# SEMIBLIND CHANNEL AND CARRIER FREQUENCY-OFFSET ESTIMATION FOR ORTHOGONALLY SPACE-TIME BLOCK CODED MIMO SYSTEMS


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## ABSTRACT

The problem of joint channel and carrier frequency offset (CFO) estimation is addressed in the context of multiple-input multiple-output (MIMO) communications using orthogonal space-time-block codes (OSTBCs). A new semiblind method is proposed to jointly estimate the channel matrix and the CFO parameter. Our method blindly estimates the CFO parameter along with a low-dimensional subspace where the channel is located, and then uses a few training blocks to extract the channel parameters from this subspace.

***Index Terms*—** Channel and frequency offset estimation, MIMO systems, orthogonal space-time block codes


## 1. INTRODUCTION

Space-time coding has recently gained a significant interest because of its ability to combat fading via exploiting spatial diversity offered by multiple-input multiple-output (MIMO) communications [1]-[3].

Among numerous space-time coding schemes proposed so far, orthogonal space-time codes (OSTBCs) are of a particular interest due to their ability to enable full diversity at a low decoding complexity. Specifically, the optimal maximum likelihood (ML) OSTBC decoder consists of a simple linear matched filter (MF) receiver followed by a symbol-by-symbol decoder. It has recently been demonstrated that for the majority of OSTBCs, the channel is blindly identifiable [4], [5]. Therefore, using OSTBCs as the underlying space-time coding scheme can potentially reduce the amount of transmitted training symbols and improve the system bandwidth efficiency.

Using the flat fading channel assumption, a blind method has been presented in [5] to estimate the channel matrix. However, the technique of [5] assumes that no carrier frequency offset (CFO) is present between the transmitter and receiver. Unfortunately, the latter assumption may be violated in practice. For example, even in the case of perfect frequency synchronization between the transmitter and receiver, frequency offsets can be caused by mobility-induced Doppler effects.

The CFO estimation problem has been recently studied in application to different communication schemes such as training-based MIMO systems [6], and orthogonal frequency-division multiplexing (OFDM)-based SISO and MIMO systems [7], [8].

In [9], we have developed a computationally efficient blind method to jointly estimate the channel matrix and the CFO parameter in orthogonally block coded MIMO systems. Although our method is applicable to the majority of OSTBCs, there are a few codes (including the celebrated Alamouti's code [2]) that suffer from an intrinsic ambiguity in joint channel, CFO, and symbol estimation. For such OSTBCs, the method of [9] is not applicable. In this paper, we develop a semiblind modification of the technique of [9] that resolves the aforementioned estimation ambiguity by means of using a few training blocks. The proposed technique can be also applied to MIMO-OFDM systems [7], [8].

## 2. BACKGROUND

The input-output relationship for a MIMO system with $N$ transmit and $M$ receive antennas and flat block-fading channel can be expressed as [10]

$$\mathbf{y}(t) = e^{j\omega_o t}\mathbf{x}(t)\mathbf{H} + \mathbf{v}(t)$$

where $\mathbf{y}(t) = [y_1(t)\ \cdots\ y_M(t)]$, $\mathbf{x}(t) = [x_1(t)\ \cdots\ x_N(t)]$, and $\mathbf{v}(t) = [v_1(t)\ \cdots\ v_M(t)]$ are the complex row vectors of the received signal, transmitted signal, and additive noise, respectively, $\omega_o$ is the CFO between the transmitter and receiver, and $\mathbf{H}$ is the $N \times M$ complex channel matrix. It is assumed that the noise is spatially and temporally white complex Gaussian with variance $\sigma^2$.

Assuming a block transmission scheme with block length $T$, the signal model for the $n$th received data block can be written as [9]

$$\mathbf{Y}(n) = \mathbf{D}(n, \omega_o)\mathbf{X}(n)\mathbf{H} + \mathbf{V}(n) \tag{1}$$

where

$$\begin{aligned}
\mathbf{Y}(n) &\triangleq \Big[\mathbf{y}^T((n-1)T+1)\ \cdots\ \mathbf{y}^T(nT)\Big]^T \\
\mathbf{X}(n) &\triangleq \Big[\mathbf{x}^T((n-1)T+1)\ \cdots\ \mathbf{x}^T(nT)\Big]^T \\
\mathbf{V}(n) &\triangleq \Big[\mathbf{v}^T((n-1)T+1)\ \cdots\ \mathbf{v}^T(nT)\Big]^T
\end{aligned}$$

are the $n$th blocks of the received signals, transmitted signals, and additive noise, respectively, $(\cdot)^T$ is the transpose operator, and the $T \times T$ complex diagonal matrix $\mathbf{D}(n, \omega_o)$ is defined as

$$\mathbf{D}(n, \omega_o) \triangleq \mathrm{diag}\Big\{e^{j\omega_o((n-1)T+1)}\ \cdots\ e^{j\omega_o(nT)}\Big\}.$$

