Direction-Finding Methods for Cyclostationary Signals in the Presence of Coherent Sources

Yung-Ting Lee and Ju-Hong Lee

Abstract—By exploiting the signal cyclostationarity, conjugate Cyclic MUSIC presented in [8], has been shown to be effective in performing signal-selective direction finding. However, a direct application of conjugate Cyclic MUSIC in the presence of coherent signals of interest (SOIs) will result in ambiguity. To tackle the drawback of conjugate Cyclic MUSIC, we present a scheme called Hankel approximation method (HAM) in conjunction with conjugate Cyclic MUSIC to cope with the performance deterioration due to coherent SOIs for a uniform linear array. Theoretical analysis shows that at least \(2K\) sensor elements are required to resolve \(K\) coherent SOIs. Making use of the forward/backward (F/B) technique presented in [6], F/B HAM is further developed, which requires \([3K/2]\) sensor elements to decorrelate \(K\) coherent SOIs, where \(\lfloor x \rfloor\) represents the integer part of \(x\). Several simulation examples are also presented for illustrating the effectiveness of the proposed methods.

Index Terms—Cyclostationary signals, direction finding, uniform linear array.

I. INTRODUCTION

Since the works of Pisarenko [1], Schmidt [2], Roy and Kailath [3], etc., eigenspace-based (ESB) methods have been a topic of great interest in estimating the directions of signals. These ESB methods, in general, utilize certain eigenstructure properties resulting from the special structure of array output covariance matrix for planar wavefronts to generate spectral peaks or nulls in the directions of arrival (DOAs). Moreover, they yield high resolution even when some of signals are partially correlated. In coherent situations such as multipath propagation, a direct application of these ESB methods, however, results in ambiguity. Several techniques have been developed to remedy this problem, of which the spatial smoothing (SS) scheme presented in [4], [5], for the case of a uniform linear array (ULA) is specially noteworthy. The solution is based on a preprocessing scheme that groups the total array of sensor elements into several overlapping subarrays and then averages the subarray output covariance matrices to form the spatially smoothed covariance matrix. It has been shown in [5] that at least \(2K\) sensor elements are required to decorrelate and resolve \(K\) coherent signals. In order to reduce the number of sensor elements required by the SS scheme, the forward/backward (F/B) SS scheme is then investigated in [6], which requires \([3K/2]\) sensor elements to estimate \(K\) coherent signals, where \(\lfloor x \rfloor\) stands for the integer part of \(x\). Moreover, the SS and F/B SS schemes can obtain asymptotical unbiased estimation of DOA irrespective of signal-to-noise ratio (SNR) and angular separations of signals. On the other hand, a novel algorithm based on the Teoplitz approximation method (TAM) was developed in [14] for decorrelating the coherent signals even when a small number of data snapshots is used. However, the theoretical analysis on TAM is still an open issue.

Recently, cyclostationary properties have been widely considered for signal processing. Cyclostationarity [8] which is a statistical property possessed by most man-made communication signals corresponds to the underlying periodicity arising from cycle frequencies or baud rates. Cyclic MUSIC and conjugate Cyclic MUSIC presented in [8], [9] accommodate multiple signals having the same cycle frequency by using the same type of subspace fitting as MUSIC [2]. Moreover, in certain cases as shown in [10], the mean-square error (MSE) of the direction estimates obtained by Cyclic MUSIC is less than the Cramér-Rao lower bound for stationary signals. However, a direct application of Cyclic MUSIC and conjugate Cyclic MUSIC in the presence of coherent signals-of-interest (SOIs) also suffers the performance degradation as the conventional ESB methods. Some previous work considering the problem has been reported in [12], [13]. A cyclic least-square method has been presented in [12] for dealing with the direction-finding problem under coherent situation. However, it is observed that this method cannot tackle the problem efficiently. In order to improve the robustness of the DOA estimation, a cyclic algorithm based on the SS or improved SS technique has been presented in [13]. Making use of the multiple lag parameters and the optimal subarray size, the method presented by [13] provides satisfactory performance even in the presence of strong signals not of interest (SNOIs).

