An Effective Transmission Beamforming Scheme for Frequency-Division-Duplex Digital Wireless Communication Systems*

Guanghan Xu and Hui Liu
Dept. of Electrical & Computer Engineering
The University of Texas at Austin, Austin, TX 78712-1084

Abstract

Most wireless communication systems use different carriers for uplinks and downlinks, hence the downlink beamforming can only be performed based on the Directions-of-Arrival (DOA) information of the uplink signals. In this paper, we propose an effective downlink transmission scheme for TDMA mobile communication systems via the integration of direction finding and blind signal estimation techniques. With an M-element antenna array, our new scheme can estimate up to $2M^2/3$ DOAs of direct path and multipath signals, while a conventional DOA estimation algorithm can resolve no more than M DOAs. RF experiments show that by incorporating these additional DOA estimates, much improved interference suppression was obtained.

1 Introduction

In an FDD wireless system, the DOAs of the uplink signals might be the only constant parameters which can be used for downlink transmission, presuming that the time elapse between the uplink and downlink time frames is insignificant. To achieve effective interference suppression by performing transmission beamforming, one needs to extract a large number of DOAs from the superposition of many possibly coherent uplink signals.

Subspace-based techniques (*e.g.,* MUSIC [1] and ESPRIT [2]) are probably the most popular high-resolution DOA estimation algorithms, among many other approaches which rely on the covariance matrix of the antenna output. The number of resolvable DOAs for these algorithms are often bounded by the number of antenna elements[1]. In the presence of coherent signals, spatial smoothing [3] and forward-backward averaging [4] need to be used to decorrelate the multipaths. In such cases, the effective aperture of the antenna array becomes even smaller. Consequently, the resolvable DOAs using an M-element antenna array is strictly less than M.

For wireless systems with d ($d > 1$) co-channel users, the antenna output can be expressed as

$$\mathbf{y}(t) = \sum_{i=1}^{d} \mathbf{a}_i s_i(t) \tag{1}$$

where $s_i(t)$ is the signal from the i^{th} user and $\mathbf{a}_i$ is its associated antenna response (herein termed as the spatial signature, or SS). While the DOAs of each path might be difficult to extract directly from the antenna covariance matrix, the spatial signatures can be estimated using the so-called property restoring algorithms, regardless of the presence of rich multipath. The exploitable properties of the signals $\{s_k(t)\}$ include the constant modulus property of AMPS signals [5], the finite-alphabet property of TDMA signals [6, 7] and spread spectrum property of CDMA signals [8].

Since $\{\mathbf{a}_i\}$ actually contain sufficient information about DOAs, we investigate the feasibility of estimating DOA directly from the spatial signatures. A DOA estimation algorithm which is capable of resolving $2M^2/3$ DOA is presented. The improvement of the beamforming performance using the DOA information was demonstrated by RF experiments.

2 Background

Consider an M-element antenna array at the base-station receiving signals from distinctively located users. The array output contain both direct path and multipath signals which are most likely from different DOAs. The *steering vector* to an incoming signal $s_1(t)$ from a direction of arrival θ has the form

$$\mathbf{a}(\theta) = [1, a_2(\theta), \ldots, a_M(\theta)], \tag{2}$$

where $a_i(\theta)$ is a complex number denoting the amplitude gain and phase shift of the signal at the i^{th} antenna in relative to that at the first antenna. For a

*This work is supported in part by University Research Institute at the University of Texas at Austin.

[1] It is possible to exceed this limit by employing some multi-dimensional searching techniques. However, their implementations are often prohibited by their computational cost

0-7803-2431-5/95 $4.00

uniform linear array, $a_i(\theta) = e^{j\frac{(i-1)2\pi\Delta \sin\theta}{\lambda}}$, where Δ is the space between adjacent antennas and λ is the wavelength of the carrier.

In a typical wireless scenario, omni-directional antenna array not only receives signals from direct path but also many reflected multipath signals with different DOAs. Therefore, the total signal vector picked up by the antenna array can be written below:

$$\mathbf{x}(t) = \underbrace{\mathbf{a}(\theta_1)s_1(t)}_{\text{direct path}} + \underbrace{\sum_{l=2}^{L_1} \alpha_l \mathbf{a}(\theta_l)s_1(t)}_{\text{multipath}} = \mathbf{a}_1 s_1(t), \quad (3)$$

where $L_1 - 1$ is the total number of multipath signals and α_l is the phase and amplitude difference between the l^{th} multipath and the direct path components.