The slow fading channel case is considered, i.e., the channel coherence time is assumed to be substantially larger than the data block length $T$.

The $T \times N$ matrix $\mathbf{X}(\mathbf{s}(n))$ is called an OSTBC [3] if all elements of $\mathbf{X}(\mathbf{s}(n))$ are linear functions of the $K$ complex variables $s_1(n), s_2(n), \ldots, s_K(n)$ and their complex conjugates, and if for any arbitrary $\mathbf{s}(n)$, $\mathbf{X}(\mathbf{s}(n))$ satisfies

$$\mathbf{X}^H(\mathbf{s}(n))\mathbf{X}(\mathbf{s}(n)) = \|\mathbf{s}(n)\|^2\mathbf{I}_N$$

where $\mathbf{s}(n)$ is the $n$th symbol vector of the length $K$, $\mathbf{I}_N$ is the $N \times N$ identity matrix, $\|\cdot\|$ is the Euclidean norm, and $(\cdot)^H$ denotes the Hermitian transpose.

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It follows from the definition of OSTBCs that $\mathbf{X}(\mathbf{s}(n))$ can be written as [11], [12]

$$\mathbf{X}(\mathbf{s}(n)) = \sum_{k=1}^{K} \left( \mathbf{C}_k \mathrm{Re}\{s_k(n)\} + \mathbf{C}_{k+K} \mathrm{Im}\{s_k(n)\} \right) \quad (2)$$

where

$$\mathbf{C}_k \triangleq \begin{cases} \mathbf{X}(\mathbf{e}_k), & \text{for } 1 \le k \le K \\ \mathbf{X}(j\mathbf{e}_k), & \text{for } K < k \le 2K \end{cases}$$

$\mathrm{Re}\{\cdot\}$ and $\mathrm{Im}\{\cdot\}$ denote the real and imaginary parts, respectively, $j = \sqrt{-1}$, and $\mathbf{e}_k$ is a vector of conformable dimension that contains one in its $k$th entry and zeros elsewhere. In fact, any OSTBC is completely defined by its *basis matrices* $\{\mathbf{C}_k\}_{k=1}^{K}$ [12].

Let us define the "underline" operator for any matrix $\mathbf{P}$ as [5]

$$\underline{\mathbf{P}} \triangleq \begin{bmatrix} \mathrm{vec}\{\mathrm{Re}(\mathbf{P})\} \\ \mathrm{vec}\{\mathrm{Im}(\mathbf{P})\} \end{bmatrix} \quad (3)$$

where $\mathrm{vec}\{\cdot\}$ is the vectorization operator stacking all columns of a matrix on top of each other.

If there is no CFO (i.e., $\omega_\mathrm{o} = 0$), then, using (2) and (3), the model in (1) can be reformulated as [12]

$$\mathbf{z}(n) \triangleq \underline{\mathbf{Y}(n)} = \mathbf{A}(\mathbf{H})\mathbf{g}(n) + \boldsymbol{\nu}(n) \quad (4)$$

where

$$\mathbf{g}(n) \triangleq \underline{\mathbf{s}(n)}$$
$$\boldsymbol{\nu}(n) \triangleq \underline{\mathbf{V}(n)}$$

and the $2MT \times 2K$ real matrix $\mathbf{A}(\mathbf{H})$ is given by

$$\mathbf{A}(\mathbf{H}) = [\underline{\mathbf{C}_1\mathbf{H}} \quad \underline{\mathbf{C}_2\mathbf{H}} \quad \cdots \quad \underline{\mathbf{C}_{2K}\mathbf{H}}].$$

It can be readily verified that, regardless of the value of the channel matrix $\mathbf{H}$, the matrix $\mathbf{A}(\mathbf{H})$ satisfies the so-called *decoupling property*, i.e., its columns have identical norms and are orthogonal to each other [12]:

$$\mathbf{A}^T(\mathbf{H})\mathbf{A}(\mathbf{H}) = \|\mathbf{H}\|_F^2\, \mathbf{I}_{2K}$$

where $\|\cdot\|_F$ denotes the Frobenius norm.

