A Novel DS-CDMA Direction of Arrival Estimator for Frequency-Selective Fading Channel with Correlated Multipath by Using Beamforming Filter

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Abstract—In this paper, a new method for estimating the direction of arrival of Asynchronous DS-CDMA signals in multipath fading channel is proposed. In the proposed method, first, for removing the effects of undesired paths, we project the coherent signals of the undesired paths perpendicularly to the under process signal, next, the signal is passed through a filter bank. By using beam forming filters, the effect of other users on the desired users signal is decreased and hence, the search area is decreased almost to one tenth. In this algorithm, searching all angles is not required, to estimate the number of sources does not require any information criteria, and also, the number of users can exceed the number of antenna arrays contrary to many of the conventional methods. Simulation results are illustrated to confirm the efficiency of the method.

Keywords: Direction of arrival estimation, orthogonal projection, beam forming, frequency-selective fading channel.

I. INTRODUCTION

The system capacity can be increased by using temporal or spatial signal processing techniques to transmit and receive signals. The smart antenna techniques, including beamforming and diversity ones, are especially useful in mobile direct-sequence code division multiple access (DS-CDMA) communication systems [1].

Here, we consider the state that a beamforming array is adopted at the base station while each mobile user transmits the signal by using a single antenna. In such a system, direction of arrival (DOA) of the received signals is a parameter for the base station to be estimated, in order to set up reliable connection for data transmission among mobile users. The DOAs of users are not available in practice and should be estimated for implementation of optimum receivers.
Furthermore in recent years, estimating the
direction of arrival has been an attractive area of
research because of its important application in radar
and wireless location finding. Among the proposed
methods, the signal subspace algorithms have attracted
a lot of interest due to their high resolution. However,
in a highly correlated or coherent environment due to
multipath propagation, the direction of coherent signals
cannot be detected via conventional subspace methods
like the Multiple Signal Classification (MUSIC)
algorithm and Estimation of Signal Parameters via
Rotational Invariance Techniques (ESPRIT), since the
spatial signatures cannot be resolved in the signal
subspace [2-4].

Furthermore, in order to estimate DOA by
conventional methods, the number of array elements
must be greater than the number of users; this
is impractical in CDMA systems with a large number
of active users. A DOA estimator employing code
matched filters and parallel MUSIC is proposed in [5].
In this method other users except of active users are
considered Gaussian noise and as interference. In [6]
a subspace method for estimating DOA for multiple
codeword narrowband signals is proposed.

In this paper, we propose a method for DS-CDMA
signal DoA estimation with an array of antennas at the
receiver. First, we decorrelate the received signal of
each path by orthogonal projection and then apply a
bank of $2M$ ($M$ is the number of array's) beam
forming filters to the received two-dimensional (2-D)
signal which results in $2M$ time domain sequences.
The total energy of interfering signals is reduced after
each beam forming filter. The energy of desired
signals also reduced, since the DOA is still unknown
at this stage. However, the proposed algorithm
together with this receiver structure is able to control
the loss of energy while maintaining the SNR level.

The paper is organized as follows. In Section II, we
describe the mathematical model of the system, set the
underlying assumptions and define the problem
objectives. In Section III, the proposed method is
developed for single path and asynchronous multipath cases. In Section IV, performance of the proposed method is evaluated by
simulation, and Section V concludes the paper.

II. MATHEMATICAL MODEL

A. Notation

The notations employed in this paper are standard.
Signals are discrete-time and complex in general.
Upper and lower-case bold letters denote matrices and
vectors, respectively. The operators $(\otimes)$ and $(\otimes')$
denote transpose and hermitianoperation respectively. Finally
$\otimes$ is Kronecker matrix product.

