vector ($MN \times 1$), that is

$$\mathbf{n}(t) = [n_{0,0}(t), n_{1,0}(t), \cdots n_{M-1,0}(t), n_{0,1}(t), \\ \cdots n_{M-1,N-1}(t)]^T . \quad (7)$$

The covariance matrix ($MN \times MN$) becomes

$$\mathbf{R} = E\{\mathbf{Z}\mathbf{Z}^H\} \quad (8)$$

where $E\{.\}$ denotes the expectation. Superscripts T and H represent transpose and hermitian complex conjugate respectively.

In the indoor environment the reflected and diffracted multipath signals can be correlated with each other and/or with the original source depending on their phase relationship. The forward/backward spatial smoothing technique uses grouped overlapping subarrays in forward and backward directions to effectively decorrelate the responses [2]. The spatially smoothed covariance matrix is given by

$$\tilde{\mathbf{R}} = \frac{1}{2L} \sum_{l=1}^{L} (\mathbf{R}_l^f + \mathbf{R}_l^b) \quad (9)$$

where the number of subarrays is $L = (M+1-Q_1) \times (N+1-Q_2)$ with subarray dimension $Q_1 \times Q_2$. $\mathbf{R}_l^f$ and $\mathbf{R}_l^b$ are the forward and backward covariance matrices of size $(Q_1 Q_2 \times Q_1 Q_2)$ respectively. The AOA of multipath signals can then be estimated using MUSIC [1] by searching for the peaks in the two dimensional angular spectrum for azimuth and elevation given by

$$\mathbf{P}(\phi_k, \theta_k) = \frac{1}{\mathbf{a}^H(\phi_k, \theta_k) \tilde{\mathbf{R}}_n \tilde{\mathbf{R}}_n^H \mathbf{a}(\phi_k, \theta_k)} \quad (10)$$

where $\tilde{\mathbf{R}}_n$ is the matrix $(Q_1 Q_2 \times (Q_1 Q_2 - K))$ of eigenvectors spanning the noise subspace.

From eqn(8), it can be seen that the estimated covariance matrix could be an average over a number of snapshots. The probability of the covariance matrix can be improved by increasing the snapshots (P) to infinity. However, in practice it is not possible to have infinite number of measurements. Furthermore, in most measurement data, differences between eigenvalues of a covariance matrix are not significant which implies that it is hard to set up a threshold between signal and noise subspaces. MDL criterion in a coherent scenario determines the number of multipath components for a finite number of snapshots without setting a threshold and is given by [3]

$$\min_{K \in \{0, \cdots MN-1\}} [\mathrm{MDL}(K)] = \frac{1}{2} K(2MN - K + 1) \log P \\ + (MN - K) P \log \left(\frac{\frac{1}{MN-K} \sum_{i=1}^{MN-K} \hat{\lambda}_i(\hat{\theta}^{(K)})}{\prod_{i=1}^{MN-K} \hat{\lambda}_i(\hat{\theta}^{(K)})^{1/(MN-K)}} \right) \quad (11)$$

in which $\hat{\theta}^{(K)}$ is given by a K-dimensional searching minimisation

$$\hat{\theta}^{(K)} = \min_{\hat{\theta}^{(K)}} \left[\log \left(\frac{\frac{1}{MN-K} \sum_{i=1}^{MN-K} \hat{\lambda}_i(\theta^{(K)})}{\prod_{i=1}^{MN-K} \hat{\lambda}_i(\theta^{(K)})^{1/(MN-K)}} \right) \right] \quad (12)$$

where $\hat{\lambda}_i$ (from 1 to $MN-K$) are the eigenvalues of the $MN \times MN$ matrix $\mathbf{P}_A^{\perp}\mathbf{R}\mathbf{P}_A^{\perp}$. $\mathbf{P}_A^{\perp}$ is the projection matrix on the noise subspace.

3. Measurement System and Environments

The algorithms presented in the previous section were applied to measured signals obtained in a classroom (a small room environment) and in the Great Hall (a large room environment) which are located in the 23rd and 5th floors respectively of a 30-storey tower building. The classroom, which contains a number of wooden desks and plastic chairs, is enclosed by a concrete wall on one side with a wide metal framed glass window. The other three sides of the room have brick internal walls. The two entrances to the room consist of two wooden doors which open into a corridor as shown in the floor plan of Fig. 1. The Great Hall is enclosed on two sides by concrete walls, one of which has a wide metal framed glass window. The other two sides of the hall consist of two brick internal walls as shown in the floor plan of Fig. 2. The Great Hall has a number of metal framed chairs and a wooden stage. All floors and ceilings are made by steel reinforced concrete.