In this paper, the direction-finding problem of conjugate Cyclic MUSIC in coherent scene is extensively considered. Based on the spatial structure of the cyclic conjugate correlation matrix when narrow-band, far-field SOIs are considered for a ULA, we propose a Hankel approximation method (HAM) in conjunction with conjugate Cyclic MUSIC to cope with the coherent situation. Theoretical analysis is presented and shows that at least \(2K\) sensor elements are required to decorrelate \(K\) coherent SOIs. Using the forward/backward (F/B) scheme of [6], we further develop a forward/backward Hankel Approximation Method (F/B HAM) which requires \([3K/2]\) sensor elements to achieve direction finding for \(K\) coherent SOIs. Simulation results show the effectiveness of the proposed methods.

This paper is organized as follows. In Section II, we briefly review the signal cyclostationarity. Then, the problem of direc-
tion finding in the presence of coherent SOIs is described. Section III presents HAM and F/B HAM to deal with the ambiguity of direction finding due to coherent SOIs. Theoretical analysis of the proposed methods are then presented in Section IV. Section V provides several simulation examples for illustrating the effectiveness of the proposed methods. Finally, we conclude this paper in Section VI.

II. BACKGROUND

A. Signal Cyclostationarity

For a signal $s(t)$, the cyclic correlation function and cyclic conjugate correlation function are defined as [8, pp. 41]

$$r_{ss}(f, \tau) = \langle s(t + \frac{\tau}{2}) s^* \left(t - \frac{\tau}{2}\right) e^{-j2\pi ft}\rangle$$ \hspace{1cm} (1)

and

$$r_{ss'}(f, \tau) = \langle s(t + \frac{\tau}{2}) s(t - \frac{\tau}{2}) e^{-j2\pi ft}\rangle$$ \hspace{1cm} (2)

respectively, where the superscript "*" denotes the complex conjugate. Then, $s(t)$ is cyclostationary if $r_{ss}(f, \tau)$ or $r_{ss'}(f, \tau)$ does not equal zero at some time delay $\tau$ and cycle frequency $f = \alpha \neq 0$. Many modulated signals exhibit cyclostationarity with cycle frequency equal to twice the carrier frequency or multiples of the baud rate or combinations of these. Moreover, when (1) and (2) do not equal zero for $f \neq 0, s(t)$ is addressed as possessing the selfcoherent and conjugate selfcoherent properties, respectively.

Let $x(t)$ be the data vector received by an antenna array. The cyclic correlation matrix and cyclic conjugate correlation matrix are given by

$$R_{xx}(f, \tau) = \langle x(t + \frac{\tau}{2}) x^H \left(t - \frac{\tau}{2}\right) e^{-j2\pi ft}\rangle$$ \hspace{1cm} (3)

and

$$R_{xx'}(f, \tau) = \langle x(t + \frac{\tau}{2}) x^T \left(t - \frac{\tau}{2}\right) e^{-j2\pi ft}\rangle$$ \hspace{1cm} (4)

respectively, where the superscript "$H$" denotes the conjugate transpose and "$T$" the transpose.

B. The Problem

Consider an $M$-element ULA excited by $K$ narrow-band, far-field SOIs which have cycle frequency equal to $\alpha$. The received data vector can be expressed as

$$x(t) = \sum_{n=1}^{K} s_n(t) a(\theta_n) + \mathbf{i}(t)$$ \hspace{1cm} (5)

where $s_n(t)$ is the $n$th SOI, $\mathbf{i}(t)$ includes all SNOIs and noise, and $a(\theta_n)$ denotes the direction vector of $s_n(t)$ impinging on the array from $\theta_n$ off broadside.

