An Improved Joint Detection Approach for TD-SCDMA System over Multipath Channels

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Abstract—This paper investigates the joint detection method for TD-SCDMA system, and derives an improved approach to eliminate inter-symbol interference (ISI) in condition of multipath channel. Analysis for the received signals exhibits its characteristics of PARAllel profiles with LINear Dependencies (PARALIND) model. The proposed blind PALALIND algorithm utilizes no channel parameter for detection, and performs better with snapshots increasing. Simulation results indicate that its performance is quite close to space-time minimum-mean-square-error (ST-MMSE) and also robust in array error condition.

Keywords—TD-SCDMA, PARALIND, zero-padding guard interval, joint detection

I. INTRODUCTION

Specifically recognized as a versatile technology for mobile communication, TD-SCDMA enables a number of advanced approaches to provide higher spectrum efficiency and larger system capacity [1], such as smart antenna techniques, multiuser detection and interference suppression [2], etc. Most methods of joint detection have been devoted to the elimination of multiple access interference (MAI) and inter-symbol interference (ISI) [3]; however, the considerable complexity within receivers stands up for a major problem of practical realizability. With reference to PARAllel FACtor (PARAFAC) analysis [4] and PARALIND model [5], we develop an improved blind joint detection approach for TD-SCDMA system over multipath fading channel, which can perform quite well and appear to be robust with array error. The proposed algorithmic model also shows uniqueness and offers a better solution for multiway data analysis [6].

The rest of this paper is structured as follows. Section II discusses the system model, and Section III is devoted to the algorithmic presentation. Section IV offers simulations, while Section VI contains the conclusion.

Notation: (.)*, (.)T and (.)† are denoted as the complex conjugation, the matrix transpose, and the Moore–Penrose inverse, respectively; ||| denotes the Frobenius norm. We also denote by the Khatri–Rao product, by ⊗ the Kronecker product, by * the Hadamard product; ε denotes the P × P identity matrix.

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II. SYSTEM MODEL

Consider the uplink of a CDMA system, where a number of K users are all employed by spread spectrum modulation of Binary Phase Shift Keying (BPSK) signals. Assume that the signal of ith user has a total of ri independent paths toward the base station. Hence, the baseband signal received by the M-element uniform circular array (UCA) can be denoted as

\[ x(t) = \sum_{i=1}^{K} \sum_{l=1}^{r_i} a_{il} b_i (t - \tau_{il}) \beta_{il} + n(t) \]  

where \( \tau_{il}, \beta_{il}, \) and \( a_{il} \) represent the time delay, channel fading, and direction vector of the lth path for the kth user, respectively; \( n(t) \) is the space-time channel white noise; \( s_i \) and \( b_i \) stand for the spread code waveform and the transmit signal of the kth user.

Now we use the chip-rate sampling for the received signal. Suppose that the number of chips for time delay is an integer which does not exceed the numerical value of spread gain \( P \). The ISI aroused by multipath spread spectrum, see Fig. 1, from where we find that the front sequence is also some part of ISI (introduced by delay of multipath), can be eliminated in condition of smaller delays. Hence, joint detection over multipath channel can be achieved by utilizing the rest parts without ISI.

In our design, a sequence of zero-padding guard intervals [7] are primarily chosen to be inserted and then removed at the receiver, for the purpose of thoroughly clearing out the existing ISI from multipath propagation. As shown in Fig. 2, the shadowing parts represent these guard intervals, where each of their length does not go beyond \( \tau_{\text{max}} \), the maximum delay.

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Hence, the following spread spectrum vector of the \( i \)-th path for the \( i \)-th user is expressed as
\[
C_\| = [0 \ldots 0 \ c(1) \ldots c(P - r_i) ]^T \in \mathbb{F}^{P \times 1}
\]
(2)
The spread matrix of \( i \)-th user for all paths can also be shown
\[
C_i = [C_{i1} \ C_{i2} \ldots \ C_{ik}] \in \mathbb{F}^{P \times G}
\]
(3)
For the sake of multiuser, its spread matrix over multipath channel should be denoted as
\[
S = [C_1 \ C_2 \ldots \ C_K] \in \mathbb{F}^{P \times GR}
\]
(4)
where \( r = \sum_{i=1}^{K} r_i \) stands for a calculation of all channel paths.