Let f_u and f_d be the carrier frequency for uplink and downlink transmission, respectively. If a vector signal $\mathbf{x}(t) = \mathbf{w}s^*(t)$ is transmitted from the base-station antenna array, the output of the i^{th} user receiver is given by

$$\mathbf{x}^H(t)\mathbf{a}_i(f_d) = \mathbf{w}^H\mathbf{a}_i(f_d)s(t),$$

where $(\cdot)^*$ and $(\cdot)^H$ denote conjugate and transpose conjugate operations, respectively.

For TDD systems, $\mathbf{a}_i(f_d) = \mathbf{a}_i(f_u)$ since $f_d = f_u$ Hence, the spatial signature captured during the uplink can be directly used for downlink weight vector design. This no longer holds for FDD systems. According to the reciprocal law, only the DOAs remain unchanged. As a consequence, only DOA-based approaches can be used in FDD systems.

Ideally, with all the knowledge of the DOAs and sufficient number of antenna elements, a weight vector can be constructed to null out most of the interference. For example, let θ_i be the DOA of the dominant path from source i, and $\theta_{j,j\neq i}$, be the DOAs associated with other users, one can send the signal to the ith user from θ_i, and at the same time, restrict its access to $\theta_{j,j\neq i}$. The weight vector $\mathbf{w}_i$ can be constructed accordingly,

$$\mathbf{w}_i^H\mathbf{a}(\theta_i) = 1 \quad \text{and} \quad \mathbf{w}_i^H\mathbf{a}(\theta_{j,j\neq i}) = 0.$$

It is conceivable that for FDD systems, DOA estimation plays the most important role in downlink beamforming.

For both DOA- and SS-based selective transmission, techniques such as constrained beamforming [9] and recently developed linear least squares estimate method [10] can be used for optimal weight vector design.

3 A New DOA Estimation Scheme

In this section, we propose a novel DOA estimation scheme which integrates the spatial signatures estimation algorithm proposed in [11] and the existing subspace DOA estimation approaches. The integrated approach estimate the DOAs irrespective of the number of users – as long as the antenna array can estimate the DOAs for a single user, it can determine the DOAs for all users. The distinctive advantages of the new scheme are (i) the number of required antennas does not increase with the number of the users, (ii) there is no association problem, each resolved multipath is naturally grouped by the algorithm.

Rewrite the spatial signature in (3) for a uniform linear array and drop its subscript for notational convenience,

$$\mathbf{a} = \sum_{i=1}^{L} \alpha_i \mathbf{a}(\theta_i) = \underbrace{\begin{pmatrix} \mathbf{a}(\theta_1) & \cdots & \mathbf{a}(\theta_L) \end{pmatrix}}_{\mathbf{A}} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_L \end{pmatrix},$$

where L ($L < M$) is the total number of paths associated with this particular user. In order to extract the DOAs using the subspace-based algorithm, we need to construct a covariance matrix whose subspace is the span of $\mathbf{A}$, or its subset which contains the first $L+i,\ i \geq 0$ rows: $\mathbf{A}(1 : L+i, :)$.

Denote $\mathbf{a}(i : i+j)$ the vector with the i^{th} to $(i+j)^{th}$ elements of $\mathbf{a}$. We apply the standard forward-backward spatial smoothing techniques [4] to the spatial signature $\mathbf{a}$, a *smoothed spatial signature* covariance matrix can be formed as

$$\mathbf{R}_{fb}(K) = \mathbf{R}_f(K) + \mathbf{J}\mathbf{R}_f^*(K)\mathbf{J} \quad (4)$$

where $\mathbf{J}$ is the permutation matrix with all zeros except 1s as the anti-diagonal elements, K is the smoothing factor, and

$$\mathbf{R}_f(K) = \sum_{i=1}^{K} \left(\mathbf{a}(i : M-K+i)\mathbf{a}(i : M-K+i)^H\right).$$

It is shown [3, 4] that rank of the smoothed covariance matrix $\mathbf{R}_{fb}(K)$ can be restored such that its column span is the same as $\mathbf{A}(1 : M-K+1)$. Therefore, subspace-based algorithm can be directly applied and up to $2M/3$ DOAs from coherent sources can be estimated. Note that the spatial signature of M users can be estimated using the blind estimation method proposed in [11], consequently, up to $2M^2/3$ DOAs can be estimated using an M-element antenna array!

We summarize the integrated DOA estimation scheme as follows,

1. Estimate the spatial signatures using the blind identification algorithm proposed in [11].
2. Construct the smoothed spatial signature covariance matrix for each spatial signature and apply the subspace-based techniques to estimate the DOAs associated with each user.