Let the phase origin be the $q$th sensor element. Then, we have

$$a(\theta_n) = [e^{j(1-q)\phi_n}, e^{j(2-q)\phi_n}, \ldots, e^{j(M-q)\phi_n}]^T$$ \hspace{1cm} (6)

where $\phi_n = (2\pi d\sin(\theta_n))/\lambda$ is the electrical angle, $d$ denotes the interelement spacing, and $\lambda$ is the wavelength of SOI. Substituting (5) into (4) yields

$$R_{xx'}(f, \tau) = \sum_{n=1}^{K} \sum_{m=1}^{K} r_{s_n s_m'}(f, \tau) a(\theta_n) a^T(\theta_m)$$

$$= \mathbf{A} S^*(f, \tau) \mathbf{A}^T$$ \hspace{1cm} (7)

where

$$\mathbf{A} = [a(\theta_1), a(\theta_2), \ldots, a(\theta_K)]$$

and $S^*(f, \tau) = \langle s(t + (\tau/2)) s^T(t - (\tau/2)) e^{-j2\pi ft}\rangle$. If the $K$ SOIs are all uncorrelated, $S^*(f, \tau)$ is diagonal and nonsingular. We note from (6) and (7) that when the SOIs are all uncorrelated, the corresponding $R_{xx'}(f, \tau)$ is a Hankel matrix. However, $S^*(f, \tau)$ becomes block diagonal and singular in the presence of coherent SOIs. Hence, the Hankel structure for $R_{xx'}(f, \tau)$ is destroyed. This leads to the result that the conventional conjugate Cyclic MUSIC [8, pp. 214–215], cannot successfully resolve the DOAs of the SOIs.

III. THE PROPOSED METHODS

Let an $M$-element ULA be divided into overlapping subarrays of size $N$, with sensor elements $\{m, \ldots, m+N-1\}$ forming the $m$th subarray. From (5), we obtain

$$x_k(t) = \sum_{n=1}^{K} s_n(t) a_k(\theta_n) + \mathbf{i}_k(t)$$

$$= \sum_{n=1}^{K} s_n(t) e^{j(k-1)\phi_n} a_k(\theta_n) + \mathbf{i}_k(t)$$ \hspace{1cm} (8)

where $x_k(t)$ and $a_k(\theta_n)$ represent the received data and direction vectors of the $k$th subarray, respectively. Next, we present a HAM to decorrelate the coherent SOIs based on the spatial smoothing (SS) scheme of [5].

A. HAM

Since the cyclic conjugate correlation matrix possesses the Hankel property instead of the Toeplitz property when all the SOIs are uncorrelated, the methods proposed by [13] are not appropriate for solving the problem. Therefore, we define a new cyclic conjugate correlation matrix of the $k$th subarray as follows to alleviate the difficulty of conjugate Cyclic MUSIC for direction finding under coherent SOIs

$$R_{xx'}(f, \tau, k) = \langle x_k(t + \frac{\tau}{2}) x_k^T(t - \frac{\tau}{2}) e^{-j2\pi ft}\rangle$$

$$= \sum_{n=1}^{K} \sum_{m=1}^{K} r_{s_n s_m'}(f, \tau) e^{j((k-1)\theta_n + (L-k)\theta_m)} a_k(\theta_n) a_k^T(\theta_m)$$ \hspace{1cm} (9)

where $L = M - N + 1$. We note from (9) that $R_{xx'}(f, \tau, k)$ is the $k$th submatrix along the backward main diagonal of the
cyclic conjugate correlation matrix of the full array. The corresponding spatial smoothed cyclic conjugate correlation matrix for the conjugate selfcoherent case is given by

$$\bar{R}_{xx'}(f, \tau) = \frac{1}{L} \sum_{k=1}^{L} R_{xx'}(f, \tau, k). \quad (10)$$

From (10), we have

$$\bar{r}^s(i, j) = \frac{1}{L} \sum_{k=1}^{L} r^s(i + L - k, j + k - 1) \quad (11)$$

where $\bar{r}^s(i, j)$ and $r^s(i, j)$ denote the $(i, j)$th elements of $R_{xx'}(f, \tau)$ and $R_{xx'}(f, \tau)$, respectively. We observe from (11) that constructing $\bar{R}_{xx'}(f, \tau)$ is equivalent to performing the Hankel approximation on the cyclic conjugate correlation matrices of the subarrays. Hence, we term the proposed scheme as HAM.