Assume that \( N \) is the length of transmitted signals, and \( b_{n,q} \) is the \( n \)-th signal (\( n = 1, 2, \ldots , N \)) transmitted by the \( k \)-th user (\( k = 1, 2, \ldots , K \)), now the source matrix for a single path can be given by
\[
B = \begin{bmatrix}
    b_{1,1} & b_{1,2} & \ldots & b_{1,K} \\
    b_{2,1} & b_{2,2} & \ldots & b_{2,K} \\
    \vdots & \vdots & \ddots & \vdots \\
    b_{N,1} & b_{N,2} & \ldots & b_{N,K}
\end{bmatrix} \in \mathbb{F}^{N \times K}
\]
(5)
Thereafter, we denote the source matrix for multipath as follows
\[
B_E = BH \in \mathbb{F}^{N \times GR}
\]
(6)
where
\[
H = \begin{bmatrix}
    1 & 0 & \ldots & 0 \\
    M & 0 & \ldots & 0 \\
    0 & L & 1 & \ldots & 0
\end{bmatrix} \in \mathbb{F}^{K \times GR}
\]
(7)
and \( 1 \) stands for a vector of \( 1 \times r_i \).

Define the space-time channel matrix as
\[
A_E = A\Gamma = [\alpha_{11} \beta_{11}, L \ \alpha_{1i} \beta_{1i}, L \ \alpha_{K1} \beta_{K1}, L \ \alpha_{Kq} \beta_{Kq} ] = [h_{11}, L \ h_{1j}, L \ h_{k1}, L \ h_{kq}, L ]
\]
(8)
where
\[
A = [\alpha_{11}, L \ \alpha_{1i}, L \ \alpha_{K1}, L \ \alpha_{Kq}, L ] \in \mathbb{F}^{M \times q}
\]
(9)
\[
\Gamma = \text{diag}([\beta_{11}, L \ \beta_{1i}, L \ \beta_{K1}, L \ \beta_{Kq}, L ] \in \mathbb{F}^{M \times q}
\]
(10)
for which \( \text{diag}(\cdot) \) is to construct a column vector with the diagonal elements out of it.

Consider now the trilinear model \([4]\) of a received signal without noise, which should be expressed in this form
\[
x_{m,n,p} = \sum_{q=1}^{r} h_{m,q} s_{p,q} b_{n,q},
\]
(11)
where \( r \) is the number of paths, \( h_{m,q} \) and \( b_{n,q} \) stands for the \((m, q)\) element of \( A_E \) (space-time channel matrix), the \((p, q)\) element of \( S \) (spread matrix) and \((m, q)\) element of \( B_E \) (source matrix), respectively. Therefore, \((x_{m,n,p}) = (m = 1, 2, \ldots , M ; n = 1, 2, \ldots , N ; p = 1, 2, \ldots , P) \) have constructed the three-way data matrix \( X \).

The trilinear model is rewritten as follows
\[
X_p = A_E D_p(S) B_E^T \quad (p = 1, 2, \ldots , P)
\]
(12)
where \( X_p \) is considered as the \( p \)-th slice along the temporal direction, both \( B_E \) and \( A_E \) can be identical as \((6)\) and \((8)\), and \( D_p(S) \) means to extract the \( p \)-th row of its spread matrix and constructs a diagonal matrix out of it.

With respect to \((12)\), when no noise is presented, the received signals are denoted as
\[
X = [X_1 \ X_2 \ \ldots \ X_P] = A_E [D_1(S) B_1^T \ D_2(S) B_2^T \ \ldots \ D_P(S) B_P^T]^T
\]
(13)

III. BLIND PARALIND ALGORITHM FOR JOINT DETECTION OVER MULTIPATH CHANNEL

A. PARALIND Algorithm

Let us firstly concern the linear dependency within PARAFAC before the construction of PARALIND model. The appropriate solution for PARAFAC can be regarded as rank deficient when linear dependencies exist, which is shown by no-guaranteed converging to the global minimum value; e.g., \( B_E \) indicates the typical problem of linear dependency, while in the collinear condition, the performance of PARAFAC-ALS is far from satisfactory \([5]\). In this subsection, we apply PARALIND algorithm to deal with the problem aforementioned. With respect to \((13)\), the received signals can be set up by the PARALIND model, of which the cost function should be
\[
\min \| \hat{X} - A_E (S \odot B_E)^T \|_F
\]
(14)
where \( \hat{X} \) stands for the received noisy signal.

