Experimental Studies of Indoor Propagation Characteristics of a Smart Antenna System at 1.8 GHz

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ABSTRACT

Smart antenna systems are becoming practical for indoor applications such as wireless local area networks (LANs). However, the challenging indoor propagation environment is one of biggest obstacles for designing smart antenna wireless networks. In order to fully understand and characterize channel propagation characteristics or *vector channels* of smart antenna systems in indoor environments, experiments are conducted using a 1.8 GHz real-time smart antenna testbed with a uniform linear array. The effects of mobile user motion on the vector channel variation are studied in line-of-sight (LOS) and non-line-of-sight (NOLOS) indoor scenarios. The experimental results on the variation of vector channel parameters such as space-time correlation properties, spatial signatures, direction-of-arrivals (DOAs), multipath angle spread, and complex path fading are presented. Results show that the vector channel varies more significantly in the NOLOS scenario than in the LOS scenario.

Keywords: indoor propagation, vector channel, smart antenna systems, space-time correlations

1. INTRODUCTION

The demand for wireless communication systems such as wireless local area networks, mobile cellular telephony, and radio paging has been greatly expanded. These wireless systems require state-of-the-art communication techniques to support many users at high data rates. Smart antenna systems¹⁻³ that use antenna arrays at the base station (BS), along with advanced space-time signal processing techniques, enable the wireless system users to realize significant increases in signal quality, capacity, and coverage.

Design and performance analysis of smart antenna systems require both the spatial and the temporal channel propagation information of the signals present at each antenna array element. Since a vector of signal samples is received/transmitted at each instant of time, the channel propagation characteristics between a mobile terminal (MT) and an antenna array is described by a *vector propagation channel*. For single antenna systems, it is acceptable to consider only scalar propagation channels that provide temporal information such as large-scale (path loss, diffraction) and small-scale (multipath fading, Doppler shift, delay spread) propagation effects. In addition to temporal channel propagation information, spatial information regarding the correlation of signals among multiple antennas, direction of arrivals (DOAs), and multipath angle spread is needed to fully characterize vector propagation channels of smart antenna systems.

The variation of vector channel parameters depends on the type of the propagation environment (indoor, rural, suburban, urban) and the radio link between the MT antenna and the BS antenna array. For instance, when the direct radio path is blocked, only multipath signal components propagate and the received signal experiences deep fade levels. Multipath signals arriving from different DOAs with almost equal strengths and opposite phases may add up constructively or even cancel out. Extensive experimental studies of vector channels in different wireless environments is paramount to an accurate vector channel model and thus an effective smart antenna system design.

With the emerging applications of smart antenna systems in indoor environments such as wireless local area networks (LANs), there is a great need to study and better understand the indoor vector propagation channel characteristics. Okamoto⁴ has recently proposed a smart wireless LAN (SWL) system which adapts smart antenna systems to wireless LANs. Several researchers^{5,6} have studied indoor radio propagation, but their work focused on the temporal properties of the indoor channel. Spatial aspects of indoor radio propagation were initially addressed in^{7,8} where data was collected with displacement around the receiver. Lo and Litva⁹ were the first to specifically

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address the DOA issue in the indoor environment. Jeng et al.¹⁰ measured the variation of spatial signatures at 900 MHz due to mobile movement in the indoor environment where only LOS existed. In this paper, we study the variation of vector propagation channels at 1.8 GHz due to mobile user movement. The difference of this study from Jeng et al.¹⁰ is that measurements are taken at 1.8 GHz in both the LOS and the NOLOS scenarios of the hallway type indoor environment. We present the experimental results of our vector channel measurements regarding the space-time correlation behavior with both the spatial (spatial signature change, DOAs, multipath angle spread) and the temporal (complex path fading) properties of the indoor radio channel. In the next section, we briefly introduce vector propagation channel concept. Then, in Section 3, we describe the experimental setup used to collect the indoor results discussed herein. Section 4 presents the data processing used to extract channel propagation information. Results and analysis are presented in Section 5 with a paper summary following.

2. VECTOR PROPAGATION CHANNEL CONCEPT

For an antenna array with M identical elements, using the baseband complex envelope representation, the signal received from d mobile sources emitting narrowband signals is modeled as

$$X(t) = \sum_{i=1}^d a_i(t)s_i(t) + n(t) \quad (1)$$

where the narrowband vector channel or *spatial signature* $a_i(t)$ associated with the signal $s_i(t)$ transmitted by the i 'th source is given by

$$\mathbf{a}(t) = \sum_{l=1}^{L_i(t)} \Gamma_l \alpha_l(t) e^{j\varphi_l(t)} \vartheta(\theta_l). \quad (2)$$

where L_i is the number of paths associated with the i 'th source, Γ_l is the large-scale propagation effects (path loss, ground reflections), $\alpha_l(t)$ is the amplitude of complex multipath fading, $\varphi_l(t)$ is the phase of the complex multipath fading, θ_l is the direction-of-arrivals (DOAs), and $\vartheta(\theta_l)$ is the $M \times 1$ *array response vector*. In the above model (1), it is assumed that the multipath delays are much smaller than the inverse signal bandwidth, i.e. $s_i(t - \Delta_l) \approx s_i(t)$.