**B. F/B HAM**

Based on the F/B SS scheme of [6], a F/B HAM scheme is proposed to obtain the F/B spatial smoothed cyclic conjugate correlation matrix as

$$\bar{R}_{xx'}^{FB}(f, \tau) = \frac{1}{L} \sum_{k=1}^{L} \left\{ \nu R_{xx'}(f, \tau, k) + (1 - \nu) I_r R_{HH}^{FB}(f, \tau, k) I_r \right\}$$

$$= \frac{1}{L} \sum_{k=1}^{L} R_{xx'}^{FB}(f, \tau, k) \quad (12)$$

where $I_r$ denotes the reflection matrix given by

$$I_r = \begin{bmatrix} 0 & 1 \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & \cdots & 0 \end{bmatrix} \quad (13)$$

0 < $\nu$ < 1, and $R_{xx'}^{FB}(f, \tau, k) = \nu R_{xx'}(f, \tau, k) + (1 - \nu) I_r R_{HH}^{FB}(f, \tau, k) I_r$. Due to that $S^H(f, \tau)$ may be a complex matrix, the factor $\nu$ is employed to avoid the situation where $\bar{R}_{xx'}^{FB}(f, \tau)$ becomes singular.

**C. The Algorithm**

Let $\bar{R}_{xx'}(\alpha, \tau, n)$ and $\bar{R}_{xx'}^{FB}(\alpha, \tau, n)$ represent the results of $R_{xx'}(f, \tau)$ and $R_{xx'}^{FB}(f, \tau)$ computed by using $n$ data snapshots when $f = \alpha$. Then, the estimated DOAs of the $K$ SOIs are obtained step-by-step as follows:

Step 1) Compute $\bar{R}_{xx'}(\alpha, \tau, n)$ and $\bar{R}_{xx'}^{FB}(\alpha, \tau, n)$ by (9), (10), and (12). Set $\bar{R}_{xx'}(\alpha, \tau, n)$ and $\bar{R}_{xx'}^{FB}(\alpha, \tau, n)$ when HAM and F/B HAM are used, respectively.

Step 2) Perform the singular value decomposition (SVD) on $\bar{R}_{xx'}(\alpha, \tau, n)$ and obtain

$$\bar{R}_{xx'}(\alpha, \tau, n) = [\hat{S}(\alpha) \hat{G}(\alpha)] \left[ \begin{array}{cc} \Sigma_{S}(\alpha) & 0 \\ 0 & \Sigma_{C}(\alpha) \end{array} \right] \times [\hat{V}_{S}(\alpha) \hat{V}_{C}(\alpha)]^H \quad (14)$$

where $[\hat{S}(\alpha) \hat{G}(\alpha)]$ and $[\hat{V}_{S}(\alpha) \hat{V}_{C}(\alpha)]$ are two unitary matrices, $\hat{S}(\alpha)$ and $\hat{V}_{S}(\alpha)$ have size $M \times K$, and $\hat{G}(\alpha)$ and $\hat{V}_{C}(\alpha)$ have size $M \times (M - K)$. Moreover, the diagonal elements of $\Sigma_{S}(\alpha)$ and $\Sigma_{C}(\alpha)$ are nonnegative and appear in decreasing order with $\Sigma_{C}(\alpha) \rightarrow 0$ as $\alpha \rightarrow \infty$.

Step 3) Find the $K$ minima of $||\hat{G}(\alpha, \phi)||^2$ or the $K$ maxima of $||\hat{S}(\alpha, \phi)||^2$, where $\hat{a}(\phi)$ denotes the direction vector corresponding to impinging angle $\phi$ and $||\cdot||$ denotes the norm operator. The $K$ found values of $\phi$ are then viewed as the DOAs of SOIs.