In the presence of CFO, the matrix

$$\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n)) \triangleq \mathbf{D}(n, \omega_\mathrm{o})\mathbf{X}(\mathbf{s}(n))$$

is a legitimate OSTBC regardless of the value of $\omega_0$, because it obeys the orthogonality property [9]:

$$\tilde{\mathbf{X}}^H(n, \omega_\mathrm{o}, \mathbf{s}(n))\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n)) = \|\mathbf{s}(n)\|^2 \mathbf{I}_N.$$

It can be readily verified that

$$\begin{aligned} &\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n)) \\ &= \sum_{k=1}^{K} \Big( \tilde{\mathbf{C}}_k(n, \omega_\mathrm{o}) \mathrm{Re}\{s_k(n)\} + \tilde{\mathbf{C}}_{k+K}(n, \omega_\mathrm{o}) \mathrm{Im}\{s_k(n)\} \Big) \end{aligned}$$

where

$$\tilde{\mathbf{C}}_k(n, \omega_\mathrm{o}) \triangleq \mathbf{D}(n, \omega_\mathrm{o})\mathbf{C}_k.$$

Note that the basis matrices $\{\tilde{\mathbf{C}}_k(n, \omega_0)\}_{k=1}^{2K}$ of $\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n))$ are time varying. Because of this, $\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n))$ is termed in [9] a *time-varying OSTBC*.

Using (5), we have that in the presence of CFO, (4) should be modified as

$$\mathbf{z}(n) = \mathbf{A}(n, \omega_\mathrm{o}, \mathbf{H})\mathbf{g}(n) + \boldsymbol{\nu}(n)$$

where

$$\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{H}) \triangleq [\underline{\tilde{\mathbf{C}}_1(n, \omega_\mathrm{o})\mathbf{H}} \quad \cdots \quad \underline{\tilde{\mathbf{C}}_{2K}(n, \omega_\mathrm{o})\mathbf{H}}].$$

As $\tilde{\mathbf{X}}(n, \omega_\mathrm{o}, \mathbf{s}(n))$ is a legitimate OSTBC, the matrix $\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{H})$ satisfies the decoupling property regardless of the values of $n$ and $\omega_\mathrm{o}$, that is,

$$\mathbf{A}^T(n, \omega_\mathrm{o}, \mathbf{H})\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{H}) = \|\mathbf{H}\|_F^2\, \mathbf{I}_{2K}.$$

Defining an equivalent *channel vector* as $\mathbf{h} \triangleq \underline{\mathbf{H}}$, let us (with a small abuse of notation) replace $\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{H})$ by $\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{h})$. As $\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{h})$ is linear in $\mathbf{h}$, we have [9]

$$\mathrm{vec}\{\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{h})\} = \boldsymbol{\Phi}(n, \omega_\mathrm{o})\mathbf{h}$$

where $\boldsymbol{\Phi}(n, \omega_\mathrm{o})$ is a $4KMT \times 2MN$ matrix whose $k$th column can be defined as

$$[\boldsymbol{\Phi}(n, \omega_\mathrm{o})]_k \triangleq \mathrm{vec}\{\mathbf{A}(n, \omega_\mathrm{o}, \mathbf{e}_k)\}$$

where $[\cdot]_k$ denotes the $k$th column of a matrix and $\mathbf{e}_k$ is the $k$th column of the identity matrix $\mathbf{I}_{2MN}$.

