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Diversity Analysis for Relay-Assisted Distributed BICM-OSTBC-OFDM System

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***Abstract*: -** Maximum spatial-frequency diversity can be achieve by combining bit-interleaved coded modulation (BICM), orthogonal space-time block coding (OSTBC) and orthogonal frequency division multiplexing (OFDM) in frequency selective multi-path fading channels, provided that perfect channel state information (CSI) is available to the receiver. In view of the fact that perfect CSI can be obtained only if a sufficient amount of resource is allocated for training or pilot data, this paper investigates DF relay based technique for the distributed BICM-OSTBC-OFDM system. Our focus is mainly on noncoherent diversity analysis. We study a class of carefully designed transmission schemes, called perfect channel identifiability (PCI) achieving schemes, and show that they can exhibit good diversity performance. Specifically, we present a worst-case diversity analysis framework to show that PCI-achieving schemes can achieve the maximum noncoherent spatial-frequency diversity of distributed BICM-OSTBC-OFDM. Simulation results are presented to confirm our theoretical claims and show that the proposed noncoherent schemes can exhibit near-coherent performance.

***IndexTerms*: -** *Bit-interleaved coded modulation (BICM), orthogonal space-time block coding (OSTBC), orthogonal frequency division multiplexing (OFDM), noncoherent decoding, diversity.*

I. INTRODUCTION

TO approach the Shannon capacity, bit-interleaved coded modulation (BICM) [1] has been popularly used for channel-coded transmission, owing to its flexibility in the tradeoff between bit error performance and decoding complexity [2]. BICM has been concatenated with orthogonal space-time block codes (OSTBCs) to harvest temporal and spatial diversities in flat fading channels [3], [4], and has also been used in conjunction with orthogonal frequency division multiplexing (OFDM) to exploit frequency diversity [5], [6]. Recently, BICM is combined with OSTBC-OFDM and it was shown in [5] that the distributed BICM-OSTBC-OFDM system is able to extract both the spatial and frequency diversities in independent and identically distributed (i.i.d.) Rayleigh fading channels. Further studies of distributed BICM-OSTBC-OFDM can be found in [7] for generalized channel models. The designs mentioned above assume that the receiver has perfect channel state information (CSI). This can be achieved only if the receiver has been well trained through a sufficient amount of training or pilot data. While such (training) pilot-aided schemes generally work well under slow time-varying channels, and are popularly implemented in current wireless communication systems, they may no longer be efficient under fast time-varying channels. With shorter coherence times, which means more frequent training, both pilot overhead and CSI estimation error could become significant issues [8].

To improve the spectral efficiency and receiver performance, noncoherent techniques, including noncoherent data detection and blind/semiblind channel estimation methods, have been proposed. The noncoherent techniques are appealing because they use only a few number of pilots, or even no pilot, for data detection and channel estimation, and thus have great potential for deployment under fast time-varying channels. However, most of the existing works focus on two separate scenarios, namely, coded flat-fading space-time systems (no OFDM) [9]–[11] and uncoded OSTBC-OFDM systems (no channel coding) [12]–[16]. While it is possible to extend the works in [9], [10] to coded OSTBC-OFDM by considering each OFDM subcarrier as an individual flat-fading channel, such natural extension requires the channel to remain static over a large number of OFDM blocks. Similarly, many of the blind channel estimation methods in [12], [13] for uncoded OSTBCOFDM also require the channel to remain unchanged for several OSTBC-OFDM blocks. These approaches are therefore suitable for slow or perhaps moderately fast fading channels. Another noncoherent approach is to employ differential space time coding schemes, e.g., [11]; however they suffer from a 3 dB signal-to-noise ratio (SNR) loss compared to the coherent receiver. In our previous works in [14]–[16], a noncoherent OSTBC-OFDM detection method based on the deterministic DF relay based technique was proposed. It was shown that this noncoherent detection method can exhibit near-coherent performance using only one OSTBC-OFDM block, thus appealing for fast time-varying channels. However, channel coding was not considered in [14]–[16].