**IV. THEORETICAL ANALYSES**

For the $K$ SOIs impinging on the array, we assume that the first $P$ SOIs are coherent and the last $(K - P)$ SOIs are incoherent. Let $\text{rank}(\hat{A})$ represent the rank of matrix $\hat{A}$.

**Theorem 1:** If the number of subarrays is greater than or equal to the number of coherent signals, i.e., if $L \geq P$, then $\text{rank}(\bar{R}_{xx'}(f, \tau))$ is equal to $K$.

**Proof:** First, we rewrite (8) as

$$x_k(t) = \left\{ \sum_{m=1}^{P} c_m e^{j(k-1)\varphi_m} a_1(\theta_m) \right\} s_1(t) + \sum_{n=P+1}^{K} s_n(t) e^{j(k-1)\varphi_n} a_2(\theta_n) + i_k(t) \quad (15)$$

where $c_m s_1(t)$ and $a_m$ denote the $m$th wavefront and electrical angle, respectively. From (9) and (15), we have

$$\bar{R}_{xx'}(f, \tau, k) = r_{s_1s_1'}(f, \tau) \left\{ \sum_{m=1}^{P} c_m c_n e^{j(k-1)\varphi_m+(L-k)\varphi_n} \times a_1(\theta_m) a_1^T(\theta_n) \right\} + \sum_{n=P+1}^{K} r_{s_n s_1'}(f, \tau) a_2(\theta_n) a_1^T(\theta_n). \quad (16)$$

The spatial smoothed cyclic conjugate correlation matrix is thus given by

$$\bar{R}_{xx'}(f, \tau) = \frac{1}{L} \sum_{k=1}^{L} \bar{R}_{xx'}(f, \tau, k)$$

$$= r_{s_1s_1'}(f, \tau) \left\{ \sum_{m=1}^{P} \sum_{n=1}^{P} c_m c_n \times \left[ \frac{L}{L} \sum_{k=1}^{L} e^{j(k-1)\varphi_m+(L-k)\varphi_n} \right] a_1(\theta_m) a_1^T(\theta_n) \right\}$$

$$+ \sum_{n=P+1}^{K} r_{s_n s_1'}(f, \tau) a_2(\theta_n) a_1^T(\theta_n). \quad (17)$$

It is easy to show that $\text{rank}(\bar{R}_{xx'}(f, \tau, k)) = K + P - 1$. Thus, $\text{rank}(\bar{R}_{xx'}(f, \tau))$ is not more than $\min\{K, K - P + L\}$, where $\min\{a, b\} = a$ if $a \leq b$. Accordingly, we note that $\text{rank}(\bar{R}_{xx'}(f, \tau)) = K$ is possible when $L \geq P$. Moreover,
the component in (17) regarding the $i$th and $j$th coherent SOIs is given by

\[
 h_{i,j} = a_i^H(\theta_i)a_j^H(\theta_j) + a_j^H(\theta_j)a_i^H(\theta_i)
\]

where

\[
 h_{i,j} = r_{s_1s_2}(f,\tau)c_{i}^*e^{j(\phi_i-\phi_j)}
\]

and

\[
 r_{s_1s_2}(f,\tau) = \sum_{k=1}^L c_k^*e^{j(k-1)\phi}e^{-(I-k)\phi}
\]

respectively. Since

\[
 (c_{i}^*e^{j(I-L)\phi} - c_{j}^*e^{(I-L)\phi})/(L(c_{i}^*e^{j\phi_i} - c_{j}^*e^{j\phi_j}))
\]

\[
 = (c_{i}^*e^{j\phi_i} - c_{j}^*e^{j\phi_j})/(L(c_{i}^*e^{j\phi_i} - c_{j}^*e^{j\phi_j}))
\]

\[
 \neq 1
\]

and

\[
 |e^{j(I-1)(\phi_i+\phi_j)}| = 1
\]

we have

\[
 h_{i,j}^2 - h_{i,i}h_{j,j} = \gamma_{s_1s_2}^2(f,\tau)c_{i}^2
\]

\[
 \times \left\{ e^{j(I-L)\phi} - e^{j\phi_i} \right\}^2
\]

\[
 \neq 0
\]