Let $n_B$ data blocks be available for each channel realization. Treating the channel vector $\mathbf{h}$, the CFO parameter $\omega_\mathrm{o}$, and the information symbols $\{\mathbf{g}(n)\}_{n=1}^{n_B}$ as unknown deterministic parameters, the ML approach was used in [9] to jointly estimate these parameters. To obtain the ML estimates of all these parameters, the log-likelihood (LL) function has to be maximized. As a result, the parameter estimates can be obtained by solving the following optimization problem:

$$\max_{\omega_\mathrm{o}, \mathbf{h}, \mathbf{S} \in \Omega} \log f\big(\mathbf{z}(1), \ldots, \mathbf{z}(n_B) \,|\, \mathbf{S},\, \mathbf{h}, \omega_\mathrm{o}\big) \quad (5)$$

where $f\big(\mathbf{z}(1), \ldots, \mathbf{z}(n_B) \,|\, \mathbf{S},\, \mathbf{h}, \omega_\mathrm{o}\big)$ is the likelihood function computed for the $n_B$ snapshots $\{\mathbf{z}(n)\}_{n=1}^{n_B}$,

$$\mathbf{S} \triangleq [\mathbf{g}(1)\ \mathbf{g}(2)\ \cdots\ \mathbf{g}(n_B)]$$

and $\Omega$ is the finite set of all possible values of $\mathbf{S}$. As the computational cost of solving (5) grows exponentially in $n_B$, the optimization problem in (5) has been simplified in [9] by relaxing the finite alphabet constraint $\mathbf{S} \in \Omega$. That is, it has been assumed in [9] that $\mathbf{S} \in \mathbb{R}^{2K \times n_B}$. Using such a relaxation, the CFO estimate $\hat{\omega}_0$ can be obtained as [9]

$$\hat{\omega}_\mathrm{o} = \arg\max_{\omega_\mathrm{o}} \lambda_{\max}\{\boldsymbol{\Psi}(\omega_\mathrm{o})\} \quad (6)$$

where $\lambda_{\max}\{\cdot\}$ denotes the largest eigenvalue of a matrix, the matrix $\boldsymbol{\Psi}(\omega_\mathrm{o})$ is defined as

$$\boldsymbol{\Psi}(\omega_\mathrm{o}) \triangleq \sum_{n=1}^{n_B} \boldsymbol{\Phi}^T(n, \omega_\mathrm{o}) \left( \mathbf{I}_{2K} \otimes \mathbf{z}(n)\mathbf{z}^T(n) \right) \boldsymbol{\Phi}(n, \omega_\mathrm{o})$$

and $\otimes$ denotes the Kronecker product. Furthermore, given the estimate of $\omega_\mathrm{o}$, the channel vector estimate can be computed as [9]

$$\hat{\mathbf{h}} = \mathcal{P}\{\boldsymbol{\Psi}(\hat{\omega}_\mathrm{o})\} \quad (7)$$

where $\mathcal{P}\{\cdot\}$ denotes the principal eigenvector of a matrix.

Once the CFO parameter and the channel vector are estimated using (6) and (7), respectively, the information symbols can be straightforwardly decoded by using the channel and CFO estimates in the well-known linear MF receiver [9].

It should be stressed that the channel estimate in (7) suffers from a real scalar ambiguity because the norm of the channel remains unknown. Therefore, the aforementioned blind channel/CFO method of [9] is not applicable to non-constant modulus constellations. Furthermore, this technique suffers from an intrinsic ambiguity in joint channel, CFO, and symbol estimation for several important OSTBCs including the celebrated Alamouti's code. As a result, the blind method of [9] is not applicable to such codes.

In the next section, we show how the training approach can be combined with the blind technique of [9] to resolve the aforementioned ambiguity using a small number of training blocks.

## 3. SEMIBLIND JOINT CHANNEL AND CFO ESTIMATION

The estimate of (7) in the previous section is based on the assumption that the largest eigenvalue of $\mathbf{\Psi}(\hat{\omega}_{\rm o})$ has no multiplicity. Although this assumption holds true for the majority of OSTBCs, there are several exceptions [5] that include the Alamouti's code. For those specific OSTBCs, $\mathbf{h}$ belongs to the subspace spanned by the corresponding multiple principal eigenvectors of $\mathbf{\Psi}(\hat{\omega}_{\rm o})$. For this case, let us develop a semiblind method to estimate the channel vector $\mathbf{h}$ from the aforementioned subspace based on a few training blocks. Let the multiplicity order of the largest eigenvalue of $\mathbf{\Psi}(\hat{\omega}_{\rm o})$ be $n_o > 1$ and the corresponding orthonormal principal eigenvectors be $\{\mathbf{u}_l\}_{l=1}^{n_o}$. As $\mathbf{h}$ belongs to the subspace spanned by $\{\mathbf{u}_l\}_{l=1}^{n_o}$, we have

$$\mathbf{h} = \sum_{l=1}^{n_o} \alpha_l \mathbf{u}_l = \mathbf{U}\boldsymbol{\alpha} \tag{8}$$

where

$$\begin{aligned} \mathbf{U} &\triangleq [\mathbf{u}_1 \ \mathbf{u}_2 \ \cdots \ \mathbf{u}_{n_o}] \\ \boldsymbol{\alpha} &\triangleq [\alpha_1 \ \alpha_2 \ \cdots \ \alpha_{n_o}]^T. \end{aligned}$$