In this paper, we consider the convolutional coded BICMOSTBC- OFDM system, and aim to develop a noncoherent distributed BICM-OSTBC-OFDM decoder that also uses one OSTBCOFDM block. We assume that the time-domain multiple-input multiple-output (MIMO) multi-path channel coefficients are i.i.d. Rayleigh distributed. By exploiting the inter-subcarrier relationship of OFDM [14], we develop a block-wise noncoherent ML decoder and present a complexity-reduced implementation method. The primary focus of this paper is on the performance aspects, aiming to show the potential performance advantages of the proposed noncoherent approach. Firstly, like most of the noncoherent methods, the presented DF relay based technique can be subject to the data ambiguity problem in the noise-free situation. We review some of the transmission schemes reported in [14]–[16], which can be directly used for the considered distributed BICM-OSTBC-OFDM system for unique codeword decoding; e.g., the pilot-efficient *perfect channel identifiability (PCI)* achieving schemes [15], [16]. Secondly, we analyze the diversity order of the noncoherent ML decoder. To distinguish it from the diversity achieved by a coherent decoder, we refer to the diversity order achieved by the noncoherent decoder as *noncoherent diversity*. While the fundamental definitions of diversity are the same for both coherent and noncoherent systems, the characterization of the noncoherent diversity is much more difficult [17], [18]. In addition, the involvement of channel coding in this work further increases the challenge of the noncoherent diversity analysis. To overcome this issue, we present a worst-case diversity analysis framework for distributed BICM-OSTBC-OFDM, and use it to show that PCI-achieving schemes can fully harvest both the maximum noncoherent spatial and frequency diversities.

The remainder of this paper is organized as follows. In Section II, the system model is introduced. In Section III, the noncoherent ML decoder is derived and a complexity-reduced implementation method is presented. Section IV presents the unique data identification conditions and noncoherent diversity analysis. Extension to the distributed scenario is presented in Section V. Simulation results are shown in Section VI. Section

II. SYSTEM MODEL

We consider a point-to-point BICM-OSTBC-OFDM system with N_t transmit antennas and N_r receive antennas. Frequency selective multi-path channel fading between the transmitter and the receiver is assumed. As illustrated in Fig. 1, the transmitter is composed of two parts: (i) the outer convolutional coded BICM part which consists of a convolutional encoder and a bit interleaver [1]; (ii) the inner OSTBC-OFDM modulator [14], [19]. The convolutional encoder, which has a code rate R_c, encodes the information bit vector $\boldsymbol{b}$ {0, 1} ¯KR_c into a length- ¯K codeword **c** $\boldsymbol{C}$ {0, 1} ¯K , where $\boldsymbol{C}$ is the convolutional code set. The codeword **c** is then processed by the interleaver, which outputs a scrambled codeword ˜**c** {0, 1} ¯K . The interleaver permutates the order of the codeword bits over the frequency domain, and, as will be shown later, can help the receiver to harvest frequency diversity. For OSTBC-OFDM modulation, the interleaved codeword ˜**c** is segmented into N_c bit vectors, say, $\boldsymbol{x}_n$ {0, 1}K_n, n = 1, . . .,N_c, where N_c is the number of subcarriers of OFDM and K_n is the number of bits transmitted over subcarrier n, which satisfies_N_c n=1 K_n = ¯K . Let $\mathbf{s}_n$ = 2$\boldsymbol{x}_n$−11}K_n be the corresponding binary bits of $\boldsymbol{x}_n$ for all n = 1, . . .,N_c. For ease of presentation, let us assume BPSK/QPSK OSTBC mappings1. For such cases, the transmitted OSTBC code over subcarrier n is given by $\mathbf{C}_n(\mathbf{s}_n)$ = 1 √K_n _K_n i=1 $\mathbf{X}_{n,i}s_{n,i}$ CT×N_t , where T is the OSTBC code length, $s_{n,i}$ 1} is the ith entry of $\mathbf{s}_n$, and $\mathbf{X}_{n,i}$ CT×N_t are the basis matrices of $\mathbf{C}_n$(・) which are designed such that $\mathbf{C}^H_n(\mathbf{s}_n)\mathbf{C}_n(\mathbf{s}_n) = \mathbf{I}_{N_t}$, $\mathbf{s}_n$1}K_n [20].