4 Experimental Results

In this section, we present our results on experimental validation of the proposed techniques. All the experiments were conducted at the J.J. Pickle Research Campus of The University of Texas at Austin, using our recently developed antenna array testbed which comprises (i) a fully adaptive uniform linear antenna array with 8 elements spacing 0.5 wavelength apart and (ii) several mobile transceiver units. The operating frequency is selected within the cellular band at 899 MHz.

4.1 DOA Estimation

We let the remote users transmit co-channel asynchronous BPSK signals and estimated the spatial signatures using the algorithm proposed in [11]. We then estimated the DOAs of all signals using different algorithms. Figure 1 depicts the results. The curves in both plots are the spatial power spectrum which serve as a reference. In the top plot, three vertical lines indicate the DOA estimates using ESPRIT and forward-backward spatial smoothing (the smoothing factor was 2) technique. Noticeably, there is at least one multipath component at $\sim -40^\circ$ which the algorithm failed to detect. Besides, it is difficult to associate each multipath component from the plot.

In the bottom plot, solid lines and dash lines show the DOA estimates of the first user and second user, respectively, using the integrated approach, *i.e.*, estimate the DOAs based on the spatial signatures obtained from the blind identification. It is seen that the new approach picked up three more multipath components and also associated each multipath component with its corresponding direct path signal. We found that the results match well with the actual surroundings such as buildings, metal doors, and automobiles which could possibly cause multipath.

Comparing these plots, we can conclude that the integrated algorithm yields favorable results in a rich multipath environment since it can resolve many more DOAs than the subspace-based approaches that directly proceeds from the data covariance matrix.

4.2 Transmission Beamforming

With the DOA and spatial signature estimates, we conducted downlink transmission using three different types of approaches, namely, the SS-based approach, the direct DOA-based approach and the newly proposed integrated DOA-based approach.

Method	Suppression: User # 1		Suppression: User #2	
	Mean [dB]	Std.	Mean [dB]	Std.
SS	17.28	3.41	16.64	3.033
SS-DOA	15.70	2.504	15.46	2.064

Table 1: Interference Suppression Summary

In order to quantify the interference suppression rate, we let the message signals for two remote receivers to be two tones at slightly different frequencies (Δf = 1KHz). In this way, the suppression can be exhibited graphically by two spikes at the receiver output spectrum.

Figures 2, 3 and 4 illustrate the results using three different approaches. The top and bottom plots in each figure are the power spectrum received from the first and second users, respectively. Figure 2 indicates that the SS-beamforming successfully suppressed the interference tone at each user. On the contrary, the direct DOA-based method using the DOA estimates from ESPRIT and spatial smoothing (Figure 3) has poor suppression since interference was leaked through those multipath DOAs which were not estimated. Figure 4 shows the results of DOA-based method using the integrated DOA estimation algorithm. The suppression is comparable to that of the the spatial signature method.

4.3 Remarks

We repeated the same experiment at 10 different sets of locations and consistent interference suppressions were obtained. The results are summarized in Table 1. In general, an above 15 dB suppression can be achieved using the SS-based method and integrated DOA-based method. It seems reasonable to believe that a much higher suppression can be achieved using a well calibrated array with more antenna elements, since the accuracy of DOA estimation relies on the precision of the antenna architecture

References

[1] R.O. Schmidt, *A Signal Subspace Approach to Multiple Emitter Location and Spectral Estimation*, PhD thesis, Stanford University, Stanford, CA, November 1981.

[2] A. Paulraj, R. Roy, and T. Kailath, "A Subspace Rotation Approach to Signal Parameter Estimation", *Proceedings of the IEEE*, 74(7):1044–1045, July 1986.

[3] T.J. Shan, A. Paulraj, and T. Kailath, "On Smoothed Rank Profile Test in Eigenstructure Ap-

proach to Direction-of-Arrival Estimation", *IEEE Trans. ASSP*, **33**(10):1377–1385, October 1987.

[4] S. Unnikrishna Pillai and B. H. Kwon, Forward/backward spatial smoothing techniques for coherent signal indentification, *IEEE Trans. Acoustics, Speech, and Signal Processing*, **ASSP-37**(1):8–15, January 1989.

[5] J.R. Treichler and B.G. Agee, "A new approach to multipath correction of constant modulus signals", *IEEE Trans. ASSP.*, **31**(2):459–472, April 1983.

[6] S. Talwar, M. Viberg, and A. Paulraj, Blind estimation of multiple co-channel digital signals using an antenna array, *IEEE Signal Processing Letters*, 1(2):29–31, February 1994.

