SEMIBLIND ML OSTBC-OFDM DETECTION IN BLOCK FADING CHANNELS

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ABSTRACT

This paper presents a semiblind maximum-likelihood (ML) detector for the orthogonal space-time block coded orthogonal frequency division multiplexing (OSTBC-OFDM) system. Many existing blind/ semiblind OSTBC-OFDM receivers typically require that the channel is static over a multitude of OSTBC-OFDM blocks. The proposed method is specifically for detection over one OSTBC-OFDM block only, and hence is well suited to block fading channels. The presented identifiability analysis shows that the data can be uniquely identified in a probability one sense by using one pilot code only, in contrast to the pilot-based least-squares channel estimator which requires at least L pilot codes where L is the channel length. Simulation examples are then presented to show the efficacy of the proposed detector.

***Index Terms*—** MIMO systems, Maximum likelihood detection, Identification, Multipath channels.

1. INTRODUCTION

In recent years, the space-time block coded orthogonal frequency division multiplexing (STBC-OFDM) system has drawn a lot of attentions because it provides a straightforward way of extending STBC techniques to frequency selective fading channels [1–7]. In particular, the STBC-OFDM system based on the orthogonal STBCs (OSTBCs) [9] maximizes the transmit diversity and has a simple Maximum-likelihood (ML) decoder given channel state information (CSI) at the receiver. To estimate CSI with high spectral efficiency, it has been a great interest to develop blind/semiblind channel estimation methods for OSTBC-OFDM systems [1–4]. However, most of the existing methods are based on the second-order statistics (SOSs) of the received signal, which usually require the channel to remain static over many OSTBC-OFDM blocks. When the channel is static only for two OSTBC-OFDM blocks, a particularly convenient blind scheme is the differentially encoded OSTBC-OFDM system [6]. It, however, incurs a 3 dB performance loss in signal-to-noise ratio (SNR).

In the paper, the channel is assumed to be *block fading*, i.e., the channel coefficients do not vary for one OSTBC-OFDM block interval but can change from block to block. By using a time-domain channel parameterization, we apply the deterministic ML criterion [10, 11] to jointly detect the data and estimate the channel with one OSTBC-OFDM signal block only. An important result shown here is that the data can be uniquely identified with probability one when there is only one pilot code transmitted. This results in a semiblind ML OSTBC-OFDM detector that uses fewer pilot codes than the conventional pilot-aided channel estimator [8]. Regarding the realization problem, it is further shown that the proposed detector can be recast as a Boolean quadratic program (BQP), which can be handled effectively by various means. Simulation results in Sec. 4 further demonstrate that the proposed detector can yield very promising performance.

2. OSTBC-OFDM SIGNAL MODEL

Consider an OSTBC-OFDM system [5, 7] equipped with N_t transmit antennas and N_r receive antennas. Let N_c denote the discrete Fourier transform (DFT) size and T be the code length. Assuming that the channel coefficients are static for T OFDM blocks, the received code matrix in subchannel n is given by [5]

$$\mathbf{Y}_n = \mathbf{C}(\mathbf{s}_n)\mathbf{H}_n + \mathbf{W}_n, \tag{1}$$

where $n = 1, ..., N_c$, and

$\mathbf{Y}_n \in \mathbb{C}^{T\times N_r}$	received code matrix for subchannel n;
$\mathbf{s}_n \in \{\pm 1\}^K$	transmitted data vector for subchannel n where K is the number of bits per code;
$\mathbf{C}(\cdot) \in \mathbb{C}^{T\times N_t}$	transmitted OSTBC ($T \geq N_t$);
$\mathbf{H}_n \in \mathbb{C}^{N_t\times N_r}$	multiple-input-multiple-output (MIMO) channel frequency response matrix for subchannel n;
$\mathbf{W}_n \in \mathbb{C}^{T\times N_r}$	AWGN matrix for subchannel n where the average power per entry is σ_w^2.