Assuming that the channels between the transmitter and the receiver remain static for T OFDM symbols, i.e., one OSTBCOFDM block, the received signal at the receiver is given by

$$\mathbf{Y}_n = \mathbf{C}_n(\mathbf{s}_n)\mathbf{H}_n + \mathbf{W}_n, \; n = 1, \ldots, N_c, \qquad (1)$$

where $\mathbf{H}_n$ CN_t×N_r and $\mathbf{W}_n$ CT×N_r are the MIMO channel frequency response matrix and the additive white Gaussian noise (AWGN) matrix for the nth subcarrier, respectively. Each entry of $\mathbf{W}_n$ is assumed to have zero mean and variance σ^2_w. While the convolutional codeword **c** is not explicitly shown in (1), it can be related to the data bits $\mathbf{s}_n$, n = 1, . . .,N_c, through a one-to-one binary mapping function μ(・) : {0, 1} → {•}1}. Specifically, suppose that the interleaver and OSTBC mapping function $\mathbf{C}_n$(・) map the kth bit of the codeword vector **c**, denoted by c_k, to the data bit $s_{n,i}$ in the nth subcarrier. The relation between $s_{n,i}$ and c_k can be expressed as

$$s_{n,i} = \mu(c_k). \qquad (2)$$

Assume that the receiver has perfect knowledge of the CSI $\mathbf{H}_1, \ldots, \mathbf{H}_{N_c}$. The coherent ML decoder for the received signal model in (1) is shown in [5] to be

$$\hat{c} = \arg \min_{c \in \mathcal{C}} \sum_{k=1}^{\bar{K}} \left\{ \min_{\substack{s_n \in \{\pm 1\}^{K_n} \\ s_{n,i} = \mu(c_k)}} \|\mathrm{Y}_n - \mathrm{C}_n(\mathrm{s}_n)\mathrm{H}_n\|_F^2 \right\}. \quad (3)$$

The above coherent ML decoding problem can be efficiently implemented by employing the Viterbi decoder (VD) that exploits the trellis structure of the convolutional code [21].

III. DISTRIBUTED BICM-OSTBC-OFDM

In this section, we extend the noncoherent ML decoder in (10) to a relay-based distributed BICM-OSTBC-OFDM system. In this system, as illustrated in Fig. 2, a set of singleantenna relays collaborate to transmit the information bits sent from the source to a destination receiver. The direct link between the source and the destination is not considered. We assume that the relays employ the decode-and-forward (DF) strategy. Moreover, we assume that there is no central control and the relays may choose to join the cooperation or not, depending on whether they can successfully decode the information bits from the source. Suppose that there are *Ns* cooperating relays, and that the relays employ the distributed OSTBC scheme in [28]. Specifically, given the information bits ***b*** ∈{0, 1}¯ *KRc*, the *m*th relay transmits the block sequence **C***n*(**s***n*)**q***m* ∈C*T* over subcarrier *n*, for *n* = 1, . . .,*Nc*, where **C***n*(**s***n*) is the OSTBC mapping function defined in Section II, and **q***m* ∈ C*Nt* is a preassigned signature sequence for the *m*th relay. The signature sequences **q**1, . . . , **q***Ns* may be designed to enhance the receiver performance [28]; here we assume that **q***m* are given and fixed. Let ***H*** ∈C*LNs*×*Nr* be the channels from all the cooperating relays to the destination. Then the received signal for subcarrier *n* is given by

$$\begin{aligned} \mathbf{Y}_n &= \mathbf{C}_n(\mathbf{s}_n)\mathbf{Q}(\mathbf{I}_{N_s} \otimes \mathbf{f}_n^T)\boldsymbol{\mathcal{H}} + \mathbf{W}_n \\ &= \mathbf{C}_n(\mathbf{s}_n)(\mathbf{I}_{N_t} \otimes \mathbf{f}_n^T)\boldsymbol{\mathcal{H}}_\mathrm{v} + \mathbf{W}_n, \end{aligned} \quad (4)$$