For measurements, vertically polarised sleeve dipole antennas were used for both transmitter and receiver. The measurements were performed using a VNA operating at 1 GHz. Due to low power output of the VNA and to offset losses in the coaxial cables, a 50 dB RF power amplifier and a 0~60 dB attenuator were employed to maintain the output power of the transmitter antenna at 30 dBm. A synthetic rectangular array of 5×5 elements was formed by moving a single receiving antenna over a horizontal plane with half wavelength spacing in both the X and Y directions. Positioning the receiving antenna was achieved using a computer controlled scanning system. At each element position of the synthetic receiver array the VNA was triggered by the system to automatically record and average 11 measurements. The procedure was repeated 50 times (as snapshots) over an area of a synthetic receiver array at each measurement location in the room. The measured data was down loaded from VNA to a PC through a GPIB interface for further analysis using MDL and spatially smoothed MUSIC with the subarray of 4×4 elements. In order to obtain the full view of AOA in a room, searching ranges were 0~360 and 0~180 degrees in azimuth and elevation respectively. An ambiguity exists in predicted elevation AOA due to the planar nature of the array. All the measurements were line of sight and performed during weekend nights to ensure minimal disturbance from movement of people near the measurement apparatus.

4. Results

A. Experimental results

In order to obtain AOA distributions of multipath signal propagation at different locations in different rooms, we varied transmitter antenna height, and transmitter and receiver locations. The transmitter antenna was positioned at two height (1.7m and 2.7m) for all transmitter locations. The receiver antenna was kept at a height of 1.7m for all receiver locations. The transmitter and receiver locations in the classroom and the Great Hall are shown in Fig. 1 and Fig. 2 respectively. The receiver locations represent the center of the synthetic array. The multipath components and their AOA, measured at different locations in the classroom and Great Hall, are shown in Table I and Table II respectively. MDL estimated 6~7 multipath components in the classroom and 2~4 in the Great Hall. From these measurements we can see that for the same transmission power, significant multipath components are reduced as a room size increases. We also obtain multipath components as a function of the distance between the transmitter and receiver. As this distance increases, the number of multipath components appear to decrease in a given room. In the case of the classroom the source signal was reflected by almost all the walls, ceiling and floor, but in the large room some reflections were too weak to be measured.

B. Computer simulation

Computer simulations were also performed to validate AOA obtained from the measurements. For all locations the measured AOA are found to compare well with the simulated results. One such comparison is explained below for the sake of clarity. The receiver antenna was assumed to be a rectangular array with 5×5 elements spaced at half wavelengths along the X and Y axes. The source signal was assumed to impinge on the array at an angle (90, 90) degree and two multipath signals were assumed to impinge at angles of (31, 33) and (129, 65) degrees respectively. All signals were assumed have a plane wavefront and be completely correlated with each other. The signal-to-noise ratio (SNR) of source signal was assumed to be 10 dB and attenuation coefficients of the multipath signals were assumed to be (-0.4, 0.6) and (-0.2, -0.3) respectively. The source vector was generated using random sampling with zero mean and pre-specified variances. The sensor and environment noises were also simulated by generating independent normally distributed random numbers. The number of snapshots considered was 500. The forward and backward smoothing was performed with subarrays of size 4×4 to generate a smoothed covarance matrix for predicting AOA. The results of the two dimensional AOA measurement and computer simulation for this example are shown in Fig. 3.

5. Conclusion

This paper presents results for AOA of multipath signal propagation in both azimuth and elevation inside a classroom and a convention hall using spatially smoothed MUSIC algorithm. The MDL criterion has been used to decide the number of significant multipath components. The algorithms used in obtaining AOA from measured data were validated by computer simulations. The measurement results indicated that for a same transmitter power, a small room has more significant multipath reflections than a big room and such multipath reflections decrease as the distance between the transmitter and a receiver increases.

Acknowledgments

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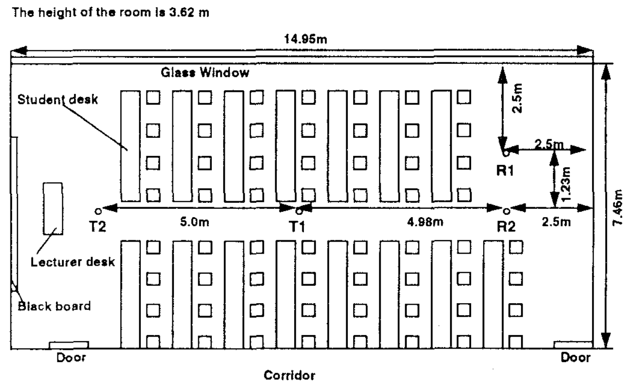


