Multipath Direction Finding with Subspace Smoothing *

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Abstract

Antenna arrays can be employed in mobile communications to increase channel capacity as well as communication quality via spatially selective reception/transmission at base stations. In most wireless communications systems, directions of arrival of multipath signals need to be found for spatial selective transmission. Unfortunately, due to the coherent nature of multipath signals, it is quite difficult to find their directions of arrival. In this paper, we will present a subspace smoothing algorithm for finding the directions of arrival of multipath signals based on the mobile terminal signals received at different time instances. More importantly, we will present our experimental results to demonstrate that the spatial diversity is present for slight movements of a mobile terminal and that the subspace smoothing approach is effective in real wireless scenarios. All of the experiments were performed using the smart antenna testbed at the University of Texas at Austin.

1 Background

Antenna arrays have been studied [1, 2, 3] to increase channel capacity and improve performance in mobile communications. High-resolution direction finding algorithms such as MUSIC [4] and ESPRIT [5] were proposed to find the direct path and multipath signals of the mobile users. Knowing the directions-of-arrivals (DOAs) of the mobile users and their multipath signals, we can design weighting vectors [6, 7] to achieve transmission beamforming. Since the source of multipath signals are coherent with the direct path, the signal eigenvectors will fail to span the signal subspace, and this loss of rank in the signal subspace will cause the ESPRIT algorithm to fail. In order to restore the dimensionality of the signal subspace, the forward and backward spatial smoothing scheme [8, 9] was used to decorrelate the coherence among multipath signals. The penalty, however, for using the extended approach is that it can only estimate up to $2M/3$ DOAs of direct path and multipath components, where M is the number of antennas. In this paper, we will present a subspace smoothing algorithm for finding the directions of arrival of multipath signals based on the mobile terminal signals received at different time instances.

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2 Subspace Smoothing Approach

At a base station, an M-element antenna array receives signals from several spatially separated users. The received waves typically contain both direct path and multipath signals which are most likely from different directions of arrival. Let us assume that the array response vector to a transmitted signal $s(t)$ from a direction of arrival θ is $\mathbf{a}(\theta) = [1, a_1(\theta), \ldots, a_M(\theta)]$, where $a_i(\theta)$ is a complex number denoting the amplitude gain and phase shift of the signal at the $(i+1)^{th}$ antenna relative to the first antenna. For a uniform linear array with separation D, as shown in Figure 1, $\mathbf{a}(\theta) = [1, e^{j2\pi f \sin\theta D/c}, \ldots, e^{j2\pi f \sin\theta(M-1)D/c}]^T$, where f, c, and ^{T} denote the carrier frequency, speed of light, and transpose operator, respectively. In a typical wireless scenario, the antenna array comprised of omnidirectional elements not only receives a signal $s(t)$ propagated along the direct path but also many multipath echos with different DOAs. Therefore, the total signal vector received by the antenna array can be written as:

$$\mathbf{x}(t) = \underbrace{\alpha_1 \mathbf{a}(\theta_1)s(t)}_{\text{direct path}} + \underbrace{\sum_{l=2}^{N_m} \alpha_l \mathbf{a}(\theta_l)s(t)}_{\text{multipath}} = \mathbf{a}s(t), \quad (1)$$

where $N_m - 1$ is the total number of multipath signals, α_l is the phase and amplitude difference between the