where **Q** = [**q**1, . . . , **q***Ns*] ∈C*Nt*×*Ns* , ***H***v _ (**Q** ⊗ **I***L*)***H*** ∈C*LNt*×*Nr* is the virtual channel, and the second equality is obtained by using the Kronecker product property (**A** ⊗ **B**)(**C**⊗**D**) = (**AC**⊗**BD**) [29]. The received OSTBC-OFDM block signal is thus given by

$$\boldsymbol{\mathcal{Y}} = \boldsymbol{\mathcal{G}}(s)\boldsymbol{\mathcal{H}}_\mathrm{v} + \boldsymbol{\mathcal{W}}, \quad (5)$$

where ***Y***, ***G***(***s***) and ***W*** are as defined in (5) and (6). For the signal model in (29), the corresponding noncoherent ML decoder can be shown to be

$$\hat{c} = \arg \max_{c \in \mathcal{C}} \sum_{k=1}^{\bar{K}} \max_{\substack{s_d \in \{\pm 1\}^{K_d} \\ s_{n,i} = \mu(c_k)}} \mathrm{Tr}\Big(\boldsymbol{\mathcal{Y}}^H \boldsymbol{\mathcal{G}}(s) \mathrm{R}^{-1} \boldsymbol{\mathcal{G}}^H(s) \boldsymbol{\mathcal{Y}}\Big) \quad (6)$$

where **R** = 1 *σ*2*h* (**QQ***H* ⊗**I***L*)−1+ 1 *σ*2*w* **I***LNt* . As one can observe from (30), the receiver requires to know exactly which relays join the cooperation since the signature matrix **Q** is required to be known. Owing to the analogy between (29) and (5), the noncoherent decoder in (10) can be applied to (29). The noncoherent decoder in (10) is able to decode **c** without the need of knowing **Q**, which is hence particularly attractive for the relay-based decentralized scenario because the number of cooperative relays may vary over time and this can cause unknown changes of the signature matrix **Q**. Interestingly, (10) can still achieve the maximum cooperative (spatial)-frequency diversity:

Theorem 2 *Assume that* **A1)** *holds, and that the matrix* **Q** *is of full rank. Suppose that Nr* = 1*. Then the worst-case diversity order achieved by the PCI-achieving schemes is given by*

$$\begin{aligned} D^\star_{\mathrm{DNC}} &\triangleq \min_{\bar{c} \neq \hat{c}} \left\{ \min_{\hat{s} \in S(\hat{c})} \mathrm{rank}((\mathrm{Q} \otimes \mathrm{I}_L)^H \Omega(\bar{s}, \hat{s})(\mathrm{Q} \otimes \mathrm{I}_L)) \right\} \\ &= \min(N_s, N_t) \min(d_\mathrm{free}, L). \end{aligned} \quad (7)$$

Proof: The worst-case diversity order *D*_ DNC can be proved following similar ideas as in Proposition 1 and in (26) and (27). To quickly see how the second equality can hold, let us consider the case of *d*free ≥ *L*. Since, by Theorem 1, **Ω**(¯***s***, ˆ***s***) has the full rank for *d*free ≥ *L*, rank((**Q**⊗**I***L*)*H***Ω**(¯***s***, ˆ***s***)(**Q**⊗ **I***L*)) = rank(**Q**⊗**I***L*) =min(*Ns*,*Nt*)*L*. The case of *d*free < *L* can be proved following similar steps in Theorem 1; the details are omitted here.

Since min(*Ns*,*Nt*) is the maximum cooperative diversity order achieved by the distributed OSTBC [28] and min(*d*free, *L*) is the maximum frequency diversity order [5], Theorem 2 implies that the noncoherent BICM-OSTBCOFDM decoder (10), using PCI-achieving schemes, achieves the maximum cooperative-frequency diversity order offered by the relay system.