Hence, the resulting matrix of (18) has rank 2. (20) reveals that the $i$th and $j$th coherent SOIs impinging from different angles can therefore be decorrelated. As a result, any two coherent SOIs can be decorrelated by using the spatial smoothed cyclic conjugate correlation matrix. Under the condition that $L \geq P$, the proof is complete.

**Theorem 2:** If the number of subarrays is greater than or equal to half the number of coherent signals, i.e., if $L \geq \frac{K}{2}$, then $L = \frac{K}{2}$.

**Proof:** We first consider the effect of using the forward/backward technique. Performing some necessary algebraic manipulations with $\Omega_{s_{1s_2}}(\theta_m) = e^{-j(M-1-2\phi_m)\theta_m}$, where $a_i(\theta_m)$ is the direction vector of the $i$th SOI at the first subarray, the component in $R_{s_{1s_2}}^f(f,\tau, k)$ regarding the $i$th and $j$th coherent SOIs is expressed as

\[
 \Omega_{s_{1s_2}}(i, j) = v_{i,j}a_i^H(\theta_i)a_j^H(\theta_j) + v_{j,i}a_j^H(\theta_j)a_i^H(\theta_i)
\]

where

\[
 v_{a,b} = \gamma_{s_1s_2}^2(f,\tau)c_{i}^2e^{j(I-1)(\phi_i+\phi_j)}
\]

\[
 + (1-\nu)^{s_1s_2}(f,\tau)c_{i}^2e^{-j(I-1)(\phi_i+\phi_j)}
\]

\[
 \times e^{-j(M+1-2\phi_m)\theta_m}
\]

\[
 \alpha \in \{i, j\} \quad \text{and} \quad \beta \in \{i, j\}.
\]

Thus, we obtain

\[
 \sigma = \frac{v_{i,j}v_{i,j} - v_{j,i}v_{i,j}}{r_{s_1s_2}(f,\tau)}
\]

\[
 = (c_{i}^*e^{j\phi_i} + c_{j}^*e^{-j\phi_j})e^{-j(M+1-2\phi_m)\theta_m}
\]

\[
 + (c_{i}^*e^{j\phi_i} - c_{j}^*e^{-j\phi_j})e^{-j(M-1-2\phi_m)\theta_m}
\]

\[
 \times \left\{ e^{j(2k-1-L)\phi_i} + e^{-j(2k-1-L)\phi_j} \right\}
\]

\[
 = \left\{ c_{i}^*e^{-j(M+1-2\phi_m)\theta_m} - e^{-j(2k-1-L)\phi_i} \right\}
\]

\[
 \times \left\{ c_{j}^*e^{j(M+1-2\phi_m)\theta_m} - e^{-j(2k-1-L)\phi_j} \right\}
\]

\[
 \neq 0
\]

and $|\sigma| \neq 0$ from (23). As a result, the $i$th and $j$th coherent SOIs can be decorrelated by the F/B technique. From *Theorem 1*, $2L = P$ is then enough to decorrelate all coherent SOIs and thus the proof is complete.

Since the number of subarrays, given by $L = M - N + 1$ and the size of each subarray $N$ must be at least $K+1$, it follows that the minimum numbers of sensor elements needed for applying HAM and F/B HAM are $(P-K)$ and $2K + 2P$, respectively, and thus $2K$ and $2P$, respectively, under the worst situation where the $K$ SOIs are all coherent, i.e., $P = K$. Moreover, the HAM and F/B HAM are developed based on the SS [5] and F/B SS [6], respectively, the conclusions obtained from the above theorems are similar to those presented in [5] and [6].

**V. COMPUTER SIMULATIONS**

In this section, two computer simulation examples performed on a PC with Pentium II-350 CPU using MATLAB programming language are presented for showing the effectiveness of the proposed methods.