The key idea of the proposed semiblind approach is to obtain the estimate of $\mathbf{U}$ blindly, while estimating the vector $\boldsymbol{\alpha}$ using training symbols. As the number of entries in $\boldsymbol{\alpha}$ is much smaller than that in $\mathbf{h}$, such semiblind estimator will require much less training data blocks than the direct training-based channel estimator which obtains all entries of $\mathbf{h}$ in a non-blind way.

Assuming that the first $n_T$ blocks contain training symbols and using (8), for any $i$th training block ($i = 1 \ldots, n_T$), it can be readliy verified that

$$\mathbf{z}(i) = \mathbf{B}(i, \omega_0, \mathbf{g}(i))\mathbf{U}\boldsymbol{\alpha} + \boldsymbol{\nu}(i) \tag{9}$$

where the $k$th column of a $2MT \times 2MN$ real-valued matrix $\mathbf{B}(i, \omega_0, \mathbf{g}(i))$ is defined as

$$[\mathbf{B}(i, \omega_0, \mathbf{g}(i))]_k \triangleq \mathbf{A}(i, \omega_0, \mathbf{e}_k)\mathbf{g}(i)\,.$$

Defining

$$\begin{aligned} \mathbf{r} &\triangleq [\mathbf{z}^T(1) \ \ \cdots \ \ \mathbf{z}^T(n_T)]^T \\ \boldsymbol{\xi} &\triangleq [\boldsymbol{\nu}^T(1) \ \ \cdots \ \ \boldsymbol{\nu}^T(n_T)]^T \\ \mathbf{Q} &\triangleq [\mathbf{U}^T\mathbf{B}^T(1, \omega_0, \mathbf{g}(1)) \ \ \cdots \ \ \mathbf{U}^T\mathbf{B}^T(n_T, \omega_0, \mathbf{g}(n_T))]^T \end{aligned}$$

we can rewrite (9) for all $i = 1, \ldots, n_T$ as

$$\mathbf{r} = \mathbf{Q}\boldsymbol{\alpha} + \boldsymbol{\xi}\,. \tag{10}$$

Using (10), the maximum likelihood (ML) estimate of the vector $\boldsymbol{\alpha}$ can be written as

$$\hat{\boldsymbol{\alpha}} = (\mathbf{Q}^T\mathbf{Q})^{-1}\mathbf{Q}^T\mathbf{r}\,. \tag{11}$$

This estimate can be used to obtain the coefficients $\{\alpha_l\}_{l=1}^{n_o}$ from a few training symbols to resolve the ambiguity in the channel vector estimate.

The following lemma helps us to simplify the computational complexity associated with computing $(\mathbf{Q}^T\mathbf{Q})^{-1}$ in (11).

***Lemma 1:*** *The columns of the matrix* $\mathbf{Q}$ *are orthogonal to each other and*

$$\mathbf{Q}^T\mathbf{Q} = \left(\sum_{n=1}^{n_T} \|\mathbf{g}(n)\|^2\right)\mathbf{I}_{n_o}\,. \tag{12}$$

***Proof:*** See [13]. ■

Using Lemma 1, one can write the ML estimate of the vector $\boldsymbol{\alpha}$ in (11) as

$$\hat{\boldsymbol{\alpha}} = \frac{1}{\sum_{n=1}^{n_B} \|\mathbf{g}(n)\|^2}\mathbf{Q}^T\mathbf{r}\,. \tag{13}$$

According to (13), the ML estimate of $\boldsymbol{\alpha}$ can be obtained from $\mathbf{r}$ in a very simple way that is devoid of matrix inverse.