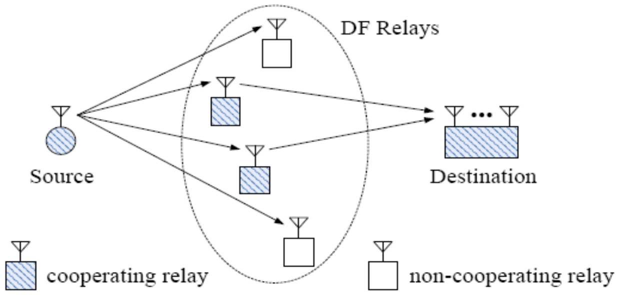


Fig. 2. Block diagram of the relay-based distributed BICM-OSTBCOFDM system.

IV. UNIQUE DATA IDENTIFIABILITY AND DIVERSITY ANALYSIS

Having considered the implementation of noncoherent ML decoding in the last section, we now turn our attention to the fundamental performance aspects. In the first subsection, we review some transmission schemes reported in [14]–[16] that can guarantee unique data identification, i.e., guarantee the codeword **c** to be uniquely decoded by the noncoherent ML decoder (10) in the noise-free situation. In the second subsection, we present our main results on the diversity order of the noncoherent ML decoder (10).

A. Unique Data and Channel Identification

As a common issue in noncoherent approaches, the noncoherent ML decoder (10) is subject to data ambiguity in the noise-free situation. In particular, one can easily verify that the two problems in (11) have the same optimal objective value since
if ***s*** is an optimal solution of the problem with *ck* = 1, then −***s*** is optimal to the other with *ck* = 0, and vice versa. This implies that the noncoherent ML decoder (10) is not able to uniquely determine whether *ck* is equal to one or zero. To ensure that **c** can be uniquely identified in the noise-free situation, we need to guarantee that the unconstrained problem (without the bit mapping constraint *sn,i* = *μ*(*ck*))

$$\max_{\boldsymbol{s}\in\{\pm 1\}^{\bar{K}}} \operatorname{Tr}\left(\boldsymbol{\mathcal{Y}}^H \boldsymbol{\mathcal{G}}(\boldsymbol{s})\boldsymbol{\mathcal{G}}^H(\boldsymbol{s})\boldsymbol{\mathcal{Y}}\right) \tag{8}$$

can uniquely identify the true ***s*** in the absence of noise. Since, by (12), problem (16) is equivalent to (14), it is sufficient to guarantee that the following ambiguity condition

$$\boldsymbol{\mathcal{G}}(\boldsymbol{s})\boldsymbol{\mathcal{H}} = \boldsymbol{\mathcal{G}}(\boldsymbol{s}')\boldsymbol{\mathcal{H}}' \tag{9}$$

holds only when ***s*** = ***s***_ and ***H*** = ***H***_, i.e., unique data and channel identification.

To this end, we need to insert some pilots in ***s***. Consider a general pilot placement as follows:

$$\boldsymbol{s} \triangleq \boldsymbol{\Pi}[\mathrm{s}_{\mathrm{p}}^T, \mathrm{s}_{\mathrm{d}}^T]^T \in \{\pm 1\}^{\bar{K}}, \tag{10}$$

where **s**d ∈{ • }1}*K*d denotes the data bit vector, and **s**p ∈{ • }1}*K*p denotes the pilot bit vector, in which *K*d and *K*p (¯*K* = *K*d + *K*p) are the numbers of data and pilot bits2, respectively. The matrix **Π** in (18) is a ¯*K* by ¯*K* permutation matrix that describes how the pilots and data are assigned. We need to carefully design **s**p and **Π** such that unique data and channel identifiability can be achieved. This design problem has been studied by the authors in [14]–[16]. Here we summarize some of the key results:

1) One-pilot-code scheme: In this scheme, only one subcarrier is dedicated to transmitting pilot codes, e.g., **s**p = **s**1. While the number of pilot codes used is far less than the channel length *L*, it is shown in [14] that this scheme can still ensure unique identification of ***s*** and ***H*** *with probability one* in i.i.d. Rayleigh fading channels. Although this scheme can exhibit promising bit error performance in the uncoded system, we will show later via both analysis and simulations that this one-pilot-code scheme may not be able to fully harvest the coding and diversity gains provided by the outer channel code.
2) L-pilot-code scheme: It is intuitive that inserting more pilots will improve the data identifiability. The *L*-pilot-code scheme allows *L* out of *Nc* subcarriers for pilot transmission, e.g., **s**p = [**s***T*1 , . . . , **s***T L*]*T* . This scheme is stronger than the one-pilot-code scheme in the sense that, with this scheme, any (nonzero) channel can be uniquely identified, regardless of its statistical distribution; that is, the ambiguity condition (17) holds only if ***H*** = ***H***_ (_= **0**). This property is called *perfect channel identifiability (PCI)* [15], [16]. We will show in the next subsection that PCI-achieving schemes can fully harvest the spatial and frequency diversity gains provided by the channel coded OSTBC-OFDM system.