Fig. 1: The floor plan of the classroom

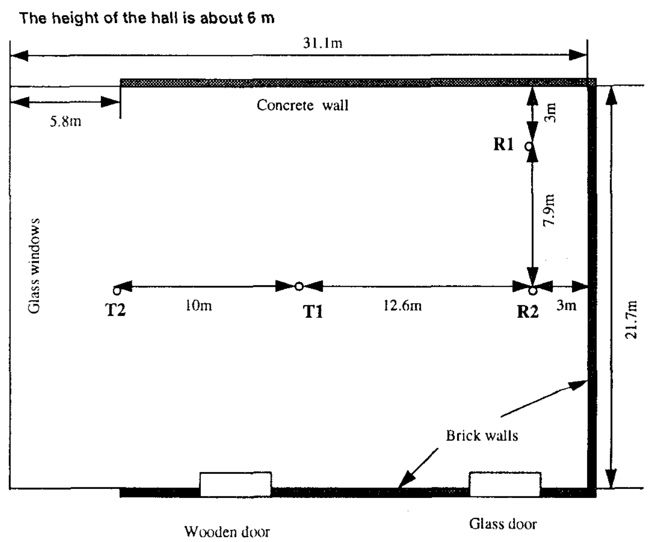


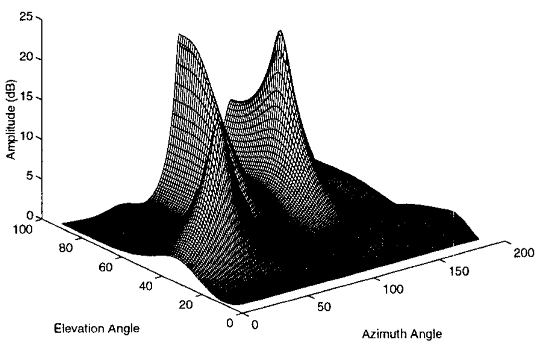
Fig. 2: The floor plan of the Great Hall

Antenna Height	H1 = 1.7m				H2 = 2.7m			
Transmitter Location	T1		T2		T1		T2	
Receiver Location	R1	R2	R1	R2	R1	R2	R1	R2
AOA degrees	133, 90	0, 90	153, 90	0, 90	130, 81	0, 81	152, 84	0, 84
(AZ, EL)	186, 90	128, 90	181, 90	145, 90	186, 90	125, 81	181, 84	145, 82
	194, 51	180, 55	189, 70	180, 70	193, 60	180, 60	189 73	180, 72
	194, 90	180, 90	189, 90	180, 90	193, 76	180, 75	189,84	180, 82
	194, 120	180, 125	189, 110	180, 110	193, 130	180, 133	189, 116	180, 116
	237, 90	236, 90	218, 90	216, 90	237, 83	236, 82	217, 83	212, 82
	349, 90		351 ,90		348, 83		351, 85	

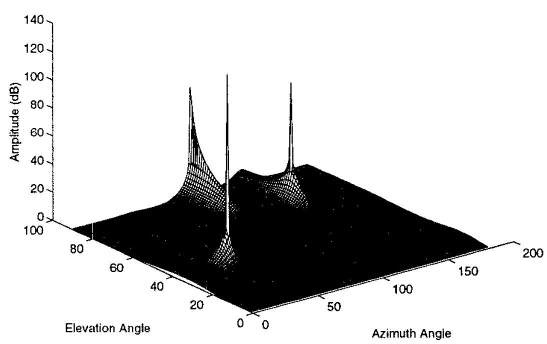
Table I: AOA in the classroom

Antenna Height	H1 = 1.7m				H2 = 2.7m			
Transmitter Location	T1		T2		T1		T2	
Receiver Location	R1	R2	R1	R2	R1	R2	R1	R2
AOA degrees	137, 90	0, 90	199,90	180, 90	136, 84	0, 83	199, 90	180, 90
(AZ, EL)	212, 90	126, 90	199,101	180, 112	211, 110	126, 90	199, 104	181, 105
	212, 107	180, 90			212, 85	180, 82		
	332, 90	180, 107			332, 85	180, 90		

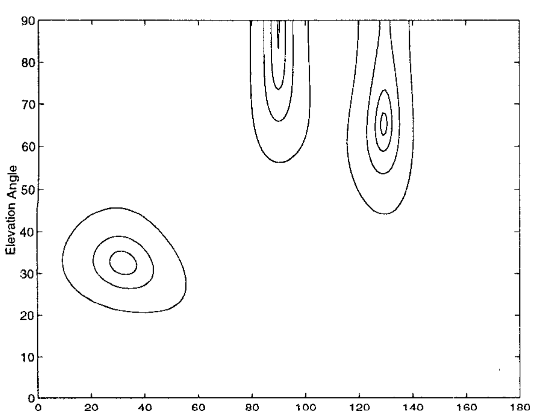
Table II: AOA in the Great Hall



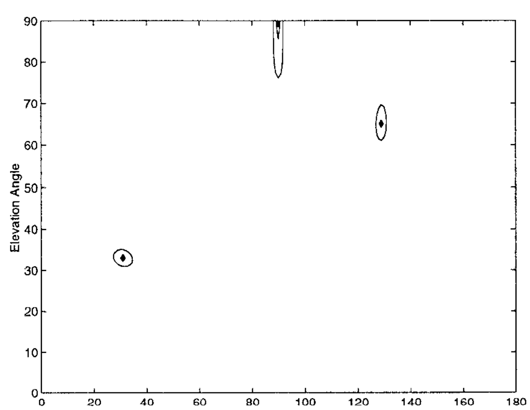
Measurement of AOA in mesh plot



Simulation of AOA in mesh plot



Measurement of AOA in contour plot



Simulation of AOA in contour plot

Fig. 3: The comparison of the measurement and computer simulation