3. OVERVIEW OF THE EXPERIMENTAL SETUP

The experimental setup consisted of a base station (BS) receiver site and a mobile terminal (MT) transmitter site. At the BS receiver site, there was a real-time smart antenna testbed with a 6-element uniform linear antenna array. The inter-element distance of the array was $\lambda/2$ (8 cm) and the elements were patch antennas. The antenna array was attached to a 2-meter woodstand. The antenna elements were connected to the smart antenna testbed that sampled received signals from the 6 channels with a frequency of 3.072 MHz. The data was buffered and monitored on a PC. At the MT transmitter site, the transmitter antenna was a 2dBi gain, omnidirectional, vertically polarized dipole antenna. It was attached to a 1.5-meter wood-stand and driven by a HP 8662A signal generator. The MT continuously sent an unmodulated sine wave carrier at a frequency of 1890.1 MHz.

Figure 1 shows the indoor experimental environment which is inside the one story Electrical Engineering Research Laboratory at the J.J. Pickle Research Campus of The University of Texas at Austin. The antenna array was placed near the door of a small room that led to a hallway. In the hallway, the MT was placed at two different locations where there was line-of-sight (LOS) (location 1) and non-line-of-sight (NOLOS) (location 2) communication links. Scatterers in the medium were the walls, ceilings, floors and several wooden-tables. The distance between the mobile transmitter and the antenna array was approximately 20 meters and 30 meters in the LOS and the NOLOS scenarios respectively. In order to study the effects of relative motion between the antenna array and the mobile transmitter on the vector channel variation, the MT was moved a short distance along a linear path with 0.2λ steps up to a total displacement of 2λ (32 cm.).

4. DATA PROCESSING

While the MT was continuously transmitting the test signal, the received data at the BS was processed in the following way for each mobile position to extract the channel propagation information. First, the signal snapshot at each antenna element for 3 milliseconds (9600 samples) was collected and an 6 by 9600 data matrix was formed.

Figure 1. indoor experimental environment

Three consecutive snapshots were taken and the data with the maximum signal-to-noise ratio was chosen. Next, the data was calibrated by removing the phase and amplitude mismatch due to the radio frequency (RF) cables and circuits. The spatial signatures or narrowband vector channels in (2) were captured via an eigenvalue decomposition of the sample covariance matrix, i.e., $\widehat{R}_x = \frac{1}{N} X X^*$, where N is the data length (9600 in this case) and $\star$ denotes the complex conjugate and transpose operation. DOAs (θ_l) were estimated using the forward smoothed ESPRIT.¹¹

5. RESULTS AND ANALYSIS

5.1. Space-Time Correlations

In designing smart antenna systems, it is very important to consider the space-time correlation behavior of the vector channel. Most of the adaptive array signal processing techniques and statistical characterization of the vector channel depends on the correlation between the received signals at each antenna array element. The space-time correlation of the spatial signatures in (2) is defined as

$$R_a(\Delta t) = E\{a(t)a(t + \Delta t)^*\} \quad (3)$$

Assuming the fading on each path is uncorrelated with the other paths, $R_a(\Delta t)$ can be rewritten as

$$R_a(\Delta t) = \sum_{l=1}^L E\{\alpha_l^2\} e^{j\Delta\phi_l} \vartheta(\theta_l) \vartheta^*(\theta_l) \quad (4)$$

where $E\{\alpha_l^2\}$ is the signal power in the l th path and $\Delta\phi_l$ is phase change in the l th path due to the movement within period Δt . Phase change is a function of the displacement Δx and direction of the movement with respect to the

receiver. If the number of paths (L) is large (*i.e.*, $L \rightarrow \infty$), the sum in (4) can be replaced with integrals. Then, $R_a(\Delta t)$ is decoupled into time correlation (ρ_t) and spatial correlation (Q_s) components, and is given by³

$$R_a(\Delta t) = \rho_t Q_s \quad (5)$$

$$\rho_t = J_0(\Delta x) \quad (6)$$

$$Q_s(m, n) = \frac{1}{2\sigma_\theta} \int_{2\sigma_\theta} \vartheta_n(\theta) \vartheta_n^*(\theta) d\theta \quad (7)$$

where $J_0(\cdot)$ is the Bessel function of the first kind and of order zero and $2\sigma_\theta$ is the angle spread.