According to \((12)\), we should have
\[
\text{vec}(X_p) = \text{vec}(B_E D_p(S) A_E^T) = \text{vec}(BHD_p(S)A_E^T)
\]
\[
\Rightarrow \text{vec}(X_p) = (A_E D_p(S) \odot B) \text{vec}(H)
\]
(15)
where \text{vec}(X) denotes obtaining a column vector by stringing out matrix \( X \) column-wise.

Meanwhile, when all slices have been considered, Eq.(15) leads to
\[
\begin{bmatrix}
    \text{vec}(X_1^T) \\
    \text{vec}(X_2^T) \\
    \vdots \\
    \text{vec}(X_P^T)
\end{bmatrix} =
\begin{bmatrix}
    A_E (D_1(S) \odot B) \\
    A_E (D_2(S) \odot B) \\
    \vdots \\
    A_E (D_P(S) \odot B)
\end{bmatrix} \text{vec}(H)
\]
(16)
which can also be denoted as
\[
\text{vec}(X^T) = [(S \odot A_E) \odot B] \text{vec}(H)
\]
(17)
Update of matrix \( H \) can be given by
\[
\text{vec}(H) = [(A_E^T A_E)^{-1}(S^T S) \odot (B^T B)]^T \text{vec}(\sum_{p=1}^{P} B^T X_p^T A_E D_p(S))
\]
(18)
And the update is followed by taking into account that
\[(S \circ A_E)^\top (S \circ A_E) = (A_E^T A_E)^* (S^T S) \quad (19)\]

Similarly, updates for matrices B, A_E, and S are denoted as
\[B = \left( \sum_{p=1}^{P} X_p B H D_p(S) \right) \left( H[I(A_E^T A_E)^* (S^T S)H]^T \right)^{-1} \quad (20)\]
\[A_E = \left( \sum_{p=1}^{P} X_p B H D_p(S) \right) \left( H[I(B^T B)^* (S^T S)]H \right)^{-1} \quad (21)\]
\[\text{diag}(D_p(S)) = \{(A_E^p A_E)^* (H[B^T B])^\dagger \} \text{diag}(H[B^T X_p A_E]) \quad (p = 1, 2, \ldots, P) \quad (22)\]

B. Uniqueness of PARALIND Model

Consider again for (12), the obtained two slices (transpose) can be shown as follows
\[X_E^T = B_E \bar{A}_E \land X_E^T = B_E D \bar{A}_E^T \quad (23)\]
where we have \(B_E = BH \), \(\bar{A}_E = A_E D_1(S)\), and \(D = D_2(S)D_1(S)^{-1}\), of which the construction of matrices must be
\[\begin{bmatrix}
    X_E^T \\
    X_E^T
\end{bmatrix} = \begin{bmatrix}
    B_E \\
    B_E D
\end{bmatrix} \bar{A}_E \quad (24)\]

Since matrix \(\bar{A}_E\) is with columns full-rank, \(\text{span}(U) = \text{span} \begin{bmatrix}
    B_E \\
    B_E D
\end{bmatrix}\) can be guaranteed; and hence, there exists a nonsingular matrix T, which satisfies
\[U = \begin{bmatrix}
    U_1 \\
    U_2
\end{bmatrix} = \begin{bmatrix}
    B_E T \\
    B_E DT
\end{bmatrix} \quad (25)\]

Now that we have constructed the auto correlation matrix and cross correlation matrix, which are given by
\[R_1 = U_1^T U_1 = T^* B_E^* B_E T = GT \quad (26)\]
\[R_2 = U_2^T U_2 = T^* B_E^* B_E DT = GDT \quad (27)\]
where \(G = T^* B_E^* B_E\).

Both \(R_1\) and \(R_2\) are square matrices with columns full-rank, hence we have
\[(R_1 R_2)^{-1} T (G^T)^{-1} T (G^{-1}) D \quad (28)\]
Therefore, \((G^T)^{-1}\) and \(D\) represent the eigenvector and corresponding eigenvalues of matrix \((R_1 R_2)^{-1} T\), respectively.

We hereby give the proof for uniqueness of PARALIND model as follows:

Eigenvalues should be unique since they are determined by the matrix, however, the corresponding eigenvector of a given eigenvalue is not unique. Hence, \(D\) is a unique matrix, while the matrix of \((G^T)^{-1}\) must be decided by scale ambiguity and permutation ambiguity. Let us obtain its transpose, which is \(G^{-1}\); get \(T = G^{-1} R_1\) from \(R_1 = GT\), obtain \(B_E = U_1 T^\dagger\) from \(U_1 = B_E T\) followed by; and finally we have \(\bar{A}_E = B_E^T R_1\) derived from \(X_E = B_E^T \bar{A}_E\). All these decisions should be made by the ambiguities mentioned above. Proof is completed.