[7] H. Liu and G. Xu, A deterministic approach to blind symbol estimation, *IEEE Signal Processing Letters*, 1(12), December 1994.

[8] B. Suard, A.F. Naguib, G. Xu, and A. Paulraj, "Performance of CDMA Mobile Communication Systems Using Antenna Arrays", In *Proc. ICASSP 93 Conf.*, Mineapolis, MN, April 1993.

[9] S. Haykin, *Adaptive Filter Theory*, Prentice-Hall, Englewood Cliffs, N.J., second edition, 1991.

[10] B. Ottersten, R. Roy, and T. Kailath, "Signal Waveform Estimation in Sensor Array Processing", In *Proc. 23rd Asilomar Conference on Signals, Systems, and Computers*, volume 2, pages 787–791, Pacific Grove, California, November 1989.

[11] H. Liu and G. Xu, Smart antennas in wireless systems: Multiuser blind channels and sequences identification, *To submit to IEEE Trans. Communication*, 1994.

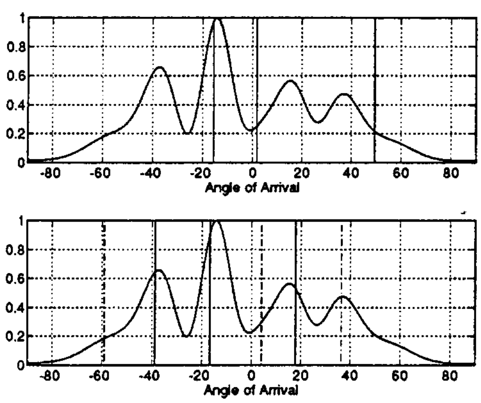

Figure 1: DOA Estimation

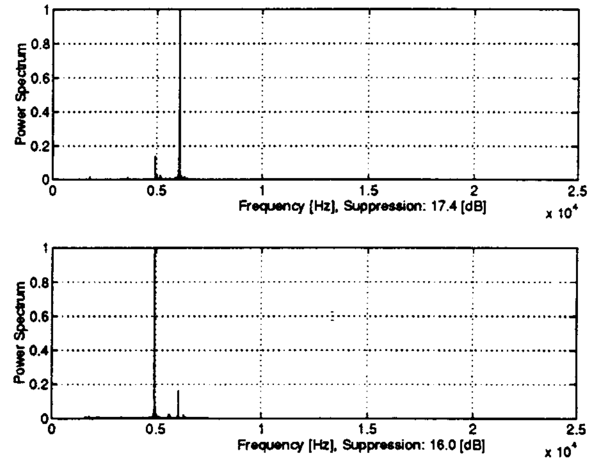

Figure 2: Spatial Signature-based Approach

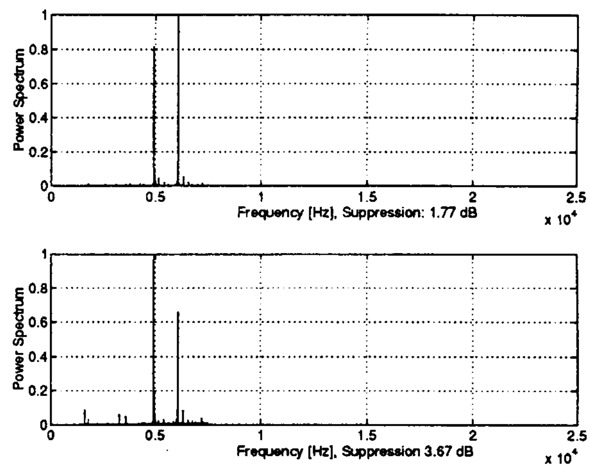

Figure 3: Direct DOA-based Approach

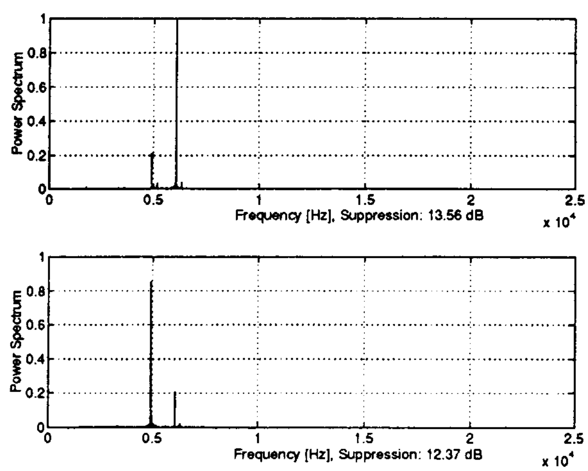

Figure 4: Integrated DOA-based Approach