Figure 2. space-time correlation in the LOS scenario

Figure 3. space-time correlation in the NOLOS scenario

The space-time correlation matrix $R_a(\Delta t)$ provides us with information about the dynamics of vector propagation channels. As the mobile terminal moves, both the amplitude and phase of the spatial signature vector changes. While the time correlation component (ρ_t) describes how fast the spatial signatures change with the time, the spatial correlation component (Q_s) characterizes the complexity of spatial signature changes across antenna elements. To observe the variation of the vector channel with movement in the indoor environment, we obtained the space-time correlation matrix $R_a(\Delta t)$ from the measurement data. The amplitude of the space-time correlations between the first antenna element and the other elements in the array is shown in Figure 2 and Figure 3 for the LOS and NOLOS scenarios respectively. It is observed that the correlations are higher in the LOS scenario than in the NOLOS scenario. The minimum correlation level in the LOS scenario is 0.65. In the NOLOS scenario, it drops to as little as 0.2. It is also seen that only the time correlations change noticeably in the LOS scenario, but both the spatial and time correlations change in the NOLOS scenario. The results imply that even the smallest movement in the propagation environment causes large phase variations in the received signal vector. Since spatial correlations (Q_s) are a function of the angle spread, spatial diversity should be larger in the NOLOS scenario than in the LOS scenario. We will explore these properties when we present multipath angle spread results.

5.2. Spatial Signature Change

The spatial signatures in (2) represent the response of an antenna array to a mobile terminal at a certain location. In a wireless communications system, the users are situated in different locations and therefore have different spatial signatures at the base station antenna array. Exploiting the differences between the spatial signatures, we can selectively receive and transmit multiple co-channel signals without creating significant interference among the users.

In order to characterize the propagation environment and effectively implement downlink beamforming schemes, we should understand the variation of spatial signatures. Since the spatial signature is a vector quantity, its variation can be quantified by measuring both the amplitude and the angle changes relative to a reference vector. Relative angle change (RAC) and relative magnitude change (RMC) of two spatial signatures $\mathbf{a}_i$ and $\mathbf{a}_j$ for an antenna array is defined as

$$RAC(\%) = 100 \times \sqrt{1 - \left| \frac{\mathbf{a}_i^*}{\|\mathbf{a}_i\|} \cdot \frac{\mathbf{a}_j}{\|\mathbf{a}_j\|} \right|^2}, \quad (8)$$

$$RMC(dB) = 20 \log \frac{\|\mathbf{a}_j\|}{\|\mathbf{a}_i\|}, \quad (9)$$

where $\|\mathbf{a}_i\|$ and $\|\mathbf{a}_j\|$ denote the norms of the spatial signature vectors $\mathbf{a}_i$ and $\mathbf{a}_j$, respectively. The relative angle change in (8) helps determine the update rate of the weight vectors for downlink beamforming. The relative amplitude change (9) gives the relative power of the received signals with spatial signatures $\mathbf{a}_i$ and $\mathbf{a}_j$.

Figure 4. spatial signature change in the LOS scenario

Figure 5. spatial signature change in the NOLOS scenario

In our indoor experiments, as we moved the mobile transmitter, we obtained spatial signature variations shown in Figure 4 and Figure 5 for the LOS and the NOLOS scenarios respectively. In both Figures, the top plot shows the relative angle change and the bottom plot shows the relative amplitude change. We see that the relative amplitude change in both scenarios is approximately the same with a peak-to-peak change of 4dB. Relative angle change in the LOS scenario is significantly larger than that in the NOLOS scenario. Relative angle change of the spatial signatures drops from 25% (14°) to 15% (8°) in the LOS scenario but it gets as close as 100% (90°) in the NOLOS scenario. 100% RAC corresponds to a case in which the spatial signatures are orthogonal. Thus, as the mobile terminal moves, the spatial signature vectors $a(t)$ in the LOS scenario will approximately point the preferred direction and their variation will be mostly in amplitude. This enables us to use spatial signature based beamforming techniques¹² for downlink transmissions from the smart antenna system. However, in the NOLOS scenario, since both the amplitude and the direction of the spatial signatures changes, better downlink transmission schemes need to be used.