B. System Model

Consider a DS-CDMA system with $K$ active users
transmitting binary information sequences of
$b_1, b_2, \ldots, b_K$ with normalized spreading waveforms
$s_1, s_2, \ldots, s_K$ that are randomly distributed in space.
A $Q$ bit transmitted baseband signal from the $k$-th user is:

$$ x_k(t) = A_k \sum_{i=1}^{Q-1} b_i(t) s_k(t-iT_k) $$
$$ k = 1, 2, \ldots, K $$

(1)

Where $T_k$ is the bit interval, $b_i(t) \in \{-1, +1\}$ is the
$i$-th bit of a sequence of independent and identically
distributed (i.i.d) random variables transmitted by the $k$-
th user and $A_k$ denotes the amplitude of the $k$-th user.
$s_k(t)$ is defined as follows and its energy is limited to
$[0, T_{k}]$:

$$ s_k(t) = \sum_{j=0}^{N_k-1} c_j \psi(t-jT_k) \quad 0 \leq t \leq T_k $$

(2)

where $N_k = \frac{T_{k}}{\tau_{\psi}}$ is the processing gain; and $\psi(t)$
is a chip waveform of duration $T_{\psi}$ and $\{c_j\}_{j=0}^{N_k-1}$
is a signature code sequence of $\pm 1$s assigned to the $k$-th
user that can be represented as

$$ c_k = [c_k(0) \; c_k(1) \; \ldots \; c_k(N_k-1)]^T $$

At the receiver, an antenna array of $M$ elements is
employed and the baseband multipath channel of the $k$-
th user can be modeled as a single-input multiple-
output channel with $M \times 1$ vector impulse response
$h_k(t)$ given as [5]

$$ h_k(t) = \sum_{\ell=1}^{L} g_{\ell k}(t-t_{\ell k}, t_{\ell k}) a_{\ell k} $$

(3)

where $L$ is the number of paths in each user's
channel, $\delta(t)$ and $\tau_{\ell k}$ are gain and delay of the $\ell$-
th path of the $k$-th user's signal respectively, $\delta(t)$ is the
Dirac delta function and $a_{\ell k} = [a_{\ell k}^1, \ldots, a_{\ell k}^M]^T$ is the
array response vector corresponding to the $\ell$-th path of
the $k$-th user's signal with DOA of $\theta_{\ell k}$.

The total received baseband signal at the $i$-th
antenna denoted by $r_i(t)$ is the superposition of the
signals from all users plus the additive ambient noise
and the $M \times 1$ vector $r(t) = [r_1(t), \ldots, r_M(t)]^T$ can be
expressed as:

$$ r(t) = \sum_{k=1}^{K} x_k(t) \ast h_k(t) + \sigma n(t) $$
$$ = \sum_{k=1}^{K} \sum_{\ell=1}^{L} A_k b_i(t) \sum_{\alpha} a_{\ell k}(\theta_{\ell k}) g_{\ell k} $$

(4)

$$ \times s_i(t-iT_k - \tau_{\ell k}) + \sigma n(t) $$

where $\ast$ denotes convolution, $\sigma^2$ is the variance of
the ambient noise at each antenna element and
$\theta_{\ell k} = \theta_k(t_i), \ldots, \theta_k(t_M)$ is a vector of independent
zero mean complex white Gaussian noise processes with unit variance, i.e. 

$$E\{n(t)n(t')^H\} = I_M \delta(t-t')$$  \hspace{1cm} (5)

Where $E$ is the expectation operator and $I_M$ is the $M \times M$ identity matrix. We also assume that the noise processes and transmitted sequences of users are statistically independent.

To find the directions of the received signals from the $i$-th path of the $k$-th user, the receiver's chip matched filter is synchronized with the delay of $\tau_{ij}$. The receiver works at the discrete-time rate. The sample of $m$-th antenna is:

$$y_{m,i}(t,j) = \int_{T_{t-\tau_{ij}}+\tau_{ij}}^{T_{t-\tau_{ij}}+\tau_{ij}+\tau_{m}} r_m(t)\psi^*(t-iT_b-\tau_{ij}-jT_c)dt$$  \hspace{1cm} (6)