In general, the OSTBCs can be represented by a linear dispersion form. Specifically, for BPSK/QPSK OSTBCs, they can be expressed as [9]

$$\mathbf{C}(\mathbf{s}_n) = \sum_{k=1}^{K} \mathbf{X}_k s_{n,k}, \tag{2}$$

where $s_{n,k} \in \{\pm 1\}$ is the kth entry of $\mathbf{s}_n$, and $\mathbf{X}_k \in \mathbb{C}^{T\times N_t}$ are the basis matrices. The basis matrices are specially designed such that for any $\mathbf{s}_n \in \{\pm 1\}^K$,

$$\mathbf{C}^H(\mathbf{s}_n)\mathbf{C}(\mathbf{s}_n) = K\mathbf{I}_{N_t}, \tag{3}$$

where $\mathbf{I}_{N_t}$ is the $N_t \times N_t$ identity matrix.

Because the time-domain channel coefficients can usually be modeled by a finite impulse response (FIR) whose length can be much less than N_c, we can parameterize $\mathbf{H}_n$ using the FIR channel coefficients. Let $\mathbf{h}_{m,j} \in \mathbb{C}^L$ be a column vector containing the time-domain channel coefficients between the mth transmit antenna and the jth receive antenna, where L is the channel length. Define

$$\boldsymbol{\mathcal{H}} = \begin{bmatrix} \mathbf{h}_{1,1} & \cdots & \mathbf{h}_{1,N_r} \\ \vdots & \ddots & \vdots \\ \mathbf{h}_{N_t,1} & \cdots & \mathbf{h}_{N_t,N_r} \end{bmatrix} \in \mathbb{C}^{LN_t\times N_r}. \tag{4}$$

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Let $\mathbf{F} \in \mathbb{C}^{N_c \times L}$ with the nth row given by

$$\mathbf{f}_n^T = \frac{1}{\sqrt{N_c}}[1, e^{-j\frac{2\pi}{N_c}(n-1)}, \ ..., e^{-j\frac{2\pi}{N_c}(n-1)(L-1)}]. \tag{5}$$

Then one can easily show that

$$\mathbf{H}_n = \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_n^T\right) \boldsymbol{\mathcal{H}}, \tag{6}$$

where $\otimes$ denotes the Kronecker product. By substituting (6) into (1), the received signal can be rewritten as

$$\mathbf{Y}_n = \mathbf{C}(\mathbf{s}_n) \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_n^T\right) \boldsymbol{\mathcal{H}} + \mathbf{W}_n. \tag{7}$$

Let $\mathbf{s} = [\mathbf{s}_1^T, \ ..., \ \mathbf{s}_{N_c}^T]^T$ and $\boldsymbol{\mathcal{Y}} = [\mathbf{Y}_1^T, \ ..., \ \mathbf{Y}_{N_c}^T]^T$. Then (7) can be further re-expressed in a compact form as

$$\boldsymbol{\mathcal{Y}} = \boldsymbol{\mathcal{C}}(\mathbf{s})\boldsymbol{\mathcal{H}} + \boldsymbol{\mathcal{W}}, \tag{8}$$

where $\boldsymbol{\mathcal{W}} = [\mathbf{W}_1^T, \ ..., \ \mathbf{W}_{N_c}^T]^T$ and

$$\boldsymbol{\mathcal{C}}(\mathbf{s}) = \begin{bmatrix} \mathbf{C}(\mathbf{s}_1) \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_1^T\right) \\ \vdots \\ \mathbf{C}(\mathbf{s}_{N_c}) \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_{N_c}^T\right) \end{bmatrix} \in \mathbb{C}^{N_c T \times L N_t}. \tag{9}$$

In the paper, our interest lies in jointly estimating $\boldsymbol{\mathcal{H}}$ and detecting $\mathbf{s}$ from $\boldsymbol{\mathcal{Y}}$. As mentioned and clarified in Sec. 1, the significance of this investigation is in the block fading scenario where $\boldsymbol{\mathcal{H}}$ may not be the same for each OSTBC-OFDM block.