l^{th} multipath and the direct path, and $\mathbf{a} = \sum_{l=1}^{N_m} \mathbf{a}(\theta_l)$, which is referred to as the *spatial signature* (SS) associated with the emitter. Let us define $\mathbf{a}^i = \sum_{l=1}^{N_m} \alpha_l^i \mathbf{a}^i(\theta_l)$ to be the spatial signature at the i^{th} time instance. In a typical mobile communication scenario, due to the relatively large distance between the subscribers and base station, the directions of arrival of both direct path and multipath components do not vary rapidly for a slight move of the subscriber, *i.e.*, $\theta_l^i \approx \theta_l^j$ or $\mathbf{a}(\theta_l^i) \approx \mathbf{a}(\theta_l^j)$ for $|i-j|$ smaller than certain time threshold, *e.g.*, a few seconds. However, the phase and amplitude difference α_l (especially the phase) usually change more rapidly, which causes the spatial signature, $\mathbf{a}^i$, to vary significantly corresponding to slight movement of a mobile user. This is mainly due to the small wavelength in mobile communications band, *e.g.*, 33cm at 900MHz. A small change in path length, *e.g.*, 16cm, may lead to a large change (180°) in phase. Despite the dramatic change of the spatial signatures in a moving environment, the spatial signatures are all confined to the same subspace defined by span$\{\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_{N_m})\}$, since

$$\mathbf{a}^i = \sum_{l=1}^{N_m} \alpha_l^i \mathbf{a}(\theta_l), \tag{2}$$

where $\{\alpha_l^i\}$ are time varying while $\{\mathbf{a}(\theta_l)\}$ are time invariant for a small period of time. With P samples of spatial signatures of a mobile user, *i.e.*, $\mathbf{a}^i$, $i = 1, \ldots, P$, where $P \geq N_m, M$, then we can form

$$\begin{aligned} \mathbf{A} = & \; [\mathbf{a}^1 \ldots \mathbf{a}^P] \\ = & \; [\mathbf{a}(\theta_1) \cdots \mathbf{a}(\theta_N)] \begin{bmatrix} \alpha_1^1 & \alpha_1^2 & \cdots & \alpha_1^P \\ \alpha_2^1 & \alpha_2^2 & \cdots & \alpha_2^P \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_N^1 & \alpha_N^2 & \cdots & \alpha_N^P \end{bmatrix}, \end{aligned} \tag{3}$$

Since the columns of $\mathbf{A}$ are linear combinations of $\{\mathbf{a}(\theta_l)\}$ and if $P, M > N_m$, we can find the signal subspace spanned by $[\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_{N_m})]$ using singular value decomposition (SVD) based on $\mathbf{A}$. Once the signal subspace is identified, we can easily find θ_l, the DOAs of the direct path and multipath signals using the subspace based DOA estimation algorithms such as MUSIC [4] and ESPRIT [5]. This is the basic idea behind the subspace smoothing approach.

3 Experiment Setup

We conducted a series of measurements outside of the Electrical Engineering Research Laboratory (EERL) at the J.J. Pickle Research Campus of The University of Texas at Austin. The environment is a paved area surrounded by several buildings and metal chain-link fences. A smart antenna testbed with an 8-element patch antenna array arranged in a linear fashion with separation of about one half wavelength was used as the base station. The carrier frequency was around 900 MHz. A dipole antenna driven by a HP 8662A synthesizer was used as the mobile unit.

4 Experimental Results

To study the performance of subspace smoothing, forward/backward spatial smoothing, and conventional beamforming techniques, the following three cases were chosen for measurement of their DOAs of direct path and multipath: (1) The base station was placed outside EERL, and the mobile transmitter was set up in an open field. There was nothing between the base station and the transmitter blocking the direct path of the outdoor line of sight (LOS) measurement. (2) The base station was placed outside EERL, and the mobile transmitter was set up in front of a research building. There was nothing between the base station and the transmitter blocking the direct path of the outdoor line of sight (LOS) measurement either. (3) The base station was located outside EERL, and the mobile transmitter was placed in a location where the LOS was blocked by a building.

In these three cases, we collected data at eight neighboring positions by moving mobile transmitter slightly along a straight line. Then the subspace smoothing, forward/backward spatial smoothing, and conventional beamforming techniques were used to detect DOAs of direct path and multipath signals of the mobile user. The results for the three cases are shown in Figures 2-4. Figure 2 shows that only one DOA was detected from all these three techniques, and the angle detected from all three techniques was very similar (10°). Figure 3 shows that only one DOA was detected from the conventional beamforming technique at a 25° angle. But two DOAs were detected from the subspace smoothing and forward/backward spatial smoothing techniques. The angles detected from these two techniques were very close, about 21° and 37°. Figure 4 shows that five DOAs were detected from the conventional beamforming technique. Limited by the number of array elements, only up to four DOAs could be detected from the forward/backward spatial smoothing technique. There were up to six DOAs detected from the subspace smoothing technique.