$M$ samples of antenna output can be represented by a $M \times 1$ vector as:

$$\mathbf{y}_{i}(t,j) = \begin{bmatrix} y_{m,i}(t,j) \\ y_{m,2}(t,j) \\ \vdots \\ y_{m,M}(t,j) \end{bmatrix}$$  \hspace{1cm} (7)

or:

$$\mathbf{y}_{i}(t,j) = \begin{bmatrix} y_{m,i}(t,j) \\ y_{m,2}(t,j) \\ \vdots \\ y_{m,M}(t,j) \end{bmatrix}$$  \hspace{1cm} (8)

By combining the vectors $\mathbf{y}_{i}(t,j)$, we define the $M \times N_c$ matrix $BL_{i}(i)$ as follows:

$$BL_{i}(i) = \begin{bmatrix} y_{i}(i,0), y_{i}(i,1), \cdots, y_{i}(i,N_c-1) \end{bmatrix}$$  \hspace{1cm} (9)

The contribution of $k$-th user at $m$-th antenna ($r_{m}(t)$) is:

$$r_{m}(t) = A_k \sum_{n=0}^{N_c-1} g_{n,k} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (10)

Therefore the contribution of $k$-th user at $y_{m,i}(t,j)$ is:

$$BL_{i}(i,j) = y_{i}(i,j) \quad 0 \leq j \leq N_c - 1$$

$$= A_i \sum_{n=0}^{N_c-1} b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \times \int_{T_{t-\tau_{ij}}+\tau_{ij}}^{T_{t-\tau_{ij}}+\tau_{ij}+\tau_{m}} s_1(t-qT_b-\tau_{kn}) \psi^*(t-iT_b-jT_c-\tau_{kn})dt$$  \hspace{1cm} (11)

Due to $\psi(t)$ waveform at $[0,T_c]$ and $s_i(t)$ at $[0,T_b]$, product of $s_k(t-qT_b-\tau_{kn})$ and $\psi(t-iT_b-jT_c-\tau_{kn})$ is always zero except in two cases:

$$iT_b + iT_c + \tau_{kn} + T_b < qT_b + \tau_{kn} + T_b$$  \hspace{1cm} (12)

$$iT_b + iT_c + \tau_{kn} < qT_b + \tau_{kn} + T_b$$  \hspace{1cm} (13)

Since the effect of $s_1$, $i$, $i+1$-th bits in integral, $y_{i}(i,j)$ simplifies to:

$$y_{i}(i,j) = A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (14)

$$+ A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (15)

$$+ A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (16)

$$+ A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (17)

$$+ A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (18)

As a result, the contribution of $n$-th user at $BL_{i}(i)$ matrix is:

$$BL_{i}(i) = A_i b_n(i) \sum_{p=0}^{N_c} g_{p,n} a_{m} (\theta_{kn}) \otimes \chi_k (t-qT_b-\tau_{kn})$$  \hspace{1cm} (19)
III. THE PROPOSED METHOD

A. Proposed method for synchronous single path case

First we consider the case where all users are transmitting synchronously in a single path fading system, i.e., $L = 1$. Without loss of generality, assume $r_1 = r_2 = ... = r_L$. In this case, $BL$ matrix is independent of indices $k$ and $l$ and simplifies to:

$$BL_k^l(i) = A_k b_l(i) g_s a(\theta_l) \otimes \xi_i$$  \hspace{1cm} (20)

A bank of $2M$ beamforming filters $W_i$ is applied to $BL$. The beamforming filterbank $W_i$ is in the form of $[W_{i,1}, W_{i,2}, ..., W_{i,2M}]$, where it has $M \times 2M$ dimension. Each beamforming filter steers at a different direction. The normalized $m$-th beamforming is set up as:

$$w_{i,m} = \frac{1}{M} [1, e^{-j \frac{m}{M}}, ..., e^{-j \frac{(M-1)(M-1)}{M}}]$$ \hspace{1cm} (21)

which steers at $\sin \theta = \frac{m}{M}$ for $1 \leq m \leq M+1$ or $\sin \theta = \frac{m - 1}{2M}$ as $m > M + 1$. The example of $M=2$ is shown in Fig. 2.