**Example 1:** Here, a ULA with number of sensor elements $M = 5$ and interelement spacing $\frac{\lambda}{2}$ wavelength of SOI is considered. The array is grouped into two overlapping subarrays with sensor elements $\alpha_i$ for the $i$th subarray, $\alpha_j$ is the DOAs for three SOIs are 5°, 10°, and 15° off array broadside, respectively. The first two SOIs are coherent, while the third SOI is uncorrelated with the others. The ensemble cyclic conjugate correlation matrix is given by $\alpha_{s_{1s_2}}^2 + a_{i}(\theta_i)a_{j}^H(\theta_j)$, where $\alpha_{s_{1s_2}} = a(\theta_1) + a(\theta_2)$ and $a(\theta_i)$ denotes the direction vector of the $i$th SOIs. We note from the theoretical analysis that the minimum numbers of sensor elements needed for HAM and F/B HAM are $(P-K)$ and $2K + 2P$, respectively, under the worst situation where the $K$ SOIs are all coherent, i.e., $P = K$. Moreover, the HAM and F/B HAM are developed based on the SS [5] and F/B SS [6], respectively, the conclusions obtained from the above theorems are similar to those presented in [5] and [6].
different methods are described and their effectiveness is demonstrated by simulation results.

VI. CONCLUSION

This paper has presented HAM to decorrelate the SOIs in direction finding for a uniform linear array. In conjunction with conjugate Cyclic MUSIC, the direction of arrival (DOAs) of all SOIs can be successfully resolved in a coherent signal scenario. Theoretical analysis has been presented and shown that at least \( 2K \) sensor elements are required for decorrelating \( K \) coherent SOIs. Utilizing the F/B concept, we have also presented F/B HAM which requires \( 3K/2 \) sensor elements for decorrelating \( K \) coherent SOIs. The effectiveness of the proposed methods for performing direction finding in a coherent scenario have also been demonstrated by simulation results.

REFERENCES


Yung-Ting Lee was born in Tainan, Taiwan, on March 31, 1971. He received the B.S. degree from the National Cheng-Kung University, Tainan, Taiwan, in 1993, the M.S. degree from the National Taiwan University, Taipei, Taiwan, in 1995, and the Ph.D. degree from Rensselaer Polytechnic Institute, Troy, NY, in 2000, all in electrical engineering.

From March 2000, he joined Network Lab of Technology Service Division, Institute for Information Industry of Taiwan, as a Senior Engineer in Wireless Communications. His current research interests include adaptive signal processing, array signal processing, and wireless communications.

Ju-Hong Lee was born in I-Lan, Taiwan, on December 7, 1952. He received the B.S. degree from the National Cheng-Kung University, Tainan, Taiwan, the M.S. degree from the National Taiwan University, Taipei, Taiwan, and the Ph.D. degree from Rensselaer Polytechnic Institute, Troy, NY, all in electrical engineering, in 1975, 1977, and 1984, respectively.

From September 1980 to July 1984, he was a Research Assistant with the Department of Electrical, Computer, and Systems Engineering with Rensselaer Polytechnic Institute, involved in research on multidimensional recursive digital filtering. From 1984 to 1986, he was a Visiting Associate Professor with the Department of Electrical Engineering, National Taiwan University. In 1986, he became an Associate Professor and in 1989, was appointed Professor. During a sabbatical leave in 1996, he was a Visiting Professor in the Department of Computer Science and Electrical Engineering, with the University of Maryland, Baltimore. His current research interests include multidimensional digital signal processing, image processing, detection and estimation theory, analysis and processing of joint vibration signals for the diagnosis of cartilage pathology, and adaptive signal processing and its applications in communications.

Dr. Lee received Outstanding Research Awards from the National Science Council (NSC) in 1988, 1989, and from 1991 to 1994. He also received the Distinguished Research Awards from the NSC in 1998 and 2001.