## 4. SIMULATION RESULTS

In our simulations, a MIMO system with $K = 4$, $T = 8$, $N = 4$, and $M = 2$ is considered. The half-rate OSTBC of [3] is used to encode the information symbols. For this code $n_o = 4$ and, therefore, the blind method of [9] is not applicable. It is assumed that a single training block is used in our semiblind approach ($n_T = 1$). Note that this amount of training is insufficient for the conventional training-based methods and, therefore, these techniques are not included in our figures. The SNR is defined as $\sigma_h^2/\sigma^2$ where $\sigma_h^2$ is the variance of each entry of $\mathbf{H}$. In each simulation run, the elements of $\mathbf{H}$ are independently drawn from a Gaussian distribution and are fixed during each run (i.e., the channel remains constant over the number of data blocks that are used to estimate the CFO and the channel). Throughout the simulations, QPSK symbols are used and $\omega_{\rm o} = 0.9$ is taken.

To quantify the performance of our technique in estimating the CFO parameter, we use the normalized mean squared error (NMSE) of CFO estimates. The NMSE can be defined as

$$\text{CFO-NMSE} \triangleq \frac{\mathrm{E}\{(\hat{\omega}_o - \omega_o)^2\}}{\omega_o^2}$$

where $\mathrm{E}\{\cdot\}$ stands for the expected value. Similarly, to quantify the performance of our method in terms of channel estimation accuracy, we use the NMSE of channel estimates (C-NMSE) defined as

$$\text{C-NMSE} \triangleq \mathrm{E}\left\{\frac{\|\hat{\mathbf{h}} - \mathbf{h}\|^2}{\|\mathbf{h}\|^2}\right\}.$$

Figs. 1 and 2 show the CFO-NMSE and C-NMSE, respectively, versus SNR for different values of $n_B$. As can be seen from the figures, even with a single training block, the proposed approach provides quite accurate estimates of the CFO and channel parameters. The quality of these estimates substantially improves when increasing $n_B$.

More simulation results on the performance of our method including bit error rate (BER) comparisons of the proposed technique with known training-based approaches will be presented in the journal version [13] of this paper.

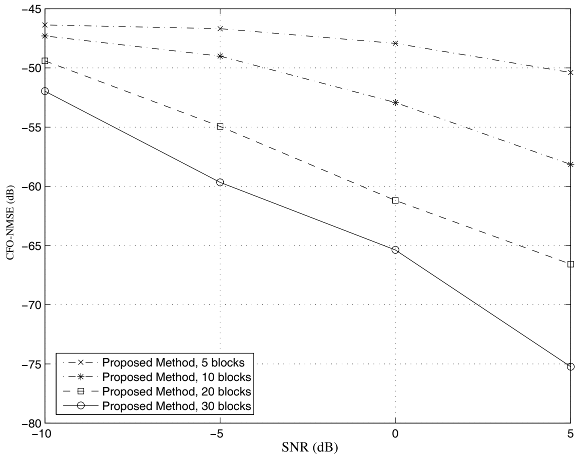


**Fig. 1**. CFO-NMSE versus SNR for different values of $n_B$.

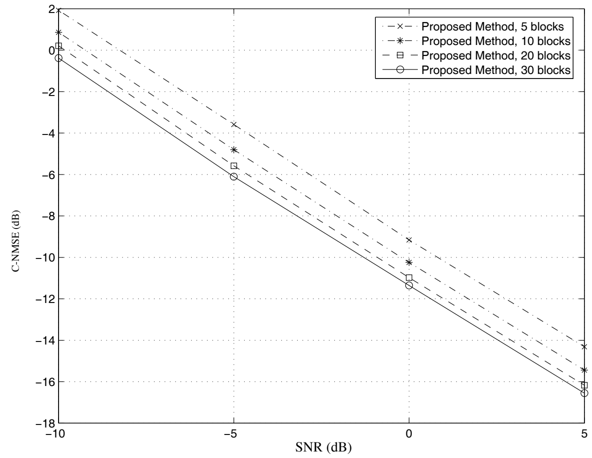


**Fig. 2**. C-NMSE versus SNR for different values of $n_B$.

## 5. CONCLUSIONS

We have presented a semiblind approach to jointly estimate the channel matrix and the CFO parameter in orthogonal space-time block coded MIMO communication systems. Our method blindly estimates the CFO parameter along with a low-dimensional subspace where the equivalent channel vector is located, and then uses a few training blocks to extract the channel matrix from this subspace. Simulation results have validated the performance of the proposed method.

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