The filter output has $2M \times M$ dimension:

$$X = W_i^H BL(i) = \begin{bmatrix} \frac{1}{M} [1, e^{-j \frac{m}{M}}, ..., e^{-j \frac{(M-1)(M-1)}{M}}] & \vdots & \frac{1}{M} [1, e^{-j \frac{m}{M}}, ..., e^{-j \frac{(M-1)(M-1)}{M}}] \\ \vdots & \ddots & \vdots \\ \frac{1}{M} [1, e^{-j \frac{m}{M}}, ..., e^{-j \frac{(M-1)(M-1)}{M}}] & \vdots & \frac{1}{M} [1, e^{-j \frac{m}{M}}, ..., e^{-j \frac{(M-1)(M-1)}{M}}] \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{2M} \end{bmatrix}$$ \hspace{1cm} (22)

The filter response for direction of $k$-th user is:

$$\Gamma_k = W_i^H a(\theta_k)$$ \hspace{1cm} (23)

And if we use uniform linear array (ULA) antenna, then:

$$\Gamma_k = \frac{1}{M^2} \sum_{m=0}^{M-1} \sum_{\theta = 0}^{\theta - M \sin \theta} e^{-j \frac{m}{M}}$$ \hspace{1cm} (24)

The signal in $i$-th block is:

$$SW = \sum_{k=1}^{K} A_k g_s \Gamma_k d_i(i) \xi_i^T$$ \hspace{1cm} (25)

If the direction of $k$-th user is desired, by assuming:

$$\begin{bmatrix} E[d_i(j_1) d_i(j_2)] = 0 & j_1 \neq j_2 \\ E[d_i(j_1) d_i(j_2)] = 0 & k \neq m \end{bmatrix}$$ \hspace{1cm} (26)

The correlation matrix for the $m$-th row (i.e. the $m$-th beam forming filter output) is:

$$R_m = E\{\xi_k \xi_k^T\} = E\{\xi_k \xi_k^T\}$$ \hspace{1cm} (27)

Where:

$$\xi_k = \sum_{k=1}^{K} A_k g_s d_i(i) \Gamma_k \xi_k$$ \hspace{1cm} (28)

Thus:

$$R_m = \left( \sum_{k=1}^{K} A_k g_s d_i(i) \Gamma_k \xi_k \right) \left( \sum_{k=1}^{K} A_k g_s d_i(i) \Gamma_k \xi_k \right)^T$$ \hspace{1cm} (29)

Where:

$$\Gamma_{k,n} = \sum_{\theta = 0}^{\theta - M \sin \theta} e^{-j \frac{m}{M}}$$ \hspace{1cm} (30)

$(e,f)$-th element of this matrix is:

$$[A_k g_s d_i(i) \Gamma_k \xi_e e^T + A_k g_s d_i(i) \Gamma_k \xi_f f^T + ... + A_k g_s d_i(i) \Gamma_k \xi_e e^T + A_k g_s d_i(i) \Gamma_k \xi_f f^T + ... + A_k g_s d_i(i) \Gamma_k \xi_e e^T + A_k g_s d_i(i) \Gamma_k \xi_f f^T]$$ \hspace{1cm} (31)

$R_m$ stands for the MAI plus noise covariance matrix:

$$R_m = R_{S,n} + |A_k g_s| \sum_{e=1}^{K} \xi_e \xi_e^T$$ \hspace{1cm} (32)

The direction finding algorithm first identifies a section that the desired signal may fall in. To determine the desired section, we use the largest responses belonging to the beam forming filter. Table 1 and Fig. 1 show the mapping for the 2-antenna system. To achieve this goal, we use the following function that is constructed for each row [7]:

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Figure 1. The beam shape at space-domain for the 2-antenna case: the power response from all beamforming filters
\[ \varphi_m = \frac{1}{\varepsilon_k \mathbf{R}^\dagger \varepsilon_k} \] (33)