3. SEMIBLIND ML DETECTION

We consider the deterministic semiblind ML criterion [10,11] where part of $\mathbf{s}$ is known at the receiver. For simplicity, assume that the first M subchannels contain pilots (generalization to other pilot placements is straightforward). Let

$$\mathbf{s} = [\mathbf{s}_{\rm p}^T, \mathbf{s}_{\rm d}^T]^T \in \{\pm 1\}^{N_c K}, \tag{10}$$

where $\mathbf{s}_{\rm p} = [\mathbf{s}_1^T, \ ..., \mathbf{s}_M^T]^T$ stands for the pilot data and $\mathbf{s}_{\rm d} = [\mathbf{s}_{M+1}^T, \ ..., \mathbf{s}_{N_c}^T]^T$ denotes the unknown data. Then the semiblind ML detector is given by

$$\{\hat{\mathbf{s}}_{\rm d}, \hat{\boldsymbol{\mathcal{H}}}\} = \arg \min_{\substack{\mathbf{s}_{\rm d} \in \{\pm 1\}^{(N_c - M)K} \\ \boldsymbol{\mathcal{H}} \in \mathbb{C}^{L N_t \times N_r}}} ||\boldsymbol{\mathcal{Y}} - \boldsymbol{\mathcal{C}}(\mathbf{s})\boldsymbol{\mathcal{H}}||_F^2, \tag{11}$$

where $|| \cdot ||_F$ denotes the Frobenius norm. We present a data identifiability analysis for (11), followed by the implementation method of the semiblind ML detector. It will be shown in Sec. 3.1 that the data identifiability can be guaranteed in a probability one sense when there is *one pilot code* transmitted, i.e., $M = 1$. Regarding the realization issue, in the next subsection, it is shown that (11) can be reformulated as a Boolean quadratic program (BQP) where efficient implementation is possible [12].

3.1. Data Identifiability

To investigate the data identifiability, the signal model in (8) in the absence of noise is considered

$$\boldsymbol{\mathcal{Y}} = \boldsymbol{\mathcal{C}}(\mathbf{s})\boldsymbol{\mathcal{H}}. \tag{12}$$

It is clear that, in the absence of noise, $\{\mathbf{s}_{\rm d}, \boldsymbol{\mathcal{H}}\}$ is a solution pair of (11). Suppose that there exist $\mathbf{s}'_{\rm d} \in \{\pm 1\}^{(N_c - M)K}$ and $\boldsymbol{\mathcal{H}}' \in \mathbb{C}^{L N_t \times N_r}$ so that $\{\mathbf{s}'_{\rm d}, \boldsymbol{\mathcal{H}}'\}$ is also a solution pair of (11). Then

$$\boldsymbol{\mathcal{C}}(\mathbf{s}')\boldsymbol{\mathcal{H}}' = \boldsymbol{\mathcal{C}}(\mathbf{s})\boldsymbol{\mathcal{H}}, \tag{13}$$

where

$$\mathbf{s}' = [\mathbf{s}_{\rm p}^T, \mathbf{s}_{\rm d}'^T]^T \in \{\pm 1\}^{N_c K}. \tag{14}$$

To ensure the data identifiability, we analyze (13) and look for conditions under which (13) holds only if $\{\mathbf{s}'_{\rm d}, \boldsymbol{\mathcal{H}}'\} = \{\mathbf{s}_{\rm d}, \boldsymbol{\mathcal{H}}\}$.

We start our analysis by considering that there are at least L pilot codes (i.e., $M \geq L$). Let

$$\boldsymbol{\mathcal{C}}_{\rm p}(\mathbf{s}_{\rm p}) = \begin{bmatrix} \mathbf{C}(\mathbf{s}_1) \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_1^T\right) \\ \vdots \\ \mathbf{C}(\mathbf{s}_M) \left(\mathbf{I}_{N_t} \otimes \mathbf{f}_M^T\right) \end{bmatrix} \in \mathbb{C}^{MT \times L N_t}. \tag{15}$$

From (13) and (15), one can obtain

$$\boldsymbol{\mathcal{C}}_{\rm p}(\mathbf{s}_{\rm p})\boldsymbol{\mathcal{H}}' = \boldsymbol{\mathcal{C}}_{\rm p}(\mathbf{s}_{\rm p})\boldsymbol{\mathcal{H}}. \tag{16}$$