In order to evaluate which technique provides us with better DOA estimates, we use the following procedure:

(1) Find the actual spatial signature from our raw data by using singular value decomposition (SVD).

(2) Reconstruct the spatial signature from the DOAs detected from the three techniques by the following formula:

$$\textit{Reconstructed Spatial Signature} = \sum_{l=1}^{N_m} \alpha_l \mathbf{a}(\theta_l), \quad (4)$$

(3) Compute the mean square error (MSE) between the actual spatial signature and the reconstructed spatial signature from the above three techniques by the following formula:

$$MSE = ||\mathbf{x} - \mathbf{y}||^2, \quad (5)$$

where $\mathbf{x}$ is the reconstructed spatial signature, $\mathbf{y}$ is the actual spatial signature and $||\mathbf{b}||$ denotes the norm of a vector $\mathbf{b}$. The method with the minimum MSE with the the actual spatial signature is the superior one.

The performance evaluation of these three techniques in the three cases based on the above procedure is shown in Tables 1-3. In case (1), since the mobile unit was set up in an open area and LOS environment, there was no dominant multipath DOA. Thus, only the DOA of the direct path was detected. The DOA detected by these three techniques was very close. The MSE of these three techniques shown in Table 1 is also very close. The mean MSE of conventional beamforming, forward/backward spatial smoothing, and subspace smoothing technique was 0.0680, 0.0697, and 0.0706 respectively. In case (2), The mobile unit was set up in front of a building and LOS environment. There were two DOAs detected by forward/backward spatial smoothing and subspace smoothing techniques. However, due to resolution limitation, there was only one DOA detected by the conventional beamforming technique. The MSE of these three techniques is shown in Table 2. The results show that the mean MSE of the conventional beamforming (0.0844) technique is inferior to that of forward/backward spatial smoothing (0.0736) and subspace smoothing (0.0669) techniques. In case (3), the mobile unit was placed in a location where the LOS was blocked by a building. Since there was no direct path, many DOAs of multipath signals were detected. Limited by the number of antenna elements, only up to four DOAs were detected by the forward/backward spatial smoothing technique. Five DOAs were detected by the conventional beamforming technique. There were up to six DOAs detected by the spatial smoothing technique. The MSE of these three techniques was shown in Table 3. The results show that the mean MSE of spatial smoothing (0.0362) is much better than that of the conventional beamforming (0.1101) and forward/backward spatial smoothing (0.0766) techniques.

5 Conclusion

We have presented a new method for finding the directions of arrival of multipath signals. The experimental results showed that the resolution of the spatial smoothing technique was better than the conventional beamforming technique. The performance of the subspace smoothing technique was as good as forward/backward spatial smoothing technique in LOS environments where fewer DOAs were present. Moreover, the performance of the subspace smoothing technique was better than that of the forward/backward spatial smoothing technique in a blocked environment where more DOAs were presented. However, it took more spatial signature samples and signal processing to estimate the DOAs. In addition, each spatial signature sample must be confined to the same subspace which implied that we need to finish calculating spatial signature in a very short time.