Now we can compute equation 33 for each rowthen select two largest values of them named $M_1$ and $M_2$. For a given $\sin \theta$ value in the desired section, we can have two response values into a vector representation as:

\[ \mathbf{b}_r(\sin(\theta)) = \left[ \begin{array}{c}
\left( \sum_{l=0}^{M_1-1} e^{jM_1 \sin(\theta)} \right)^2 \\
\left( \sum_{l=0}^{M_2-1} e^{jM_2 \sin(\theta)} \right)^2 
\end{array} \right] \] (34)

Where $\sin \theta$ ranges from 0 to $\frac{1}{2M}$. After identification of target section, a fine search is performed. $\mathbf{b}_r(\sin(\theta))$ can be treated as a steering vector to search in the range $\sin \theta = 0 \sim \frac{1}{2M}$. By collecting the two largest soft values from (33) to form a vector and constructing an orthogonal projector, we obtain:

\[ \mathbf{\hat{P}} = \begin{bmatrix} \mathbf{\hat{P}}_{M_1} \\ \mathbf{\hat{P}}_{M_2} \end{bmatrix} \] (35)

\[ \mathbf{P}_\theta = \frac{\mathbf{\hat{P}}}{{\mathbf{\hat{P}}}^T \mathbf{\hat{P}}} \] (36)

\[ \sin(\hat{\theta}) = \arg \max_{\sin(\theta)} \left| \mathbf{b}_r(\sin(\theta))^T (\mathbf{I} - \mathbf{P}_\theta) \mathbf{b}_r(\sin(\theta)) \right| \] (37)

Let $\sec$ stands for the estimated section, then the angle $\hat{\theta}_k$ can be obtained by:

\[ \hat{\theta}_k = \begin{cases} 
\sin^{-1}(\sin(\hat{\theta})) + (\sec - 2M - 1) \frac{1}{2M} \text{ if odd} \\
\sin^{-1}(\frac{1}{2} \sin(\hat{\theta})) - (\sec - 2M - 1) \frac{1}{2M} \text{ if even}
\end{cases} \] (38)

B. Proposed method for asynchronous multipath case

The algorithm for asynchronous multipath fading is an extension of the method for the single-path synchronous case. In this case, we collect the signals of the desired user from all L different paths. The method of DOA estimation for the single-path case (relation (38)) is not applicable directly since the correlation between signals from different paths of the k-th user will hinder its applicability. We should try to decorrelate the received signal of each path from other paths of the k-th user. Without loss of generality, we assume that the different paths of users are numbered in increasing order of path delays, i.e., $\tau_{s_k} \leq \tau_{s_{k+1}} \leq \ldots \leq \tau_{s_K}$ for $k \in \{1,...,K\}$. The received vector of $N_c$ samples of chip matched filter synchronized with $\tau_{s_k}$ (the delay of the l-th path of the k-th user) at any antenna will contain interference of the same symbol from the m-th path of the k-th user, which can be represented by a $N_c \times 1$ vector as:

\[ \mathbf{t}_m = [t_m(0), \ldots, t_m(N_c - 1)]^T \] (39)

\[ \mathbf{t}_m(j) = \int_{T_{s_k} + \tau_{s_k}}^{t_j + \tau_{s_k}} s_k(t - \tau_{s_k}) \psi_p(t - jT_c - \tau_{s_k}) dt \] (40)

In fact $\mathbf{t}_m$ is the interference of m-th path of the k-th user on the l-th path of the k-th one. We define the $N_c \times (L - 1)$ matrix $\mathbf{C}_m$ with columns $\mathbf{t}_m$ for $m = 1, \ldots, L \neq l$

\[ \mathbf{C}_m = [t_1; t_2; \ldots; t_{s_k}; \ldots; t_L] \] (41)