It is not hard to show that $\boldsymbol{\mathcal{C}}_{\rm p}(\mathbf{s}_{\rm p})$ is of full column rank for $M \geq L$. Hence, (16) results in $\boldsymbol{\mathcal{H}}' = \boldsymbol{\mathcal{H}}$, i.e., the channel can be uniquely identified. However, channel identification does not imply data identification because, if $\mathbf{H}_n = \mathbf{0}$ for some n, then the data $\mathbf{s}_n$ can never be recovered even when full CSI is available. However, the probability that this channel nullity occurs is quite low for an MIMO fading channel. Let us consider the following channel assumption:

A1) The channel $\boldsymbol{\mathcal{H}}$ is Gaussian distributed and at least one column of $\boldsymbol{\mathcal{H}}$ has a positive definite covariance matrix.

One can see that independent identically distributed (i.i.d.) Rayleigh fading channels satisfy $\mathbf{A1}$). Under $\mathbf{A1}$), one can show that the probability of the event $\{\mathbf{H}_n = \mathbf{0}\}$ is of measure zero. Thus we conclude that the data can be identified with probability one if there are at least L pilot codes. In practice, given $M \geq L$, the channel can be estimated by a least-squares (LS) channel estimator [10, 15]

$$\hat{\boldsymbol{\mathcal{H}}} = \left(\boldsymbol{\mathcal{C}}_{\rm p}^H(\mathbf{s}_{\rm p})\boldsymbol{\mathcal{C}}_{\rm p}(\mathbf{s}_{\rm p})\right)^{-1} \boldsymbol{\mathcal{C}}_{\rm p}^H(\mathbf{s}_{\rm p})\boldsymbol{\mathcal{Y}}_M, \tag{17}$$

where $\boldsymbol{\mathcal{Y}}_M = [\mathbf{Y}_1^T, \ ..., \mathbf{Y}_M^T]^T$.

In the paper, instead of using L pilot codes, we show that a single pilot code is sufficient to ensure probability one data identifiability. Let us look at the following lemma:

***Lemma 1*:** *Assume that* $\mathbf{A1}$) *holds and that there is no noise. Suppose that* $\boldsymbol{\mathcal{C}}(\mathbf{s})$ *satisfies the following condition:*

C1) *Let* $\mathbf{s}' = [\mathbf{s}_{\rm p}^T, \mathbf{s}_{\rm d}'^T]^T \in \{\pm 1\}^{N_c K}$. *There does not exist a matrix* $\mathbf{U} \in \mathbb{C}^{L N_t \times L N_t}$ *such that*

$$\boldsymbol{\mathcal{C}}(\mathbf{s}')\mathbf{U} = \boldsymbol{\mathcal{C}}(\mathbf{s}), \tag{18}$$

for any $\mathbf{s}'_{\rm d} \neq \mathbf{s}_{\rm d}$.

Then the data $\mathbf{s}_{\rm d}$ *can be uniquely identified with probability one.*

The proof of Lemma 1 is given in the Appendix. One can see that the aforementioned LS method (which uses at least L pilot codes) is an approach to make **C1)** hold and thereby can have the probability one data identifiability. However, by exploiting the special structure of $\mathbf{F}$, we can show that a single pilot code is sufficient to achieve **C1)**. Consider the following lemma.

Lemma 2: *Let* $\mathbf{s}, \mathbf{s}' \in \{\pm 1\}^{N_c K}$. *There exists a matrix* $\mathbf{U} \in \mathbb{C}^{LN_t \times LN_t}$ *such that*

$$\boldsymbol{\mathcal{C}}(\mathbf{s}')\mathbf{U} = \boldsymbol{\mathcal{C}}(\mathbf{s}) \tag{19}$$

if and only if there exists a matrix $\mathbf{Q} \in \mathbb{C}^{N_t \times N_t}$ *such that*

$$\mathbf{C}(\mathbf{s}_n')\mathbf{Q} = \mathbf{C}(\mathbf{s}_n), \tag{20}$$

for all $n = 1, ..., N_c$.