5.3. DOAs and Multipath Angle Spread

The spatial properties of the vector channel are determined by the direction-of-arrivals (DOAs) θ_l of the impinging signal waveforms and the multipath angle spread. Equation 2 implies that the spatial signature $a(t)$ is a linear combination of array response vectors $\vartheta(\theta_l)$; these vectors form the basis of a vector subspace. Multipath angle spread is defined as the spread of DOAs of multipath components. The distribution of multipath angle spread is critical to determining spatial correlation component of the space-time correlation matrix $R_a(\Delta t)$ in (5). It is also important to evaluate the feasibility of using DOA based selective reception/transmission techniques. If the angle spread is small, all the array response vectors will be confined to a certain direction and it will be extremely difficult for the base station to separate the two mobile users and isolate interference. A useful measure of the angle spread is most often described in terms of the root mean square (RMS) angle spread which is given by,

$$\sigma(\theta) = \sqrt{\bar{\theta}^2 - (\bar{\theta})^2} \quad (10)$$

where

$$\bar{\theta} = \frac{\sum_{l=1}^L \|z_l\|^2 \theta_l}{\sum_{l=1}^L \|z_l\|^2}, \quad \bar{\theta}^2 = \frac{\sum_{l=1}^L \|z_l\|^2 (\theta_l)^2}{\sum_{l=1}^L \|z_l\|^2},$$

where $z_l = \alpha_l(t)e^{j\varphi_l(t)}$ is the complex path fading in (2).

The DOA spectrum estimated via the MUSIC algorithm is shown in Figures 6 and 8 for the LOS and NOLOS scenarios respectively. It is evident from these figures that DOAs do not change much with the small displacement of 2λ . The multipath angle spread results are shown in Figures 7 and 9 for the LOS and the NOLOS respectively. The angle spread in the NOLOS (with mean 25.5) is much larger than that in the LOS (with mean 4.8). Hence, these results explain why we obtained large relative angle changes in the spatial signatures and low space-time correlations.

Figure 6. DOA spectrum in the LOS scenario

Figure 7. multipath angle spread variation in the LOS scenario

5.4. Complex Multipath Fading Parameters

The complex multipath fading parameter $z_l(t) = \alpha_l(t)e^{j\varphi_l(t)}$ accounts for the amplitude and phase variations in the received signal vector caused by the reflection coefficient of the scatterer and the path length difference with respect to the strongest path. As the mobile terminal moves a short distance, the multipath signals are most likely scattered from the same scatterer but they will experience a phase change due to the changing path length. Multipath fading parameters z_l can be estimated by least-squares (LS) fitting of the measured spatial signatures $a_{mes}(t)$ to the model

Figure 8. DOA spectrum in the NOLOS scenario

Figure 9. multipath angle spread variation in the NOLOS scenario

in (2),

$$a_{mes}(t) \stackrel{\text{LS}}{=} \sum_{l=1}^L z_l \vartheta(\theta_l). \quad (11)$$

Figures 10 and 11 show the variation of the multipath fading parameters with changing mobile position in the indoor LOS and NOLOS scenarios respectively. In the LOS, there exists a multipath signal which is approximately 20dB weaker than the direct path signal. However, the strengths of the two multipath signals in the NOLOS are approximately the same. The relative multipath phases change significantly in both scenarios.

Figure 10. complex path fading variation in the LOS scenario

Figure 11. complex path fading variation in the NOLOS scenario

6. SUMMARY

In this paper, we have studied the variation of channel propagation characteristics (vector channel parameters) of narrowband smart antenna systems with the mobile terminal movement in a hallway-type indoor propagation environment. Measurements of vector channel parameters are taken by using a 1.8 GHz real-time smart antenna testbed with a uniform linear array at the base station. The mobile transmitter was placed in the hallways in such locations that both the line-of-sight (LOS) and the non-line-of-sight (NOLOS) indoor scenarios could be studied. Experimental results on the variation of vector channel parameters are presented. As the mobile terminal moves within a short distance of 2λ , channel characteristics change more significantly in the NOLOS scenario than in the LOS scenario. In the NOLOS scenario, both spatial and time correlation components of the space-time correlation matrix $R_a(\Delta t)$ of the spatial signature vector $a(t)$ were changed and fluctuations in $a(t)$ were both in amplitude (4dB peak-to-peak) and in angle (40%-98%). However, in the LOS scenario, only the time correlation component of $R_a(\Delta t)$ was changed and $a(t)$ pointed in a preferred direction (angle change between 15%-25%). It was also observed that multipath angle spread was larger in the NOLOS scenario than in the LOS scenario.

ACKNOWLEDGMENTS

This work was sponsored in part by an NSF Career Award under grant MIP-9502695, Texas Advanced Research Program, the Office of Naval Research under grant N00014-95-1-0638, the Joint Services Electronics Program under contract F49620-95-C-0045, Southwestern Bell Technology Resources Inc., TI Raytheon, equipment donation from Intel. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

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