C. Joint Detection for TD-SCDMA System with inserted zero-padding guard intervals

Up to now, we have discussed the improved approach to achieve joint detection for TD-SCDMA system over multipath channels. Utilizing blind PARALIND algorithm, the concrete method can be shown step by step as below:

1) Initialization for the matrices of \(B\) (source matrix), \(A_E\) (source matrix) and \(S\) (spread spectrum matrix). The dependency matrix \(H\) is known;
2) update for \(B\) with respect to (20);
3) update for \(A_E\) with respect to (21);
4) update for \(S\) with respect to (22);
5) repeat step 2 to step 4 until convergence;
6) make decision for the estimated matrix \(B\).

IV. SIMULATIONS

In this Section, we adopt the 8-element uniform circular array (UCA) (with one-wavelength radius) and BPSK modulated signals (where the spread gain is 64) to testify the proposed method. We also consider mobile environment of multipath fading channels in all simulations. Note that the number of time-delay chips should be an integer which is smaller than spread gain, while the length of zero-padding guard interval is larger than maximum chip numbers. \(N\) and \(K\) are the number of symbol-snapshots and users, respectively.

To evaluate bit error rate (BER) performance of the PARALIND algorithm aforementioned, we present Monte Carlo simulations where the number of trials is set to 1000. Fig. 3 depicts the performance of PARALIND under different \(N\). Practically, we consider 4 users and each user can be arranged with double channel paths, for which their DOAs are located at \((25^\circ, 60^\circ), (8^\circ, 55^\circ), (12^\circ, 50^\circ), (20^\circ, 45^\circ), (16^\circ, 40^\circ), (30^\circ, 35^\circ), (35^\circ, 30^\circ), (40^\circ, 25^\circ)\), respectively. Set the snapshot number \(N\) as 50, 100 and 200. From Fig. 3, we conclude that the PARALND algorithm offers considerably close performance comparing to nonblind ST-MMSE [8], in which the receiver assumes perfect knowledge of DOA, SNR and channel fading information. The larger number of snapshots \(N\) comes, the better performance that our algorithm can achieve. Notably, the PARALIND algorithm that we presented requires no information of DOA or channel fading.

![Fig. 3. Performance comparisons between PARALAND (zero-padding guard interval) and ST-MMSE algorithm](image-url)
Then we study the performance of PARALIND in condition of different $K$ in Fig. 4. Set the user number as 3, 4, and 5, where each user takes up two paths with time-delay of 5 chips at the most, and snapshots $N = 100$. It is indicated that when the user number expands, the performance gradually gets worsen.

![Figure 4](image)

**Fig. 4.** Performance comparisons of PARALAND algorithm under different $K$

Since gain and phase errors normally exist in practical arrays other than expected (where the amplitude and/or phase response by each antenna corresponding to a known signal may occur differently), the performance of blind PARALIND in array error condition has been investigated thereafter. We take advantage of the same information for DOAs as Fig. 3 mentioned above, and also consider the similar channel environment adopted for Fig. 4. The array error vector (gain error and phase error both), is hereby supposed as $g = [1, 0.6071-0.6953i, 1.0083+0.9059i, 0.3497-0.7167i, 0.9693+1.2916i, 0.5343+0.3883i, 0.7330+1.5894i, 0.8878-1.5133i]$. Fig. 5 presents the algorithmic performance of PARALIND in array error condition, where we find that PARALIND maintains good performance in contrast to the ideal array condition. Hence, our algorithm illustrates robust characteristics to array error, and also suggests a feasible approach for joint detection.

![Figure 5](image)

**Fig. 5.** Performance of PARALIND algorithm with array error

V. CONCLUSION

We have derived the problematic link of joint detection for TD-SCDMA system to the PARAllel profiles with LINear Dependencies, and presented a blind PARALIND algorithm which has quite close performance to nonblind ST-MMSE. The algorithm that we presented provides a better resolution to inter-symbol interference, and also works well in array error condition. Our algorithm requires neither DOA knowledge nor channel fading information, indicates robust specialty, and prospects a wider approach for signal detection methods of mobile communication.

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