Effects of Angle Spread in a Complex Outdoor Environment at 2.4 GHz

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I. Introduction

There is much interest in the use of antenna arrays at mobile radio base stations for applications such as angle-of-arrival (AOA) estimation and beamforming [1]. In general, the signal arriving at a base station antenna array is spread in angle, due to scattering. In outdoor situations, however, the antenna array is typically placed well above local scatterers. Then, the channel tends to be dominated by scatterers close to the mobile transmitter, with the result that the angle spread at the base station becomes relatively small: Previous studies have estimated that the spreading is often on the order of $10°$ or less [2], [3]. In such cases, it may be a good approximation to assume that the signal arriving at the array is a plane wave [4]. This is highly desirable in practice: Although techniques for dealing with more complex scenarios exist [5], these methods tend to be extremely sensitive to model assumptions and therefore tend not be reliable in practical applications [4]. Thus, it is useful to know the true extent of angle spreading – specifically, it's effect on AOA estimation and beamforming – in a variety of environments.

This paper presents a study of angle spread at 2.4 GHz in a complex, outdoor environment. Due to limitations in array aperture and stationarity of the propagation channel, direct measurements of angle spread are extraordinarily difficult and unreliable. In this study, we instead demonstrate the effects of angle spread by comparing measurements of the angle spectrum and spatial covariance to those obtained in a carefully-controlled line-of-sight (LOS) scenario. For the scenarios evaluated here, it is found that the environment has a dramatic effect on both the ability to form beams and the rank of the spatial covariance matrix.

II. Experiment Design

The measurements were performed in vicinity of the ElectroScience Laboratory (ESL), located on the West Campus of the Ohio State University in Fall 2001. The transmitter uses an arbitrary function generator running at 40 million samples per second (MSPS) to create a 1.25 Mbaud binary phase shift keying (BPSK) signal centered at 15 MHz. The modulated data consists of a known, repeating 218-bit PN sequence. The output is lowpass filtered to suppress aliasing and then mixed with a local oscillator at 2.45 GHz, resulting in identical modulated carriers at 2.435 GHz and 2.465 GHz. Both signals are amplified using a linear power amplifier such that the received signal was close to full scale at the output of the receivers, but with sufficient headroom to avoid compression and clipping. The transmit antenna was a commercially-available monopole antenna intended for 2.4 GHz wireless LAN use. The transmit antenna was mounted on the end of a pole approximately 1.5 m long and moved continuously by hand over a volume of about 2 m $\times$ 2 m in footprint and about 1 m to 2 m above the ground. Thus, the measurements represent many possible realizations of the fading channel over that volume. The transmit antenna was oriented such that it was approximately vertically-polarized throughout the measurements. At no time were there any obstructions within 20 m that could present a shadow boundary within the measurement volume with respect to the most direct path of propagation; thus, we are confident that all variations observed are due to classical fast fading mechanisms.

The antenna array used for receive was located on the roof of ESL, about 10 m above ground. A uniform linear array of 8 vertically-polarized half-wavelength printed circuit dipoles, designed and built at ESL, was used. The array was backed by a ground screen, resulting in a high front-to-back ratio. The spacing between elements was about 0.4λ, re-

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sulting in significant electromagnetic coupling between elements. The array's plane wave manifold (i.e., the responses due a single plane wave from each possible AOA) was measured using ESL's indoor antenna measurement (compact range) facility. We used this direct measurement of the array manifold in our data reduction. Additional details on this array and our measurements of it's manifold are given in [6].

The array receiver was a custom system developed at ESL. The output of each of the antenna elements is divided in two to allow simultaneous tuning to the two transmit frequencies. The resulting 16 signals are processed through a bank of identical, coherent downconverters, shifting about 3.3 MHz of spectrum at the desired frequency to a common analog intermediate frequency (IF) of 7.5 MHz. The analog IF is sampled using a bank of 16 12-bit A/Ds at 10 MSPS. For each acquisition, 16384 samples per element are captured and stored to the hard drive of a PC. All subsequent processing is done off-line. Detailed information on the array receiver is given in [7].

Note that the duration of a single acquisition – 1.6 ms – is a tiny fraction of the channel coherence time, which is on the order of 100 ms for a pedestrian scenario. The propagation channel is therefore effectively stationary during an acquisition. The time between acquisitions is approximately 1 s, which is much greater than the channel coherence time.