Due to space limit, the proof of Lemma 2 (which will be reported in [13]) is omitted here. However, a special case of Lemma 2 where $N_t = 1$ and $T = 1$ (uncoded SIMO OFDM system) has been implicitly proved in [14]. Consider the case of $M = 1$, i.e., $\mathbf{s}_{\rm p} = \mathbf{s}_1 = \mathbf{s}_1'$. If (20) holds, we obtain $\mathbf{Q} = \mathbf{I}_{N_t}$ and subsequently, $\mathbf{s}_n' = \mathbf{s}_n$ for $n = 2, ..., N_c$, i.e., $\mathbf{s}_{\rm d}' = \mathbf{s}_{\rm d}$. Hence, by Lemma 2, (19) holds only if $\mathbf{s}_{\rm d}' = \mathbf{s}_{\rm d}$, which means that **C1)** is achieved. Therefore, the data identifiability can be guaranteed by merely transmitting one pilot code. We can now formally summarize the above analysis as follows:

Theorem 1: *Assume that* $\mathbf{A1}$*) holds and that there is no noise. If any one of the subchannels carriers a pilot code, then the data* $\mathbf{s}_{\rm d}$ *can be uniquely identified with probability one.*

3.2. Realization of ML Detector

In this subsection, we show how the proposed detector can be realized. For simplicity, we consider $M = 1$ which is the focus of this paper (generalization to $M > 1$ is straightforward). Recall from (11) that the semiblind ML detector for $M = 1$ is given by

$$\{\hat{\mathbf{s}}_{\rm d}, \hat{\boldsymbol{\mathcal{H}}}\} = \arg \min_{\substack{\mathbf{s}_{\rm d} \in \{\pm 1\}^{(N_c - 1)K} \\ \boldsymbol{\mathcal{H}} \in \mathbb{C}^{LN_t \times N_r}}} ||\boldsymbol{\mathcal{Y}} - \boldsymbol{\mathcal{C}}(\mathbf{s})\boldsymbol{\mathcal{H}}||_F^2, \tag{21}$$

By using the same reformulation as in [12], one can turn (21) to the following BQP

$$\hat{\mathbf{s}}_{\rm d} = \arg \max_{\mathbf{s}_{\rm d} \in \{\pm 1\}^{(N_c - 1)K}} \mathbf{s}_{\rm d}^T \boldsymbol{G} \mathbf{s}_{\rm d} + 2\mathbf{s}_1^T \widetilde{\boldsymbol{G}} \mathbf{s}_{\rm d}, \tag{22}$$

where

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{G}_{2,2} & \cdots & \boldsymbol{G}_{2,N_c} \\ \vdots & \ddots & \vdots \\ \boldsymbol{G}_{N_c,2} & \cdots & \boldsymbol{G}_{N_c,N_c} \end{bmatrix}, \tag{23}$$

$$\widetilde{\boldsymbol{G}} = [\boldsymbol{G}_{1,2},\ \boldsymbol{G}_{1,3},\ \ldots,\ \boldsymbol{G}_{1,N_c}], \tag{24}$$

$$[\boldsymbol{G}_{m,n}]_{k,\ell} = \mathrm{Re}\left\{ \mathrm{tr}\left\{ \gamma_{m,n} \mathbf{Y}_m^H \mathbf{X}_k \mathbf{X}_\ell^H \mathbf{Y}_n \right\} \right\}, \tag{25}$$

for $k, \ell = 1, ..., K$, where $\mathrm{tr}(\cdot)$ denotes the trace of a matrix and $\gamma_{m,n} = \mathbf{f}_m^T \mathbf{f}_n^*$. Therefore, the semiblind ML detector can be implemented by solving this BQP. In recent years, there have been several efficient methods proposed for handling the BQP [12]; for example, the sphere decoder, the norm relaxation method and the semidefinite relaxation (SDR) algorithm [12]. To understand how these methods can be applied, please refer to [12].

Although the aforementioned methods can be used to implement the ML detector, the complexity can still be an issue when the DFT size N_c is very large. To tackle this problem, the subchannel grouping method in [14] can be used. The application of subchannel grouping to the problem here is straightforward, and is currently being investigated.