The column space of matrix $\mathbf{C}_m$ (space spanned by columns of $\mathbf{C}_m$) is in fact the interference space caused by the different paths of the k-th user on the l-th path of the k-th user. To decorrelate the received signal from the l-th path of the k-th user and the other paths of the k-th user, we need to project the received vector of $N_c$ samples of the chip matched filter into a space orthogonal to the column space of matrix $\mathbf{C}_m$. The projection operator into the orthogonal space of $\mathbf{C}_m$ is [8]:

\[ \mathbf{P}_m^\perp = \mathbf{I} - \mathbf{C}_m(\mathbf{C}_m^H \mathbf{C}_m)^{-1} \mathbf{C}_m^H \] (42)

In other words, the vector $\mathbf{B}_m^\perp(i)$ is not affected by other paths and is totally decorrelated from the users of other path signals, then we can apply the previous method to $\mathbf{B}_m^\perp$ and estimate the direction of the arrival.

IV. SIMULATION

In this section, the performance of the proposed method is evaluated in a multipath DS-CDMA system using gold code sequences of length 31. In all simulations, the receiver has a uniform linear array
with half wavelength spacing between adjacent antennas and the antenna elements are assumed to be omnidirectional. There are eight active users (K=8) and three paths for each user. The real and the imaginary parts of the complex channel gains have been generated randomly by a zero mean Gaussian distribution with unit variance.

The root mean square error (RMSE) and bias versus number of data samples, SNR and number of array elements are evaluated for the first, second and third paths of 1-th user and plotted in Fig.2-7. To compare the performance of the algorithm, we compare this method with the proposed algorithms in [5], [8] and [9] in Fig. 8 and 9. In Fig. 10 and 11, the bias and RMSE of proposed algorithm for DOA estimation are illustrated for different value of SNR respectively. As we expected, with increase of SNR, bias and RMSE of proposed algorithm for DOA estimation has been decreased. In the following, to show the consistency of our algorithm the RMSE of proposed algorithm for DOA estimation is illustrated for different value of the data samples in Fig. 13. As we see in simulation result with increase of the number of data samples RMSE tend to zero. This clearly shows the consistency of the proposed algorithm for DOA estimation.
Figure 7. Bias versus Number of Array Elements

Figure 8. Comparison of RMSE against SNR for three methods

Figure 9. Comparison of RMSE against Number of Array Elements for three methods

Figure 10. Bias versus SNR for proposed method

Figure 11. RMSE versus SNR for proposed method

Figure 12. RMSE versus the number of data samples for proposed method
TABLE I. THE MAPPING OF SECTIONS AND BEAMFORMING FILTERS.

<table>
<thead>
<tr>
<th>section</th>
<th>range for 2-antenna</th>
<th>2-antenna, m</th>
</tr>
</thead>
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<tr>
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<td>-1/3,4</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>-3/4, -2/4</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>-2/4, -1/4</td>
<td>4.1</td>
</tr>
<tr>
<td>4</td>
<td>0/4, 1/4</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>1/4, 2/4</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
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<td>2.3</td>
</tr>
<tr>
<td>8</td>
<td>3/4, 1</td>
<td>3.2</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper a new method for estimating the direction of arrival of signals in frequency-selective fading channel with correlated multipaths is proposed. At first, we decorrelated the received signal of each path from other paths, and then passed it from a beam forming filter. In this approach in contrast to other DOA estimation approaches, it was not required to search all angles, and it did not need EVD. Due to the equivariance of the scenario to a DOA estimation of single source in the noise environment, AIC and MDL criteria were not required for estimating the number of sources. Since beam forming filters were used, the destroying effect of other users on the desired user signal was also decreased and the efficiency of the algorithm was increased. The search area was decreased almost to one tenth. Some of the other advantages of the proposed method are: forming of correlation matrix including vectors with smaller dimension which results in lower complexity of calculation. Also, Simulations have shown that the suggested approach works properly in the case that the number of sources exceeds the number of array elements. The simulation results show that the proposed method has good stability in the multipath fading channel and the estimates of the proposed method are consistent. Intensification of the multipath fading reduces the performance of estimator. This efficiency decrease can be compensated by increasing.

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