3) xL-pilot-bit scheme: The *xL*-pilot-bit scheme proposed in [15] is a scheme that can also achieve PCI, but consumes a smaller number of pilot bits than the *L*-pilot-code scheme. One of the key ingredients that makes the *xL*-pilot-bit scheme PCI achieving is the so called non-intersecting subspace (NIS) OSTBCs. Readers may refer to [25] for the detailed properties and construction method of NIS-OSTBCs3. Here we only emphasize how the *xL*-pilot-bit scheme can be constructed. Let **C**NIS(・) denote the NIS-OSTBC and let **C**O(・) denote an arbitrary OSTBC with the same dimension as **C**NIS(・). The *xL*-pilot-bit scheme can be built as follows [15]:

xL-**pilot-bit scheme**: Let $N \subset \{1, \ldots, Nc\}$, $|N| = L$, be the subcarrier subset for which NIS-OSTBCs are allocated. Set

$$\mathrm{C}_n(\mathrm{s}_n) = \mathrm{C}_{\mathrm{NIS}}(\mathrm{s}_n)\ \forall n \in \mathcal{N},$$
$$\mathrm{C}_n(\mathrm{s}_n) = \mathrm{C}_{\mathrm{O}}(\mathrm{s}_n)\ \forall n \in \{1, \ldots, N_c\} \setminus \mathcal{N}. \quad (11)$$

Moreover, for each $n \in N$, assign x pilot bits to $sn,1, \ldots, sn,x$, where $1 \leq x \leq Kn$.

As will be shown in the simulation section, $x = 3$ is sufficient to achieve good decoding performance in general.

B. Noncoherent Diversity Analysis

Diversity order is an important performance measure for space-time-frequency coded systems. For the coherent BICMOSTBC- OFDM system, the coherent diversity order has been analyzed in [5]. However, the analysis techniques used there is not applicable to the noncoherent diversity analysis. In fact, transmission schemes that achieve the full coherent diversity order do not necessarily achieve the full noncoherent diversity order.

For the considered noncoherent BICM-OSTBC-OFDM, as will be seen below, the associated diversity order is difficult to characterize due to the involvement of outer channel coding. We will derive a *worst-case noncoherent diversity order* that can capture the worst diversity characteristic of the noncoherent ML decoder (10).

We simply assume that the receiver has only one antenna, i.e., $Nr = 1$. For $Nr > 1$, the diversity order is Nr times larger. In this case, the signal model in (5) reduces to

$$\boldsymbol{y} = \boldsymbol{\mathcal{G}}(\boldsymbol{s})\boldsymbol{h} + \boldsymbol{w}, \quad (12)$$

where $\boldsymbol{h}$ C*LNt* and $\boldsymbol{w}$ C*NcT* are respectively the channel vector and noise vector for $Nr = 1$. The noncoherent ML decoder in (10) (taking into account the pilot placement in (18)) reduces to

$$\hat{\mathrm{c}} = \arg \max_{\mathrm{c}\in\mathcal{C}} \sum_{k=1}^{K_{\mathrm{d}}} \max_{\substack{\mathrm{s_d}\in\{\pm1\}^{K_{\mathrm{d}}} \\ s_{n,i}=\mu(c_k)}} \boldsymbol{y}^H \boldsymbol{\mathcal{G}}(\boldsymbol{s})\boldsymbol{\mathcal{G}}^H(\boldsymbol{s})\boldsymbol{y}. \quad (13)$$