4. SIMULATION RESULTS

This section presents two simulation examples to justify the efficacy of the proposed semiblind ML detector. The coefficients of $\boldsymbol{\mathcal{H}}$ are zero-mean i.i.d. complex Gaussian distributed, and change from one OSTBC-OFDM block to another. The SNR per subchannel is defined as

$$\mathrm{SNR} = K \frac{E\{\|\boldsymbol{\mathcal{H}}\|_F^2\}}{TN_c\sigma_w^2}.$$

The DFT size was 32 ($N_c = 32$) and the number of receive antennas was two ($N_r = 2$). The signal constellation was QPSK. For the proposed detector, the pilot code was placed at subchannel 1, and the associated BQP in (22) was handled by the SDR algorithm [12]. The detector performance was measured in terms of the average bit error rate (BER). We compared the proposed detector to the coherent ML detector (with perfect CSI) and the pilot-based LS channel estimator mentioned in Sec. 3.1. For the LS channel estimator, L pilot codes were used. Let $\mathcal{S}$ be the subset of subchannel indices where the pilot codes for LS method are placed. In the simulation, it was set to be

$$\mathcal{S} = \left\{1, 1 + \tfrac{N_c}{L}, 1 + \tfrac{N_c}{L} \cdot 2, \ldots, 1 + \tfrac{N_c}{L} \cdot (L-1)\right\}. \tag{26}$$

It can be shown [10,15] that, for fixed L pilot codes, the pilot placement in (26) leads to the minimum mean-squared channel estimation error. The differential OSTBC-OFDM scheme [6] was also considered for comparison, which was obtained by applying the differential OSTBC scheme [16] to each subchannel. There were $15,000$ trials performed in our simulation examples.

Figure 1 presents the results when the complex Alamouti code ($T = 2$, $N_t = 2$) was used and $L = 4$. One can see, from this figure, that the proposed detector outperforms both the pilot-based LS method and the differential scheme. Moreover, the performance difference between the proposed detector and the coherent ML detector at BER$= 10^{-4}$ is around 1 dB only. Similar results can also be observed in Fig. 2 where the complex 4×3 OSTBC (Eqn. (120) of [17]) ($T = 4$, $N_t = 3$) was used and $L = 8$.

5. CONCLUSIONS

In the paper, we have proposed a semiblind ML detector for OSTBC-OFDM in block fading channels. The proposed detector, using the FIR channel parameterization, can perform data detection in one OSTBC-OFDM signal block. Our analysis shows that data identifiability with probability one is guaranteed as long as one pilot code is used. It is also shown that the proposed detector can be efficiently realized by solving a BQP. The presented simulation results further reveal that the proposed detector outperforms the pilot-based LS method and the differential method.

6. APPENDIX
PROOF OF LEMMA 1

Let $\mathbf{s}' = [\mathbf{s}_{\rm p}^T, \mathbf{s}_{\rm d}'^T]^T \in \{\pm 1\}^{N_c K}$, $\mathbf{s}_{\rm d}' \neq \mathbf{s}_{\rm d}$ and $\boldsymbol{\mathcal{H}}' \in \mathbb{C}^{LN_t \times N_r}$, $\boldsymbol{\mathcal{H}}' \neq \boldsymbol{\mathcal{H}}$. We show that if **C1)** holds, then the probability that $\{\mathbf{s}_{\rm d}', \boldsymbol{\mathcal{H}}'\}$ is a solution pair of (11) is of measure zero.

Assuming that $\{\mathbf{s}_{\rm d}', \boldsymbol{\mathcal{H}}'\}$ is a solution pair of (11), one can have (13). Let

$$\mathbf{U} = \left(\boldsymbol{\mathcal{C}}^H(\mathbf{s}')\boldsymbol{\mathcal{C}}(\mathbf{s}')\right)^{-1} \boldsymbol{\mathcal{C}}^H(\mathbf{s}')\boldsymbol{\mathcal{C}}(\mathbf{s}). \tag{27}$$