Calibration of the array receiver was accomplished by injecting sinusoidal (CW) signals, centered in the bandpass at each of the two frequencies of interest, using a separate antenna mounted underneath the array. The calibration signal was turned on throughout the experiment, and so calibration data is embedded in the measured data. The calibration signal is analyzed and coherently subtracted from the data during data reduction, so it does not affect the measurements of the mobile transmitter. The transfer function from the terminals of the calibration antenna to the terminals of the array elements was measured before the experiments, and so were known before data reduction. Given this information and the measured gain and phase of the calibration signal in each of the receiver channels, it was possible to estimate and compensate for the gain and phase differences among receiver channels. Although this is strictly a narrowband calibration (i.e., does not take into account variations in the bandpass response), this technique was found to be adequate for the purposes of this study.

Following calibration, we obtain what we refer to as an *array response vector* (ARV) $\mathbf{x}[l]$ for each 1.6 ms acquisition at each frequency. Each element of the ARV is in effect the output of a single-finger RAKE (correlation) receiver [8] computed over that interval. This improves the signal-to-noise ratio (SNR), reduces interference, and suppresses delays longer than the inverse bandwidth of the transmit signal (about 800 ns, corresponding to 240 m). The spatial covariance matrix $\mathbf{R}$ is computed over the previous $L = 100$ ARVs (therefore, also over many fades) as follows:

$$\mathbf{R} \approx \frac{1}{L} \sum_{l=1}^{L} \mathbf{x}[l] \, \mathbf{x}^H[l] \ , \tag{1}$$

and the power measured by the beam which maximizes gain in the direction θ subject to no other constraints is

$$S(\theta) = \mathbf{a}^H(\theta) \; \mathbf{R} \; \mathbf{a}(\theta) \tag{2}$$

where $\mathbf{a}(\theta)$ is value of the measured (*a priori*) plane wave manifold at θ.

III. Results

Close-Range LOS Scenario (Experiment Validation): We first performed a series of measurements with the mobile transmitter on the same rooftop as the array, with LOS. The purpose was to validate the instrumentation and analysis methods, and to provide a baseline for comparison in less certain conditions. For these measurements only, the transmit antenna was a cylindrical horn antenna with half-power beamwidths of about 60° and 90° in the E- and H-planes respectively, in order to limit multipath generation. The transmit antenna was mounted about 32 m away and approximately at the same height as the receive array. Figure 1(a) shows $S(\theta)$, obtained by rotating the receive array. Note that the agreement with the known plane wave manifold is excellent. Also, this scenario was verified to be "approximately rank 1" in the sense that the ratio between the two largest eigenvalues of $\mathbf{R}$ was always at least 20 dB. These results verify that the scenario is in fact dominated by a single plane wave, and also that the instrumentation is working properly in field conditions.

Mobile at SCF and RP: The two sites used for the field measurements and their locations relative to the ESL receive site are shown in Figure 1(b). The site labeled "SCP" is 700 m from ESL and has optical LOS to the receive array, whereas the site labeled "RP" is 500 m from ESL and is behind a cluster of industrial buildings with varying heights. Figure 2 shows the angle spectra for the SCF and RP measurements, computed in the same manner as for Figure 1(a). Significant angle spreading is apparent for both sites. In contrast to the close-range LOS case considered previously, neither SCF nor RP can be considered to be dominated by a single plane wave. It is interesting to note that the LOS SCF scenario is not much better than the non-LOS RP scenario in this regard. Figure 3 shows the eigenvalues of $\mathbf{R}$. While the ratio of the two largest eigenvalues is larger for the LOS SCF case than for the non-LOS RP case, neither case approaches the 20 dB ratio of largest eigenvalues observed in the close range LOS case.

Conclusions: From these two cases and by comparison with the close range LOS scenario, two conclusions become apparent: First, it may not be possible to create well-formed beams, or obtain reasonable AOA estimates using methods that assume a single incident plane wave, in the field conditions described here. Second, it is clearly not safe to assume that optical LOS (as in the SCF case) implies significantly better beamforming or AOA estimation.

Acknowledgments

The author acknowledges the support of the following people who contributed to the effort of building instrumentation and performing measurements in support of this study: J. Baxter, I.J. Gupta, G. Hampson, J. Hetrick, M. Lee, and R. Vasan. This work was sponsored in part by Lucent Technologies and ETRI (South Korea).