We first analyze the pair-wise error probability (PEP) of the noncoherent ML decoder (22), that is, the probability that the noncoherent ML decoder mistakes the true transmitted codeword ¯**c** ∈ ***C*** for a distinct codeword ˆ**c** ∈ ***C***. Let *d*free be the free Hamming distance (i.e., the minimum Hamming distance) of the convolutional code ***C***. Let *k*1, . . . , *kd* be the bit indices for which ¯*ck*_ _= ˆ*ck*_ for all _ = 1, . . . , *d*, where *d* ≥ *d*free. Moreover, let ¯*sn*_,*i*_, the *i*_th entry of ¯**s***n*_ in subcarrier *n*_ ∈{1, . . .,*Nc*}, be the binary bit mapped from the codeword bit ¯*ck*_ , i.e., ¯*sn*_,*i*_ = *μ*(¯*ck*_), for all _ = 1, . . . , *d*. We prove in Appendix A the following proposition:

Proposition 1 *The PEP of the noncoherent ML decoder* (22) *is upper bounded as*

$$\Pr(\bar{\mathrm{c}} \to \hat{\mathrm{c}}|\bar{\mathrm{c}}) \leq \beta_1 \sum_{\hat{s}\in\boldsymbol{S}(\hat{\mathrm{c}})} \det^{-1}\left(\mathrm{I}_{LN_t} + \frac{\sigma_h^2\beta_2}{\sigma_w^2}\Omega(\bar{s},\hat{s})\right) \quad (14)$$

where *β*1 > 1 2 , 0 < *β*2 ≤ 1 16 *are constants,* ¯***s*** = **Π**[**s***T*p , ¯**s***T*d]*T* , ˆ***s*** = [(ˆ***s***(1))*T* , . . . , (ˆ***s***(*d*))*T*]*T* , ˆ***s***(_) = **Π**[**s***T*p , (ˆ**s**(_) d)*T*]*T* ,

$$S(\hat{\mathrm{c}}) = \{\hat{s}|\hat{\mathrm{s}}_{\mathrm{d}}^{(\ell)} \in \{\pm1\}^{K_{\mathrm{d}}}, \hat{s}_{n_\ell,i_\ell}^{(\ell)} = \mu(\hat{c}_{k_\ell}), \ell=1,\ldots,d\},$$
$$\Omega(\bar{s},\hat{s}) \triangleq \mathrm{I}_{LN_t} - \frac{1}{d}\sum_{\ell=1}^{d} \mathcal{G}^H(\bar{s})\mathcal{G}(\hat{s}^{(\ell)})\mathcal{G}^H(\hat{s}^{(\ell)})\mathcal{G}(\bar{s}). \quad (15)$$

The PEP upper bound in (23) is considerably different from those for coherent BICM-OSTBC-OFDM systems [5] and uncoded space-time systems [20]. The only resemblance one may roughly see is that each constituent term det−1 _**I***LNt* + *σ*2 *hβ*2 *σ*2*w* **Ω**(¯*s*, ˆ*s*)_ of (23) is somehow similar to the PEP upper bound for uncoded space-time systems [20]; the precise expression is nevertheless different upon close inspection, and we have to deal with a sum of such terms in (23).

Proposition 1 gives an important insight into analysis on the noncoherent BICM-OSTBC-OFDM diversity. As in the coherent scenario, the noncoherent diversity is defined as the high-SNR slope of the PEP in a log-log scale over all possible pairs of ¯**c** and ˆ**c** [27]:

$$D_{\mathrm{NC}} = \min_{\bar{\mathrm{c}} \neq \hat{\mathrm{c}}} \left\{ \lim_{\sigma_h^2/\sigma_w^2 \to \infty} \frac{-\log \Pr(\bar{\mathrm{c}} \to \hat{\mathrm{c}} | \bar{\mathrm{c}})}{\log(\sigma_h^2/\sigma_w^2)} \right\}. \quad (16)$$

Substituting (23) into (26), we show in Appendix B that the noncoherent diversity order of the BICM-OSTBC-OFDM system is lower bounded as

$$D_{\mathrm{NC}} \geq D_{\mathrm{NC}}^{\star} \triangleq \min_{\bar{\mathrm{c}} \neq \hat{\mathrm{c}}} \left\{ \min_{\hat{s} \in \boldsymbol{S}(\hat{\mathrm{c}})} \mathrm{rank}(\boldsymbol{\Omega}(\bar{s}, \hat{s})) \right\}. \quad (17)$$