Premultiplying $\left(\mathcal{C}^H(\mathrm{s}')\mathcal{C}(\mathrm{s}')\right)^{-1}\mathcal{C}^H(\mathrm{s}')$ on both sides of (13) results in

$$\mathcal{H}' = \mathbf{U}\mathcal{H}. \tag{28}$$

Substituting (28) into (13) yields

$$\left(\mathcal{C}(\mathrm{s}) - \mathcal{C}(\mathrm{s}')\mathbf{U}\right)\mathcal{H} = \mathbf{0}. \tag{29}$$

Let $\mathbf{\Phi} = \mathcal{C}(\mathrm{s}) - \mathcal{C}(\mathrm{s}')\mathbf{U}$. Under **C1)**, we have $\mathbf{\Phi} \neq \mathbf{0}$. The probability that (29) holds is given by

$$\begin{aligned}\Pr\{\mathbf{\Phi}\mathcal{H} = \mathbf{0}\} &= \Pr\left\{\bigcap_{j=1}^{N_r} \mathbf{\Phi}\mathcal{H}\mathbf{e}_j = \mathbf{0}\right\} \\ &\leq \Pr\{\mathbf{\Phi}\mathcal{H}\mathbf{e}_i = \mathbf{0}\}, \end{aligned} \tag{30}$$

for some i, where $\mathbf{e}_i \in \mathbb{R}^{N_r}$ denotes a unit vector with the ith entry equal to unity. According to **A1)**, let the ith column of $\mathcal{H}$ be Gaussian distributed with a positive definite covariance matrix. Then one can show that $\Pr\{\mathbf{\Phi}\mathcal{H}\mathbf{e}_i = \mathbf{0}\}$ is of measure zero. Hence, (13) holds with probability zero. Therefore, the data $\mathbf{s}_\mathrm{d}$ can be uniquely identified with probability one. $\square$

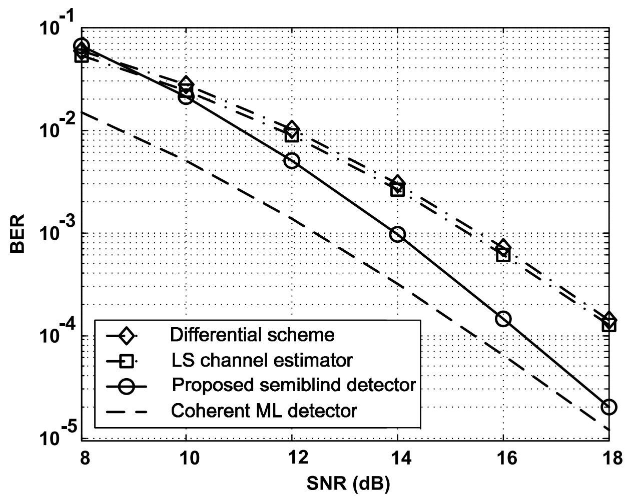

Figure 1. Performance (BER vs. SNR) of the proposed detector for complex Alamouti code and $L = 4$.

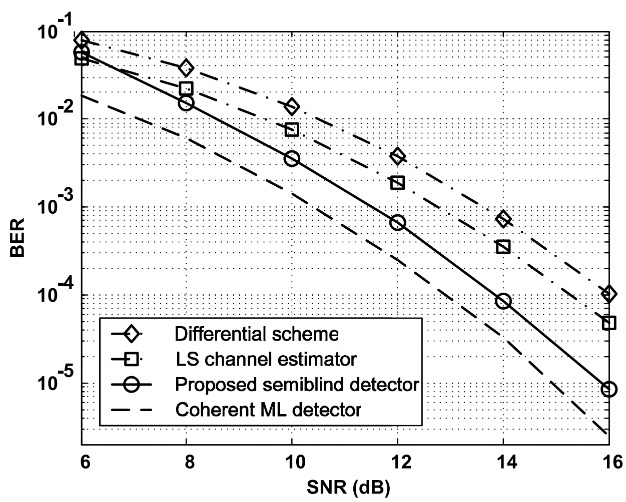

Figure 2. Performance (BER vs. SNR) of the proposed detector for complex 4×3 OSTBC and $L = 8$.

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