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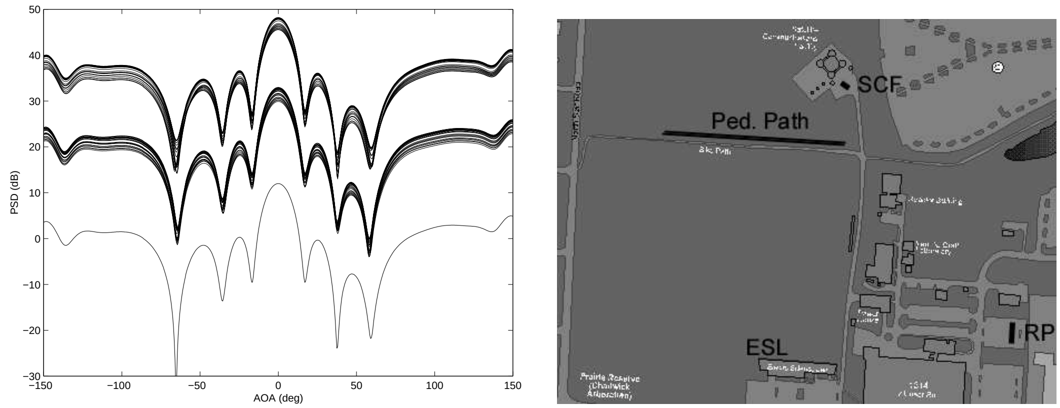
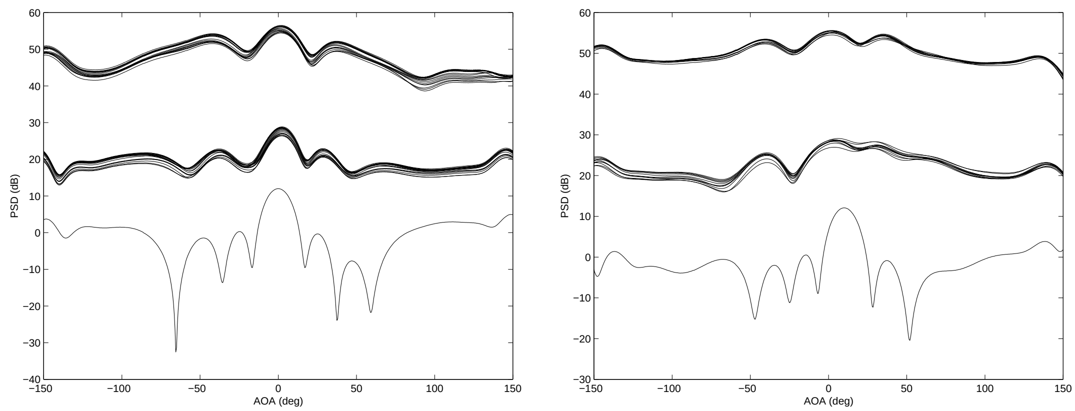


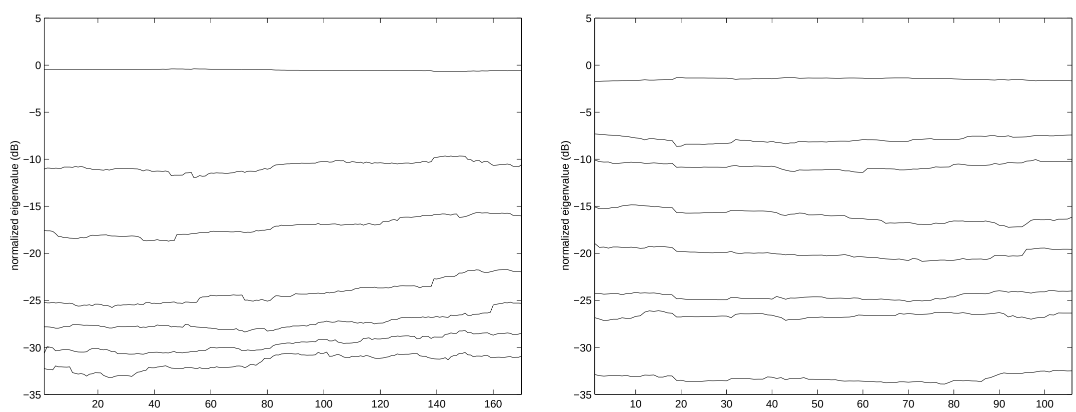
(a) (b)

Fig. 1. (a) Angle spectra for the close-range LOS scenario. The top and middle sets of curves are from measurements at 2.435 GHz and 2.465 GHz respectively. The bottom curve is the theoretical result for 2.435 GHz using the known plane wave manifold. Vertical spacing between the three sets of results is arbitrary. For measured data, 23 trials are shown. (b) Location of the ESL, SCF, and RP sites.



(a) SCF (0°). (b) RP (+10°).

Fig. 2. Angle spectra for the SCF and RP cases. The true bearing to the mobile transmitter is indicated in parentheses. The top and middle sets of curves are from measurements at 2.435 GHz and 2.465 GHz respectively. The bottom curve is the theoretical result for the indicated (true) line of bearing and 2.435 GHz, using the known plane wave manifold. Vertical spacing between the three sets of results is arbitrary. For measured data, 90 trials are shown.



(a) SCF, 2.435 GHz (b) RP, 2.435 GHz

Fig. 3. Eigenvalues of $\mathbf{R}$, normalized such that the sum of the eigenvalues per trial is 1.