The intuition behind (27) is that the PEP upper bound in (23) is asymptotically dominated by the constituent term det−1 _**I***LNt* + *σ*2*h β*2 *σ*2*w* **Ω**(¯*s*, ˆ*s*)_ that is least diminishing with the SNR, and *D*_ NC in (27) captures the worst diversity order of that term among all possible pairs of ¯**c** and ˆ**c**. We will henceforth call *D*_ NC the *worst-case noncoherent diversity order*.

Next we analyze the worst-case noncoherent diversity orders of the three transmission schemes presented in the previous subsection. We will need the following assumption on the bit interleaver:

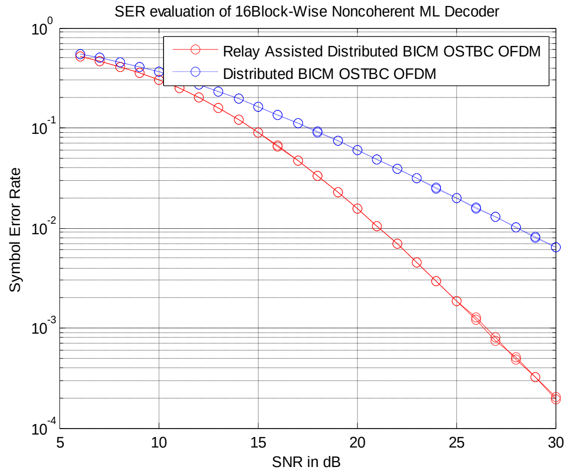
A1) *For any codeword pair* ¯**c** *and* ˆ**c**, *there exists a subindex set {k_1 , . . . , k_d*free*} ⊆{k*1*, . . . , kd} such that {¯ck_1 , . . . , ¯ck_d* free *} are mapped by the bit interleaver onto different subcarriers, say, {n_1, . . . , n_d*free*} ⊆{n*1*, . . . , nd} where n_i _= n_k for all i _= k.*

Assumption **A1)** basically says that the bit interleaver has to be 'random' enough. Under **A1)**, we prove in Appendix C the following theorem on the noncoherent diversity:

Theorem 1 *Assume that* **A1)** *holds. If the PCI-achieving schemes, e.g., the L-pilot-code scheme and the xL-pilot-bit scheme, are employed, then D*_ NC = *Nt* min(*d*free, *L*).

Since *Nt* min(*d*free, *L*) is also the maximum diversity that can be achieved by the coherent ML decoder in (3) [5], Theorem 1 indicates that the *L*-pilot-code scheme and the *xL*pilot- bit scheme can achieve the maximum spatial-frequency diversity offered by the system in a noncoherent manner. Interestingly, the one-pilot-code scheme, which is not PCIachieving, may not benefit from the use of BICM to harvest the frequency diversity:

V. RESULTS AND DISCUSSION



SER evaluation of 16 Block wise Noncoherent ML Decoder

Fig shows the simulation results for various values of *L* and *Ns*. From this figure, one can see that the diversity order of both the *xL*-pilot-bit scheme and LS channel estimator improves as *Ns* increases from one to two or as *L* increases from two to eight. For *L* = 2, we see that the diversity performance does not improve as *Ns* increases from two to three because, by Theorem 2, the maximum cooperative diversity is given by min*{Nt,Ns}*.

VI. CONCLUSION

In this paper, we have presented a relay assisted distributed BICM-OSTBC-OFDM system, and a complexity-reduced implementation method. In addition, we have analyzed the diversity order of the distributed BICM-OSTBC-OFDM system. We have presented a worst-case diversity analysis framework and have shown that the PCI-achieving schemes, such as the L-pilot-code scheme and the xL-pilot-bit scheme, can achieve the maximum spatial-frequency diversity of the distributed BICM-OSTBC-OFDM system. All our theoretical claims have been corroborated by the presented simulation results.

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