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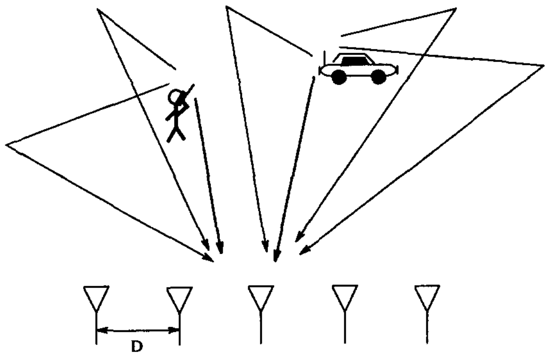

Figure 1: A uniform linear antenna array and two co-channel sources

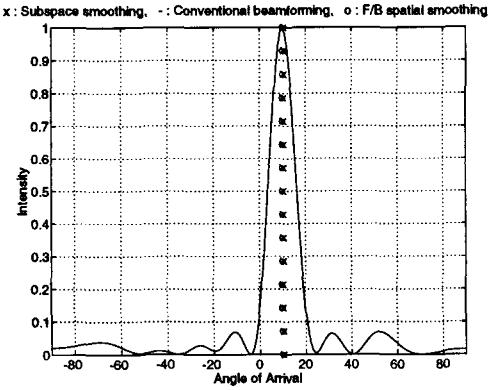

Figure 2: DOAs detected in case (1)

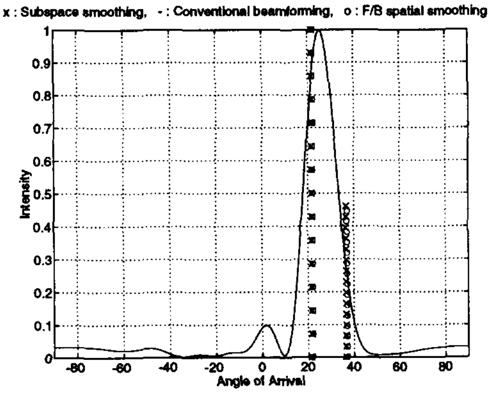

Figure 3: DOAs detected in case (2)

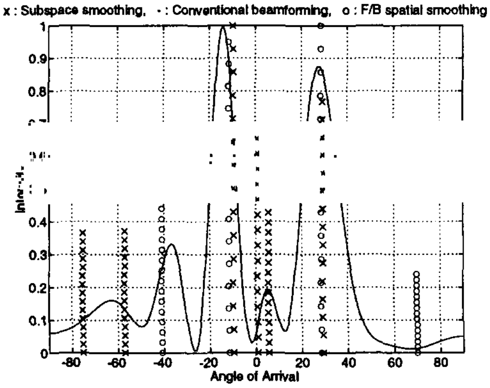

Figure 4: DOAs detected in case (3)

	Conventional BF	F/B Smoothing	Subspace Smoothing
1	0.0868	0.0890	0.0892
2	0.0847	0.0864	0.0896
3	0.0670	0.0688	0.0679
4	0.0620	0.0625	0.0604
5	0.0753	0.0775	0.0765
6	0.0513	0.0534	0.0546
7	0.0555	0.0568	0.0609
8	0.0613	0.0630	0.0654
Mean	0.0680	0.0697	0.0706

Table 1: Mean square error between the actual spatial signature and the three techniques in case (1)

	Conventional BF	F/B Smoothing	Subspace Smoothing
1	0.0655	0.0650	0.0589
2	0.0952	0.0952	0.0679
3	0.1047	0.1070	0.0702
4	0.1058	0.0520	0.0647
5	0.1076	0.0528	0.0932
6	0.0493	0.0744	0.0642
7	0.0746	0.0728	0.0606
8	0.0722	0.0697	0.0556
Mean	0.0844	0.0736	0.0669

Table 2: Mean square error between the actual spatial signature and the three techniques in case (2)

	Conventional BF	F/B Smoothing	Subspace Smoothing
1	0.0946	0.1169	0.0723
2	0.1268	0.0347	0.0527
3	0.1596	0.0579	0.0426
4	0.1397	0.0765	0.0403
5	0.1618	0.0568	0.0279
6	0.0405	0.0657	0.0124
7	0.0530	0.0811	0.0165
8	0.1051	0.1235	0.0251
Mean	0.1101	0.0766	0.0362

Table 3: Mean square error between the actual spatial signature and the three techniques in case (3)